Wildfire exposure and health outcomes: An umbrella review of systematic reviews and meta-analyses

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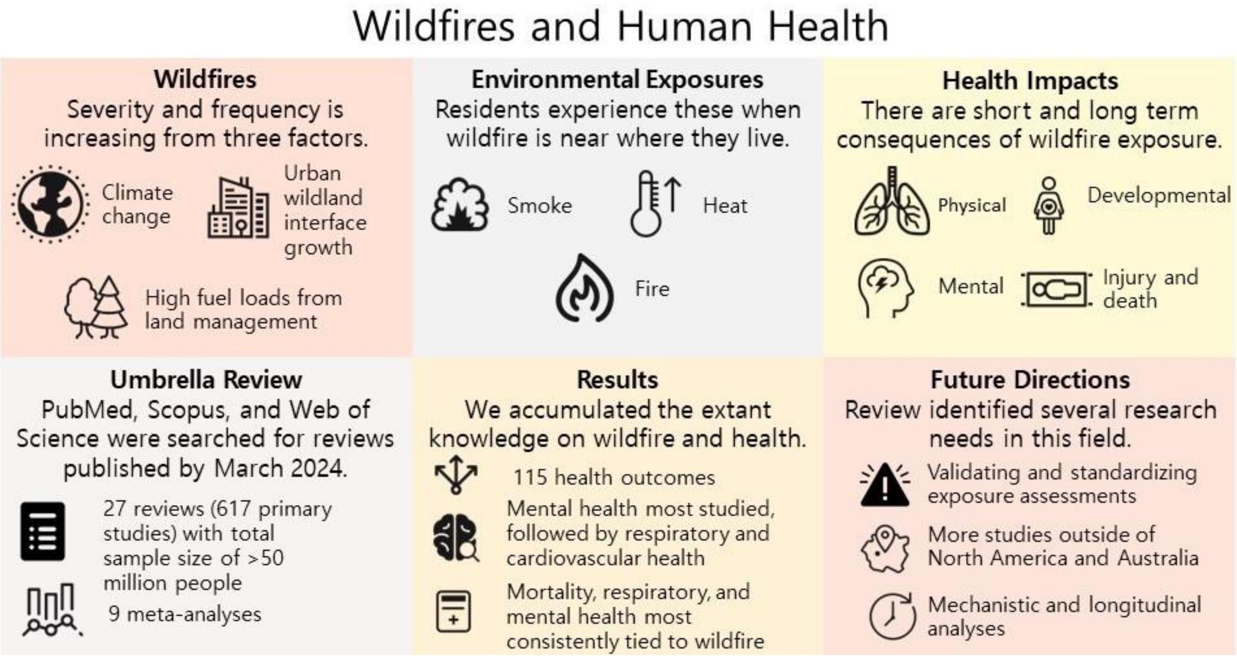
Graphical Abstract



Wildfires and Human Health

Wildfires
Severity and frequency is increasing from three factors.
- Climate change
- Urban wildland interface growth
- High fuel loads from land management

Environmental Exposures
Residents experience these when wildfire is near where they live.
- Smoke
- Heat
- Fire

Health Impacts
There are short and long term consequences of wildfire exposure.
- Physical
- Developmental
- Mental
- Injury and death

Umbrella Review
PubMed, Scopus, and Web of Science were searched for reviews published by March 2024.
- 27 reviews (617 primary studies) with total sample size of >50 million people
- 9 meta-analyses

Results
We accumulated the extant knowledge on wildfire and health.
- 115 health outcomes
- Mental health most studied, followed by respiratory and cardiovascular health
- Mortality, respiratory, and mental health most consistently tied to wildfire

Future Directions
Review identified several research needs in this field.
- Validating and standardizing exposure assessments
- More studies outside of North America and Australia
- Mechanistic and longitudinal analyses

Highlights

- First umbrella review on wildfire smoke exposure and health outcomes.
- Included 27 SRMAs with findings from 617 primary studies.
- Documented 115 health outcomes related to wildfire smoke exposure.
- Consistent associations found between wildfire-specific PM2.5 and all-cause mortality, respiratory morbidity, and mental health.
- Studies from broader geographic settings with established environmental health research guidelines are required.

Abstract

Introduction: Wildfires are a growing concern due to their significant impact on wildlife, air quality, and health, and are increasing under climate change. Although several systematic reviews have explored the relationship between wildfire smoke and human health outcomes, a comprehensive overview of the overall epidemiological evidence remains needed. Thus, this umbrella review aimed to comprehensively synthesize the overall epidemiological evidence on the human health effects of wildfire smoke.

Methods: This umbrella review followed PRISMA guidelines and was registered on PROSPERO (ID: CRD42024529782). We systematically searched PubMed, Scopus, and Web of Science for systematic reviews published up to March 25, 2024, using terms related to wildfires and health outcomes. The risk of bias was assessed using the AMSTAR-2 tool.

Results: A total of 27 reviews were included in the analysis: 9 systematic reviews with meta-analyses and 18 systematic reviews without meta-analyses, published between 2010 and 2024. A total of 115 different health outcomes were examined, with respiratory morbidity being the most frequently reported. Other key health outcomes reported included mortality, cardiovascular conditions, mental health, and adverse birth outcomes. The review identified consistent associations between wildfire smoke exposure and all-cause mortality, respiratory morbidity, and mental health conditions such as PTSD, depression, and anxiety. However, findings related to cause-specific mortality, cardiovascular outcomes, and other health effects were less consistent. The quality assessment revealed a high proportion of systematic reviews and meta-analyses had critically low quality, coupled with inadequate reporting and risk assessment practices.

Conclusion: Wildfires present significant health risks, impacting the respiratory system, birth outcomes, and mental health. Future research should utilize longitudinal and mechanistic studies to elucidate long-term effects and biological pathways of wildfire smoke, improve exposure assessment methods with advanced technologies, and review studies should adhere to established environmental health research review guidelines to enhance methodological rigor and global understanding.

Keywords: *Wildfire; Health; Mortality; Respiratory outcome; cardiovascular diseases; Systematic review*

1. Introduction

Wildfires have become increasingly frequent and severe, with a likely to increase up to 50% by 2100 globally (Kelley et al., 2022; United Nations Environment Program, 2022). The Intergovernmental Panel on Climate Change (IPCC) predicted that temperatures will rise by 1.5°C by 2050, which is likely to increase the intensity and frequency of wildfires in the 21st century (Goss et al., 2020; Gould et al., 2024). Additionally, land management practices have led to an increase in fuel loads for potential wildfires, which, combined with the growing number of people living at the wildland-urban interface, has become a dangerous and costly driver of more frequent and faster-spreading wildfires (Pausas & Keeley, 2021). The data from 2001–2018 shows that global wildfire activity has fluctuated but remained substantial, with an annual average of 463 million hectares burned (Lizundia-Loiola et al., 2020). A sharp increase in wildfire frequency and intensity has been observed, particularly highlighted by events like the 2019 wildfire season, where nearly five times more fires were recorded compared to 2018 (European Space Agency, 2019). Recent wildfires in Northern America, Australia, Asia, and Europe signify that such events have increased both in frequency and severity, causing substantial damage (Barkoski et al., 2024). For example, in 2019, Canada experienced about 4000 wildfires that consumed an area of 1.8 million hectares. In the two following years, particularly in 2021, the wildfire rate in Canada increased by 18% (Barros et al., 2023). In the US, over 70,000 wildfires have occurred annually since 2000 on average (Burke et al., 2021).

The environmental and health impacts of wildfires pass geographical boundaries, as pollutants including carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and particulate matter with aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) are carried by winds hundreds of kilometers away (Halofsky et al., 2020). Recent studies found that wildfires generate carbon dioxide emissions ranging from 1.75 to 13.5 billion tons, which persist in the atmosphere for several months, thereby worsening the air quality and climate change, further enabling the recurrence of wildfires (Jiao et al., 2024; Johns, 2020). Wildfires cause a wide range of health impacts, heightening public concerns about their increase in severity and frequency (Liu et al., 2015). The US Forest Service described forest fire and smoke as hazardous to health in 2010 Wildfires can induce a wide range of health impacts, heightening public concerns about their increase in severity and frequency (Liu et al., 2015). The US Forest Service described forest fire and smoke as hazardous to health in 2010 (Jiao et al., 2024), and a growing body of literature has explored the health impacts (G. Chen et al., 2021; Gao et al., 2024; Wei et al., 2023). Since 2000, the mortality rate in numerous nations has grown, including the United States, where the annual death toll from wildfires surpasses 15,000 persons (Burke et al., 2021). Globally, vegetation fire smoke, particularly PM2.5, is responsible for over 300,000 premature deaths each year (Johnston et al., 2012). In southern and eastern Europe, wildfire-related PM2.5 contributed to an estimated 1,080 premature deaths in 2008 alone (Kollanus et al., 2017). Wildfire smoke can directly impact respiratory organs with declining lung function inducing or triggering exacerbation of already existing respiratory conditions such as asthma, acute bronchitis, chronic obstructive pulmonary disease (COPD), pneumonia, and respiratory infection (Reid et al., 2016). Studies have also shown associations between particulate matter (PM) from wildfire smoke and cardiovascular disease (CVD) including heart failure, ischemic heart disease, and arrhythmias (H. Chen et al., 2021; Heaney et al., 2022). Maternal exposure to PM from wildfires has been associated with adverse pregnancy outcomes such as low birth weight, birth defects, preterm birth, and stillbirth (Evans et al., 2022; Foo et al., 2024). Though all ages can be affected, children, pregnant women, older persons, and adolescents are more vulnerable due to a combination of factors such as lower baseline health status for older persons and developing respiratory systems for infants (Eisenman and Galway, 2022; Zhang et al., 2023).

Additionally, wildfires can cause devastating environmental degradation and socio-economic destruction that can cast long shadows over mental and social health communities affected (Fann et al., 2018; Mao et al., 2024). Data suggest that survivors of wildfire often suffer from general anxiety disorder (GAD) and major depression disorder (MDD) (Agyapong et al., 2020; Powell et al., 2021). These post-disaster mental health concerns can be extremely important as they have the potential to contribute to trauma-related symptoms (Weilnhammer et al., 2021). Traumatic events can also result in post-traumatic stress disorder (PTSD), a condition with negative reciprocal effects on mood states, emotional control, sleep, and more (Bonita et al., 2024). Children and younger adults often experience mental health problems such as agitated behavior, nightmares, sleep disruption, and anxiety to varying extents after disastrous events (Adu et al., 2023). In addition, studies have shown that if these issues are not treated, they may result in cognitive damage and memory impairment (Barros et al., 2023).

With the continuing rise in climate change, wildfires are to become more severe and frequent (Ford et al., 2018). Consequently, the impact on human health is a pressing concern, prompting the need to adapt, manage, and strengthen our healthcare services (Heaney et al., 2022; Henry et al., 2021). Furthermore, by emphasizing the substantial health burden brought on by wildfires, policies aimed to lessen the impact of wildfires and protect public health are necessary. In recent years, this emerging issue has drawn the attention of many researchers, as a sizeable number of recent studies have examined the health effects of wildfire-related air pollution exposure on human health. As a result, to this date, several studies have attempted to systematically address and review single health impacts, for example, respiratory diseases (Heaney et al., 2022; Henry et al., 2021; Jiao et al., 2024), cardiovascular diseases (H. Chen et al., 2021; Heaney et al., 2022) or mental health alone (Bonita et al., 2024; To et al., 2021; Zhang et al., 2023). Only a few studies have addressed multiple health outcomes along with mental health issues caused by wildfire (Barros et al., 2023; Gould et al., 2024; Weilnhammer et al., 2021; Zhang et al., 2023) within a specific age group or community or regional scale (Finlay et al., 2012; Reid et al., 2016; Weilnhammer et al., 2021; Zhang et al., 2023) However, there is a lack of a comprehensive synthesis of epidemiological associations between wildfire exposure and health outcomes, including both physical and mental health effects, covering all population groups in terms of age, sex, or gender. Through this study, we aimed to fill these gaps by providing a comprehensive and systematic summary of current evidence. Using an umbrella review approach, our goal was to synthesize existing reviews and meta-analyses to capture and systematically assess the evidence between wildfire exposure and health outcomes.

2. Methods

2.1. Study protocol and reporting

The umbrella review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) standards, with details reported in **Table S1** of the supplementary document (Page et al., 2021). The protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO) (ID: CRD42024529782) and is available at https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=529782.

2.2. Search strategy and study selection

For this umbrella review, we systematically performed the literature search in three electronic databases, including Medline (via PubMed), Scopus, and Web of Science, for articles published by March 25, 2024. We developed inclusion and exclusion criteria based on population, exposure, comparator, outcome, and study design (PECOS) framework. This framework reduces the possibility of bias in the review process and ensures the included review articles comply with the research question (Hu et al., 2021; Lam et al., 2021; Zare Sakhvidi et al., 2023). Table 1 outlines the detailed inclusion and exclusion criteria for this umbrella review. We utilized various. The search queries for each database were developed by doing separate searches for exposure and outcome elements of the PECOS terms, including exposure (i.e., forest fire, wildfire, wild fire, wildland fire, fire smoke, wild smoke, etc.) and outcome (i.e., health outcome, health impact, mortality, death, morbidity, hospital admission, pregnancy, birth outcome, mental health, etc.), and review (i.e., systematic review, literature review, meta-analysis, and pooled-analysis). Then, the queries of each element were merged using the AND operator. Table S1 presents the detailed search strategy for the abovementioned databases. We selected the keywords based on previously published systematic, scoping, and umbrella reviews (Barkoski et al., 2024; Foo et al., 2024; Lam et al., 2021; Yang et al., 2021). In addition, we conducted a manual check of the reference lists of the collected review articles to seek out any additional relevant literature. Two independent authors (M.B. and M.J.Z) performed the electronic database search. Table S1 shows the number of review articles retrieved from each database.

After completing the database search, one author (M.M.P.) imported all articles into a reference manager (Endnote v. 20.0.1) and removed duplicates. Rayyan platform (https://www.rayyan.ai/) was used for title and abstract screening according to the study PECOS. Four authors (M.R., M.A.R., M.B., and M.M.P.) conducted the initial screening of articles based on titles and abstracts. Articles that passed this stage were then selected for full-text screening. Any disagreements between the authors were resolved through discussion.

Table 1. Inclusion and exclusion criteria.

PICOS component	Inclusion criteria	Exclusion criteria
Population	Human populations with no age, sex, race, geographical region, and health status restrictions.	Non-human populations.
Exposure	Review studies focused on wildfire exposure (exposure to wildfire, forest fire, bushfire, peat fire, vegetation fire) and their impacts on health.	Review studies discussing wildfire in a general sense but not investigating any impact on health. Also, review studies related to fires that occurred in kitchens, residences, and industries were excluded.

Comparators	Review studies considered the intervention (i.e., exposed) group compared against a non-exposed or less exposed group (i.e., unexposed to wildfire events). The exposed and unexposed/less exposed group could be the same population during different time periods.	NA
Outcome	Review articles that considered the incidence or severity of physical and mental health conditions due to wildfire exposure.	Review articles that did not consider health as an outcome. Also, articles discussing ambiguous health impact data from mixed exposures such as wildfire and other extreme climatic events.
Study design	Review studies that conducted a review of observational study designs (e.g., cohorts, case-control, cross-sectional, case-crossover, ecological, and time series).	Review studies that considered intervention and experimental primary studies.
Study type	Systematic review and/or meta-analysis	Primary studies and conference abstract.
Language	English	Non-English

2.3. Data extraction

Four authors (M.R., M.A.R., M.B., and M.M.P.) extracted data from the selected full texts. To minimize the heterogeneity and disagreement in the data extraction process, a standard data extraction table was prepared and used throughout the extraction process. The data extraction considered the study's general characteristics (e.g., author, publication year, type of reviews, database searched, searching time frame, reported review guidelines, number of primary studies included, study designs of primary studies, geographical coverage of the reviews), participants' characteristics (e.g., location, total sample size, population type), exposure description (including time period, data sources, and type of exposure, exposure assessment method), outcome description (type of reported outcomes, outcome data source (s), quality assessment (Risk of Bias (RoB) tool used, and Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) assessment).

2.4. Quality assessment

The methodological quality of the included reviews was evaluated using the AMSTAR-2 (A Measurement Tool to Assess Systematic Reviews) checklist (Shea et al., 2017). The AMSTAR-2 quality appraisal tool contains 16 items. Seven of them were identified as critical domains, including (1) a priori protocol registered for the review, (2) adequacy of the literature search strategy, (3) reporting of the justification for the excluded articles in the reviews, (4) the risk of bias assessment for individual review studies that were included in the reviews, (5) proper analytical methods for any meta-analyses conducted, (6) assessment of the potential risk of bias when interpreting the findings of the review, and (7) evaluation of the likelihood of publication bias and its possible influence on the reviews. The rest of the domains were considered non-critical domains, including (1) the utilization of the PECO framework as the review question or inclusion criteria, (2) study design's selection criteria, (3) number of authors conducting the literature selection, (4) number of authors involved in extracting the data, (5) inclusion of detailed information about the characteristics of the review studies included, (6) disclosure of the funding sources for the review studies included, (7) assessment of the risk of bias in the review studies included on the pooled results, (8) rationale for any heterogeneity found in the review, and (9) reporting of any conflicts of interest in the review. In this study, we used seven critical domains to assess the quality of the included reviews. The quality was classified as high (zero or one non-critical weakness), medium (more than one non-critical weakness), low (one critical flaw with or without non-critical weaknesses), or critically low (more than one critical flaw with or without non-critical weaknesses) (Table S2) (Zang et al., 2022). Two authors (M.M.P. and M.B.) assessed the methodological quality, while the third author (M.H.E.M.B.) resolved any discrepancies raised through discussions.

3. Results

3.1. Study selection

A total of 852 review articles were initially identified through selected database searches. After removing duplicates, 682 review articles remained for title and abstract screening. Of these, 586 review articles were excluded based on the inclusion criteria through title and abstract assessment. Consequently, 96 review articles were deemed eligible for full-text evaluation. Following a thorough evaluation against the inclusion and exclusion criteria, 27 review articles were ultimately included in our review (Figure 1).

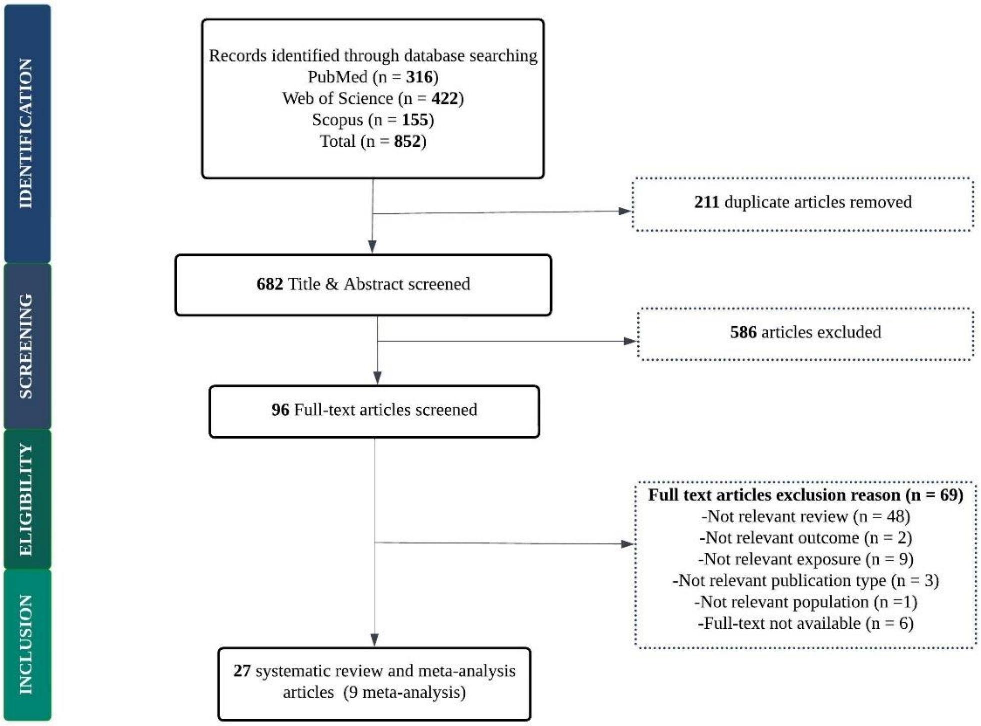


Figure 1. PRISMA flow chart of the study selection process.

3.2. Characteristics of included review

Out of the 27 review articles considered for our umbrella review, 9 were systematic reviews with meta-analyses (SRMAs), and 18 were systematic reviews without meta-analyses. These articles were published between 2010 and 2024. Authors from various parts of the world contributed to these articles, with most from the U.S. (n=10) followed by Australia (n=9), Canada (n=3), and others. Most reviews applied widely used databases, such as PubMed, EMBASE, Scopus, Web of Science, CINAHL, and Medline. The keyword search timeframe generally covered the period published through 2023. For the primary study selection process, 20 studies followed PRISMA reporting guidelines and one followed Meta-Analysis of Observational Studies in Epidemiology (MOOSE), while the guidelines for the study selection process were not specified in six studies (Barros et al., 2023; Burhan & Mukminin, 2020; Kochi et al., 2010; Liu et al., 2015; Segal & Giudice, 2022; Youssouf et al., 2014). The study search timeframe of the included studies ranged from as early as 1946 to as recent as 2023. The total number of primary studies across all SRMAs, including duplicates, was 617. The highest number of primary studies in a single review was 94 (Youssouf et al., 2014), and the lowest was 3 (Weilnhammer et al., 2021) (Table 3).

In terms of the included primary studies across the reviews, cohort study design was the most prevalent (n=99), followed by the cross-sectional design (n=93), time-series (n=89), ecological design (n=49), case-control (n=27), case-crossover (n=26), pre-post study (n=5), panel study (n=2), descriptive study (n=1), case study (n=1) and case report (n=1) (Table 2). The geographical coverage of the included primary studies had a strong focus on North America, and by individual country, studies were predominantly included from the U.S. (n=224) followed by Australia (n=107), Canada (n=37), Brazil (n=35), Malaysia (n=13), Indonesia (n=11), Portugal (n=7), and others. The populations included in the studies varied widely, from general populations to specific groups like firefighters, children, pregnant women, and older persons with chronic diseases. Across all reviews, the total sample size exceeded 50 million participants, including over 3 million children, 35 million pregnant women and their infants, and 5,038 firefighters. The included studies employed a variety of RoB tools to assess the quality of evidence. The most frequently used was the Newcastle-Ottawa Scale (NOS) (n=5) followed by the Joanna Briggs Institute (JBI) (n=3), Office of Health Assessment and Translation (OHAT) (n=3), National Heart, Lung, and Blood Institute (NHLBI) tool (n=2) and one each review used Synthesis without meta-analysis reporting guideline (SWiM), Cochrane risk of a bias assessment tool for non-randomized studies of interventions (ACROBATNRSI), World Health Organization (WHO) guideline, National institute for health and care excellence quality appraisal checklist (NICE) and Navigation Guide Framework. Notably, nine studies did not use any RoB assessment, and two studies were unclear about the RoB reporting tool. Only three studies employed the GRADE assessment to evaluate the certainty of the evidence (Table 3).

3.3. Exposure assessment

The reviews reported the associations for different pollutants measured by different methods. The most frequently studied pollutant was $PM_{2.5}$ (n=20) followed by particulate matter with aerodynamic diameter $\leq$ 10 μm (PM_{10}) (n=13), CO (n=6), NO_2 (n=6), aerosol index (n=5), ozone (O_3) (n=4), aerosol optical depth (AOD) (n=3), SO_2 (n=2), PHAs (n=2), air quality index (AQI) (n=2) and one each for CO_2, total suspended particles (TSP), suspended particulate matter (SPM) and hydrocarbons. Other reported exposures were wildfire event occurrence (n=9), number of heat spots (n=3), proximity to wildfire (n=2), self-reported smoke smells (n=2), and smoke intensity (n=1). To estimate the exposures, the most frequently reported method was ground-based monitoring station data (n=11), which estimated pollution by subtracting background PM from the total PM and usually estimated the long-term mean or median level of PM concentration on non-wildfire days in a specific region (Jiao et al., 2024). Another frequently reported method was the use of satellite image data (n=10) derived from the moderate resolution imaging spectroradiometer (MODIS) or other National Oceanic and Atmospheric Administration (NOAA) satellites. Atmospheric modeling was reported in ten studies, frequently referencing various types of atmospheric transport models. Among them, chemical transport models (CTMs) were commonly used, including models such as the Goddard Earth Observing System-Chem (GEOS-Chem) and the Community Multiscale Air Quality Modeling System (CMAQ). The Weather Research and Forecasting with Chemistry model (WRF-Chem) and CTMs integrated with ensemble-based machine learning models were also highlighted. Additionally, atmospheric dispersion models were frequently mentioned, such as the CALPUFF dispersion model, the Hybrid Single Particle Lagrangian Integrated Transport model (HYSPLIT), the BlueSky smoke forecasting model, and the NOAA smoke forecasting model, along with other smoke dispersion models used for simulating the transport and dispersion of pollutants. Another frequently employed method was self-reported questionnaires (n=10) on wildfire event occurrences and wildfire proximity. Less commonly applied methods were deployed sampling devices (e.g., air sampler analyzer) (n=2), proxy measurement (e.g., area burned) (n=2), forest activity tracking system (n=1), and smoke surface concentration maps (n=1) (Table 2).

Table 2. Exposure assessment details.

Author (s), Year	**Particulate matter**	**Other pollutants**	**Other exposure**	**Assessment**
(Amjad et al., 2021)	PM2.5 & PM10	TOMS aerosol index;	Proximity to wildfire; Heat spots	NOAA & MODIS satellite data, and ground-based monitoring data for PM2.5 & PM10; Self-reported location at residence for wildfire proximity.
(Arriagada et al., 2019)	PM2.5	NR	NR	WRF-chemical model, Surface monitor, atmospheric dispersion model, exposure prediction model, chemical transport model, smoke dispersion model, Blue sky forecasting model, and other forecasting model.
(Barbosa et al., 2022)	NR	NR	Occupation exposure to smoke	NR
(Barros et al., 2023)	PM2.5 & PM10	CO, SO2, NO2, and O3	NR	Frequently used methods:- i) local air quality monitoring stations, ii) high-resolution coupled atmospheric chemistry models and/or atmospheric transport models (e.g., Community Multiscale Air Quality model); and iii) satellite data (e.g., MODIS, etc.); Less frequently used methods: i) phone surveys to monitor WF smoke perception, ii) forest activity tracking system data related to prescribed burnings and iii) optimized Statistical Smoke Exposure Model to estimate hourly exposure levels based upon air quality monitoring stations data.

(Bell et al., 2020)	PM2.5	NR	NR	NR
(Bonita et al., 2024)	NR	NR	Wild fire events	Self-reported
(Burhan and Mukminin, 2020)	PM2.5 & PM10	AOD	NR	NR
(Cianconi et al., 2020)	NR	NR	Wild fire events	Self-reported
(Clark and Sheehan, 2023)	PM2.5 & PM10	CO, NO2, AQI	Bush fire events	Frequently used method: Satellite and self-reported smoke; Less frequent: local fire cluster, percentage of land area burned.
(Foo et al., 2024)	PM2.5 & PM10	CO, TOMS aerosol index;	Proximity to wildfire; Heat spots	Satellite image (MODIS/NOAA) based modeling; 3-D Chemical transport modeling; Ensemble-based (machine learning) modeling; Ground Monitoring data; Self-reported location.
(Gao et al., 2023)	PM2.5	NR	NR	Wildfire events, self-report, wildfire-impacted time and location, air pollutants level associated with wildfires, and residential proximity to wildfire-affected regions.
(Gould et al., 2024)	PM2.5	NR	NR	Ground monitoring data; satellite-derived measures; atmospheric chemical transport models; Dispersion models using meteorological data; Hybrid models, combining CTMs and statistical approaches
(Groot et al., 2019)	PM2.5	CO, NO2	Wild fire events, days, and season	NR
(Henry et al., 2021)	PM2.5 & PM10	O3	NR	Satellite data; WRF-Chem modeling; locally deployed sampling devices, often through access to government- or agency-based air quality monitoring programs tapered element oscillating microbalance devices.
(Isaac et al., 2021)	NR	NR	Wild fire events	Self-reported
(Jiao et al., 2024)	PM2.5 & PM10	NR	NR	Ground monitoring station data; Atmospheric transport modeling such as GEOS-CHEM, WRF-Chem, CMAQ; Atmospheric dispersion models such as CALPUFF and HYSPLIT; U.S. National Oceanic and Atmospheric Administration (NOAA) Smoke Forecasting System; the Blue Sky Western Canada Wildfire Smoke Forecasting Framework; Smoke plume data by NOAA
(Karanasiou et al., 2021)	PM2.5 & PM10	NR	Smoke (yes vs no)	Ground monitoring station data; Smoke surface concentration maps; Satellite data; Atmospheric model; Factor based receptor model.
(Kochi et al., 2010)	PM2.5 & PM10	NR	NR	NR
(Kondo et al., 2019)	PM2.5	NR	NR	WRF-Chem modeling, HYSPLIT modeling, Geos-Chem modeling, GWR modeling

(Liu et al., 2015)	PM2.5 & PM10	CO, CO2, O3, NOx, aerosol, TSP, hydrocarbon	NR	Satellite image data; Land-based air pollutant monitor; air quality modeling; air sample analyzer; personal exposure survey; personal report; personal photometer.
(Melody et al., 2019)	PM2.5 & PM10	Mean aerosol index	Number of heat spots	Satellite image data; Monitoring network; Assessed by degree of property damage; Environmental exposure survey
(Segal and Giudice, 2022)	PM2.5	PAHs	NR	NR
(Varshney et al., 2023)	NR	NR	Bushfire events	Self-reported
(Weilnhammer et al., 2021)	NR	NR	Forest fire events	NR
(Youssouf et al., 2014)	PM2.5 & PM10	NO2, SO2, CO, AOD, PHAs	NR	Ground-based air quality monitoring; satellite imagery; chemical transport models; the daily burned area as a proxy; the number of known wildfires as a proxy; Self-administrated questionnaires
(Zhang et al., 2022)	NR	NR	Wild fires events	Self-reported questionnaires
(Zhang et al., 2024)	PM2.5 & PM10	NO2, O3, AOD; AQI; SPM; Aerosol index	Wildfire event days; Smoke intensity; Self-reported smoke smell	GEO-Chem or/and machine learning model; EMEP/MSC-W model; Satellite data; Ground monitoring station data; self-reported questionnaires

Note: PM2.5 & PM10: Particulate Matter less than 2.5 micrometers and 10 micrometers in diameter; TOMS aerosol index: Total Ozone Mapping Spectrometer aerosol index; CO: Carbon Monoxide; SO2: Sulfur Dioxide; NO2: Nitrogen Dioxide; O3: Ozone; AOD: Aerosol Optical Depth; AQI: Air Quality Index; SPM: Suspended Particulate Matter; TSP: Total Suspended Particles; PHAs: Polycyclic Aromatic Hydrocarbons; NR: Not Reported; NOAA: National Oceanic and Atmospheric Administration; MODIS: Moderate Resolution Imaging Spectroradiometer; WRF-Chem: Weather Research and Forecasting-Chemistry model; GEOS-CHEM: Goddard Earth Observing System global chemical transport model; CMAQ: Community Multiscale Air Quality model; CALPUFF: California Puff atmospheric dispersion modeling system; HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory model; GWR: Geographically Weighted Regression model; PAHs: Polycyclic Aromatic Hydrocarbons; EMEP/MSC-W: European Monitoring and Evaluation Programme/Modeling and Emissions of Pollutants at a regional scale - Western Hemisphere.

3.4. Association between wildfire exposure and health outcomes

A total of 115 different health outcomes were reported in relation to wildfire smoke across 27 SRMAs. We categorized this health, reported by the following groups: mortality, respiratory outcomes (e.g., morbidity), cardiovascular outcomes (e.g., morbidity), pregnancy and birth outcomes, cancers, infectious diseases, mental health conditions, and other outcomes. Among these, mental health outcomes represented the most diverse category (n=30, 26%), followed by respiratory outcomes (n=20, 17%), cardiovascular outcomes (n=17, 15%), pregnancy and birth outcomes (n=15, 13%), mortality (n=17, 6%), cancers (n=2, 2%) and infectious diseases (n=2, 2%) (Figure 2).

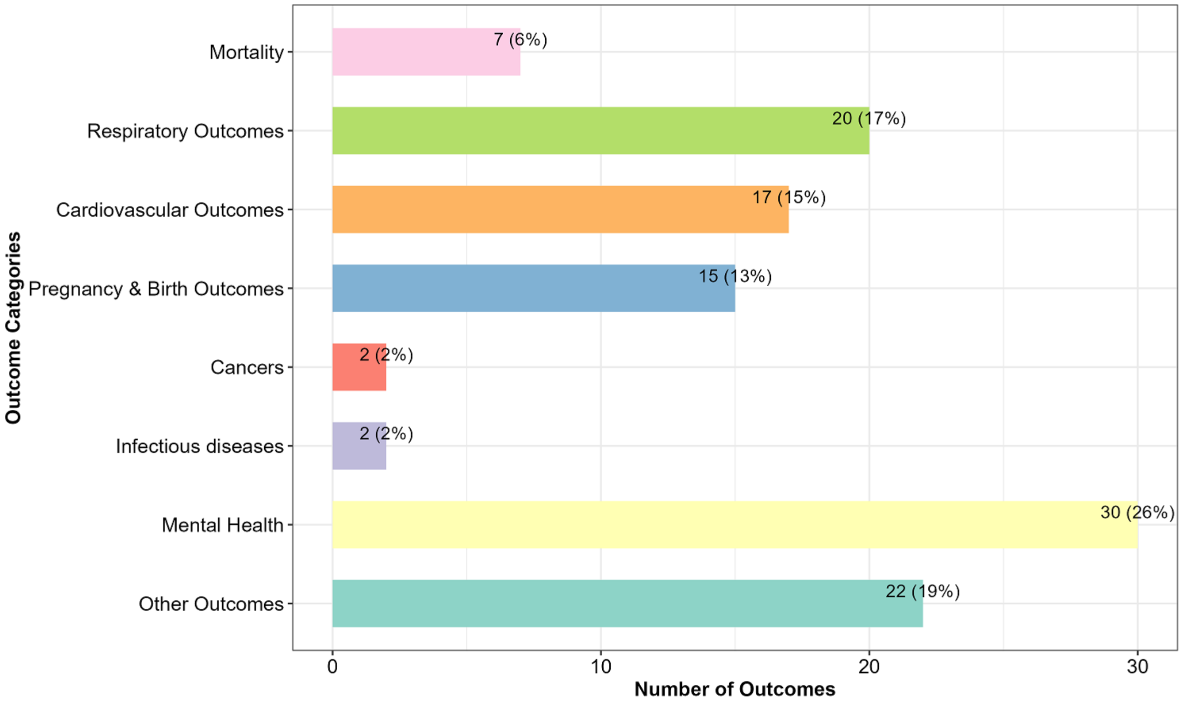


Figure 2. Distribution of health outcomes related to wildfire exposure across the 27 systematic reviews and meta-analyses.

3.4.1. Mortality

Eleven reviews evaluated associations between wildfire exposure and all-cause mortality as well as cause-specific mortality. Of them, eight investigated associations between wildfire and all-cause mortality. Six reported consistent evidence of a positive association between an increase in wildfire-specific $PM_{2.5}$ and all-cause mortality (Barros eta al., 2023; Gould et al., 2024; Karanasiou et al., 2021; Liu et al., 2015; Weilnhammer et al., 2021; Youssouf et al., 2014). Only two reported a meta-estimate of the wildfire and mortality association. One meta-analysis reported that a 1-µg/m^3 increase in wildfire-specific $PM_{2.5}$ was associated with a 0.15% (0.01%-0.28%, n=8) increase in all-cause mortality (Gould et al., 2024). Another meta-analysis reported a 2.61% (95% confidence interval (CI)=1.02-4.20, n=4) increased risk of all-cause mortality on smoky days compared to non-smoky days (Karanasiou et al., 2021).

Nine reviews reported on associations between wildfire exposure and cause-specific mortality. Seven reported on respiratory mortality (Barros et al., 2023; Jiao et al., 2024; Kochi et al., 2010; Liu et al., 2015; Weilnhammer et al., 2021; Youssouf et al., 2014; Zhang et al., 2024), with only two showing a consistent association between wildfire PM2.5 and an increased risk of respiratory death (Barros et al., 2023; Weilnhammer et al., 2021). One review specifically reported COPD-related mortality but did not find any significant association with wildfire PM2.5 (Liu et al., 2015). Similarly, seven reviews examined cardiovascular mortality (Barros et al., 2023; Gao et al., 2023; Karanasiou et al., 2021; Kochi et al., 2010; Weilnhammer et al., 2021; Youssouf et al., 2014; Zhang et al., 2024), but only two found a consistent link between wildfire PM2.5 and cardiovascular mortality (Gao et al., 2023; Weilnhammer et al., 2021). One review reported a positive association between wildfire PM2.5 and mortality due to acute myocardial infarction (Gao et al., 2023). Two reviews also reported that wildfire exposure exacerbated COVID-19 mortalities (Clark & Sheehan, 2023; Gao et al., 2023), and one reported an association with unintentional coastal drowning fatalities (Clark & Sheehan, 2023).

3.4.2. Morbidity

Eighteen reviews reported on associations between wildfire exposure and one or more morbidities. Of these, 17 reported on respiratory outcomes (Arriagada et al., 2019; Barbosa et al., 2022; Barros et al., 2023; Bell et al., 2020; Burhan & Mukminin, 2020; Gao et al., 2023; Gould et al., 2024; Groot et al., 2019; Henry et al., 2021; Jiao et al., 2024; Karanasiou et al., 2021; Kochi et al., 2010; Kondo et al., 2019; Liu et al., 2015; Weilnhammer et al., 2021; Youssouf et al., 2014; Zhang et al., 2024), nine reported on CVD outcomes (Barros et al., 2023; Bell et al., 2020; Gould et al., 2024; Groot et al., 2019; Karanasiou et al., 2021; Kochi et al., 2010; Liu et al., 2015; Youssouf et al., 2014; Zhang et al., 2024), two reported on cancers (Gao et al., 2023; Groot et al., 2019) and six reviews reported on other morbidities including physician visits for otitis media, acute appendicitis and long bone fractures-related emergency department (ED) visits, diabetes (Barros et al., 2023; Clark & Sheehan, 2023; Gao et al., 2023; Groot et al., 2019; Liu et al., 2015; Zhang et al., 2024).

3.4.2.1. Respiratory outcomes

A total of 17 reviews reported an association between wildfire smoke and various respiratory outcomes. Of them, 13 reviews reported on respiratory morbidities (e.g., hospitalizations, ED visits, physician visits, symptoms), six focusing specifically on asthma, three on COPD, and three on lung function. Most (n=12) reviews found consistently harmful associations between wildfire smoke and respiratory hospitalizations and ED visits (Barros et al., 2023; Burhan & Mukminin, 2020; Gao et al., 2023; Gould et al., 2024; Henry et al., 2021; Jiao et al., 2024; Karanasiou et al., 2021; Kochi et al., 2010; Kondo et al., 2019; Liu et al., 2015; Youssouf et al., 2014; Zhang et al., 2024). Three out of five meta-analyses found positive associations between wildfire-specific PM and respiratory morbidity. One meta-analysis found that wildfire-specific $PM_{2.5}$ was positively associated with all respiratory outcomes combined (odds ratio [OR]=1.03, 95% CI=1.01-1.05, n=4) (Barros et al., 2023). Another meta-analysis found a 1-µg/m³ increase in wildfire-specific $PM_{2.5}$ was associated with a 0.25% increase in respiratory hospitalizations and a 0.36% increase in respiratory ED visits (Gould et al., 2024). Additionally, another meta-analysis reported that respiratory hospitalizations and ED visits peaked on smoky days (% change=10.52, 95% CI=3.87-17.18, n=7) (Karanasiou et al., 2021). A separate meta-estimate showed a 10 µg/m³ increase in wildfire-specific $PM_{2.5}$ was associated with a 10% increase in upper respiratory infections (relative risk (RR)=1.13, 95% CI=1.05-1.23, n=2) (Zhang et al., 2024).

Consistent evidence also associated wildfire smoke with increased asthma morbidities, including hospitalizations and ED visits (Arriagada et al., 2019; Henry et al., 2021; Karanasiou et al., 2021; Kochi et al., 2010; Youssouf et al., 2014). One meta-analysis found that for every 10 µg/m³ increase in $PM_{2.5}$ levels due to landscape fire smoke, there was an associated rise in asthma hospitalization rates (RR=1.06, 95% CI=1.02-1.09, n=6) and ED visits (RR=1.07, 95% CI=1.04-1.09, n=8) (Arriagada et al., 2019). Another meta-analysis reported a 38.3% increased risk of asthma on smoky days compared to non-smoky days (95% CI=7.91-68.60, n=6) (Karanasiou et al., 2021). There was also suggestive evidence of the association between wildfire smoke and COPD outcomes (Bell et al., 2020; Karanasiou et al., 2021; Youssouf et al., 2014). One meta-analysis study reported that COPD admission rates were high (% change=13.3%, 95%CI=7.31-19.34, n=4) on smoky days compared to non-smoke days (Karanasiou et al., 2021). Three reviews reported on lung function (Barbosa et al., 2022; Gao et al., 2023; Groot et al., 2019), of which two reported reduced lung function associated with wildfire exposures (Gao et al., 2023; Groot et al., 2019). One review reported on peak expiratory flow rate but did not find a positive association with wildfire exposure (Liu et al., 2015). Further, there was limited evidence regarding the impact of wildfire smoke on respiratory symptoms, medication use, and physician visits (Arriagada et al., 2019; Jiao et al., 2024; Liu et al., 2015). Only one study performed a GRADE evaluation and found a ‘Moderate’ certainty of evidence for hospital admissions and ED visits for respiratory and asthma exacerbations and a ‘Low’ certainty of evidence for outpatient clinic visits for asthma exacerbation (Henry et al., 2021).

3.4.2.2. Cardiovascular disease

Studies reported on various CVD morbidities, including congestive heart failure (CHF), ischemic heart disease (IHD), arrhythmias, and myocardial infarction. However, limited evidence reported regarding the impact of wildfire events on cardiovascular hospital admissions and ED visits. Three meta-analyses examined associations between wildfire smoke and CVD morbidity (Barros et al., 2023; Gould et al., 2024; Karanasiou et al., 2021), with only one found a statistically significant adverse association between wildfire-specific $PM_{2.5}$ exposures and all cardiovascular outcomes among the elderly (Barros et al., 2023).

3.4.2.3. Cancers

Two reviews reported the association between wildfire exposure and cancer risk. One focused specifically on lung cancer (Gao et al., 2023), while the other reviewed all types of cancer (Groot et al., 2019). However, neither review provided suggestive evidence supporting a strong association between wildfire exposure and cancer outcomes.

3.4.2.4. Infectious diseases

Three reviews examined the association between wildfire exposure and infectious diseases, including COVID-19 infections (Clark & Sheehan, 2023), influenza rates (Gao et al., 2023), and diarrhea-related hospital admissions (Liu et al., 2015). Among these, both COVID-19 incidence and influenza were found to have positive associations with wildfire exposure.

3.4.2.5. Other morbidities

Several other morbidities were reported in relation to wildfire exposure. Two reviews on all-cause hospitalizations found no significant association with wildfire exposure (Gao et al., 2023; Zhang et al., 2024). Similarly, three reviews on diabetes also did not report a positive link to wildfire exposure (Barros et al., 2023; Liu et al., 2015; Zhang et al., 2024). One each review investigated oxidative stress and inflammatory responses, injuries, and musculoskeletal morbidity (Groot et al., 2019), as well as physician visits for otitis media and emergency department visits for acute appendicitis and long bone fractures (Barros et al., 2023) did not observe any significant relationship with wildfire exposure.

3.4.3. Pregnancy and birth outcomes

A total of nine reviews reported the association between wildfire exposure and pregnancy as well as birth outcomes. There was consistent evidence supporting a harmful association between wildfire smoke and adverse birth outcomes, including reduced birth weight (Amjad et al., 2021; Foo et al., 2024; Karanasiou et al., 2021; Melody et al., 2019), low birth weight (LBW) (Foo et al., 2024; Karanasiou et al., 2021; Melody et al., 2019; Segal & Giudice, 2022), and preterm birth (PTB) (Amjad et al., 2021; Foo et al., 2024;

Karanasiou et al., 2021; Segal & Giudice, 2022). One meta-analysis indicated that a 10 μg/m³ increase in wildfire-specific $PM_{2.5}$ was associated with a 21.7 g reduction in birth weight (95% CI, -32.9 to -10.5; n=3) (Zhang et al., 2024). Only one study performed a GRADE evaluation and found a 'Low' certainty of evidence for reduced birth weight and a 'Very low' certainty of evidence for PTB (Amjad et al., 2021). Another meta-analysis on wildfire smoke on LBW and BWR reported inconclusive evidence (Foo et al., 2024). Four reviews reported on infant mortality (Amjad et al., 2021; Foo et al., 2024; Gao et al., 2023; Karanasiou et al., 2021), and only one review found a harmful association with wildfire exposure (Karanasiou et al., 2021). Two reviews reported birth defects (Segal & Giudice, 2022; Zhang et al., 2024), and one observed a positive association with wildfire exposure (Segal & Giudice, 2022). A number of reviews reported on small for gestational age (SGA) (Amjad et al., 2021; Foo et al., 2024; Zhang et al., 2024), stillbirth (SB) (Foo et al., 2024; Melody et al., 2019; Zhang et al., 2024), gestational length (GL) (Foo et al., 2024; Melody et al., 2019), gestational diabetes mellitus (GDM) (Foo et al., 2024), gestational hypertension (GHT) (Foo et al., 2024), birth cohort size (Melody et al., 2019), lifelong health condition for children Segal & Giudice, 2022), congenital anomalies (Foo et al., 2024), obstetric outcome (Foo et al., 2024) and did not observe consistent association with wildfire exposure.

3.4.4. Mental health

Most studies with mental health outcomes consistently reported a harmful association between wildfire events and mental health outcomes, including PTSD (Bonita et al., 2024; Cianconi et al., 2020; Gao et al., 2023; Groot et al., 2019; Varshney et al., 2023; Zhang et al., 2022), depression (Bonita et al., 2024; Cianconi et al., 2020; Clark & Sheehan, 2023; Varshney et al., 2023), anxiety (Bonita et al., 2024; Cianconi et al., 2020; Clark & Sheehan, 2023; Varshney et al., 2023), psychological distress (Bonita et al., 2024; Zhang et al., 2022; Varshney et al., 2023), insomnia (Bonita et al., 2024; Isaac et al., 2021; Varshney et al., 2023), sleep disturbances (Isaac et al., 2021), sleep quality (Isaac et al., 2021), somatization (Varshney et al., 2023; Cianconi et al., 2020), psychological well-being (Clark & Sheehan, 2023) and behavioral problems (Cianconi et al., 2020). One meta-analysis reported a pooled prevalence of 14% (95% CI 12%–16%; n=2) for psychological distress in the highly affected communities at 2–4-year post-bushfire compared to low affected communities (Zhang et al., 2022), but the GRADE assessment showed 'low' certainty of evidence. Reviews reported on substance abuse disorders (Cianconi et al., 2020; Zhang et al., 2022), anger (Gao et al., 2023), stress (Bonita et al., 2024; Groot et al., 2019), fear (Bonita et al., 2024), and sleeping difficulty (Bonita et al., 2024; Cianconi et al., 2020) did not observe association with wildfire exposure.

3.4.5. Other health outcomes

Several other health outcomes were examined in relation to wildfire exposure. Of them, two reviews reported an association between wildfire smoke exposure and shorter height of children (Gao et al., 2023) and eye, nose, and throat symptoms (Henry et al., 2021). However, other outcomes, including disability-adjusted life years (Barros et al., 2023), blood mercury level and hearing loss (Groot et al., 2019), bone marrow content, blood biomarker concentration, ophthalmic symptoms, injuries, physical strength, and overall health (Liu et al., 2015); and skin inflammations, height-for-age, sore throat, headache, and physical activity (Zhang et al., 2024) did not observe consistent associations with wildfire exposure.

Table 3. Characteristics of reviews included in this umbrella review (n = 27).

Author and year	Synthesis type	Databases and timeframes searched	Number and design of reviewed studies	Geographical coverage	Sample sizes and populations	Reporting guidelines	Risk of bias tools	Exposure(s)	Outcome(s)	Main finding(s)	Certainty of the evidence
Amjad et al., 2021	SR	MEDLINE, EMBASE, CINAHL, Web of Science Core Collection, Greenfile, ProQuest Earth Atmospheric and Aquatic Science Database, CABI, Health and Environment Research Online (HERO); Until June 2020	8 total: Cohort (5), Cross-sectional (1), Ecological (1), Time-series (1)	U.S. (4), Australia (2), Indonesia (1), Brazil (1)	1,702,252; Mother-offspring dyads	PRISMA	SWiM	Wildfire-specific $PM_{2.5}$ and PM_{10}; TOMS aerosol index; proximity to wildfire; Heat spots	BWR; SGA; PTB; Mortality	Most studies reported maternal wildfire exposure in late pregnancy were associated with BWR and PTB but inconclusive with SGA and infant mortality.	GRADE; **Low**: BWR; **Very low**: SGA, PTB, Mortality
Arriagada et al., 2019	SR & MA	PubMed, Medline, EMBASE, and Scopus; Until 2 May 2018	20 total: Case-crossover (2), Time-series (7), Time stratified case-crossover (5), Panel study (1), Ecological (5)	U.S. (8), Canada (4), Australia (8)	Not specified; General population	PRISMA	NOS	Landscape fire smoke (LFS)-specific $PM_{2.5}$	Asthma-related HA, EDV, physician visits, Salbutamol dispensations, and medication use	In the meta-analysis, each 10 µg/m³ increase in LFS PM2.5 levels was significantly associated with a higher risk of asthma hospitalizations (RR = 1.06, 95% CI: 1.02–1.09, n=6) and emergency department (ED) visits (RR = 1.07, 95% CI: 1.04–1.09, n=8). Additionally, LFS PM2.5 was positively associated with increased physician visits and Salbutamol dispensations, though no significant association was found with overall medication use.	Not specified
Barbosa et al., 2022	SR & MA	PubMed, Web of Science, Scopus and Science Direct; August 1990–March 2021	9 total: Cross-sectional (3), cross-shift (3), cross-season (3)	U.S. (5), Portugal (1), Greece (1), France (1), Italy (1)	693; Firefighters	PRISMA	NHLBI	Wild land fire	Lung function	Exposure to wildland fires was not associated with lung function in firefighters.	Not specified
Barros et al., 2023	SR & MA	Web of Science, Science Direct, Scopus, PubMed; January 2016-31 December 2021	52 total: Cross-sectional (30), Time-series (10), Case-crossover (2), Time stratified	U.S. (33), Canada (4), Columbia (1), Portugal (3), Spain (1), UK (1), Australia (5), Thailand	Not specified; General population	Not specified	WHO Guideline	Wildfire-specific $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3	All-cause & cause-specific mortality; Cardiorespiratory morbidity (EDV, HA, symptoms);	The meta-analysis showed that for every 10 µg/m³ increase in wildfire-specific PM2.5 exposure, there was a positive association with all	Not specified

			case-crossover (5), Case-control (1), Cohort (2), Ecological (2)	(2), Malaysia (1), Multi-country (1)					DALY; Diabetes; Acute appendicitis and long bone fractures-related EDV; Physician visits for otitis media; Mental health	respiratory outcomes (OR = 1.03, 95% CI: 1.01–1.05) and asthma-related outcomes (OR = 1.08, 95% CI: 1.06–1.11) in the U.S..	
Bell et al., 2020	SR	PubMed, Scopus, EMBASE, and Web of Science; Until April 2019	6 total: Cohort (6)	U.S. (5), Malaysia (1)	391,381; Older adults with chronic disease	PRISMA	NOS and NHLBI	Wildfire-specific $PM_{2.5}$	COPD and CHF disease-related HA and EDV	Most studies reported a significant positive association between COPD-related outcomes and wildfire $PM_{2.5}$ among young adults.	Not specified
Bonita et al., 2024	SR	PubMed, PsychINFO, and Embase; Until June 2023	13 total: Cohort (6), Cross-sectional (7)	Australia (8), Israel (2), Greece (2), Canada (1)	4,345; Firefighters	PRISMA	Not specified	Wild fire events	Mental health	Exposure to wildfire was linked to an increased risk of PTSD, depression, anxiety, psychiatric impairment, insomnia, and other psychological distress after the events.	Not specified
Burhan & Mukminin, 2020	SR	PubMed, EBSCOhost, and Google Scholar; Until December 23, 2019	4 total: Cross-sectional (2); Cohort (1); case-crossover (1)	U.S. (3), Australia (1),	5,942,238; General population	Not specified	ACROBAT NRSI	Wildfire-specific $PM_{2.5}$, PM_{10}, and AOD	Respiratory (pneumonia, bronchitis, bronchiolitis, and upper respiratory infection) EDV	Increased $PM_{2.5}$, PM_{10} & AOD concentration during wildfire was associated with an increased risk of ED visits due to upper respiratory infection, pneumonia, bronchitis, and bronchiolitis.	Not specified
Cianconi et al., 2020	SR	PubMed, EMBASE, and Cochrane; 1996-2019	9 total: Not specified	Not specified	Not specified; General population	PRISMA	Not specified	Wild fire events	Mental health	Exposure to wildfire is linked to a risk of developing general mental health problems, PTSD, major depression, anxiety, somatization, and behavioral problems.	Not specified
Clark & Sheehan, 2023	SR	PubMed and Scopus; Until 13 November 2022	19 total: Ecological (11), Cross-sectional (7), Cohort (1),	U.S. (13), Australia (5), Brazil (1)	>197,250, incidence rates for 231 counties, 5 cities, and 129 local government areas;	PRISMA	Not specified	Wildfire-specific $PM_{2.5}$, PM_{10}, CO, and NO_2; AQI, general bushfire events	COVID-19 infections & mortality; Mental health; unintended fatal drowning	Most studies reported that exposure to wildfires exacerbated COVID-19 infections and mortality. Further, bushfire exposure exacerbated depression, anxiety, loneliness	Not specified

					General population					conditions, and reduced psychological well-being.	
Foo at el., 2024	SR & MA	CINAHL Complete, Ovid/EMBASE, Ovid/MEDLINE, ProQuest, PubMed, Scopus, Web of Science, and Google Scholar; Until September 2023	31 total: Cohort (20), six case-control (6), Cross-sectional (2), Case-crossover (1), Ecological (1), Semi-ecological (1).	U.S. (13), Brazil (5), Australia (4), Indonesia (1), South Korea (1), Thailand (1). Multi-country (6)	35,555,556; Pregnant women and/or their infants and young children	PRISMA	OHAT	Wildfire-specific PM$_{2.5}$, PM$_{10}$, and CO; TOMS aerosol index; proximity to wildfire; Heat spot	BW, LBW, PTB, GL, SGA, GDM, GHT, SB, congenital anomalies, obstetric outcomes, early childhood respiratory infection, and child mortality	There was suggestive evidence indicating that wildfire smoke exposure during pregnancy was associated with elevated risk of LBW and BWR, PTB, some congenital anomalies, and some obstetric outcomes.	Not specified
Gao et al., 2023	SR	Ovid MED LINE, Embase via Ovid and Scopus; Until 8 November 2022	33 total: Cohort (13), Cross-sectional (10), Ecological (5), Case-control (1), Time-series (2), Case-crossover (1), Panel study (1)	Brazil (2), Australia (10), U.S. (7), Canada (9), Malaysia (1), Israel (1), Thailand (1), India (1), Multi-country (1)	2,907,271; General population	PRISMA	NOS and OHAT	Wildfire-specific PM$_{2.5}$	Cause-specific mortality; Child deaths; All-cause HA; Respiratory HA; Asthma incidence; Influenza disease; Cancer disease; Mental health; Lung function; Children height;	Long-term exposure to non-occupational wildfire exposure was associated with mortality (COVID-19 mortality, cardiovascular disease mortality, and acute myocardial disease mortality), morbidity (mainly respiratory diseases), mental health disorders (mainly PTSD), shorter height of children, reduced lung function and poorer general health status.	Not specified
Gould et al., 2024	SR & MA	PubMed; Until 16 March 2023	23 total: Time-series (16), Case-crossover (7)	Finland (2), U.S. (14), Brazil (2), Multi-country (1), Australia (4)	Not specified; General population	MOOSE	Not specified	Wildfire-specific PM$_{2.5}$	All-cause mortality; Cardio-respiratory EDV & HA	In the meta-analysis, each 1 μg/m³ increase in wildfire-specific PM2.5 was associated with a 0.15% increase in all-cause mortality, a 0.25% increase in respiratory hospitalizations, and a 0.36% increase in respiratory emergency department (ED) visits.	Not specified
Groot et al., 2019	SR	MEDLINE (including e-publications ahead of print, in-process, and other non-indexed citations), Embase, and Environment Complete;	31 total: Cohort (19), Cross-sectional (7), Case-control	U.S. (16), Canada (1), Israel (2), Australia (8), France (1),	7,711 individuals and 867 fire events;	PRISMA	Not clear	Wildfire-specific PM$_{2.5}$, CO and NO$_2$; Wildfires	Cancer morbidity; cardiovascular morbidity; respiratory	Occupational exposure to wildland fires affects lung function in the short term and may increase the risk	Not specified

		1 January 1946 – 3 January 2017	(1), Ecological (1), Descriptive (1), Case study (1), Case report (1)	Portugal (1), Italy (1)	General population			events, days and seasons	morbidity (lung function, respiratory symptoms); oxidative stress and inflammatory response; injuries and musculoskeletal morbidity; mental health; high blood mercury level; hearing loss; electrical hazards; health system use	of hypertension in the long term. Exposure to wildland fires is also associated with PTSD. However, there was insufficient evidence on the most long-term risks, particularly respiratory disease or cancer risks.	
Henry et al., 2021	SR	Medline (Ovid MEDLINE(R) ALL), Embase (Ovid interface), CINAHL Plus with Full Text (EBSCOhost interface), Greenfile (EBSCOhost interface), Web of Science CABI: CAB Abstracts and Global Health, Proquest Earth, Atmospheric & Aquatic Science Database, Scopus, and HERO- Health and Environmental Research Online, Google and Google Scholar; Until 21 December 2020	16 total: Pre-post (5), Cross-sectional (11)	U.S. (11), Canada (1), Australia (3), Spain (1)	565,321; Children	PRISMA	OHAT	Wildfire-specific PM$_{2.5}$, PM$_{10}$, and O$_3$	Outpatient clinic visits for respiratory cause & asthma exacerbation; EDV for respiratory cause & asthma exacerbation; HA for respiratory cause & asthma exacerbation; self-reported respiratory symptoms; eye, nose, and throat symptoms	Most studies reported a positive association between wildfire smoke exposure and outpatient clinic visits for respiratory causes, ED visits for respiratory causes, hospitalization for respiratory and asthma exacerbations, as well as eye, nose, and throat symptoms.	GRADE; **Moderate**: ED visits & hospitalizations for respiratory causes and asthma exacerbation; **Low:** Outpatient clinic visits for respiratory causes; eye, nose and throat symptoms; **Very low:** Outpatient clinic visits for asthma exacerbation; self-reported respiratory symptoms
Isaac et al., 2021	SR	EBSCO, PsychINFO, Medline, Springer Link, CINAHL Complete, EMBASE, PubMed, Scopus	5 total: Not specified	U.S. (3), Canada (1), Greece (1)	1,296; General population	PRISMA	JBI	Wildfire events	Sleep disturbances	Sleep disturbances were highly prevalent in wildfire survivors, with insomnia (63–72.5%) and	Not specified

		and Cochrane Library, Google Scholar; January 2012-March 2021								nightmares (33.3–46.5%) being the most prevalent sleep disturbances.	
Jiao et al., 2024	SR	PubMed, Web of Sciences, Scopus, and EMBASE; 2000-2022	35 total: Time-series (24), case-crossover (9), cohort (2)	U.S. (22), Canada (5), Australia (3), Brazil (2), Finland (1), Thailand (1), Multi-country (1)	Not specified; General population	PRISMA	NOS and OHAT	Wildfire-specific $PM_{2.5}$ and PM_{10}	Respiratory mortality, HA, EDV, medicine dispensations, emergency ambulance dispatches, and lung functions	Most studies supported positive associations between short-term exposure to wildfire-specific PM and the risk of respiratory morbidity, especially for $PM_{2.5}$ and all-cause respiratory ED visits. However, evidence was limited on wildfire exposure and respiratory mortality.	Not specified
Karanasiou et al., 2021	SR & MA	PubMed, ISI, and Scopus; 1980-2020	36 total: Not specified	U.S. (14), Australia (11), Canada (3), Brazil (2), Malaysia (2), Singapore (2), Indonesia (1), Spain (1)	Not specified; General population	PRISMA	Not clear	Smoke (yes vs. no); Wildfire-specific $PM_{2.5}$ and PM_{10}	All-cause mortality; CVD mortality; Morbidity-respiratory disease; Morbidity-asthma (all ages); Morbidity-COPD; Morbidity-CVD; , Morbidity-IHD; PTB, BW, Early life mortality	Meta-analysis reported that all respiratory (RR=10.5, 95%CI=3.87-17.18, n=7), asthma (RR=38.26, 95%CI=7.91-68.60, n=6), and COPD (RR=13.33, 95%CI=7.31-19.34, n=4) HA and ED visits were high on smoky days compared to non-smoke days.	Not specified
Kochi et al., 2010	SR	Econlit, Medline, Google; Not specified	22 total: Historical control method (aggregate level data) (10), Time-series (12)	U.S. (6), Australia (7), Malaysia (3), Brazil (3), Singapore (2), Thailand (1)	Not specified; General population	Not specified	Not specified	Wildfire-specific $PM_{2.5}$ and PM_{10}	All-cause and cardio-respiratory mortality; HA & EDV for asthma, respiratory and cardiovascular system;	Most studies found consistent increases in general respiratory-related and asthma-related hospital admissions and ED visits during wildfire events. However, less evidence was found for mortality and cardiovascular hospital admission & ED visits during the wildfire period.	Not specified
Kondo et al., 2019	SR & MA	Web of Science, PubMed, and Ovid; Until October 2017	10 total: Time series (5), Case crossover (2),	U.S. (9), Mexico (1)	Not specified; General population	PRISMA	Not specified	Wildfire-specific $PM_{2.5}$	Respiratory-related HA and EDV	Meta-analysis found evidence of a greater effect of wildfire smoke on	Not specified

			Time-stratified case-crossover (1), Ecological (2)							respiratory health among females relative to males for asthma (RRR: 1.035, 95% CI: 1.013, 1.057) and COPD (RRR: 1.018, 95% CI: 1.003, 1.032) and a lower relative risk for all respiratory outcomes among youth compared to adults (RRR: 0.976, 95% CI: 0.963, 0.989).	
Liu et al., 2015	SR	PubMed, Scopus; 1 Jan 1986-30 May 2014	61 total: Not specified	U.S. (20), Canada (3), Australia (15), Indonesia (4), Singapore (2), Malaysia (2), Thailand (1), Greece (1), Portugal (1), Spain (1), Finland (2), Russia (1), Brazil (7), Multi-country (1)	Not specified; General population	Not specified	Not specified	Wildfire-specific $PM_{2.5}$, PM_{10}, CO, CO_2, O_3, and NO_x, aerosol, TSP, hydrocarbon	All-cause mortality; Respiratory and COPD mortality; Cardiovascular morbidity; Respiratory morbidity; Diabetes, Diarrhea admissions; Birth weight; Bone marrow content; Blood biomarker concentration; Ophthalmic symptoms; Injuries; PEFR; physical strength & overall health	Most studies reported that wildfire smoke was positively associated with mortality and respiratory morbidity.	Not specified
Melody et al., 2019	SR	PubMed, Cochrane Library, EMBASE, Science Direct, Web of Science, ProQuest, GreenFILE and Scopus; Until January 2018	6 total: Cohort (6)	U.S. (1), Brazil (3), Australia (1), Indonesia (1)	1,056,245; Infants	PRISMA	NOS	Wildfire-specific $PM_{2.5}$ and PM_{10}; Mean aerosol index; number of heat spots	BW, LBW, GL, PTB, SB, Birth cohort size,	Some evidence was reported on a positive association between maternal exposure to wildfire and BWR, LBW and decrease in live births.	Not specified
Segal & Giudice, 2022	SR	PubMed and Web of Science; Until April 2022	Not specified	Not specified	Not specified; Reproductive health care providers	Not specified	Not specified	Wildfire-specific $PM_{2.5}$, and PAHs	LBW, Lifelong health conditions in children, PTB, Birth defects	Studies reported that maternal exposure to wildfire-specific $PM_{2.5}$ was positively associated with LBW and PTB, as well as the risk of birth defects.	Not specified

Varshney et al., 2023	SR	Ovid MEDLINE, EMBASE, CINAHL and Ovid PsycINFO; Until 22 March 2022	6 total: Cross-sectional (5), Cohort (1),	U.S. (1), Canada (1), Australia (2), Greece (2)	6,006; General population	PRISMA	JBI	Bushfires events	Mental health	Studies reported that vulnerable people often experienced mental health problems such as PTSD, anxiety, depression, anger, psychosis, paranoia, insomnia, somatization, and substance abuse disorder after the events.	Not specified
Weilnhammer et al., 2021	SR	Medline (PubMed), Embase (Ovid) and Cochrane Central Register of Controlled Trials (Wiley Online Library); January 1, 2007 to May 17, 2020	3 total: Time-series (1), Case-crossover (1), Ecological (1)	Greece (1), Spain (1), Multi-country (1)	2,036,722 residents and >78,568 deaths; General population	PRISMA	NICE	Forest fires events	All-cause mortality; Cardiovascular mortality; Respiratory mortality & morbidity; Mental health	Some evidence showed that exposure to forest fire was positively associated with all-natural causes, cardiovascular causes, respiratory causes mortality, and substance abuse disorder.	Not specified
Youssouf et al., 2014	SR	PubMed, ISI, and Google Scholar; Until April 2014	94 total: Not specified	Not specified	Not specified; General population	Not specified	Not specified	Wildfire-specific PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, AOD, and PHAs	All-causes and cardio-respiratory mortality; Cardio-respiratory morbidity; Birth weight	Consistent evidence was found for a positive association between wildfire-specific PM and all-cause mortality, respiratory and asthma admissions. Less evidence was found on maternal exposure to wildfire and LBW.	Not specified
Zhang et al., 2022	SR & MA	Embase Classic, Embase, Medline(R), PsycINFO, Scopus, and Web of Science; 1980-30 September 2021	5 total: Cohort (4), Cross-sectional (1)	Australia (5)	2,815; General population, Children, Adults, Firefighters, Burns patients	PRISMA	JBI	Bushfires events	Mental health	Meta-analyses showed a pooled prevalence of 14% (95% CI 12%-16%) for psychological distress in high-affected communities at 2–4 years post bushfire compared to low-affected communities. The overall prevalence of long-term psychological problems (PTSD and psychiatric impairment) in firefighters at 2–7 years ranged from 28% to 47.6%.	GRADE **Low:** Psychological distress; PTSD

Zhang et al., 2024	SR & MA	MEDLINE, EMBASE, and Scopus; Until 11 October 2022	59 total: Ecological (20),Case-control (19), Cohort (13), and cross-sectional (7)	U.S. (23), Canada (4), Brazil (10), Chile (1), Australia (8), Portugal (1), Spain (2), Indonesia (3), Thailand (1), Malaysia (3), India (1), Multi-country (2)	Not specified; Children and Adolescents	PRISMA	Navigation Guide framework	Wildfire-specific $PM_{2.5}$, PM_{10}, NO_2, O_3, and AOD; AQI; SPM; Aerosol index; Wildfire event days; Smoke intensity; Self-reported smell of smoke	All-cause mortality; Cardio-respiratory mortality; All-cause HA; Cardio-respiratory morbidities; Birth outcomes (BW, LBW, SGA, PTB, SB, birth defects); eye symptoms; skin inflammations; and other health outcomes covering height for age, diabetes, sore throat, headache, and physical activity	Meta-analysis results presented a pooled relative risk (RR) for 1.13 (95% CI, 1.05–1.23) for upper respiratory infection, whilst - 21.71 g for birth weight (95% CI, - 32.92 to - 10.50) per 10 µg/ m^3 increment in wildfire-specific $PM_{2.5}$ during wildfire event.	Not specified

SR, systematic review; MA, meta-analysis; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses; MOOSE, Meta-analysis Of Observational Studies in Epidemiology; SwiM, Synthesis without meta-analysis reporting guideline; NOS, Newcastle-Ottawa Quality Assessment Scale; NHLBI, the National Heart, Lung and Blood Institute's Quality Assessment Tool; ACROBATNRSI, Cochrane risk of a bias assessment tool for non-randomized studies of interventions; WHO, World Health Organization; OHAT, The National Toxicology Program's Office of Health Assessment and Translation tool; JBI, Joanna Briggs Institute Critical Appraisal Checklist; NICE, National institute for health and care excellence quality appraisal checklist; EDV, Emergency department visits; HA, Hospitalization admissions; DALY, Disability-adjusted life years; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease ; CVD, Cardiovascular disease; IHD, Ischemic heart disease; TOMS, Total Ozone Mapping Spectrometer; AQI, Air quality index; BW, Birth weight; LBW, Low birth weight; PTB, Preterm birth; GL, Gestational length; SGA, Small-for-gestational age; GDM, Gestational diabetes mellitus; GHT, Gestational hypertension; BWR, Birth weight reduction; SB, Stillbirth; PAHs, Polycyclic aromatic hydrocarbons; SPM, Suspended particulate matter; RRR, Ratio of relative risks.

3.5. Risk of bias assessment

The details of the RoB assessment for the included SRMAs are presented in Table S2. Of the 27 SRMAs evaluated, only six (22%) were rated as having a 'Low' RoB according to the AMSTER-2 tool. The remaining 21 (78%) were classified as 'Critically low' risk, primarily due to the presence of one or more critical flaws with or without non-critical weaknesses. Ten (37%) SRMAs lacked protocol registration. Twenty-six (96%) did not explicitly report the excluded studies with reasons. Nine (33%) did not employ methods for assessing the RoB in primary studies. Sixteen (59%) failed to account for the impact of RoB in primary studies on the overall review findings. Six (22%) did not adequately investigate publication bias and its potential influence on the results when they performed meta-analyses.

4. Discussion

4.1. Characteristics of the reviews and main findings

This umbrella review synthesized evidence across 27 SRMAs, including nine with meta-analyses, of health outcomes associated with wildfire smoke exposure. Overall, this substantial body of evidence supports that exposure to wildfire smoke is associated with a wide range of adverse health outcomes. These were published between 2010 and 2024 with increasing numbers in more recent years, reflecting growing concern and research interest in the health impacts of wildfire smoke.

Our findings highlight a broad spectrum of health outcomes associated with wildfire smoke exposure, emphasizing the consistency in certain associations and discrepancy in others. Respiratory morbidity emerged as the most frequently studied outcome, appearing in 59% of the reviews followed by mental health outcomes, cardiovascular morbidity, and mortality. Notably, wildfire-related $PM_{2.5}$ was consistently associated with increased risk of all-cause mortality and respiratory outcomes, particularly hospitalizations and ED visits related to respiratory disease and asthma. Additionally, PTSD, depression, and anxiety, showed consistent associations with wildfire exposure. Adverse birth outcomes such as reduced birth weight reduction, LBW and PTB were associated with wildfire smoke in several studies, although the certainty of evidence was not the same. These findings align with scoping reviews that have concluded wildfire smoke is consistently associated with all-cause mortality (Phung et al., 2022; Reid et al., 2016), respiratory outcomes (Grant and Runkle, 2022; Phung et al., 2022; Reid et al., 2016; Skinner et al., 2022) and mental health (Adu et al., 2023; Koopmans et al., 2022; To et al., 2021; Woodland et al., 2023). In contrast, the findings related to cause-specific mortality, cardiovascular outcomes and other morbidities, such as cancer and lung function disease, were less consistent. While some studies reported significant associations between wildfire smoke and cardiovascular morbidity, others found limited or no evidence, particularly concerning specific conditions like CHF and IHD. Similarly, the evidence for other health effects, including cancer, diabetes, and oxidative stress, was sparse and inconclusive. These findings align with scoping reviews that have concluded wildfire smoke is consistently associated with all-cause mortality (Phung et al., 2022; Reid et al., 2016), respiratory outcomes (Grant and Runkle, 2022; Phung et al., 2022; Reid et al., 2016; Skinner et al., 2022) and mental health (Adu et al., 2023; Koopmans et al., 2022; To et al., 2021; Woodland et al., 2023). In contrast, the findings related to cause-specific mortality including respiratory and cardiovascular mortality, cardiovascular morbidity and other morbidities, such as cancers, infectious diseases were less consistent. While some studies reported significant associations between wildfire smoke and cardiovascular morbidity, others found limited or no evidence, particularly concerning specific conditions like CHF and IHD.

4.2. Methodological considerations and limitations

One of the limitations identified in this umbrella review was the high methodological heterogeneity across the primary studies. This heterogeneity stemmed from differences in study design, exposure assessment, and outcome measurement, which complicated synthesizing the body of evidence. The included review studies in this umbrella review reported significant limitations in exposure assessment and a wide range of methods, each with their own advantages and limitations. A primary challenge was the reliance on indirect markers and proxies, such as satellite-based air quality data or heat hotspots, which could inaccurately capture the specific pollutants emitted by wildfires (Amjad et al., 2021), although they have advantages of providing exposure estimates in times and locations without monitors. Many studies used wildfire events as the primary measure of exposure, which introduced potential misclassification due to the time-varying nature of wildfire extent and intensity and thereby not fully capturing the dynamic changes in wildfire smoke. As wildfires fluctuate in intensity and spread over time, relying on a single event or limited timeframe may not accurately reflect the true exposure experienced by populations (Gao et al., 2023). Proximity-based methods, which use distance from wildfire-affected areas as a proxy for exposure do not account for variations in smoke intensity caused by wind and other factors (Amjad et al., 2021). The limitations extend to spatial and temporal coverage, where ground-based monitors and satellite data may not provide comprehensive or localized exposure assessments. Satellite data, while providing broad spatial coverage, may lack the precision of ground-based measurements, especially in urban areas where local sources of pollution may influence $PM_{2.5}$ levels (G. Chen et al., 2021). Additionally, the variability in the chemical composition of wildfire smoke, influenced by combustion conditions and local vegetation, is rarely. As wildfires fluctuate in intensity and spread over time, relying on a single event or limited timeframe may not accurately reflect the true exposure experienced by populations (Gao et al., 2023). Proximity-based methods, which use distance from wildfire-affected areas as a proxy for exposure may not account for variations in smoke intensity caused by wind and other factors (Amjad et al., 2021). The limitations extend to spatial and temporal coverage, where ground-based monitors and satellite data may not provide comprehensive or localized exposure assessments. Satellite data, while providing broad spatial coverage, may lack the precision of ground-based measurements, especially in urban areas where local sources of pollution could influence $PM_{2.5}$ levels (Chen et al., 2021). Additionally, the variability in the chemical composition of wildfire smoke, influenced by combustion conditions and local vegetation, is rarely incorporated in wildfire and health studies due to the lack of available information (Liu et al., 2015). Lastly, a significant limitation in the extant research is the reliance on ambient data to infer individual-level exposure, which may not fully capture the nuanced health effects experienced by specific populations. This discrepancy arises due to differences between ambient wildfire smoke concentrations and actual personal exposures, including factors like indoor air quality, indoor/outdoor activity patterns, built environment characteristics, and evacuation behaviors during wildfire events. The imperfect assessment of wildfire smoke pollution may result in an incomplete understanding of the true extent of personal exposure and its associated health impacts (Gould et al., 2024).

Another limitation faced by available reviews on wildfire and health is the lack of uniformity in reporting study results and association estimates. Heterogeneities in study design, exposure definitions, outcome evaluations, and statistical approaches complicate comparisons across studies and may lead to inconsistent pooled findings. The reviewed studies also varied in their control for important confounders, such as ambient air pollution and examination of populations at greater risk (e.g., those with pre-existing health conditions) (Amjad et al., 2021). The role of other variables like temperature, stress, sociodemographic variables, and mobility patterns has not been fully addressed, leading to potential bias in the observed outcomes (Foo et al., 2024). In some cases, such information is unavailable in epidemiological studies (e.g., mobility patterns). Many studies examined the general population and some investigated potentially at-risk groups, but further research is needed on vulnerable groups such as children, pregnant women, the elderly, and those with pre-existing conditions (Gao et al., 2023).

The episodic nature of wildfires and the reliance on short-term exposure assessments could have complicated the analysis of their long-term health effects (Gao et al., 2023). Moreover, the lack of longitudinal studies further constrained understanding of how health outcomes, such as sleep disturbances (Issac et al., 2021) or respiratory issues (Gould et al., 2024), evolve over time following wildfire exposure. Variability in the timing of assessments across studies also made it challenging to draw consistent conclusions about the temporal relationship between exposure and health outcomes.

Another limitation in this body of research is the lack of studies in low- and middle-income countries (LMICs). This limitation significantly constrains the generalizability of our results, as it fails to capture the substantial geodemographic variations in climatic factors, mitigation and adaptation strategies, and population characteristics that are unique to LMICs. In regions like Africa and South Asia, which are under-represented in our data with only a few studies, the effects of wildfire smoke on health outcomes may be more pronounced due to factors such as higher rates of adverse birth outcomes, lack of adequate mitigation and adaptation resources, and weaker healthcare systems (Giudice et al., 2021). This limitation significantly constrains the generalizability of our results, as it fails to capture the substantial geodemographic variations in climatic factors, mitigation and adaptation strategies, and population characteristics that are unique to LMICs. In regions like Africa and South Asia, which are under-represented in our data with only a few original studies, the effects of wildfire smoke on health outcomes may be more pronounced due to factors such as generally poorer health status, lack of adequate mitigation and adaptation resources, and weaker healthcare systems (Giudice et al., 2021). These regions are likely to experience heightened effects of climate change, exacerbated by indirect impacts like infection and food insecurity. Moreover, the lack of exposure data and individual-level electronic health records in LMICs pose significant challenges for conducting large-scale, population-based longitudinal studies (Frøen et al., 2016). In these contexts, the Demographic Health Survey (DHS), despite its limitations, is often the most nationally representative dataset available (Goyal et al., 2019; Odo et al., 2023). Recent research has linked fine spatiotemporal pollution data with DHS datasets to provide epidemiological evidence in LMICs, showing associations between medium-term exposure to landscape fire and infant mortality across multiple LMICs (Xue et al., 2021). Similarly, studies examining long-term exposure to landscape fire smoke have also reported increased risks of acute respiratory infections among children in these regions (Li et al., 2023). Moreover, the lack of exposure data and individual-level electronic health records in LMICs pose significant challenges for conducting large-scale, population-based longitudinal studies (Frøen et al., 2016). In these contexts, the Demographic Health Survey (DHS), despite its limitations, is often the most nationally representative dataset available (Goyal et al., 2019; Odo et al., 2023). Recent research has associated fine spatiotemporal pollution data with DHS datasets to provide epidemiological evidence in LMICs, showing associations between medium-term exposure to landscape fire and infant mortality across multiple LMICs (Xue et al., 2021). Similarly, studies examining long-term exposure to landscape fire smoke have also reported increased risks of acute respiratory infections among children in these regions (Li et al., 2023).

A final limitation is the inconsistent use of RoB assessment tools across the included reviews and the inconsistency in the tools applied. Most reviews applied tools like the NOS and JBI. Only one used a

Navigation guide framework, while others did not clearly specify their methods for assessing the risk of bias, potentially impacting the reliability of the findings.

A further limitation is that many applied tools were largely designed to assess quality in other types of studies (e.g., clinical trials) and are not perfectly matched to the epidemiological design. Another limitation was the inconsistent use of RoB assessment tools across the included reviews. Most reviews applied tools such as the NOS and JBI tool. Only one used a navigation guide framework, while others did not clearly specify their methods for assessing the risk of bias, potentially impacting the reliability of the findings. It is recommended to assess the risk of bias in primary studies within SRMAs by employing frameworks such as the Office of Health Assessment and Translation (OHAT) (OHAT, 2015) or the Navigation Guide systematic review approaches (Woodruff and Sutton, 2014). Another limitation was the infrequent assessment of the overall certainty of evidence (e.g., using the GRADE framework) in the included systematic reviews. Only three reviews applied GRADE, and we recommend future studies evaluate the credibility of the evidence using tools such as GRADE framework, which are widely used for evaluating medical evidence in environmental and occupational health research (Morgan et al., 2016).

4.3. Plausible mechanisms linking wildfire and human health

Wildfires cause direct injuries and deaths via burns and suffocation (Othman and Kendrick, 2010). Moreover, they can induce adverse health effects indirectly, through a number of biological mechanisms. The plausible mechanisms underlying the association between wildfire exposure and various health outcomes are multifaceted and complex. Wildfire smoke contains a mixture of PM, gases, and chemicals, including CO, NO_2, VOCs, and PAHs., among others. While the biological mechanisms through which wildfire smoke impacts human health are not fully understood, the associations could possibly be explained by the following pathways.

Wildfire-specific $PM_{2.5}$ contains high levels of proinflammatory and oxidative components, such as PAHs and VOCs, that generate reactive oxygen species (ROS), leading to oxidative stress and inflammation. The resulting oxidative stress triggers the transcription of pro-inflammatory factors, leading to widespread inflammation—a key mechanism behind respiratory and other systemic health problems (Franzi et al., 2011; Tsoumakidou and Siafakas, 2006; Weichenthal et al., 2013; Xu et al., 2020). Wildfire smoke also tends to have a higher proportion of ultrafine particles, which are particularly reactive and capable of producing hydrogen peroxide, further exacerbating oxidative stress and inflammation. This heightened inflammatory response can lead to severe respiratory conditions, cardiovascular issues, and other health complications, which collectively increase the risk of mortality, particularly in vulnerable populations (Kim et al., 2018). Additionally, wildfires cause direct injuries and deaths via burns and suffocation (Othman and Kendrick, 2010). The pollutants in wildfire smoke can induce cellular and molecular damage, including DNA damage and epigenetic changes, further aggravating health risks and potentially leading to long-term adverse effects. The combination of these factors significantly increases the risk of mortality during and after wildfire events (Liu et al., 2022; Ward-Caviness et al., 2016). Wildfires typically occur during the warm season, often accompanied by extreme heat and increased ambient levels of pollutants like carbon monoxide and nitrogen oxides from other sources. The interaction between these factors and wildfire $PM_{2.5}$ can amplify the adverse health effects, particularly respiratory and cardiovascular issues (Dong et al., 2017; Heaney et al., 2022; Xu et al., 2020). Wildfire-specific $PM_{2.5}$ often contains high levels of proinflammatory and oxidative components, such as PAHs and VOCs, that can generate reactive oxygen species (ROS), leading to oxidative stress and inflammation. The resulting oxidative stress triggers the transcription of proinflammatory factors, leading to widespread inflammation—a key mechanism behind respiratory and other systemic health problems (Franzi et al., 2011; Tsoumakidou and Siafakas, 2006; Weichenthal et al., 2013; Xu et al., 2020). Wildfire smoke also tends to have a higher proportion of ultrafine particles, which are particularly reactive and capable of producing hydrogen peroxide, further exacerbating oxidative stress and inflammation. This heightened inflammatory response can lead to respiratory conditions, cardiovascular issues, and other health complications, which collectively can increase the risk of mortality, particularly in vulnerable populations (Kim et al., 2018). The pollutants in wildfire smoke can induce cellular and molecular damage, including DNA damage and epigenetic changes, further aggravating health risks and potentially leading to long-term adverse effects. The combination of these factors significantly can increase the risk of mortality during and after wildfire events (Liu et al., 2022; Ward-Caviness et al., 2016). Moreover, wildfires typically occur during the warm season, often accompanied by extreme heat and increased ambient levels of pollutants such as ozone. The interaction between these factors and wildfire $PM_{2.5}$ can amplify the adverse health effects, particularly respiratory and cardiovascular issues (Dong et al., 2017; Heaney et al., 2022; Xu et al., 2020).

Ultrafine particles in wildfire smoke can cross the blood-placental barrier, entering the bloodstream and disrupting maternal-fetal blood circulation, which impairs fetal development (Chen et al., 2021). These particles can penetrate deep into the lungs' alveolar sacs, causing respiratory issues and entering the bloodstream, where they may trigger systemic effects linked to physical health disorders (Basilio et al., 2022). Further, maternal exposure to these particles leads to vascular inflammation, oxidative stress, and cellular dysfunction, causing placental stress and dysfunction, potentially resulting in preterm birth (PTB) and other adverse birth outcomes (Holstius et al., 2012).

The long-term exposure to toxic compounds in wildfire smoke, including polycyclic aromatic hydrocarbons and other carcinogens, may increase the risk of developing cancers, although the evidence is currently limited (Korsiak et al., 2022). Additionally, wildfire smoke has been associated with a range of other morbidities, including lung function impairments, diabetes, and exacerbation of chronic conditions, likely due to the cumulative effects of inflammation, oxidative stress, and immune system disruption (Cascio, 2018). The long-term exposure to toxic compounds in wildfire smoke, including polycyclic aromatic hydrocarbons and other carcinogens, may increase the risk of developing cancers, although the evidence is currently limited (Korsiak et al., 2022).

The psychological stress of experiencing or being exposed to wildfires, coupled with the physiological effects of heavy metal and metalloids by inhaling toxic smoke, can contribute to the development or exacerbation of mental health conditions such as PTSD, depression, anxiety, and psychological distress (Boaggio et al., 2022). The disruption of daily life, displacement, and loss of property or loved ones during wildfires can further compound mental health issues (To et al., 2021).

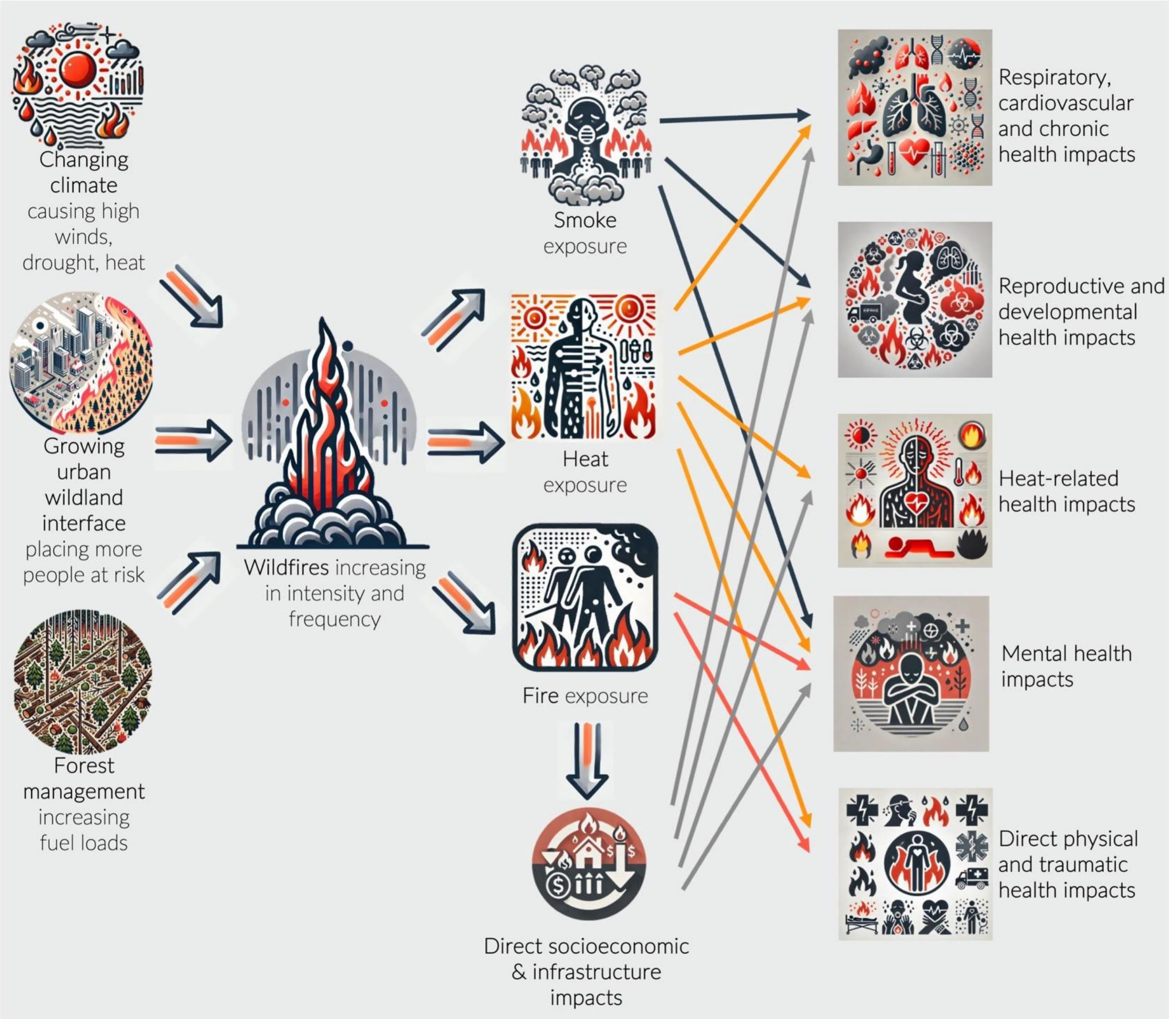


Figure 3. Mechanisms of wildfire exposure and its impact on various health outcomes.

4.4. Future research directions

Future research on the health impacts of wildfire smoke should prioritize longitudinal and mechanistic studies to better understand the long-term effects of exposure, as well as the chemical structure of particles and the air pollution mixture. Investigating the biological and mechanistic pathways—such as oxidative stress, inflammation, and cellular damage—that link wildfire smoke to various health outcomes is crucial for understanding the health impacts. Additionally, expanding research efforts to include LMICs and under-represented regions is essential. These areas may face unique vulnerabilities and challenges due to limited resources and healthcare infrastructure. By addressing these gaps, researchers can gain a more comprehensive understanding of the global impact of wildfire smoke.

Improving exposure assessment methodologies is also vital. Current methods often fail to fully capture the spatial and temporal variations in wildfire smoke intensity. Although the development and validation of advanced technologies, such as personal exposure monitors and localized air quality data, enhance the precision of exposure measurements, these approaches are not ideally suited for long-term studies. Their limitations include an inability to differentiate between pollution sources and a reliance on sustained data collection, which is essential for understanding air quality trends over time. Additionally, registering review protocols can minimize duplication, and systematic reviews should consistently perform quality or risk of bias assessments to enhance methodological rigor, where applicable. Future review studies should focus on addressing methodological limitations by adhering to established review guidelines, such as Navigation guide framework (Woodruff and Sutton, 2014), OHAT framework (OHAT, 2015) or new Conduct of Systematic Reviews in Toxicology and Environmental Health Research (COSTER) guidelines for environmental health research (Whaley et al., 2020). Additionally, registering review protocols can minimize duplication, and systematic reviews should consistently perform quality or risk of bias assessments to enhance methodological rigor, where applicable. Prominent quality assessment tools, such as the Navigation Guide framework (Woodruff and Sutton, 2014) or OHAT tools (OHAT, 2015), could be employed to ensure thorough evaluation of bias and GRADE approach to best report overall confidence in findings (Morgan et al., 2016).

Furthermore, research should include less-studied health outcomes such as infectious disease, hypertension, metabolic syndrome, cancers, diabetes, lung function impairments and other less-studies major contributor to the global burden of disease. Investigating the cumulative effects of wildfire smoke on multiple health conditions will provide a more complete picture of its overall impact on well-being. The psychological and social impacts of wildfire smoke exposure also require further exploration. Research should focus on mental health disorders and social stressors related to wildfire events, with the aim of developing targeted interventions to support affected communities. Understanding these impacts is important for creating holistic public health strategies and support systems. Furthermore, research should prioritize studying the health impacts of wildfire smoke on vulnerable populations, including children, pregnant women, racial/ethnic minority subpopulations, forest-dependent communities, persons with disabilities, those with low socio-economic status, older persons, and individuals with pre-existing health conditions. These groups are at higher risk for adverse health outcomes due to their physiological and developmental sensitivities, as well as their capacity to adapt, such as access to healthcare. Future research should address these methodological limitations, improve causal relationship estimation, and ensure more comprehensive coverage of vulnerable populations and diverse geographical regions.

4.5. Strength and limitations of this current review

This umbrella review provides a comprehensive synthesis of evidence from 27 SRMAs, encompassing both meta-analyses and non-meta-analyses, and is, to the best of our knowledge, the first of its kind on wildfire smoke’s health impacts to date. By including review studies published between 2010 and 2024, the review reflects on recent research trends and offers an up-to-date perspective on how wildfire smoke can affect health. The broad range of health outcomes covered—spanning mortality, respiratory, cardiovascular, mental health, and adverse birth outcomes—provides a thorough understanding of the multifaceted impacts of wildfire smoke as evidenced in the available literature. The identification of consistent associations, such as respiratory morbidity, all-cause mortality, and mental health conditions, underscores the robustness of the evidence and highlights key areas for public health focus. Additionally, the review's identification of gaps in the literature, such as the lack of data from low- and middle-income countries and inconsistencies in exposure assessment, offers valuable insights for guiding future research. Importantly, the review adhered to rigorous methodological standards by registering the protocol in PROSPERO, following PRISMA guidelines, and using AMSTAR-2 for risk of bias assessment, which enhances the reliability and transparency of the findings.

Our umbrella review has several limitations. The literature search was restricted to specific leading databases and articles published in English, potentially missing studies published in non-indexed sources or non-English languages, which could affect the generalizability of our findings. The majority of SRMAs were rated as having a 'Critically low' quality according to the AMSTER-2 tool due to issues included the lack of protocol registration, inadequate reporting of excluded studies and insufficient assessment of risk of bias, lack of reporting the impact of risk of bias on overall review findings, and lack of publication bias investigation.

5. Conclusion

This umbrella review provides a comprehensive synthesis of evidence from 27 SRMAs, nine with meta-analyses, on the health impacts of wildfire exposure. It covered a broad range of health outcomes, including respiratory, cardiovascular, mental health, and adverse birth outcomes. We identified consistently harmful associations between wildfire and respiratory morbidity, all-cause mortality, and mental health conditions such as PTSD, depression, and anxiety. However, findings on cause-specific mortality, cardiovascular outcomes, and other health effects were less consistent. The high proportion of reviews with critically low level of quality, coupled with inadequate reporting and risk assessment practices, highlights the need for improved methodological rigor in future research. Addressing these limitations and expanding research efforts to include underrepresented populations and regions will be crucial for advancing our understanding of wildfire smoke's health effects. Future research should emphasize longitudinal and mechanistic studies to elucidate long-term effects of wildfire smoke and their underlying biological pathways, improve exposure assessment methods with advanced technologies, and adhere to established environmental health research review guidelines to enhance methodological rigor and global understanding. It is equally important to broaden research efforts to include LMICs and underrepresented regions, as these areas often face unique vulnerabilities stemming from limited resources and healthcare infrastructure.

Conflicts of interest

No authors report conflicts of interest.

Author contributions

M.M.P., M.B., M.H.E.B., P.D., M.J.Z.S, M.L.B., & T.A.B. conceptualized the study, created the methodology; M.M.P., M.B., M.R.R, M.A.R., conducted data curation, and wrote the original draft. M.M.P. conducted analysis; M.M.P & M.H.E.B. created visualizations. All authors contributed to reviewing and editing.

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