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Association between ambient particulate matter and semen quality parameters: a systematic review and meta-analysis

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Abstract

Background The adverse consequences of ambient particulate matter (PM) on human health have been extensively studied. However, the association between PM2.5 and PM10 µm, two common sizes of particulate matter, and semen quality remains a subject of debate. This systematic review and meta-analysis aim to investigate the relationship between ambient PM2.5 and PM10 µm exposure and semen quality parameters.

Main text A systematic literature search was conducted using electronic databases to identify relevant studies investigating the association between (PM2.5 µm and PM10 µm) exposure and semen quality, covering the period from January 2000 to April 2023. Standard mean difference (SMD) was used to calculate pooled effect estimates with 95% confidence intervals (CIs). Furthermore, meta-regression and subgroup analyses provided additional insight into potential factors contributing to heterogeneity. The meta-analysis included a comprehensive review of nine studies with a total of 6264 participants. The findings demonstrated a significant negative correlation between ambient exposure to PM2.5 µm and PM10 µm and various parameters related to semen quality. The analysis revealed that PM2.5 exposure was linked to reduced semen volume (SMD = –0.028; 95% CI –0.055 to –0.01), total sperm count (SMD = –0.027; 95% CI –0.052 to -0.02), sperm motility (SMD = –0.156; 95% CI –0.26 to -0.04), and progressive motility (SMD = –0.194; 95% CI –0.38 to –0.01). Likewise, exposure to PM10 was associated with decreased sperm concentration (SMD = –0.036; 95% CI –0.06 to –0.01) and sperm motility (SMD = –0.93; 95% CI –0.15 to –0.02).

Conclusion This systematic review and meta-analysis demonstrate a consistent negative association between ambient PM10 and PM2.5 µm exposure and semen quality parameters. The findings suggest that increased levels of ambient particulate matter may have an adverse influence on sperm count and motility. The results highlight the importance of addressing environmental air pollution as a potential risk factor for male reproductive health.

Keywords Semen quality, Particulate matter, Ambient air pollution, Meta-analysis

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Introduction

Air pollution and particulate matter (PM) have become a major global public health concern due to their detrimental effects on human health. The presence of these pollutants in the atmosphere poses a serious threat to human well-being [1, 2]. The accelerated socioeconomic progress in numerous areas has led to significant air pollution, exceeding the World Health Organization's (WHO) recommended guidelines due to high levels of PM2.5 (particulate matter measuring 2.5 µm or less in diameter) and PM10 (particulate matter measuring 10 µm or less in diameter) [3, 4]. The negative consequences associated with exposure to PM, ranging from subclinical outcomes to mortality, have amplified attention toward examining the influence of PM on reproductive health [5]. Although the respiratory and cardiovascular effects of particulate matter have been extensively studied, there has been a growing interest in its effects on reproductive health in recent years [6, 7]. Recent studies have highlighted a potential link between PM exposure and decreased semen quality, which is recognized as a significant contributor to infertility. However, the conflicting outcomes observed in previous research on the relationship between PM and semen quality can be attributed primarily to the limited number of epidemiological studies conducted in this area of investigation [8, 9].

Despite these findings, several limitations exist in the current body of research, including inconsistent results, inaccurate individual PM exposure assessment, small sample sizes, and selection bias [10, 11]. Moreover, these studies have commonly presumed a linear relationship between exposure to particulate matter (PM) and the quality of semen, neglecting the possibility of non-linear relationships [12]. Earlier studies exploring the relationship between air pollution and semen quality parameters have focused on the impact of PM exposure within the 90-day timeframe leading up to semen collection, which is consistent with the estimated duration of sperm development. However, the distinct impacts of PM exposure during the various critical stages of sperm development, which include epididymal storage, sperm motility development, and spermatogenesis, have not been adequately studied [13, 14].

This study aims to comprehensively investigate the potential negative impacts of PM10 and PM2.5 exposure on sperm quality parameters in men. Through establishing a direct link between ambient PM and semen parameters, this study seeks to expand the existing knowledge base and shed light on the potential reproductive health risks in relation to PM exposure. The findings will have important implications for public health policy and initiatives geared towards mitigating the detrimental effects of air pollution on human fertility.

Method

Protocol and registration

In order to ensure transparency and adhere to strict standards, this systematic review and meta-analysis study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) guide. In addition, the study was prospectively registered in PROSPERO, a widely recognized database for the registration of systematic reviews [15, 16] (CRD42023440843).

Eligibility criteria

The selection criteria for studies included in this systematic review and meta-analysis were as follows: (I) observational studies that investigated the association between ambient particulate matter (PM2.5 and PM10) and outcomes related to semen quality; (III) studies published between January 2010 and April 2023; (III) studies provided data on the following semen quality parameters: semen volume (ml), total motility, progressive motility, total sperm count, and sperm concentration (10^6/ml); (IV) in addition, research studies involving human participants should be published in peer-reviewed English-language journals; and (V) study selection criteria encompass the evaluation of the exposure window lag, which spans from 0 to 90 days. This specified timeframe enables the thorough investigation of potential impacts and associations between exposures and outcomes, specifically focusing on the analysis of semen quality.

Studies were excluded if they were reviews, letters, editorials, animal research, intervention studies, or conference proceedings. Additionally, studies without extractable data were also excluded.

Literature search

A comprehensive literature search was conducted in multiple electronic databases, including PubMed, Web of Science, Scopus, Cochrane Library, and Google Scholar. The search covered articles published between January 2010 and April 2023. The search strategy employed relevant keywords such as "ambient particulate matter," "PM2.5," "PM10," "semen quality," "air pollution," "sperm count," "sperm concentration," and "sperm motility." The search strategy combined these keywords using appropriate Boolean operators (e.g., AND, OR).

Study selection

Two independent investigators (S.B. & M.A.) conducted the initial search and screened the identified studies based on titles and abstracts. Full-text articles were then retrieved for the selected studies. Any discrepancies or inconsistencies in the selection of studies were resolved through discussion and consensus among the researchers, and a third reviewer was consulted as needed.

Data extraction

A standardized data extraction form was developed and used to extract relevant information from the selected studies [17–19]. The extracted data included study characteristics (e.g., author, year of publication, study location), study design, participant characteristics (e.g., sample size, age range), PM exposure assessment methods, semen quality outcomes measured (semen volume (ml), total motility, progressive motility, total sperm count (10^6), and sperm concentration (10^6/ml)), and other relevant findings (Table 1).

Quality assessment

The methodological quality and potential bias of the studies included in the analysis were assessed utilizing suitable tools, specifically the Newcastle-Ottawa scale, renowned for its application in observational studies (Table 2). This scale evaluates the quality of non-randomized studies by considering criteria related to study selection, comparability, and outcome assessment. Two reviewers independently evaluated each study, and any discrepancies were resolved through discussion or with the assistance of a third reviewer [26].

Statistical analysis

The data extracted from the included studies were synthesized utilizing meta-analysis techniques. Standardized mean differences (SMD) and 95% confidence intervals (CI) were calculated to assess the effect sizes of semen quality outcomes, including semen volume, sperm count, sperm concentration, total motility, and progressive motility, before and after exposure to air pollution [27, 28]. This process involved meticulously examining the data to determine the extent of variation in the said parameter. The comprehensive assessment provided insights into the impact of air pollution on semen quality, considering both the baseline value and exposure-induced change. Heterogeneity among the studies was evaluated using the I^2 statistic and Cochran's Q test. Publication bias was assessed using Egger's tests [29]. All statistical analyses were performed using Comprehensive Meta-Analysis (CMA) v3.7z software.

Results

Characteristics of the included studies

The search strategy yielded a total of 911 articles in the initial database search. After removing 137 duplicate records, 683 articles were excluded based on title and abstract evaluation. The remaining 91 articles underwent a full-text assessment, resulting in the exclusion of 38 studies for various reasons. Finally, nine studies met the pre-established selection criteria, encompassing a total of 6264 participants. Further details can be found in Fig. 1.

Association and comparison details

The study involved a meticulous analysis of 9 selected studies with a total sample size of 6264 participants. The primary objective was to investigate the association between particulate matter (PM2.5 and PM10) and semen quality. In addition, subgroup and meta-regression analyses were performed to examine potential sources of heterogeneity, including factors such as body mass index (BMI), age, total sample size, and study year. This comprehensive methodology has improved our understanding of the association between particulate matter and semen quality while shedding light on possible factors contributing to the observed heterogeneity.

Relationship between semen quality outcomes and ambient particulate matter

Meta-analysis

The meta-analysis demonstrated a significant relationship between ambient particulate matter exposure and semen quality outcomes. For PM2.5, the pooled SMD analysis revealed a decrease in semen volume (SMD = −0.028; 95% CI −0.055 to −0.01; p = 0.036), total sperm number (SMD = −0.027; 95% CI −0.052 to −0.02; p = 0.037), sperm motility (SMD = −0.156; 95% CI −0.26 to −0.04; p <001), and progressive motility (SMD = −0.194; 95% CI −0.38 to −0.01; p = 0.048). Similarly, for PM10, significant reductions in sperm concentration (SMD = −0.036; 95% CI −0.06 to −0.01; p <001), sperm motility (SMD = −0.93; 95% CI −0.15 to −0.02; p <001), and progressive motility as non-significant (SMD = −0.16; 95% CI −0.34 to 0.01; p =071) was observed. The forest plots illustrating the meta-analysis results are presented in Figs. 2 and 3.

Subgroup analysis

Subgroup analyses were conducted to explore potential sources of heterogeneity and assess the impact of specific factors on the association between ambient particulate matter and progressive motility [30, 31]. The analyses aimed to investigate the influence of these factors on the observed association between the variables. These analyses were conducted considering factors such as study design (cross-sectional study and longitudinal study), semen analysis method (CASA and WHO-guided semen analysis), and region of study (America, Asia, and Europe). The results of subgroup analyses demonstrated consistent associations between ambient particulate matter and semen quality outcomes across different subgroups, thereby highlighting the robustness of the observed relationship. Detailed subgroup analyses findings are presented in Table 3.

The overall pooled effect in the subgroup analyses remained consistent across various potential sources of

Table 1 Characteristics of the studies included in the systematic review and meta-analysis

Author (Ref)	Year	Country	Study design	No. of semen samples	Exposure assessment	Exposure window	Semen analysis method	Age (years) Mean/SD	BMI (kg/m) Mean/SD	Outcome
Cheng et al. [8]	2022	China	Cross-sectional study	1607	IDW model	lag 0–90 days Lag 0–1 year	WHO-guided semen analysis	30.9 (4.2)	25.7 (2.8)	Semen volume, sperm concentration, total sperm number, total motility, progressive motility
Farhat et al. [20]	2016	Brazil	Longitudinal study	56	Grid air pollution	Lag 80–88 days	WHO-guided semen analysis	29.8 (8.9)	NA	Sperm concentration, total sperm number
Hansen et al. [13]	2010	USA	Longitudinal study	228	The U.S. environmental protection agency air quality system data mart	Lag 0–90 days	CASA	29.5 (2.1)	NA	Sperm concentration, total sperm number, normal forms
Nobles et al. [21]	2018	USA	Longitudinal study	501	Community multiscale air quality models	Lag 0–72 days	CASA	31.8 (4.8)	29.9 (5.6)	Semen volume, total sperm number, total motility
Qiu et al. [22]	2020	China	Longitudinal study	4841	Chengdu metropolitan monitor stations	Lag 0–90 days	WHO-guided semen analysis	27.78 (5.35)	22.57 (2.43)	Semen volume, sperm concentration, total sperm number, progressive motility
Radwan et al. [23]	2016	Poland	Cross-sectional study	285	Air quality information system	Lag 0–90 days	CASA	32.3 (4.4)	112 (34.3)	Sperm concentration, total sperm number, total motility
Wu et al. [9]	2017	China	Longitudinal study	2184	IDW model	Lag 0–90 days	CASA	34.4 (5.4)	24.4 (3.4)	Semen volume, sperm concentration, total sperm number, total motility, progressive motility
Yang et al. [24]	2021	China	Longitudinal study	1991	China network environment monitoring center	Lag 0–90 days	CASA	25.61 (4.99)	22.34 (1.97)	Sperm concentration, total sperm number, total motility, progressive motility
Zhou et al. [25]	2020	China	Cross-sectional study	382	Ordinary Kringing model	Lag 0–90 days	WHO-guided semen analysis	29.71 (4.08)	26.3 (3.2)	Semen volume, sperm concentration, total sperm number, total motility

BMI Body mass index, *CASA* Computer-assisted semen analysis, *IDW* Inverse distance weighting, *NA* Not available, *SD* Standard deviation

Table 2 Quality assessment of studies included in this meta-analysis based on the Newcastle-Ottawa scale

Author, yr	Selection				Comparability	Exposure			Score
	An adequate definition of case	Representativeness of the case	Selection of controls	Definition of controls	Cases and controls matched and/or adjusted by factors	Assessment of exposure	The same method of ascertainment for cases and controls	The same response rate for both groups	
Cheng et al., 2022 [8]	★	★	★	★	★	★	★	★	8
Farhat et al., 2016 [20]	★	★	–	★	★	★	★	–	6
Hansen et al., 2010 [13]	★	★	★	★	★	★	★	★	8
Nobles et al., 2018 [21]	★	★		★	★	★	★	-	6
Qiu et al., 2020 [22]	★	★	★	★	★	★	-	★	7
Radwan et al., 2016 [23]	★	★	–	★	★	★	★	★	7
Wu et al., 2017 [9]	★	★	-	★	★	★	★	s	7
Yang et al.,2021 [24]	★	★	★	★	★	–	★	–	6
Zhou et al., 2020 [25]	★	★	–	★	★★	–	★	★	7

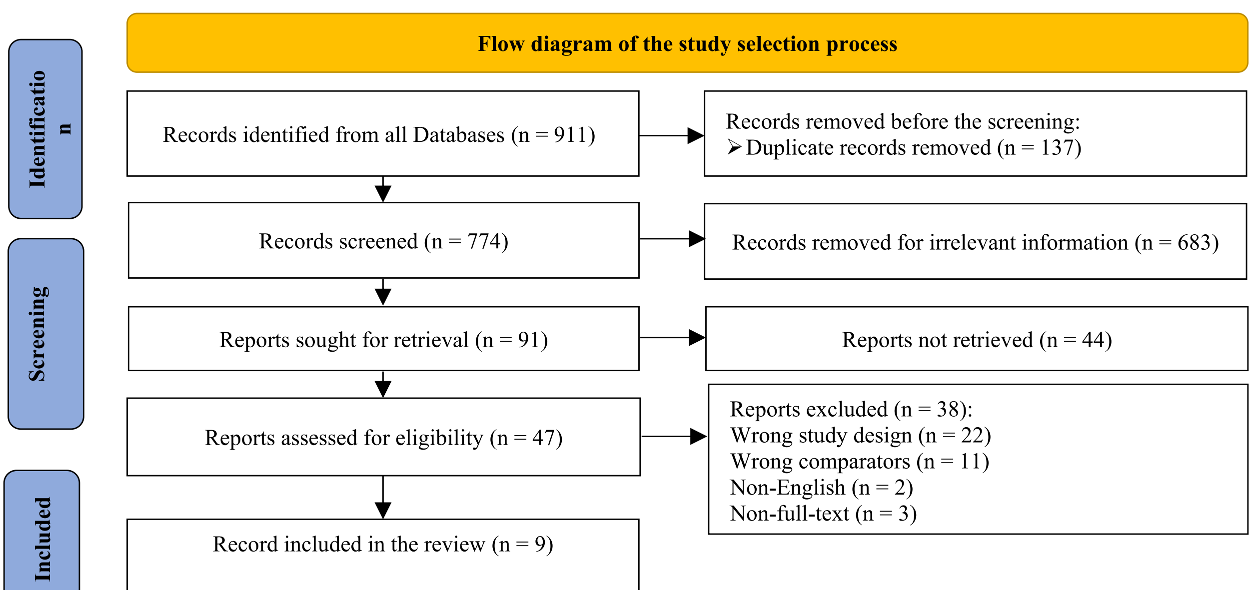

Fig. 1 The flow diagram of the study selection was adjusted by PRISMA

heterogeneity, such as study design and semen analysis method. American groups demonstrated lower semen quality in men (SMD = −0.15; 95% CI −0.27 to 0.03; p = 0.01), indicating a significant correlation between the region and semen quality parameters following exposure to PM2.5. Furthermore, a considerable variation in

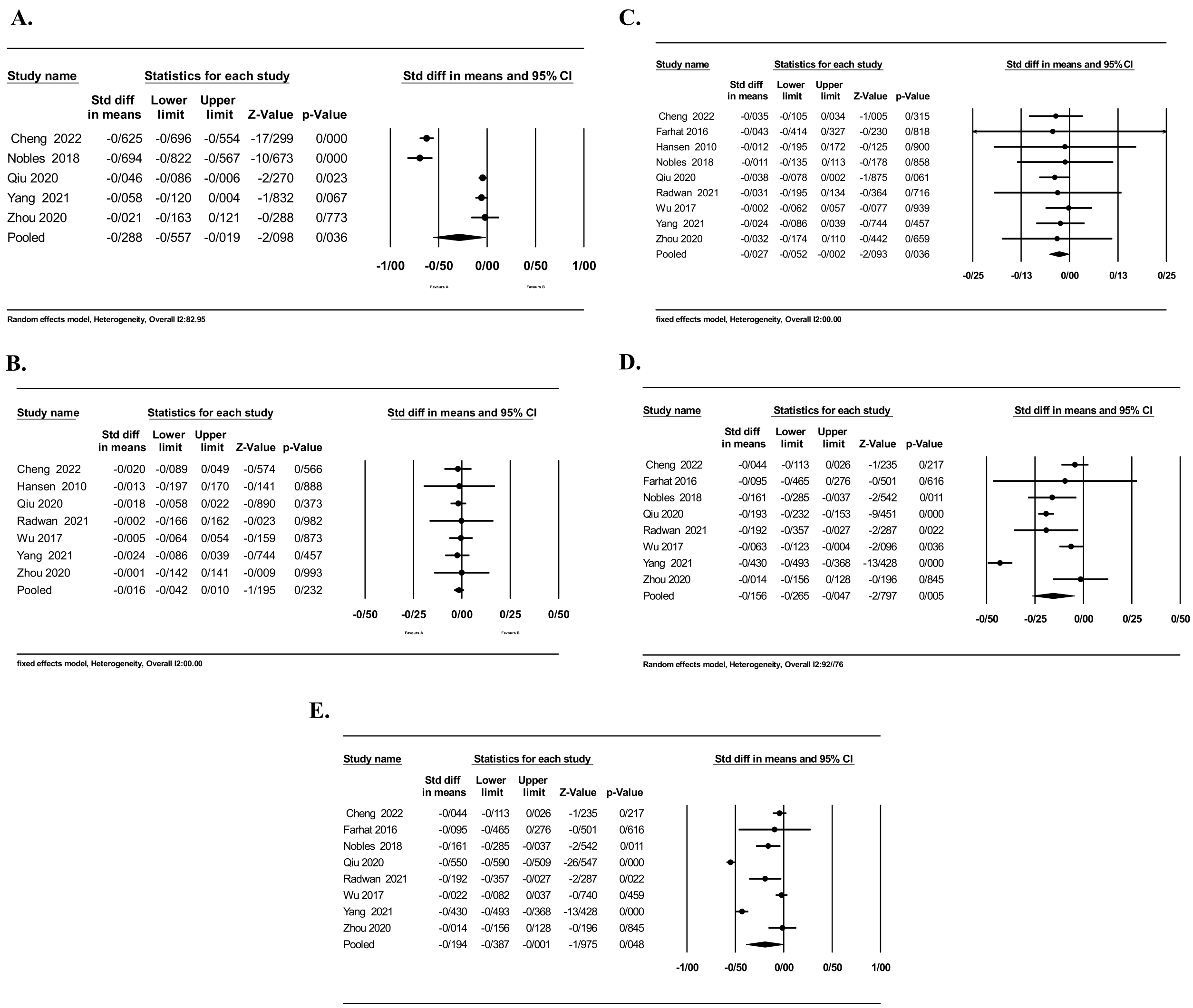

Fig. 2 Forest plots show the relationship between PM2.5 exposure and the following semen parameters: **A** semen volume, **B** sperm concentration, **C** total sperm count, **D** total motility, and **E** progressive motility

semen quality parameters was observed among different study designs after exposure to PM2.5. A significant relationship existed between longitudinal studies and lower semen quality parameters following exposure to PM2.5 (SMD = −0.25; 95% CI −0.15 to 0.18; $p = 0.04$). Moreover, no significant difference was found between the semen analysis method and semen quality parameters after exposure to pm2.5 and pm10.

Meta-regression analysis

A meta-regression analysis was performed to investigate the potential influence of different factors on the observed relationship between ambient particulate matter and progressive motility. The analysis encompassed the examination of factors such as the exposure window, BMI, and age, which are detailed in Table 4.

The results of our study suggest a relationship between BMI and semen quality among individuals exposed to 10 PM (meta-regression coefficient: 0.083; 95% CI 0.023 to 0.105; $p = 0.02$). Additionally, the findings indicate a correlation between age and semen quality in the group exposed to 2.5 PM (meta-regression coefficient: 0.052; 95% CI 0.008 to 0.101; $p = 0.02$).

Sensitivity analysis and publication bias

Sensitivity analysis was conducted to assess the robustness of the meta-analysis results. The removal of each study from the analysis did not significantly alter the

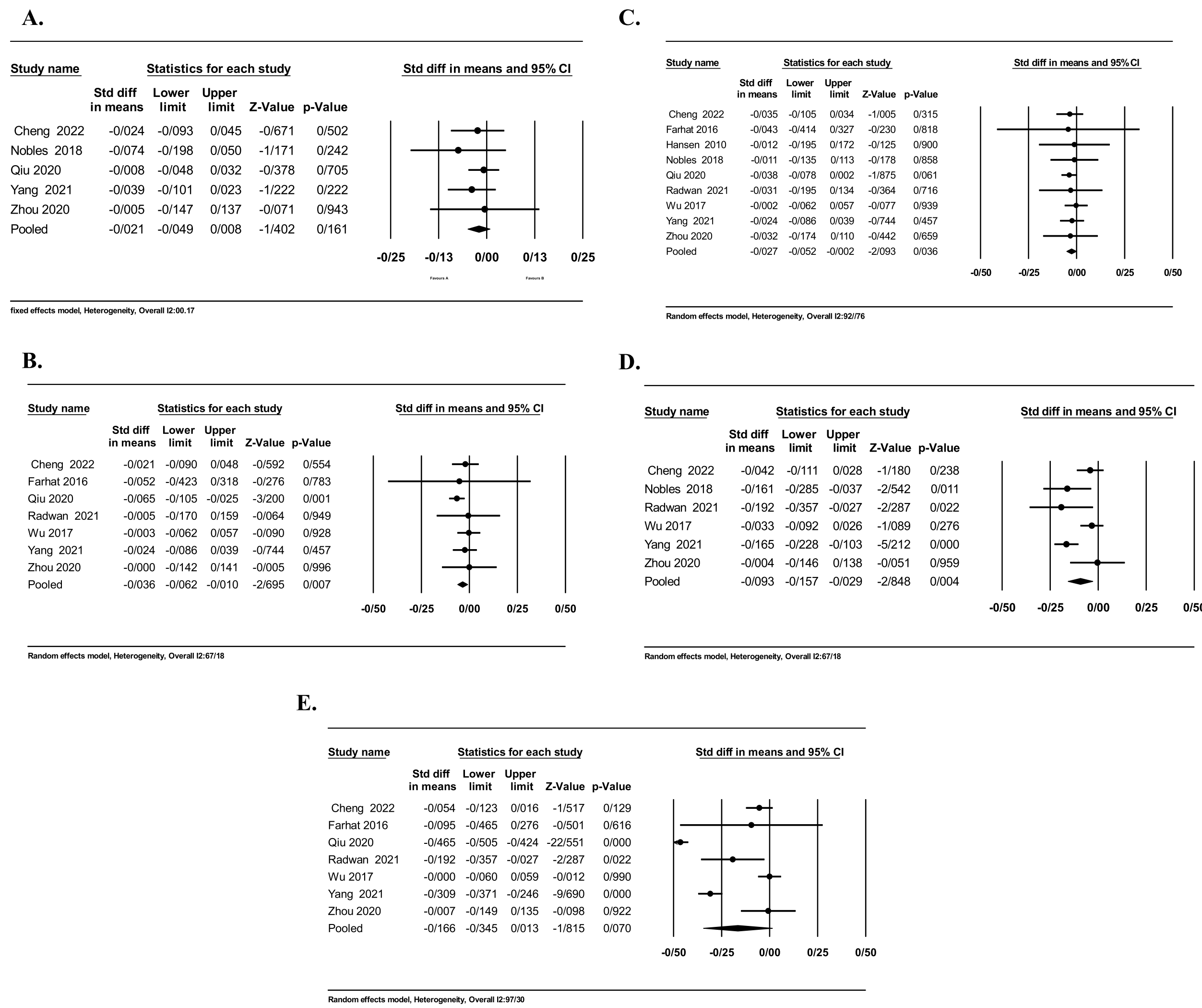

Fig. 3 Forest plots show the relationship between PM10 exposure and the following semen parameters: **A** semen volume, **B** sperm concentration, **C** total sperm count, **D** total motility, and **E** progressive motility

overall conclusions, indicating the stability of the findings. Publication bias was assessed by applying Egger's test and visual inspection of the funnel plot. The results of Egger's test indicate that there is no significant evidence of publication bias for PM2.5 and PM10. The semen volume coefficient for PM2.5 is 8.96 (standard error (SE): 2.45; 95% CI −35.76 to 18.34, *P*=0.381). The sperm concentration for PM2.5 is 0.18 (SE: 0.17; 95% CI −0.16 to 0.65, *P*=0.352). The total sperm count for PM2.5 is 0.14 (SE 2.04; 95% CI −12.50 to 9.40, *P*=0.176). The total motility for PM2.5 is 6.03 (SE: 1.74; 95% CI −5.58 to 17.65, *P*=0.250). The progressive motility for PM2.5 is −1.54 (SE: 1.77; 95% CI −6.10 to 3.02, *P*=0.424). In addition, the semen volume coefficient for PM10 is 0.76 (SE: 0.67; 95% CI −2.72 to 1.19, *P*=0.30). The sperm concentration for PM10 is 0.71 (SE: 0.60; 95% CI −0.83 to 2.26, *P*=0.287). The total sperm count for PM10 is 0.26 (SE: 0.25; 95% CI −0.55 to 1.08, *P*=0.464). The total motility for PM10 is 5.13 (SE: 0.57; 95% CI −6.63 to 16.90, *P*=0.312). The progressive motility for PM10 is 1.24 (SE: 1.38; 95% CI −4.10 to 3.02, *P*=0.726). This conclusion is supported by the symmetrical distribution of data points in the funnel plot (refer to Supplementary Figs. 4 and 5)

Discussion

Ambient PM is a complex mixture of solid and liquid particles suspended in the air, which are primarily generated from industrial activities, vehicle emissions, and natural sources [23, 32]. In recent years, research has increasingly focused on understanding the potential adverse effects of PM on human health. The purpose of this paper is to examine the relationship between exposure to ambient PM and both fertility and semen quality, shedding light on the potential implications for reproductive

Table 3 Subgroup meta-analysis of the included studies

Subgroup analysis	No. studies	Test of association		Heterogeneity	
		SMD (95% CI)	P_{value}	Isquare	P_{value}
Study design PM2.5					
Cross-sectional	3	−0.061 (−0.15, 0.18)	0.12	35.11	0.21
Longitudinal study	5	−0.254 (−0.15, 0.18)	0.04	98.39	<001
Study design PM10					
Cross-sectional	3	−0.063 (−0.15, 0.01)	0.10	34.02	0.22
Longitudinal study	4	−0.237 (−0.48, 0.02)	0.07	98.15	<001
Semen analysis method PM2.5					
CASA	4	−0.190 (−0.44, 0.04)	0.11	96.80	<001
WHO-guided semen analysis	4	−0.186 (−0.53, 0.16)	0.30	98.30	<001
Semen analysis method PM10					
CASA	3	−0.164 (−0.39, 0.06)	0.15	95.96	<001
WHO-guided semen analysis	4	−0.162 (−0.45, 0.12)	0.27	97.60	<001
Region PM2.5					
America	2	−0.156 (−0.27, 0.03)	0.01	0.00	0.74
Asia	5	−0.211 (−0.46, 0.04)	0.10	98.76	<001
Europe	1	−0.194 (−0.35, 0.02)	0.02	0.00	<001
Region PM10					
America	1	−0.092 (−0.46, 0.27)	0.61	0.00	
Asia	5	−0.175 (−0.38, 0.04)	0.11	98.18	0.38
Europe	1	−0.193 (−0.35, 0.02)	0.02	0.00	<001

Table 4 Meta-regression analysis for the potential variables between studies

	No. studies	Coefficient	Standard error	*p*	*95% CI*
Exposure window					
PM2.5	7	0.062	0.00	0.57	−0.001 to 0.002
PM10	6	0.056	0.00	0.61	−0.000 to 0.023
BMI					
PM2.5	7	0.042	0.03	0.14	−0.016 to 0.115
PM10	6	0.083	0.03	0.02	0.023 to 0.105
Age					
PM2.5	7	0.052	0.023	0.02	0.008 to 0101
PM10	6	0.041	0.02	0.76	−0.004 to 0.087

health. In other words, this systematic review and meta-analysis investigated the association between particulate matters (PM2.5 and PM10) and semen quality based on observational studies published between January 2010 and April 2023. Our analysis revealed that exposure to PM2.5 and PM10 during the 0–90 days preceding semen collection was associated with decreased total sperm count, total motility, and progressive motility. However, no significant association was observed between air pollution and sperm concentration or semen volume in some cases. Our findings align with previous studies that have explored the relationship between ambient air pollution and semen quality [11, 22]. Previous studies have reported varying degrees of association between air pollution and semen parameters such as sperm concentration, total sperm count, motility, and normal forms [8, 21]. Some studies failed to detect significant effects on some semen parameters, suggesting a limited association between air pollution and reproductive health [25]. Subgroup analyses were performed to investigate potential sources of heterogeneity and determine the impact of specific factors on the relationship between ambient PM and semen quality parameters. These analyses considered various factors, such as study design (cross-sectional or longitudinal), method of semen analysis (CASA or WHO-guided analysis), and region (America, Asia, Europe). Based on the results of the subgroup analysis, it appears that studies conducted in American geographic regions had smaller effect sizes compared to other regions. Interestingly, it was observed that studies conducted in Asian regions were effective in reducing sperm quality for smaller particles (PM2.5 μm). In addition, studies that followed WHO guidelines showed more diminutive changes in sperm quality reduction. Longitudinal studies also revealed more prominent changes in the reduction of sperm quality parameters compared to other study designs.

In addition, meta-regression results revealed a positive association between BMI and semen quality in individuals exposed to 10 pm. This implication suggests that higher BMI may have a negative effect on fertility. In addition, a correlation between age and semen quality was observed within the group exposed to PM2.5, indicating a potential decline in semen quality with advancing age. These findings emphasize the importance of maintaining a healthy weight and considering age as a critical factor in assessing reproductive health.

The observed association between ambient particulate matters (PM2.5 and PM10) and reduced semen quality raises questions about the potential biological mechanisms underlying this relationship. Several pathways have been proposed to explain the detrimental effects of air pollution on male reproductive health. Firstly, it is well-established that PM can induce oxidative stress [33, 34]. PM2.5 and PM10 contain various toxic compounds, such as heavy metals and polycyclic aromatic hydrocarbons, which generate reactive oxygen species (ROS) upon inhalation [35, 36]. These products can disrupt the delicate balance between oxidation and antioxidant defense systems in the male reproductive system, leading to increased oxidative stress. This oxidative stress can damage sperm DNA, impair sperm function and motility, and ultimately result in reduced semen quality [37]. Secondly, air pollution can affect semen quality through systemic inflammation. The inhalation of PM can trigger inflammatory responses in the respiratory system, provoking the release of proinflammatory cytokines and subsequent systemic inflammation. This systemic inflammation can adversely affect testicular function and spermatogenesis. Inflammatory mediators can disrupt the blood-testicular barrier, impair hormone production, and alter the microenvironment necessary for sperm development, thereby compromising sperm quality [37, 38]. Furthermore, exposure to PM has been linked to endocrine disruption. Air pollutants, including PM2.5 and PM10, may contain endocrine-disrupting chemicals that can interfere with hormone-signaling pathways [32, 39]. Disruption of hormonal balance, particularly androgen and estrogen levels, can disrupt spermatogenesis and negatively impact semen quality. Moreover, alterations in hormone levels may contribute to abnormalities in sperm production, motility, and morphology [40].

Our study has several strengths that enhance the validity and reliability of the findings. First, we conducted a systematic review and meta-analysis that allowed us to synthesize the available evidence from multiple studies and estimate the overall effect size. This approach increases the statistical power and generalizability of the results. Second, we focused specifically on the effects of PM2.5 and PM10 to provide targeted insights into the impact of PM on semen quality. This allows for a more focused understanding of the potential risks associated with these specific air pollutants. In addition, our analysis included a comprehensive assessment of various semen quality parameters, including sperm concentration, total sperm count, motility, and morphology. This broad assessment provides a comprehensive overview of the effects of air pollution on different aspects of semen quality.

Despite these strengths, our study is not without limitations: First, the included studies were observational, which limits our ability to establish a causal relationship between ambient PM and semen quality. Further prospective cohort or experimental studies are needed to confirm the observed associations. Second, heterogeneity was observed among the included studies due to differences in study design, population characteristics, exposure assessment methods, and semen quality analysis. Although we performed meta-regression and subgroup analyses to explore potential sources of heterogeneity, residual heterogeneity may still exist. Third, most studies relied on city-level air pollution data or indirect exposure assessment methods, which may lead to exposure misclassification and underestimation of actual effects. Future studies should incorporate individual-level exposure data at a higher spatial resolution to improve the accuracy of exposure assessment. Fourth, most of the included studies were conducted in specific regions, primarily in China, which limits the generalizability of our results to other populations and geographic areas. Future research should include more diverse populations from different regions to increase the external validity of the results.

Conclusion

This meta-analysis revealed a consistent and significant association between exposure to particulate matter (PM2.5 and PM10) and reduced semen quality. These results highlight the potential adverse effects of ambient PM on male reproductive health. However, further research is warranted to understand better the underlying mechanisms and potential prevention strategies to mitigate the effects of PM exposure on semen quality.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43043-023-00162-6.

Additional file 1: Supplementary Fig 4. Funnel plot to assess the presences of publication bias about PM2.5 exposure and semen parameters, including A) semen volume, B) sperm concentration, C) total sperm count, D) total motility, and E) progressive motility. **Supplementary Fig 5.** Funnel plot to assess the presences of publication bias about PM10 exposure and semen parameters, including A) semen volume, B) sperm concentration, C) total sperm count, D) total motility, and E) progressive motility.

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Authors' contributions
SB contributed to the conception, data analysis, manuscript preparation, and monitoring, while MD, RM, and MA contributed to the manuscript search, preparation, and data analysis. HG and MZ contributed to the search strategy, article search, and manuscript preparation. The manuscript was reviewed and approved by all authors.

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Availability of data and materials
The meta-analysis data and results that support the findings of this study can be accessed on "Figshare" through the following link: https://doi.org/https://doi.org/10.6084/m9.figshare.23592372.v1.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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

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