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REVIEW ARTICLE

Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis

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Abstract

Air pollution is a major cause of specific deaths worldwide. This review article aimed to investigate the results of cohort studies for air pollution connected with the all-cause, cardio-respiratory, and lung cancer mortality risk by performing a meta-analysis. Relevant cohort studies were searched in electronic databases (PubMed/Medline, Web of Science, and Scopus). We used a random effect model to estimate the pooled relative risks (RRs) and their 95% CIs (confidence intervals) of mortality. The risk of bias for each included study was also assessed by Office of Health Assessment and Translation (OHAT) checklists. We applied statistical tests for heterogeneity and sensitivity analyses. The registration code of this study in PROSPERO was CRD42023422945. A total of 88 cohort studies were eligible and included in the final analysis. The pooled relative risk (RR) per 10 μg/m^3 increase of fine particulate matter ($PM_{2.5}$) was 1.080 (95% CI 1.068–1.092) for all-cause mortality, 1.058 (95% CI 1.055–1.062) for cardiovascular mortality, 1.066 (95%CI 1.034–1.097) for respiratory mortality and 1.118 (95% CI 1.076–1.159) for lung cancer mortality. We observed positive increased associations between exposure to $PM_{2.5}$, PM_{10}, black carbon (BC), and nitrogen dioxide (NO_2) with all-cause, cardiovascular and respiratory diseases, and lung cancer mortality, but the associations were not significant for nitrogen oxides (NOx), sulfur dioxide (SO_2) and ozone (O_3). The risk of mortality for males and the elderly was higher compared to females and younger age. The pooled effect estimates derived from cohort studies provide substantial evidence of adverse air pollution associations with all-cause, cardiovascular, respiratory, and lung cancer mortality.

Keywords Air pollution · All-cause mortality · Cardiovascular mortality · Lung cancer · Respiratory mortality

Introduction

Air pollution is a well-known risk factor for mortality and burden of disease [1]. Recent estimates from the Global Burden of Disease (GBD) study estimated that ambient air pollution caused 4.2 (95% confidence interval 3.7–4.8) million excess deaths (7.6% of total global mortality) for the year 2015 [2]. World Health Organization (WHO) in 2019, estimated that 99% of the global population lived in areas where air quality levels exceeded the air quality guideline values [3]. The major ambient air pollutants include particulate matter (PM), nitrogen dioxide (NO_2), nitrogen oxide (NO), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and volatile organic compounds (VOCs) [4, 5]. PM is classified according to particle size. Fine particulate matter ($PM_{2.5}$) is defined as particles with a diameter equal to or less than 2.5 μm and coarse particulate matter (PM_{10}) is defined as particles with a diameter of 10 μm or less [6].

Long-term exposure to air pollution induces many health problems such as respiratory problems, cardiovascular disease, neurologic disorders, stroke, and cancer [6–8]. Air pollution is also recognized as the fourth largest risk factor for premature and lung cancer death [6–9]. Among air pollutants, $PM_{2.5}$ and PM_{10} have been strongly connected to mortality and morbidity [10–12]. $PM_{2.5}$ exposure in the long term increases the relative risk of all-cause mortality by 8% and cardiovascular events by as much as 10% [13–15]. The presence of NO_2 and ground-level O_3 have been reported as important contributors to mortality or morbidity due to respiratory and cardiovascular diseases [5, 16, 17]. NO_2 is positively linked to increased mortality from cancer [18].

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Evidence also documented that higher levels of O_3 are connected with a higher risk of cognitive disorders, preterm birth, and reproductive health [19, 20].

Several studies are available that investigated the adverse health effects of air pollution [21], but the findings are inconsistent because air pollution is a complex mixture of pollutants from various sources. Some recent meta-analysis and cohort studies found an increased risk of mortality accompanied by air pollution [6, 22–27]. For instance, a cohort study by Peng et al. (2017) indicated that exposure to $PM_{2.5}$ was significantly connected with mortality from all-cause (HR 1.30, 95% CI 1.19–1.42), respiratory diseases (HR 1.19, 95% CI 1.02–1.38), lung cancer (HR 1.72, 95% CI 1.36–2.19) and other cancers (HR 1.76, 95% CI 1.33–2.32) [23]. Kim et al. (2018) in a meta-analysis of cohort studies indicate that exposure to $PM_{2.5}$, PM_{10}, and NO_2 were associated with increased mortality from all cancers [28]. Conversely, Tseng et al. (2015) in a cohort study found that exposure to $PM_{2.5}$ was not significantly connected to all-cause (HR 0.92, 95% CI 0.72–1.17) and cardiovascular (HR 0.80, 95% CI 0.43–1.50) mortality [29].

Most existing meta-analysis focus on short-term effects of air pollution, especially for cardio-respiratory mortality [11, 30, 31], and the pooled associations between long-term exposure to air pollution with cardio-respiratory and lung cancer health is poorly understood. Further, some recent reports providing additional evidence of the associations from areas with low levels of air pollution, which found stronger associations between ambient air pollution, and all-cause, cardio-respiratory, and lung cancer mortality. Similarly, considering the gaseous air pollutants, the estimated associations between these pollutants (e.g. SO_2, NO, NO_2, and O_3) with specific causes of mortality in long-term are still unclear. Thus, we decided to carry out a comprehensive literature review of cohort studies and perform a meta-analysis on the long-term association between particulate and gaseous air pollutants with all-cause and specific-cause of mortality. This review also systematically summarizes the effects of air pollution and mortality based on latest published evidence. The main goal of this systematic review and meta-analysis was to summarize the findings of cohort studies linked to air pollution with all-cause, cardiovascular, respiratory, and lung cancer mortality.

Method

Search of studies and selection

The current meta-analysis complies with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) methods (Table S1). The protocol of this study was registered on PROSPERO (https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=422945 with registration code = CRD42023422945). Electronic databases including Google Scholar, PubMed, Scopus, and Web of Science were independently searched by two researchers (B.K. and S.S.) to obtain the eligible studies up to 30 May 2022. The search for relevant literature was conducted with no restriction for regarding language, or publication date using appropriate keywords in the title and abstract, as well as Medical Subject Headings (MeSH). The search strategy is detailed in Appendix A (Supplementary Table). The reference lists of relevant studies were investigated for additional papers. We applied a combination of the following keywords: "air pollution", "air pollutant*", "particulate*", "particle*", "PM_{10}", "$PM_{2.5}$", "nitrogen oxide*", "nitrogen dioxide", "NO_2", "sulfur dioxide", "SO_2", "black carbon", "BC", "ozone", "O_3", "carbon monoxide", "CO" linked with "mortality", "all-cause mortality", "cardiovascular mortality", "respiratory mortality", "lung cancer mortality". The search was narrowed to prospective and retrospective cohort studies.

The title and abstract of the studies were screened and the full text of the selected studies was investigated for further assessment. The following inclusion criteria were applied for the extraction of information: (1) cohort studies explored the risk of mortality for all-cause, cardiovascular, respiratory, and lung cancer (2) studies investigated the exposure concentrations to PM_{10}, $PM_{2.5}$, BC, NO_2, NO, SO_2 and O_3 (3) studies provided information about relative risk (RR), hazard ratio (HR), odds ratio (OR) and beta slope of regression models with 95% CIs (Confidence Intervals) which linked with air pollutants. All included studies clearly described the outcomes according to the International Classification of Diseases (ICD) codes including ICD-10 A00-R99 or ICD-9 001–779 to describe all-causes mortality, ICD-10 I10–I70 or ICD-9 400–440 to explain cardiovascular mortality, ICD-10 J00–J99 or ICD-9 460–519 to explain respiratory mortality and ICD-9 C34 to define lung cancer mortality. Review studies, letters to the editor, news articles, poster and conference abstracts were excluded. The detailed stepwise literature selection is presented in Fig. 1.

Collection of data

Two investigators (B.K and S.S) separately extracted information including study location, study design, publication years, sample size, period of follow-up, method of exposure measurement, the concentration of air pollutants and their corresponding standard deviations, risk estimates of outcomes (RR, OR, HR) and their associated 95% CIs, mortality diagnosis by ICD codes, death rate, main findings and adjustment covariates (Table 1). We also reviewed the extracted data by the authors for quality control and assurance.

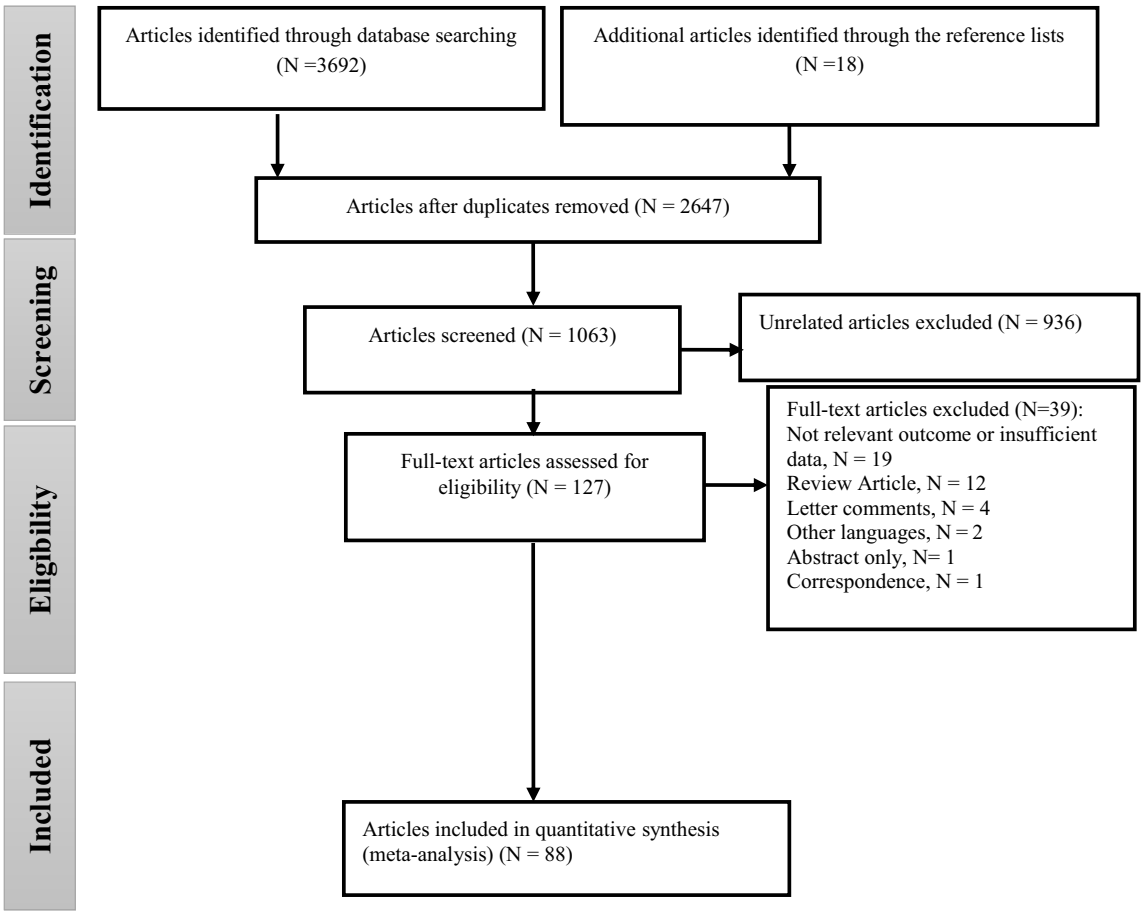


Fig. 1 Summary of the study selection procedures by the PRISMA flow diagram

Risk of bias assessment

The risk of bias and internal validity of studies was assessed by the Office of Health Assessment and Translation (OHAT) method as suggested by the National Institutes of Environmental Health Sciences-National Toxicology program [32]. Six domains including selection bias, confounders variable, exposure measurement bias, assessment of outcome, selective reporting bias, and missing data bias were evaluated. The risk of bias is categorized per domain as "*low*", "*probably low*", "*probably high*", "*high*" and "*not applicable*" (Table 3 and see additional Table S2-S89). Furthermore, the Newcastle–Ottawa Quality Assessment Scale (NOQAS) method was also applied to evaluate the methodological quality of the selected studies. The methodological quality for each study is based on estimated scores categorized as "≥ 7, *high*", "4–6, *intermediate*" and "≤ 3, *low*" (see Table S90- S91).

Data synthesis

Risk estimates obtained from included studies were expressed as RR, OR, HR, or beta (β) coefficients of regression. Estimates of OR, and HR were converted to RR by the following formulas:

$$RR = \frac{OR}{(1-r)+(r\times OR)} \quad (1)$$

$$RR = \frac{1-EXP(HR\times \ln(1-r)}{r} \quad (2)$$

where r is the rate of death among the reference group. If r was not proved in the studies, the Human Mortality Database was used to obtain death rates based on gender, and age, and the year of study [28, 33]. The percent change of mortality is computed from the following equation (Percent change (%) = (RR-1) × 100%) [6, 33]. To obtain the RR of mortality

Table 1 Summary of selected studies characteristics

#	Author and years	Location	Follow up period	Sample size	Male, N (%)	Mean age	Pollutants	Exposure assessment	Type of events	Deaths number
1	(Jerrett et al., 2009)	Canada	1992–2002	2,360	1,128 (48)	60	NO_2	LUR	ACM, CVM, RD, LCM	456
2	(Hales et al., 2021)	New Zealand	2013–2016	2,347,467	1,054,254 (47.3)	30	$PM_{2.5}$, NO_2	MS and VEM	ACM, CVM, RD	110,016
3	(Bauwelinck et al., 2022)	Belgian	2001–2011	5,474,470	2,769,925 (50.6)	52.6	$PM_{2.5}$, BC, NO_2, O_3	LUR and DM	ACM, CVM, RD, LCM	1,076,239
4	(So et al., 2022)	Denmark	2000–2017	3,083,227	1,488,951 (48.3)	53.0	$PM_{2.5}$, BC, NO_2, O_3	hybrid LUR	ACM, CVM, RD, LCM	-
5	(Krewski et al., 2005)	USA	1988–2000	1.2 million	5,580,000 (46.5%)	30	$PM_{2.5}$, SO_2	MS	ACM, CVM, RD, LCM	-
6	(Li et al., 2018)	China	2008- 2014	13 344	5657 (42%)	89	$PM_{2.5}$	SBP	ACM	-
7	(Kim et al., 2020)	Korean	2002–2013	436,933	218,466.5 (51%)	47.8	$PM_{2.5}$	MS	ACM, CVM	8041
8	(Yang et al., 2018)	Hong Kong	1998–2011	66,820	19,739 (32.6	70.2	$PM_{2.5}$, BC, NO_2	LUR	ACM, CVM, RD	
9	(Zhang et al., 2022)	China	2010–2018	30,843	14,958.86 (48.5)	48.5	NO_2	SBP	ACM	1662
10	(Villeneuve et al., 2002)	USA	1974–1991	105,714	-	60	$PM_{2.5}$	MS	ACM	1430
11	(Zhang et al., 2021)	Ontario, Canada	2009–2017	88,615	39,448 (44.5%)	52.1	$PM_{2.5}$, NO_2	SBP	ACM, CVM, RD	-
12	(So et al., 2020)	Denmark	1993 –2013	24,541	Female	53.2	$PM_{2.5,}$ PM_{10}, NO_2	DM	ACM, CVM, RD	3708
13	(Klompmaker et al., 2020)	Dutch, Netherlands	2013–2017	244,814	132,444.4 (54.1)	63	NO_2, PM_{10}, $PM_{2.5}$	LUR	ACM, CVM, RD, LCM	39,530
14	(Hanigan et al., 2019)	Australia	2006–2009	75,268	35,793 (47.6%)	65	$PM_{2.5,}$ NO_2	LUR	ACM	266,969
15	(Crouse et al., 2019)	Canada	2001–2011	2,400,825	1,159,598 (48.3)	57	$PM_{2.5}$	SBP	ACM	61,410
16	(Dehbi et al., 2017)	England	1989–2015	7529	2591 (34.4%)	48.45	$PM_{2.5,}$ $PM_{10,}$ BC, $NO_{2,}$ $NOx_{,}$ SO_2	LUR	CVM	1739
17	(Xi et al., 2022)	USA	2011–2016	314,079	131,209 (43.9	63.6	$PM_{2.5}$	LUR	ACM, CVM	82,567
18	(Li et al.)	UK	2006–2018	400,259	180,516.8 (45.1)	55.97	$PM_{2.5}$, $PM_{10,}$ NO_2, NOx	LUR	ACM, CVM, RD	21,612
19	(Weichenthal et al., 2017)	Canadian	2001- 2011	2,448,500	1,185,500	56	$PM_{2.5}$, O_3, NO_2	SBP	ACM, CVM, RD	331,440
20	(Jalali et al., 2021)	Isfahan, Iran	2001	3081	1589 (51.6)	49.55	$PM_{2.5}$	SBP with LUR	CVM	241
21	(Christidis et al., 2019)	Canadian	1981–2016	4,452,700	1,995,100	54	$PM_{2.5}$	SBP and LUR	ACM	50,700
22	(Tseng et al., 2015)	Taiwan	1989–1992	43,227	24,630	44.5	$PM_{2.5}$	MS	ACM, CVM	2222

Table 1 (continued)

#	Author and years	Location	Follow up period	Sample size	Male, N (%)	Mean age	Pollutants	Exposure assessment	Type of events	Deaths number
23	(Dimakopoulou et al., 2014)	European	1985–2005	307,553	-	49	$PM_{2.5,}$ $PM_{10,}$ $NO_{2,}$ NOx	LUR	ACM	1559
24	(Gan et al., 2013)	Canada	1994–1998	467,994	219,957.18 (47%)	62.3	BC, $PM_{2.5}$, NO_2, NO	LUR	ACM	541
25	(Carey et al., 2013)	USA	2003–2007	835,607	404,716	64	PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3	EBM	CVM, RD, LCM	83,103
26	(Di et al., 2017)	USA	2000–2012	60,925,443	26,807,195(44%)	70.1	$PM_{2.5}$, O_3	SBP with ANN	ACM	17,470,128
27	(Lefler et al., 2019)	USA	1987–2014	635,539	283,069.1 (45)	45.3	$PM_{2.5}$, PM_{10}	MS and LUR	ACM, CVM	149,580
28	(Sanyal et al., 2018)	France	1999–2012	13,239	-	-	$PM_{2.5}$, PM_{10}, NO_2, O_3	CTM	ACM, CVM, RD	700,747
29	(Kim et al., 2017)	South Korean	2002–2006	275,337	149,735	42	PM_{10}	Kriging	ACM, CVM, RD, LCM	5129
30	(Zhang et al., 2011)	Shenyang, China	1998–2009	9941	4824 (48.53)	60	PM_{10}, NO_2, SO_2	MS	ACM, CVM	394
31	(Enstrom, 2005)	Californians, USA	1959–2002	49,975	-	65	$PM_{2.5}$	MS	ACM	39,846
32	(Héritier et al., 2019)	Switzerland	2000–2008	4 404 046	2,113,942 (48)	52.4	$PM_{2.5}$, NO_2	MS and LUR	ACM	19,261
33	(Pope III et al., 2019)	USA	1986–2014	1,599,329	754,083.6 (47.5)	43.9	$PM_{2.5}$	kriging	ACM, CVM, LCM	267,204
34	(Yin et al., 2017)	China	1390–2005	189,793	Only men	54.8	$PM_{2.5}$	SBP	ACM, CVM, RD, LCM	83,393
35	(Fischer et al., 2015)	Netherland	2004–2011	7.1 million	3,444,166 (47.7)	60	PM_{10}, NO_2	LUR	ACM, CVM, RD, LCM	997,013
36	(Cesaroni et al., 2013)	Rome, Italian	2001–2010	1,265,058	-	67	$PM_{2.5,}$ NO_2	LUR	ACM, CVM, RD, LCM	227,321
37	(Ostro et al., 2010)	California, USA	2002–2007	45,000	Female	54.5	$PM_{2.5}$	MS	ACM, CVM, RD, LCM	2600
38	(Zeger et al., 2008)	USA	2000–2005	13.2 million	-	74	$PM_{2.5}$	MS	ACM	849,000,000
39	(Beelen et al., 2008)	Dutch, Netherland	1987–1996	120,852	58,279	64	$PM_{2.5}$, BC, NO_2, SO_2	LUR	ACM, CVM, RD, LCM	26,651
40	(Bentayeb et al., 2015)	France	1989–2013	20,327	14,790 (72.8)	43.7	PM_{10}, $PM_{2.5}$, NO_2, SO_2	CTM	ACM, CVM, RD	2416
41	(Cesaroni et al., 2012)	Rome, Italy	1995–2007	684,000	306,018	65	NO_2	LUR	ACM	45,006
42	(Strak et al., 2021)	European countries	1990–2010	325 367	167,655.8 (44%)	48.7	$PM_{2.5}$, BC, NO_2, O_3	LUR	ACM, CVM, RD	47,131
43	(Abbey et al., 1999)	California, USA	1977–1992	6,338	639	59	PM_{10}, SO_2, O_3, NO_2	MS	ACM, CVM, RD, LCM	1628

Table 1 (continued)

#	Author and years	Location	Follow up period	Sample size	Male, N (%)	Mean age	Pollutants	Exposure assessment	Type of events	Deaths number
44	(Cao et al., 2011)	China	1999–2000	169,871	36,537.71 (51.5)	55.8	NOx, SO_2	MS	ACM, CVM, RD, LCM	8319
45	(Zhou et al., 2014)	China	1990–2006	71,431	Only men	53.4	PM_{10}	MS	ACM, CVM, RD, LCM	10,711
46	(Pope et al., 1995)	USA	1982–1989	552,138	298,154.5 (54%)	56.5	SO_2, $PM_{2.5}$	MS	ACM, CVM, LCM	38,963
47	(Raaschou-Nielsen et al., 2012)	Netherlands	1993–2009	52 061	24 734 (47.5%)	56.1	NO_2	DM	ACM, CVM	6819
48	(Hales et al., 2012)	New Zealand	1996–1999	1 364 451	661 314	52	PM_{10}	DM	ACM, CVM, RD, LCM	32,943
49	(Filleul et al., 2005)	French	1974–1997	14 284	6802	42.2	PM_{10}, BC, NO_2, SO_2	MS	ACM, CVM, LCM	2531
50	(Heinrich et al., 2013)	Germany	1985–1994	4800	Female	55	PM_{10}, NO_2	MS	ACM, CVM, RD, LCM	740
51	(Jerrett et al., 2005)	Los-Angeles, USA	1982–2000	2,905	-	-	$PM_{2.5}$	Kriging	ACM, CVM, LCM	9426
52	(Hoek et al., 2002)	USA	1986–1994	5000	1859 (46%)	61	BC, NO_2	IDW	ACM, CVM, RD, LCM	734
53	(Beelen et al., 2014)	European countries	1992–2007	367,251	176,280.5 (48%)	55.5	$PM_{2.5}$, PM_{10}, NO_2, NOx	LUR	ACM	29,076
54	(Lipfert et al., 2006)	USA	1997–2001	28,635	-	60	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}	VEM	ACM	5638
55	(Coleman et al., 2022)	USA	1997–2014	403,748	182,791(45.3%)	45.88	$PM_{2.5}$	IEG	ACM, CVM, LCM	39,528
56	(Gehring et al., 2006)	Germany	1980–1990	4800	Female	55	NO_2, PM_{10}	MS	ACM, CVM	556
57	(Eftim et al., 2008)	USA	2000–2002	40 million	-	75	$PM_{2.5}$	MS	ACM	7,333,040
58	(Hansell et al., 2016)	England and Wales	1971–2009	367 658	175,532(47.7%)	32	PM_{10}, BC	LUR	ACM, CVM, RD	174,089
59	(Bauleo et al., 2019)	Italy	1996–2013	71 362	34 016 (47.7)	45	PM_{10}, NOx	DM	ACM, CVM, RD, LCM	14,844
60	(Pope Iii et al., 2002)	USA	1982–1998	1.2 million	-	66	$PM_{2.5}$, SO_2	MS	ACM, CVM, LCM	-
61	(Stafoggia et al., 2022)	European country	2000–2017	28,153,138	13,513,506(48%)	54	$PM_{2.5}$, BC, NO_2, O_3	LUR	ACM, CVM, RD, LCM	3,593,741
62	(Yazdi et al., 2021)	USA	2000–2016	40 million	18,729,280(46·3%)	75	$PM_{2.5}$, NO_2, O_3	SBP and LUR	ACM	27,800
63	(Pope III et al., 2004)	USA	1972–2000	1.2 million	-	45	$PM_{2.5}$	MS	ACM, CVM	-

Table 1 (continued)

#	Author and years	Location	Follow up period	Sample size	Male, N (%)	Mean age	Pollutants	Exposure assessment	Type of events	Deaths number
64	(Peng et al., 2017)	China	2003–2013	4444	3290 (74.0%)	46	$PM_{2.5}$	MS	ACM, CVM, LCM	891
65	(Liang et al., 2022)	Shanghai, China	2010– 2017	90,672	39,351.65 (43%)	46.2	$PM_{2.5}$	SBP and CTM	CVM	92,247
66	(Hystad et al., 2020)	Asian countries	2003–2018	157 436	66 193 (42.0%)	50.2	$PM_{2.5}$	MS and BHM	ACM, CVM	26 089
67	(Niu et al., 2022)	China	2010–2018	96 955	44 324 (45.7%)	46·5	O_3	RFM	CVM	2064
68	(Pope III et al., 2015)	Columbia	1982– 1983	669 046	-	60	$PM_{2.5}$	Hybrid LUR	ACM, CVM, RD	382,994
69	(Hayes et al., 2020)	USA	1995–2014	565,477	339 133 (60%)	60	$PM_{2.5}$	Hybrid LUR	CVM	41 286
70	(Chen et al., 2017)	China	1975–1998	39,054	19,460(49.8)	44.29	PM_{10}, SO_2	MS	CVM	1435
71	(Dong et al., 2012)	China	1973–2009	9,941	4,824 (48.53%)	58.09	PM_{10}, NO_2, SO_2	MS	RD	505
72	(Hvidtfeldt et al., 2019a)	Denmark	1993–2015	49,564	23,295.08 (47%)	56.3	$PM_{2.5}$	MMS	ACM, CVM, RD	10,193
73	(Wang et al., 2022b)	Atlanta, USA	2000–2016	13,590,387	5,943,391(43.70%)	74	$PM_{2.5}$	SBP	ACM	4,898,015
74	(Kazemiparkouhi et al., 2022)	Boston, MA, USA	2000–2008	15.4 million	6,405,516 (41.6%)	60	$PM_{2.5}$	MS	ACM, CVM, RD, LCM	3,049,738
75	(Beelen et al., 2015)	Copenhagen,Denmark	1985–2007	291,816	-	52	$PM_{2.5}$	LUR	ACM	25,466
76	(Sommar et al., 2021)	Roskilde, Denmark	1990–2014	43,216	20,743.68 (48%)	40	$PM_{2.5}$	MMS	ACM, CVM, RD	1517
77	(Chen et al., 2021b)	Louis, MO, USA	2006–2018	443,200	12,630 (43.86)	57.10	$PM_{2.5}$	SBP	ACM, CVM, RD	1960
78	(Wang et al., 2014)	Neuherberg, Germany	1985–2007	322,291	-	52	$PM_{2.5}$	LUR	CVM	9545
79	(Liu et al., 2021)	Wuhan, China	2010–2017	14,331	6979.197 (48.7%)	45.0	$PM_{2.5}$	SBP	CVM	1575
80	(Pond et al., 2022)	Pittsburgh, USA	1986–2015	617,966	278,084.7 (45%)	45.30	$PM_{2.5}$	LUR	ACM	103,454
81	(Ostro et al., 2015)	California, USA	2001–2007	133,479	Only women	57.3	$PM_{2.5}$	LUR	ACM, CVM, RD	6285
82	(Badaloni et al., 2017)	Netherlands, Italy	2001–2010	1,249,108	568,701 (45.5)	61	$PM_{2.5}$	LUR	ACM, CVM	223,995
83	(Liu et al., 2022)	Wuhan, China	2010 – 2017	30,524	14,804.14 (48.5%)	45.7	$PM_{2.5}$	V4.CH.02	ACM	1210
84	(Pinault et al., 2017)	Canadian	1998–2011	2,448,500	1,185,500	54	$PM_{2.5}$	SBP and MS	ACM, CVM, RD, LCM	347,000
85	(Crouse et al., 2012)	Canada	1991–2001	2,145,400	1,059,400 (49%)	49	$PM_{2.5}$	MS	ACM, CVM	200,000
86	(Lepeule et al., 2012)	USA	1979–2009	8,096	3667.49 (45.3%)	49.6	$PM_{2.5}$	MS	ACM, CVM, LCM	4493.28

Table 1 (continued)

#	Author and years	Location	Follow up period	Sample size	Male, N (%)	Mean age	Pollutants	Exposure assessment	Type of events	Deaths number
87	(Cesaroni et al., 2013)	Italy	2001–2013	1,265,058	-	68	NO_2	LUR and DM	ACM	144,441
88	(Raaschou-Nielsen et al., 2013)	European country	12.8 years	312 944	-	58	PM_{10}, NO_2	LUR	LCM	2095

Abbreviations: *VEM* vehicle emissions modelling tool, *ANN* artificial neural network, *CTM* chemistry transport model, *IDW* inverse distance squared weighted interpolation, *IEG* Integrated empirical geographic modeling, *RFM* Random forest model, *MMS* Multiscale modelling system, *LUR* land-use regression models, *DM* dispersion model, *MS* Environmental Monitoring station, *SBP* satellite-based predicting model or satellite remote sensing, *BHM* Bayesian hierarchical model, *ACM* All-cause mortality, *CVM* Cardiovascular mortality, *RD* Respiratory death, *LCD* Lung cancer Mortality, *GP* General population, *HB* Hospital- based population

from the beta (β) coefficients, we exponentiated the regression coefficient. Additionally, 95% Cl was estimated using an exponentiated regression coefficient with their standard error [β ± (1.96*SE)] [6, 34].

When exposure measurements were reported as ppb or ppm, these findings converted to μg/m^3 as follows: NO_2, 1 ppb = 1.88 μg/m^3; O_3, 1 ppb = 1.96 μg/m^3; SO_2, 1 ppb = 2.66 μg/m^3; CO, 1 ppb = 1.15 μg/m^3 [35]. If studies did not report the RR based on a unit of 10 μg/m^3 increment in each pollutant, the estimates of RR across studies were standardized using the following formula [34]:

$$RR_{Stdardized} = e^{\left(\frac{Ln(RR_{Origin}}{Increment_{Origin}} \times Increment_{Standardized}\right)} \quad (3)$$

Meta-analysis

Statistical analyses and forest plots were created by STATA12 and R version 3.6.1. The pooled effect (RR) of studies was computed using the random-effect and fixed-effect model based on the Mantel–Haenszel procedure. The presence of statistical heterogeneity between the estimated effect of studies was evaluated by I^2 and Cochran's Q-test (Significance level < 0.1). The I^2 value equals 25% indicating a "*low*" degree of heterogeneity, 50% moderate, and I^2 exceeds 75% suggesting a "*high*" degree of heterogeneity [36]. To assess the possible sources of heterogeneity, subgroup analyses were performed for sex, mean of age, and study location (Asia, Europe, Canada, and the United States). The presence of publication bias was evaluated by a funnel plot of the log RR against the standard error (SE). Funnel plot asymmetry was also tested by Egger's test with a significance level < 0.10. We applied the trim-and-fill method for detecting and adjusting the publication bias in our meta-analysis [6, 36]. Sensitivity analyses were achieved to investigate the robustness of our main analyses by analyzing the impact of excluding each study on the consistency of the results.

Results and discussion

Studies included

After searching databases, 3692 records were recognized. Eighteen publications were also added from the reference lists. Removing the duplicates and unrelated articles after the screening of abstracts, 127 studies were eligible to assess the title and full text. Finally, 88 articles were included in the meta-analysis and fulfilled the quality assessment criteria (Fig. 1) [14, 23–27, 29, 37–116]. Eighty-one studies involved an adult population with both genders, and five studies included only adult females [44, 67, 80, 86, 110]

and two studies included only adult males [64, 75]. Among the included studies, 66 studies investigated all-cause mortality, 64 studies evaluated cardiovascular mortality, 37 studies assessed respiratory mortality, and 31 studies considered lung cancer mortality as an outcome. The included studies were carried out in Europe (31 studies), the United States (27 studies), Canada (8 studies), and Asia (22 studies) (Fig. 2A and B). The total number of participants in these studies was 270877792 individuals (Table 1).

The concentrations of pollutants and methods of exposure assessment are diverse between the studies. The overall mean concentration of $PM_{2.5}$ derived from studies was 19.47 ± 4.26 μg/m^3, with a mean concentration of 39.81 ± 0.78 μg/m^3 in Asia, 14.92 ± 2.20 μg/m^3 in Europe, 19.69 ± 3.33 μg/m^3 in the USA, and 10.7 ± 2.08 μg/m^3 in Canada, (Fig. 3, See more in Table S3). Pooled average concentrations of PM_{10}, NO_2, SO_2, and O_3 derived from studies were 45.3 ± 17.68, 23.54 ± 8.92, 16.1 ± 4.65 and 60.67 ± 14.96 μg/m^3, respectively (Table 2). We found higher levels of air pollution in Asian developing countries (Fig. 3).

Methodological quality and risk of bias

The risk of bias rating based on investigated studies is presented in Table 3 (also see more detailed of risk of bias assessment in supplementary Table S4-S91). All individual studies had a high quality. The findings showed that the risk of bias for exposure measurement, assessment of outcome, and selective reporting bias differed among the studies. Selection bias for one study was rated as "*probably high*" risk [42] while other studies were "*low*" risk. For exposure measurement bias, 7 studies were rated as "*probably high*" risk because the sampling technique of these studies was not clearly described [27, 29, 42, 54–57]. Outcome assessment bias for 11 studies rated as "*probably high*" risk [41, 42, 51, 53, 57–59, 81–84]. The selective reporting bias of 10 studies rated as "*probably high*" risk [29, 41, 42, 48, 53–55, 57–59]. Results of the risk of bias assessment are displayed in Table 3, and summary tables justify for the judgments given for each bias domain presented in supplementary Table S4-S91.

Air pollutants and mortality

This is a meta-analysis investigating the relationship between exposure to air pollutants with the risk of mortality for all-cause, cardiovascular, respiratory, and lung cancer. We used data derived from 88 cohort studies carried out in 20 countries involving more than 270 million subjects. Using a random-effect model, exposure to $PM_{2.5}$, PM_{10}, NO_2, and SO_2 was strongly linked with mortality, whereas O_3 was not significantly related. The pooled estimates of all-cause mortality with air pollutants are presented in Table 4. Positive and significant associations were observed between the percent changes of all-cause mortality with a 10 μg/m^3 increment in $PM_{2.5}$ (RR 1.08, 95% CI 1.07–1.09), PM_{10} (RR 1.10, 95% CI 1.06–1.14), and BC (RR 1.04, 95% CI 1.02–1.07) (Fig. 4a-c). The estimates of heterogeneity between studies

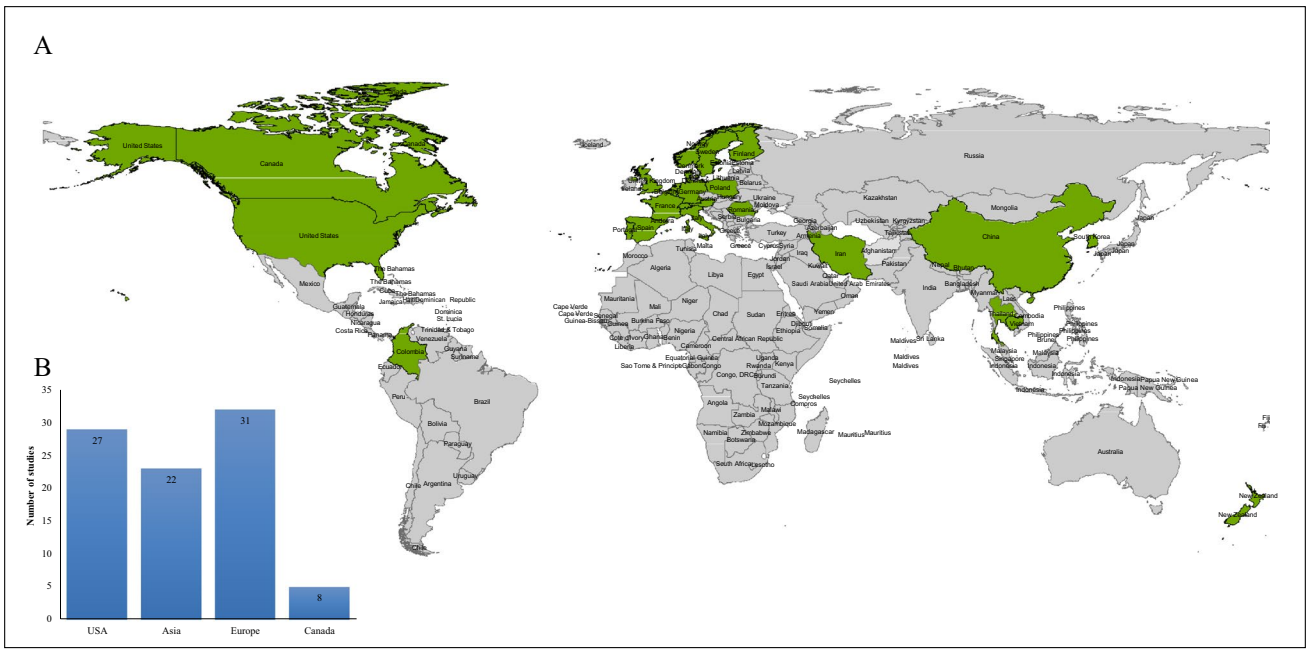


Fig. 2 **A** Geographic location of included studies and (**B**) the number of publications reporting the association between air pollutants with mortality

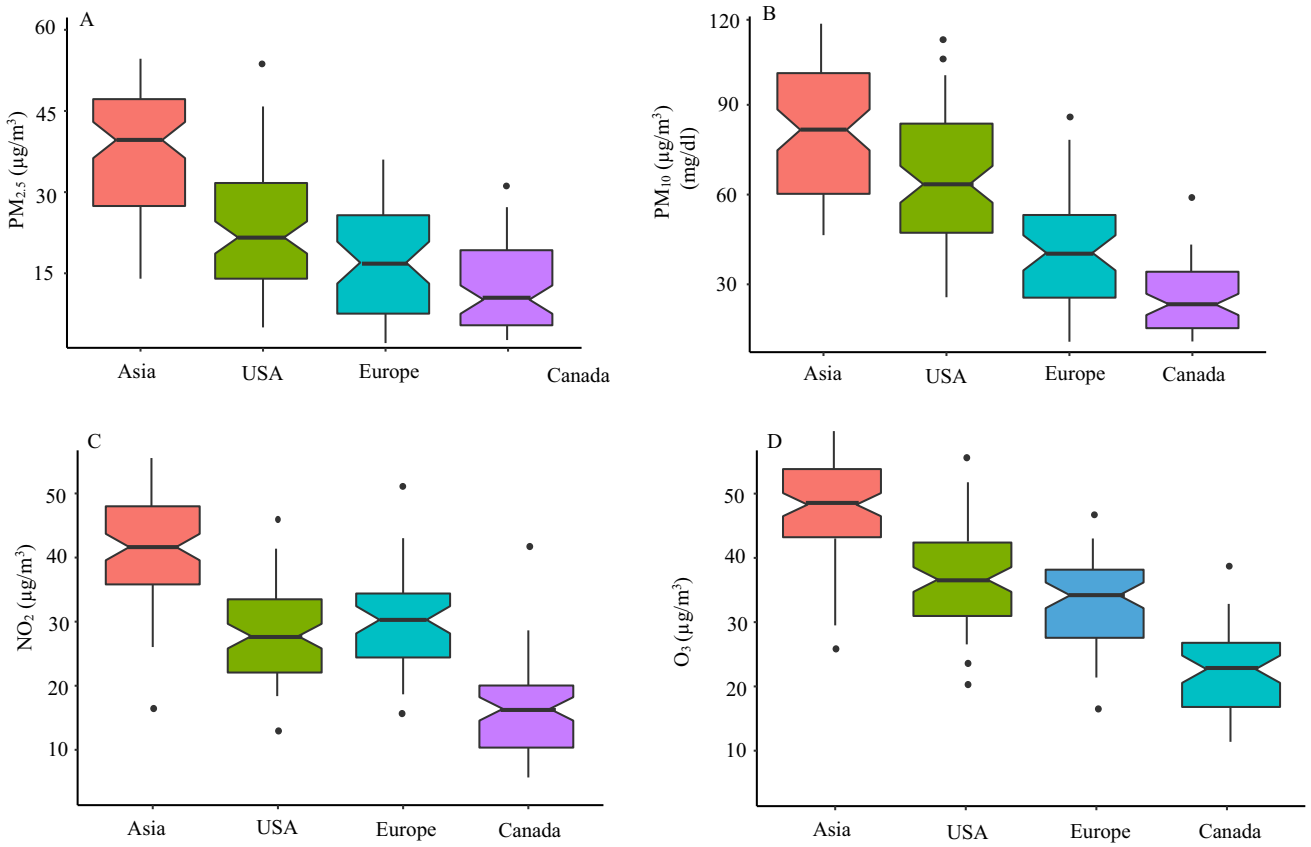


Fig. 3 The pooled concentration of $PM_{2.5}$ (**A**), PM_{10} (**B**), NO_2 (**C**), and O_3 (µg/m^3) (**D**) stratified by location

Table 2 Pooled concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 and CO (µg/m^3) derived from studies

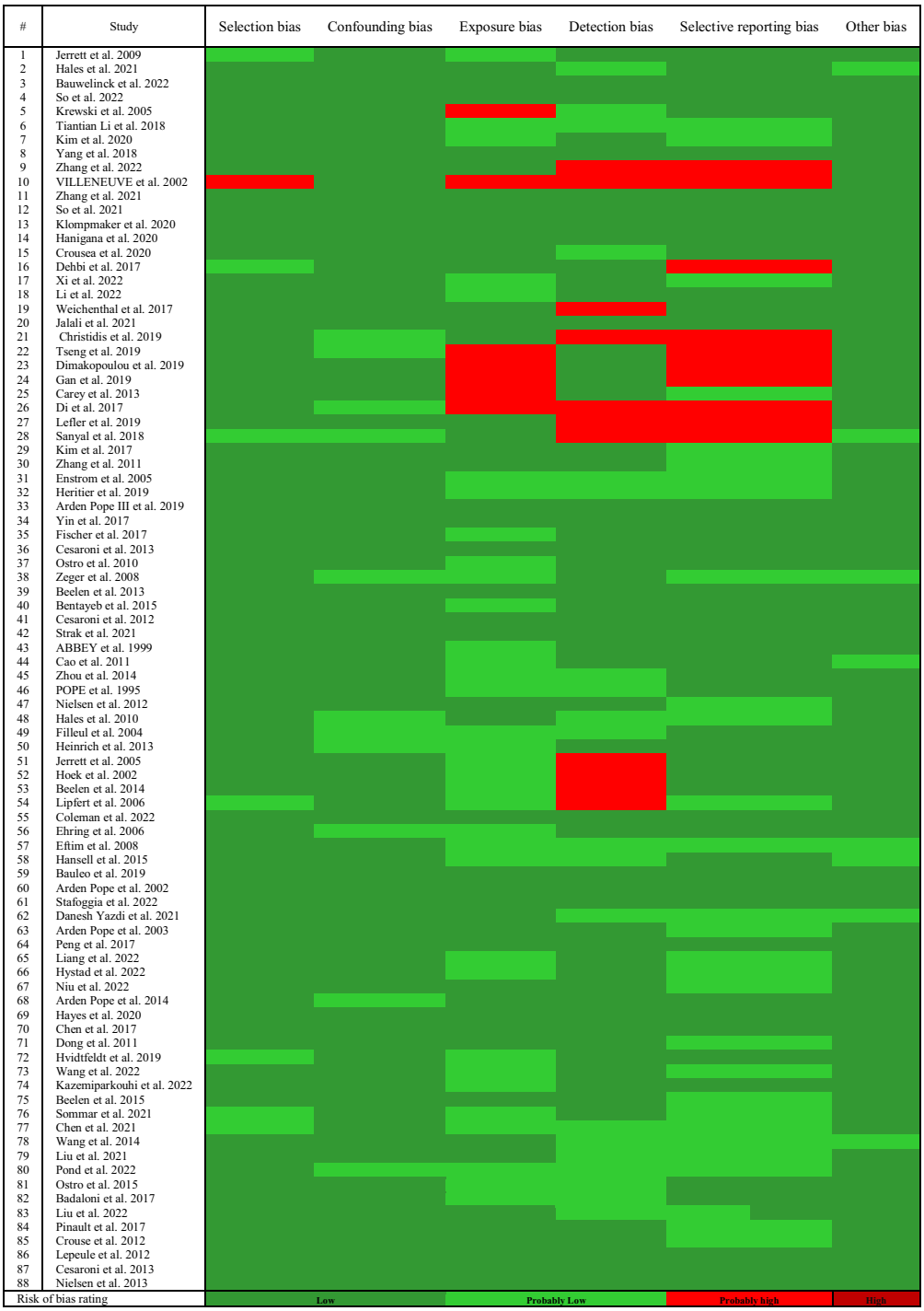
Pollutants (µg/m^3)	Mean	Sd	Lower	Upper	Cochran's Q	df	H	I^2	tau^2	*P*-value
$PM_{2.5}$	19.49	4.267	9.22	34.48	2935.32	61	6.94	97.9%	12.90	0.000
PM_{10}	45.29	17.68	24.48	368.79	266.57	20	3.651	92.5%	324.38	0.000
O_3	60.67	14.94	22.77	105.88	36.71	11	1.827	70.0%	122.02	0.000
NO_2	23.54	8.92	7.125	60.14	74.99	21	1.890	72.0%	17.53	0.000
SO_2	16.10	4.66	5.21	40.66	27.90	9	1.761	67.7%	1.4326	0.001
CO	1.04	0.26	0.4	3.72	39.51	7	2.376	82.3%	0.0170	0.000

were found to be high for $PM_{2.5}$, PM_{10}, and BC (Table 4, see Forest plot in Supplementary Fig. S1-7). Elevated risk of all-cause mortality significantly linked with a 10 µg/m^3 increment in NO_2 (RR 1.04, 95% CI 1.03–1.06), NO_x (RR 1.02, 95% CI 1.01–1.04) and SO_2 (RR 1.03, 95% CI 1.00–1.06) (Fig. 4a-c), but the association was not significant for O_3 (RR 0.98, 95% CI 0.97–1.01) (Table 4, see Forest plot in Supplementary Fig. S1-7). Heterogeneities between the studies were found to be high for NO_X, NO_2, SO_2, and O_3.

The highest elevated risk of cardiovascular mortality was significantly linked with a 10 µg/m^3 increment in PM_{10} (RR 1.15, 95% CI 1.08–1.22), the second highest with NO_2 (RR 1.06, 95% CI 1.04–1.08), followed by SO_2 (RR 1.06, 95% CI 1.01–1.11), $PM_{2.5}$ (RR 1.06, 95% CI 1.05–1.06), NO_x (RR 1.03, 95% CI 1.01–1.06), and BC (RR 1.03, 95% CI 1.01–1.05) (Fig. 4a-e). A non-significant association was observed between the risk of cardiovascular mortality with exposure to O_3 (RR 0.99, 95% CI 0.95–1.03) (Table 4, see Forest plot in Supplementary Fig. S8-14). The relationships between the risk of cardiovascular mortality with exposure to PM_{10}, $PM_{2.5}$, BC, NO_2, NOx, SO_2, and O_3 were investigated by 46, 17, 13, 24, 5, 9, and 9 studies, with "*high*" levels of heterogeneities ($I^2 > 75\%$) (Table 5).

Significant positive relations were observed between the risk of respiratory mortality with a 10 µg/m^3 increment in $PM_{2.5}$ (RR 1.066, 95% CI 1.034–1.097), PM_{10} (RR 1.196, 95% CI 1.114–1.279), BC (RR 1.048, 95% CI 1.025–1.07)

Table 3 Risk of bias rating for each study



and NO_2 (RR 1.061, 95% CI 1.033–1.089), except for NOx (RR 1.026, 95%CI 0.998–1.055), SO_2 (RR 1.041, 95% CI 0.964–1.118) and O_3 (RR 0.971, 95% CI 0.944–0.998) (Table 4, Supplementary Fig. S15-21).

We observed significant relations between the risk of lung cancer mortality with a 10 μg/m^3 increment in $PM_{2.5}$ (RR 1.118, 95% CI 1.076–1.159, I^2 77.40%, τ^2 0.0042), PM_{10} (RR 1.127, 95%CI 1.029–1.224), BC (RR 1.048, 95% CI 1.025–1.07), NO_2 (RR 1.067, 95%CI 1.039–1.095), NO_x (RR 1.057, 95%CI, 1.005–1.11), and SO_2 (RR 1.087, 95% CI 1.011–1.163). Applying the forest plot, the risk of lung cancer mortality was negatively related to exposure to O_3 (RR 0.921, 95% CI 0.865–0.978) (Table 4, Supplementary Fig. S22-28).

Table 4 The estimated pooled RR of mortalities associated with air pollutants using the random effect model

Parameters	RR	95% CI	Cochran's Q	H	I^2 (%)	tau^2	*P*-value
All-Cause mortality							
$PM_{2.5}$	1.080	1.068–1.092	2572	6.660	97.70	0.0014	0.000
PM_{10}	1.104	1.064–1.144	1211	7.985	98.40	0.0060	0.000
BC	1.043	1.021–1.066	127.8	3.768	93.00	0.0010	0.000
NO_2	1.045	1.033–1.057	1341	6.577	97.70	0.0009	0.000
O_3	0.987	0.971–1.003	531.4	8.150	98.50	0.0005	0.000
SO_2	1.031	1.000–1.062	50.05	2.674	86.00	0.0012	0.000
NO_x	1.024	1.007–1.042	12.58	2.048	76.20	0.0002	0.006
Cardiovascular mortality							
$PM_{2.5}$	1.058	1.055–1.062	797.0	4.208	94.40	0.0033	0.000
PM_{10}	1.149	1.080–1.218	615.1	6.200	97.40	0.0149	0.000
BC	1.028	1.004–1.052	79.88	2.979	88.70	0.0009	0.000
NO_2	1.063	1.043–1.084	834.6	6.024	97.20	0.0016	0.000
O_3	0.993	0.952–1.035	306.1	6.186	97.40	0.0037	0.000
SO_2	1.059	1.004–1.114	68.54	2.927	88.30	0.005	0.000
NO_x	1.034	1.011–1.057	5.99	1.731	55.60	0.0003	0.083
Respiratory mortality							
$PM_{2.5}$	1.066	1.034–1.097	170.1	2.780	87.10	0.0028	0.000
PM_{10}	1.196	1.114–1.279	391.8	5.714	96.90	0.0141	0.000
BC	1.051	1.03–1.070	45.60	4.753	74.80	0.0005	0.000
NO_2	1.061	1.033–1.089	493.2	5.386	96.60	0.0024	0.000
O_3	0.971	0.944–0.998	91.42	3.614	92.30	0.0010	0.000
SO_2	1.041	0.964–1.118	24.24	2.010	75.20	0.0061	0.000
NO_x	1.026	0.998–1.055	0.55	0.741	0.00	0.0000	0.000
Lung cancer mortality							
$PM_{2.5}$	1.118	1.076–1.159	79.77	2.105	77.40	0.0042	0.000
PM_{10}	1.127	1.029–1.224	139.5	3.735	92.80	0.0155	0.000
BC	1.048	1.025–1.070	20.60	1.853	70.90	0.0005	0.002
NO_2	1.067	1.039–1.095	104.9	2.956	88.60	0.0015	0.000
O_3	0.921	0.865–0.978	32.27	2.840	87.60	0.0027	0.000
SO_2	1.087	1.011–1.163	16.80	1.673	64.30	0.0048	0.000
NO_x	1.057	1.005–1.110	5.92	1.721	66.20	0.0011	0.029

Exposure to $PM_{2.5}$ per 10 μg/m^3 increment is associated with an elevated risk of mortality for all-cause (8%), cardiovascular (6%), respiratory (7%), and lung cancer (11.8%). Less or more the same associations have been reported between exposure to $PM_{2.5}$ and all-cause mortality by two other studies [117, 118]. Our finding was higher than that (3.9%) obtained by Hart et al. [119], but considerably lower than those findings (53% and 17%) reported by studies conducted in China and the United States [37, 120]. The association between exposure to $PM_{2.5}$ and cardiovascular mortality in the current study was comparable to that finding previously reported by Pope Lii et al. [90], but higher than the result obtained by a cohort study conducted in the United States [121]. The same but not significantly elevated risk was reported by Beelen et al. [69]. Consistent with our findings, several studies found an elevated relationship between exposure to $PM_{2.5}$ with mortality due to respiratory disease and lung cancer [69, 80, 122, 123]. Air pollution related to traffic is likely to contribute as a source of $PM_{2.5}$, which possibly leads to elevated deaths due to lung cancer [124].

The association between exposure to PM_{10} and all-cause mortality in the present study (10%) was considerably lower than the result reported by a previous study of meta-analysis (18%) [28], but the association was substantially higher than the estimated percent changes of 5% and 3.9% obtained two studies [36, 119]. The onset of mortality associated with exposure to $PM_{2.5}$ and PM_{10} could be explained through numerous underlying mechanisms such as oxidative stress and systemic inflammation, which leads to direct neurotoxicity, hormonal dysregulation, promotion of cell turnover, epigenetic changes in the genome, suppression of DNA repair, DNA methylation, and consequently prompt carcinogenesis [125–130]. $PM_{2.5}$ has also improved the production of inflammatory cytokines (interleukin (IL) -6 and IL-8) due to

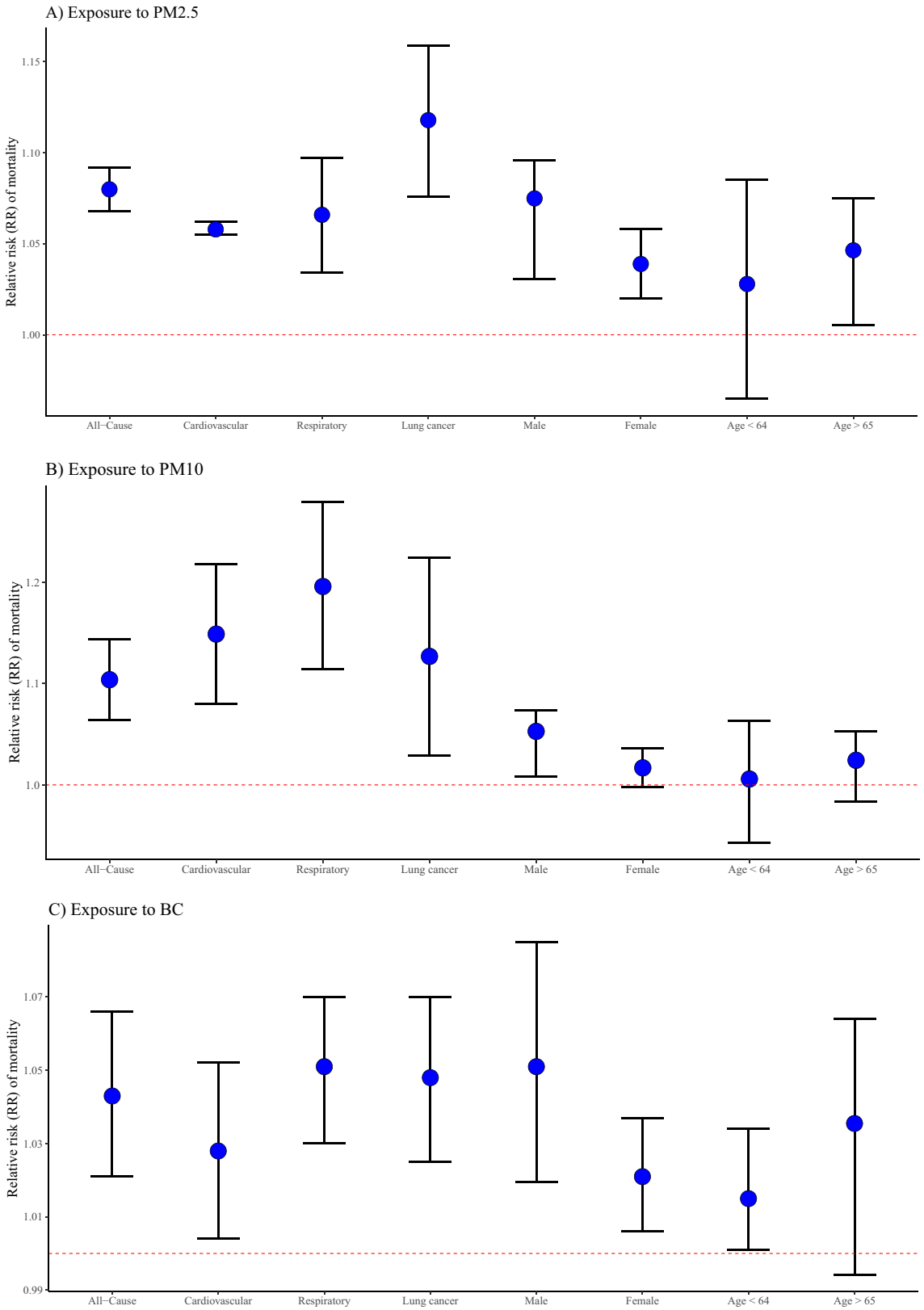


Fig. 4 The pooled relative risk of all-cause mortality associated with $PM_{2.5}$ (**A**), PM_{10} (**B**), BC (**C**), NO_2 (**D**), SO2 (**E**), and O_3 (**F**) exposure stratified by cause-specific mortality, gender (male and female) and age (< 64 years and ≥ 65 years)

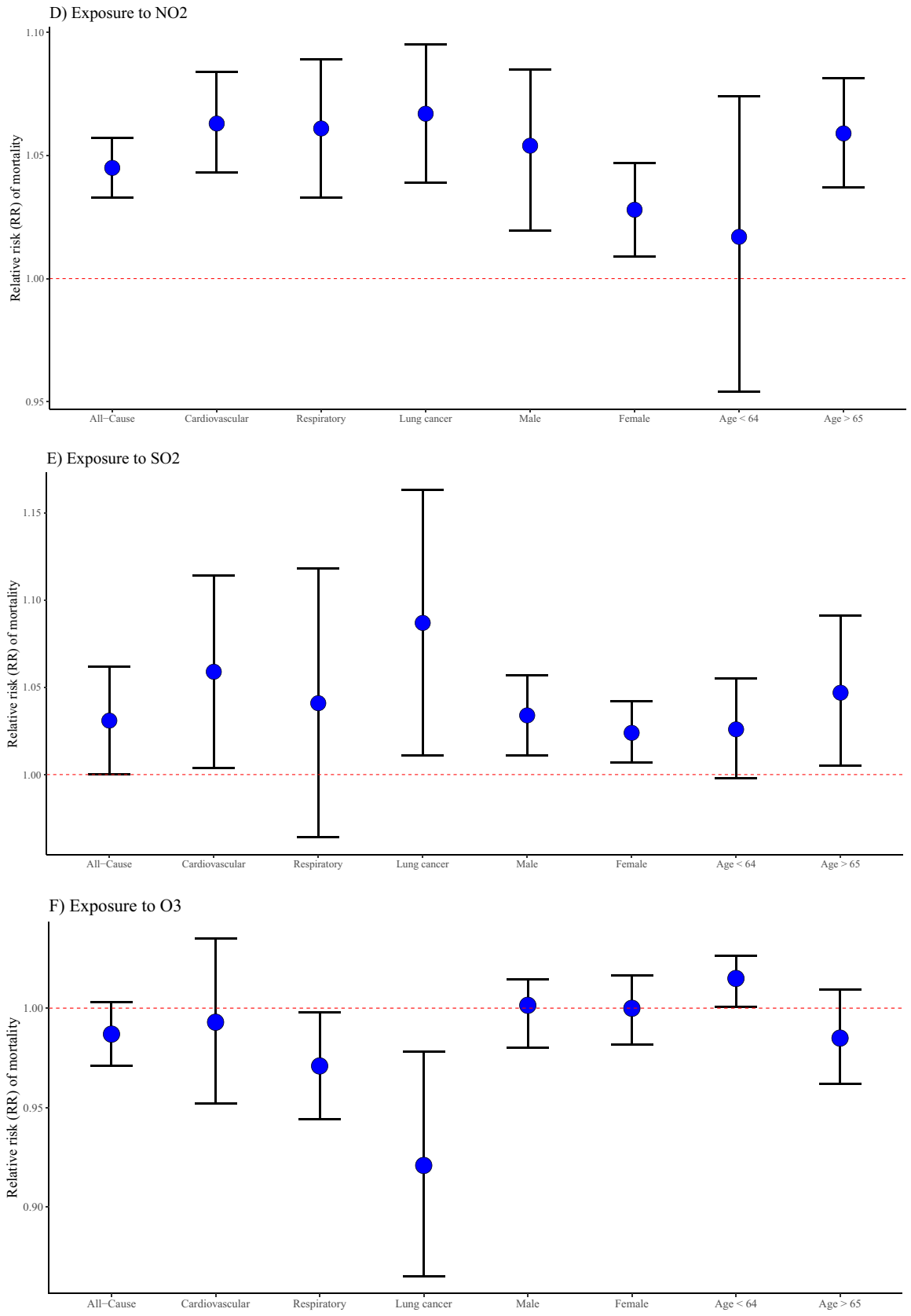


Fig. 4 (continued)

Table 5 The results of Egger's and trim-and-fill test with the number of imputed studies to complete asymmetry in the Funnel plot

Parameters	Egger's test	Number of original studies (N)	Adjusted estimate			Number of imputed studies (N)	*P*-value
			Mean	95% CI			
All-Cause							
$PM_{2.5}$	0.520	59	1.074	1.062	1.086	7	0.001
PM_{10}	0.330	20	1.104	1.064	1.144	0	0.006
BC	0.450	11	1.043	1.020	1.066	0	0.001
NO_2	0.500	36	1.035	1.022	1.049	4	0.001
O_3	0.030	10	0.985	0.969	1.000	1	0.001
SO_2	0.005	10	1.011	0.978	1.044	2	0.002
NO_x	0.012	5	1.023	1.006	1.040	0	0.009
Cardiovascular							
$PM_{2.5}$	0.430	46	1.111	1.090	1.131	2	0.003
PM_{10}	0.055	17	1.149	1.080	1.218	0	0.015
BC	0.042	13	1.018	0.994	1.042	3	0.001
NO_2	0.032	24	1.063	1.043	1.084	0	0.002
O_3	0.044	9	0.993	0.952	1.035	0	0.004
SO_2	0.033	9	1.059	1.004	1.114	0	0.005
NO_x	0.054	5	1.034	1.013	1.056	1	0.112
Respiratory							
$PM_{2.5}$		23	1.066	1.034	1.097	0	0.003
PM_{10}	0.028	13	1.196	1.114	1.279	0	0.014
BC	0.030	8	1.046	1.024	1.069	1	0.001
NO_2	0.005	18	1.061	1.033	1.089	0	0.002
O_3	0.012	8	0.971	0.944	0.998	0	0.001
SO_2	0.036	7	1.041	0.964	1.118	0	0.006
NO_x	0.025	3	1.026	0.997	1.055	1	0.577
Lung Cancer							
$PM_{2.5}$	0.030	20	1.099	1.057	1.141	6	0.005
PM_{10}	0.005	12	1.121	1.023	1.219	0	0.016
BC	0.012	8	1.046	1.024	1.069	1	0.001
NO_2	0.030	13	1.067	1.039	1.095	0	0.002
O_3	0.005	6	0.914	0.855	0.972	1	0.003
SO_2	0.012	9	1.063	0.979	1.147	2	0.007
NO_x	0.025	4	1.054	1.001	1.108	1	0.001

the mitochondrial generation of hydroxyl radical ($^{\bullet}OH$) as a reactive oxygen species (ROS) [126, 131–135].

The estimated percent changes of all-cause mortality per 10 μg/m^3 increment in exposure to NO_2 (4.5%), and SO_2 (3.5%) in the present study were less or more similar to those findings obtained by meta-analyses studies [36, 136, 137]. In the present investigation, the significant relations between exposure to NO_2 with all-cause (4.5%), cardiovascular (6.3%), and respiratory (6.1%) mortality were markedly higher than those findings reported by an earlier study of meta-analysis including all-cause (1.58%), cardiovascular (1.72%) and respiratory (2.05%) mortality [30]. Findings of a recent pooled analysis of 67 studies showed elevated associations between exposure to SO_2 with respiratory (1.0067) and all-cause (1.0059) mortality, but the findings were lower than our results [31]. Our finding for all-cause mortality was substantially lower than the previous results obtained for NO_2 (8.2% and 14%) and SO_2 6.9% [79]. NO_2 and SO_2 can exacerbate the effects of oxidative stress and promote the progression of respiratory disease and lung cancers [138, 139].

No significant associations in the present study were found between exposure to O_3 with all-cause (RR 0.99) and respiratory (RR 0.97). Similar results were reported by a study of meta-analysis for all-cause (RR 0.97) and respiratory (RR 0.99) mortality [136]. The same findings were also reported by a previous study [140].

Subgroup analyses

Figure 4A–E presents the pooled effects of air pollutants on cause-specific mortality with stratification for sex

(male and female) and age (< 0–64 and ≥ 65). The RR of all-cause mortality related to $PM_{2.5}$ exposure was highest in males (RR per 10 μg/m^3 = 1.075, 95% CI = 1.030–1.09) compared to the female (1.039, 95% CI: 1.02–1.058) and individuals with age ≥ 65 years (RR per 10 μg/m^3 = 1.046, 95% CI = 1.005–1.075), compared to the individuals with age < 64 years (1.028, 95% CI = 0.965–1.085) (Fig. 4). The RR of all-cause mortality due to PM_{10}, NO_2 and SO_2 for male and individual age ≥ 65 years were also highest compared to the female and individuals with age < 64 years.

In sex-stratified analysis detected a significant association between exposure to $PM_{2.5}$, PM_{10}, BC NO_2, and SO_2, and mortality in males compared with females, but no significant association was found for O_3. This finding could be related to diverse physiological functions in men and women. Moreover, individual characteristics (e.g., smoking, physical activity, alcohol consumption, work- exposures, etc.) are an important risk factor in air pollution-related mortality [122, 141]. Similarly, the risk of mortality from coronary heart disease, cardiorespiratory disease, and myocardial infarction, which is attributed to air pollution was higher in males and the elderly [142, 143].

Individual over 65 years old was more susceptible to ambient $PM_{2.5}$, NO_2, and SO_2 exposure, while the younger (< 65 years old) age were more susceptible to BC and O_3. Previous studies supported these findings [141, 142, 144, 145]. The elderly are typically more exposed to outdoor air pollution compared to the younger age [141, 146]. The physiological structures and body functions diminish with age, which might enhance the risks of air pollution-related mortality among the elderly [147].

Additional analyses

According to Egger's test, we found significant publication bias for O_3 (*P-value* 0.03), SO_2 (*P-value* 0.005), and NOx (*P-value* 0.012) with all-cause mortality, but not for $PM_{2.5}$ (*P-value* 0.52), PM_{10} (*P-value* 0.33) and BC (*P-value* 0.44). The sub-stratified analysis of the association between all-cause mortality with $PM_{2.5}$ by location illustrated that the RR was higher in studies conducted in Canada (RR 1.17, 95% CI 1.15–1.20, I^2 68.0%, *p-value* 0.008) compared with Asia (RR 1.04, 95% CI 1.01–1.08, I^2 98.1%, *p-value* 0.000) and United states (1.08, 95% CI 1.06–1.09, I^2 91.8%, *p-value* 0.000) (Supplementary Fig. S29-S35).

The trim and fill method result shows that about 7 records are essential to creating a complete asymmetry in the Funnel plot (*P-value* < 0.001) of All-Cause with $PM_{2.5}$ (Table 5, Supplementary Fig. S36-S59). The graphical funnel plots appeared to be slightly asymmetrical for exposure to PM_{10}, BC, NO_x, O_3, and SO_2, suggesting the presence of publication bias for studies (*p-value* ≤ 0.05). Sensitivity analyses showed that the results were stable for the combination of pollutants with all-cause cardiovascular, and respiratory mortality, and the pooled RR did not alter when any individual record was excluded, indicating the robustness of the results (Table 5).

The current study has some limitations. First, we included only cohort studies, and other types of study designs such as case–control, cross-sectional, time-series, or case-crossover designs were not evaluated. Second, most of the included studies were performed in developed countries especially in urban areas of Europe and North America, while there was no study available for African countries. Third, the exposure measurements were conducted in outdoor environments, and indoor air pollution (e.g. home, school, office) was not considered. Fourth, we were also unable to perform meta-regression analyses to identify the sources of heterogeneity for some air pollutants due to low sample size.

Conclusion

The most considered air pollutants were associated with an increased risk of mortality due to cardiovascular and respiratory diseases, but the effects of PM_{10} and $PM_{2.5}$ were stronger. Exposure to PM_{10} and $PM_{2.5}$ is the predominant factor for mortality risk, contributing to RR 1.104 and 1.08 in all-cause mortality and RR 1.149 and 1.058 in cardiovascular mortality. The highest respiratory and lung cancer mortality was associated with exposure to PM_{10} (1.196 and 1.127), followed by $PM_{2.5}$ (RR 1.066 and 1.118). The male and elderly adults seemed to be more susceptible to exposure to particle air pollution compared to the female and younger age groups. Thus, policymakers need to pay more attention to establishing new regulations and intervention strategies to enhance air quality. This subsequently leads to a diminishing of morbidity and mortality. Further population-based studies in this field are required to enhance the understanding of the adverse health effects of air pollution among vulnerable subgroups.

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Author contributions B.K. and S.S. conceived of the presented idea, designed the study, participated in the data collection and wrote the main manuscript. B.K. performed the statistical analysis and assisted in the data collection and approved the final version. All authors discussed the results, reviewed the paper and contributed to the final manuscript. Corresponding Author: Behrooz Karimi. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This paper is the result of a research project supported by the Arak University of medical sciences, Arak, Iran.

Consent to participate Not applicable (The manuscript does not report on or involve the use of any animal or human data or tissue).

Consent to publication Arak University of medical sciences has allowed to publish the information obtained from this research. This work was supported by the Arak University of medical sciences, Arak, Iran.

Competing interests The authors declare that they have no known competing financial interests.

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