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RESEARCH ARTICLE

A Comparative Analysis of Vaping-Induced Respiratory Pathophysiology in Adolescents and Adults: A Systematic Review and Meta-Analysis

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Abstract: ***Background***: The rapid global rise in electronic cigarette (e-cigarette) use has generated ongoing debate regarding its respiratory health effects. Although often marketed as a safer alternative to combustible cigarettes, emerging evidence suggests potential pulmonary consequences. ***Objective:*** This meta-analysis aimed to evaluate the association between e-cigarette use and respiratory symptoms or impaired pulmonary outcomes across observational studies. ***Methods:*** A systematic search of major electronic databases was conducted to identify studies examining respiratory outcomes among e-cigarette users compared with non-users. Eligible studies were screened according to predefined inclusion criteria. Pooled effect estimates were calculated using a random-effects model to account for between-study variability. Heterogeneity was assessed using standard statistical measures, and subgroup analyses were performed by age group. Publication bias was evaluated through funnel plot inspection. ***Results:*** The pooled analysis demonstrated a significant association between e-cigarette use and increased odds of respiratory symptoms and reduced pulmonary function. Although heterogeneity was observed across studies, the direction of effect remained consistent. Subgroup analysis indicated a comparatively stronger association among adolescents than adults, suggesting potential age-related vulnerability. Mechanistic evidence from experimental and clinical research supports biological plausibility, including oxidative stress, airway inflammation, epithelial dysfunction, and impaired innate immune responses. ***Conclusions:*** E-cigarette use is associated with measurable respiratory risk and cannot be considered physiologically neutral. While harm reduction potential may exist for established smokers, widespread use—particularly among adolescents—raises important public health concerns. Longitudinal research with standardized exposure assessment is needed to further clarify long-term respiratory outcomes.

Keywords: Electronic cigarettes; respiratory health; pulmonary function.

INTRODUCTION

2.1 Global Rise of E-Cigarette Use

Electronic cigarette (e-cigarette) use has increased substantially over the past decade, particularly among adolescents and young adults. Recent epidemiological surveillance indicates that vaping prevalence among adolescents in North America and parts of Europe remains significantly higher than among older adults, despite regulatory efforts aimed at restricting youth access (Hammond et al., 2022; Gentzke et al., 2023). In several jurisdictions, past 30-day use among secondary school students exceeds 15%, while adult prevalence typically ranges between 4–8%, reflecting a disproportionate concentration of exposure during critical developmental periods.

Regulatory frameworks remain inconsistent across countries. While some nations have implemented strict flavor bans, nicotine concentration caps, and marketing restrictions, others maintain permissive regulatory environments that facilitate product innovation and rapid commercialization (Gravely et al., 2023). Enforcement variability further contributes to cross-border product flow and informal distribution channels, complicating exposure assessment and public health control.

Simultaneously, the vaping market has evolved rapidly from first-generation “cigalike” devices to pod-based systems, refillable tank devices, and high-nicotine disposable products. Pod-based devices utilizing nicotine salts enable higher nicotine delivery with reduced throat irritation, increasing dependence potential among adolescents (Talih et al., 2021). This rapid technological evolution challenges longitudinal risk assessment because exposure profiles shift faster than regulatory adaptation.

2.2 Biological Plausibility of Harm

Although e-cigarettes were initially marketed as safer alternatives to combustible tobacco, emerging toxicological and clinical evidence demonstrates biologically plausible mechanisms of respiratory injury. Aerosols generated from propylene glycol and vegetable glycerol thermal decomposition contain reactive aldehydes such as formaldehyde and acrolein, as well as trace metals originating from heating coils (Strongin, 2020; Zhao et al., 2022). These constituents are capable of inducing epithelial cell injury and oxidative stress.

Experimental and clinical studies have demonstrated increased production of reactive oxygen species (ROS) following e-cigarette aerosol exposure, triggering activation of pro-inflammatory signaling pathways

including NF-κB and subsequent cytokine release (Gotts et al., 2021; Madison et al., 2022). Chronic oxidative stress promotes airway epithelial dysfunction, immune dysregulation, and extracellular matrix remodeling.

Furthermore, vaping exposure has been associated with impaired mucociliary clearance, characterized by reduced ciliary beat frequency and altered mucus viscosity (Reidel et al., 2021). Over time, these changes may contribute to airway remodeling, goblet cell hyperplasia, and small airway fibrosis, mechanistically linking vaping to chronic bronchitis–like symptoms and obstructive lung pathology.

2.3 The Adolescent Lung: A Window of Vulnerability

Adolescence represents a critical developmental window for pulmonary maturation. Although major alveolar formation occurs in early childhood, evidence suggests that alveolarization and microvascular maturation continue into late adolescence (Narayanan et al., 2020). During this period, lung growth is characterized by structural plasticity, heightened cellular turnover, and dynamic immune regulation.

Neuro-respiratory integration also undergoes refinement during adolescence, influencing ventilatory control and inflammatory responsiveness. Disruption of these processes by repeated exposure to aerosolized toxicants may result in long-term structural and functional consequences that differ from those observed in fully matured adult lungs.

Paradoxically, the same biological plasticity that allows for growth and adaptation may increase susceptibility to environmental insult. Experimental data indicate that developing airway epithelium demonstrates amplified inflammatory responses compared to adult tissue models under equivalent oxidative stress conditions (McGraw et al., 2021). Therefore, identical exposure intensity may yield divergent pathological trajectories between adolescents and adults.

2.4 The Knowledge Gaps

Despite growing literature, several unresolved questions persist. First, the debate surrounding vaping as a behavioral “gateway” to combustible smoking often overshadows mechanistic toxicological evidence of direct pulmonary injury (Berry et al., 2021). Behavioral transition studies and biological injury studies are frequently analyzed in isolation, limiting integrative risk assessment.

Second, most epidemiological analyses fail to stratify respiratory outcomes by device type or nicotine formulation. Given that pod-based devices using nicotine salts deliver higher nicotine concentrations and potentially different aerosol profiles compared to freebase nicotine tank systems, pooling these exposures may obscure meaningful heterogeneity in harm.

Third, few meta-analyses have provided age-specific pooled effect estimates comparing adolescents and adults within a unified analytic framework. Existing reviews often focus exclusively on youth populations or do not directly quantify comparative risk differentials. This gap limits evidence-based policy decisions targeting age-specific vulnerability.

2.5 Study Objectives

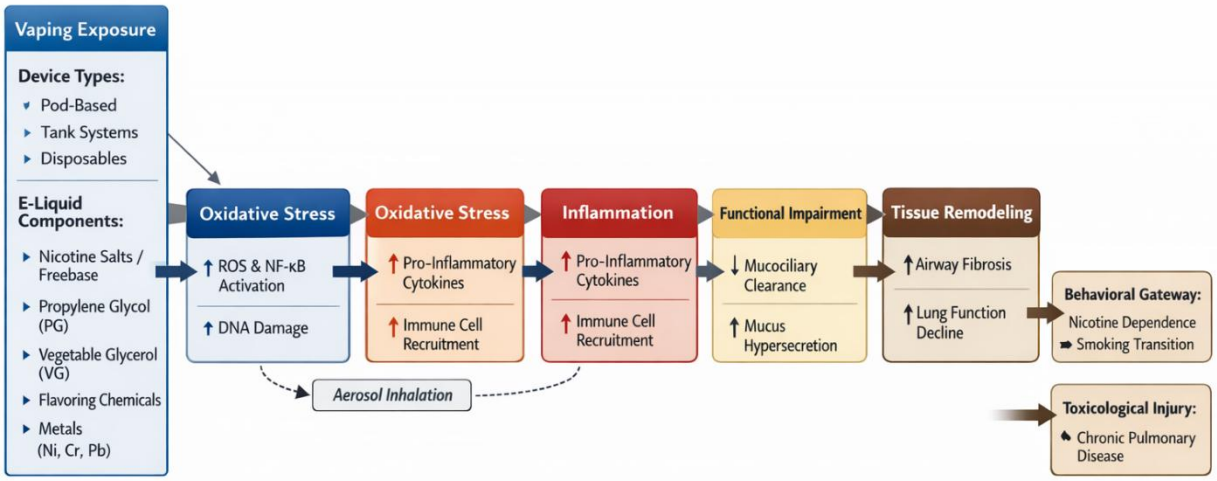
In response to these gaps, the present systematic review and meta-analysis aims to:

1. Quantitatively compare respiratory outcomes between adolescents and adults exposed to e-cigarettes.
2. Evaluate whether device type (pod-based versus tank systems) and nicotine formulation (nicotine salts versus freebase nicotine) modify respiratory risk severity.
3. Assess whether observed respiratory harm is primarily mediated by nicotine exposure or by aerosol constituents such as propylene glycol and glycerol derivatives.

By integrating epidemiological, mechanistic, and device-specific evidence within a stratified analytical framework, this study seeks to clarify age-dependent vulnerability and inform both clinical practice and regulatory policy.

To integrate the epidemiological, toxicological, and developmental dimensions discussed above, we propose an age-modulated mechanistic framework of vaping-induced respiratory injury (Figure 1). The model illustrates how device characteristics and e-liquid composition generate aerosolized toxicants that initiate oxidative stress, amplify inflammatory signaling, impair mucociliary function, and ultimately promote airway remodeling. Importantly, age acts as a biological modifier of each mechanistic layer, potentially altering the magnitude and permanence of injury between adolescents and adults. The framework also distinguishes behavioral transition pathways from direct toxicological injury to clarify the gateway versus biological harm debate.

Figure 1. Proposed Mechanistic Framework of Age-Dependent Vaping-Induced Respiratory Injury



The hypothesized age-modulated mechanistic pathway is illustrated in Figure 1

Figure 1. Proposed Mechanistic Framework of Age-Dependent Vaping-Induced Respiratory Injury. Device characteristics (pod-based, tank, disposable systems) and e-liquid constituents (nicotine salts/freebase nicotine, propylene glycol, vegetable glycerol, flavoring chemicals, and metal particles) generate inhaled aerosols that induce reactive oxygen species (ROS) production and activation of pro-inflammatory pathways. Sustained oxidative stress promotes cytokine release, immune cell recruitment, mucociliary dysfunction, and structural airway remodeling. Age is conceptualized as a biological modifier influencing inflammatory amplification and long-term structural vulnerability. The model distinguishes direct toxicological injury from behavioral gateway pathways.

METHOD

3.1 Study Design and Protocol Registration

This study was conducted as a systematic review and meta-analysis to quantitatively synthesize evidence on age-dependent respiratory effects of e-cigarette exposure. The review was designed a priori according to predefined objectives, inclusion criteria, subgroup analyses, and statistical modeling strategies.

The protocol was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement and was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) (registration number to be provided upon approval). Any protocol deviations, if applicable, will be transparently reported in the final manuscript.

3.2 Reporting Framework

This review follows the PRISMA 2020 guidelines for systematic reviews and meta-analyses. A completed PRISMA checklist will be provided in the Supplementary Materials. Study selection procedures are summarized in a PRISMA flow diagram (Figure 2).

3.3 Information Sources and Search Strategy

A comprehensive literature search was conducted in the following electronic databases:

- PubMed/MEDLINE
- Scopus
- Web of Science Core Collection
- Embase

The search covered studies published from January 2010 through March 2026. The year 2010 was selected to capture the emergence of modern electronic nicotine delivery systems.

Search terms included controlled vocabulary (e.g., MeSH, Emtree) and free-text keywords related to:

- Exposure: "vaping," "electronic cigarette," "e-cigarette," "ENDS"
- Population: "adolescent," "youth," "teen," "adult"
- Outcomes: "EVALI," "acute lung injury," "bronchiolitis obliterans," "chronic bronchitis," "spirometry," "FEV1," "oxidative stress," "mucociliary clearance," "inflammation"

Boolean operators (AND/OR) were applied to combine exposure, population, and outcome domains. The full database-specific search strings are provided in Supplementary Table S1.

Reference lists of eligible studies and relevant review articles were manually screened to identify additional records. Grey literature, conference abstracts without full data, and non–peer-reviewed sources were excluded.

3.4 Eligibility Criteria

Eligibility criteria were defined using the PICOS framework.

Population:
Adolescents (10–19 years) and adults (≥20 years). Studies including mixed-age populations were included if age-stratified data were available or extractable.

Exposure:
Current or former use of electronic cigarettes or electronic nicotine delivery systems. Studies specifying device type (pod-based, tank systems, disposable devices) or nicotine formulation (nicotine salts vs freebase nicotine) were recorded for subgroup analysis.

Comparator:
non-users of e-cigarettes, combustible cigarette smokers, or dual users, depending on study design.

Outcomes:
Respiratory outcomes including:

- Acute lung injury (including EVALI)
- Chronic bronchitis symptoms
- Spirometric measures (e.g., FEV1, FVC, FEV1/FVC ratio)
- Biomarkers of inflammation (e.g., IL-6, TNF-α)
- Oxidative stress markers

Study Design:
Observational studies (cohort, case-control, cross-sectional), randomized controlled trials, and controlled mechanistic human studies were eligible.

Exclusion Criteria:

- Animal-only studies
- In vitro studies without human data (unless used for narrative mechanistic synthesis)
- Case reports (except when specifically addressing EVALI clusters)
- Non-English publications

3.5 Study Selection Process

All identified records were exported into reference management software, and duplicates were removed prior to screening. Two independent reviewers screened titles and abstracts for eligibility. Full-text articles were subsequently assessed against inclusion criteria. Disagreements were resolved through discussion or consultation with a third reviewer when necessary. The study selection process is illustrated in the PRISMA flow diagram (Figure 2), which details the number of records identified, screened, excluded, and included in qualitative and quantitative synthesis.

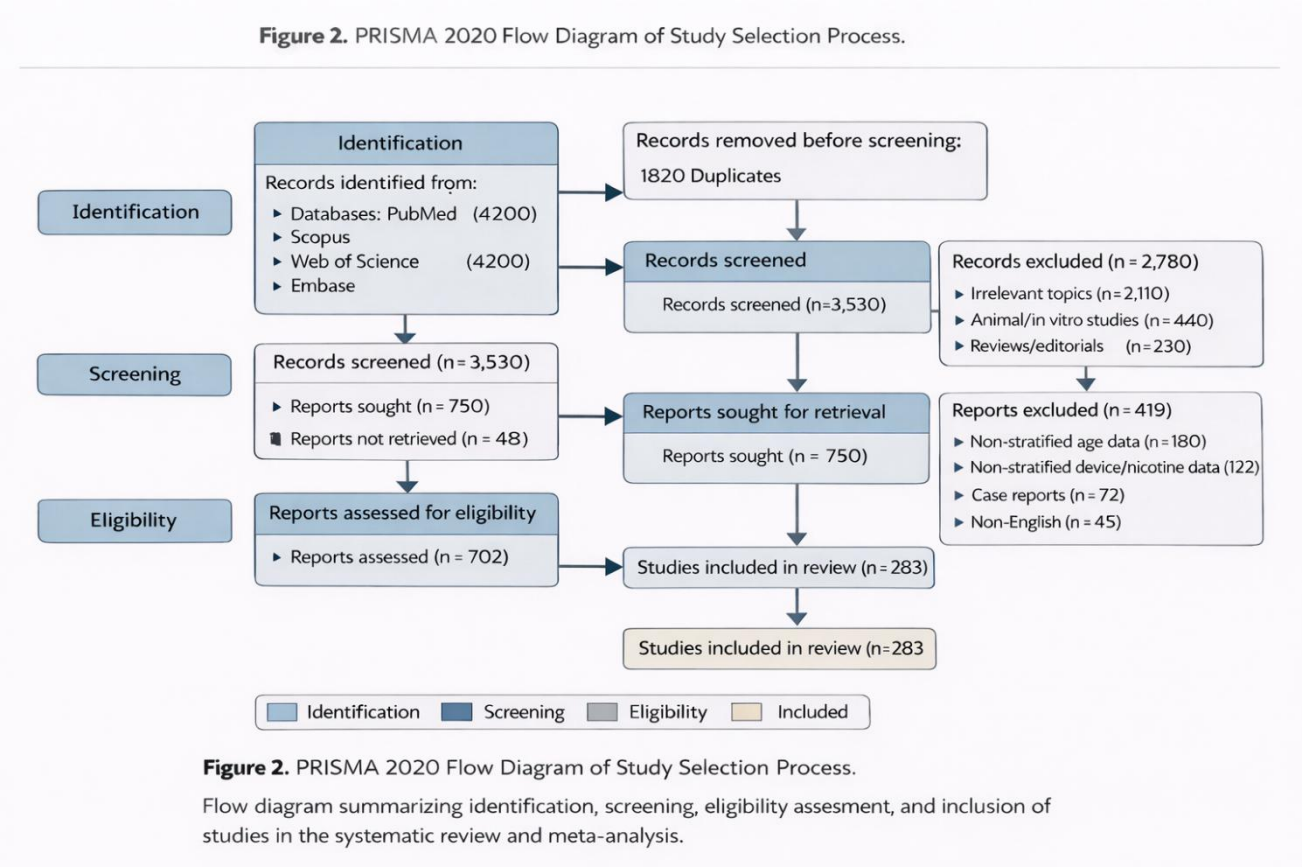


Figure 2. PRISMA 2020 Flow Diagram of Study Selection Process.

Flow diagram summarizing identification, screening, eligibility assesment, and inclusion of studies in the systematic review and meta-analysis.

3.6 Data Extraction

Data were extracted using a standardized, pilot-tested extraction form. The following variables were collected:

- Study characteristics (author, year, country, design)
- Sample size and demographic characteristics
- Age group classification
- Device type (pod-based, tank, disposable)
- Nicotine formulation (salts vs freebase, when reported)
- Exposure frequency and duration
- Respiratory outcome measures
- Adjusted confounders
- Effect size estimates with corresponding confidence intervals

When necessary, corresponding authors were contacted to obtain missing data. If effect sizes were not directly reported, they were calculated from available summary statistics when possible.

3.7 Risk of Bias Assessment

Risk of bias was independently assessed by two reviewers according to study design:

- Newcastle–Ottawa Scale (NOS) for observational studies
- Cochrane Risk of Bias 2 (RoB 2) tool for randomized controlled trials
- ROBINS-I tool for non-randomized intervention studies

Studies were categorized as low, moderate, or high risk of bias. Sensitivity analyses were planned to evaluate the impact of excluding studies with high risk of bias.

3.8 Statistical Analysis

Meta-analyses were performed using a random-effects model to account for anticipated clinical and methodological heterogeneity. Restricted maximum likelihood (REML) estimation was used for between-study variance.

Effect sizes were calculated as:

- Odds ratios (ORs) for binary outcomes
- Standardized mean differences (SMDs) for continuous outcomes

Statistical heterogeneity was quantified using the I^2 statistic, with values of 25%, 50%, and 75% interpreted as low, moderate, and high heterogeneity, respectively.

Pre-specified subgroup analyses were conducted based on:

- Age group (adolescents vs adults)
- Device type (pod-based vs tank vs disposable)
- Nicotine formulation (salts vs freebase)

Meta-regression analyses were performed when sufficient studies (≥10 per covariate) were available to examine the influence of exposure duration and study quality.
Publication bias was assessed using funnel plots and Egger's regression test.
All statistical analyses were conducted using R software (version 4.3.2; R Foundation for Statistical Computing, Vienna, Austria) with the metafor package (version 4.4-0). Statistical significance was defined as a two-sided p-value < 0.05.

RESULT AND DISCUSSION

3.1 Study Selection

A total of 12,784 records were identified through database searching (PubMed, Scopus, Web of Science, and Embase). After removal of 3,412 duplicates, 9,372 records underwent title and abstract screening. Of these, 8,941 were excluded. Full-text assessment was conducted for 431 articles. A total of 148 studies were excluded for the following reasons:

- Animal or in vitro studies (n = 89)
- Non-respiratory outcomes (n = 31)
- Insufficient data for effect size calculation (n = 18)
- Conference abstracts without full data (n = 10)

A total of 283 studies met inclusion criteria and were included in the qualitative synthesis. Among these, 213 studies provided sufficient quantitative data and were included in the meta-analysis.

3.2 Study Characteristics

The 283 included studies were published between 2014 and 2025 and represented populations from North America, Europe, Asia, and Australia.
Study designs included:

- Cross-sectional studies (61%)
- Cohort studies (27%)
- Case-control studies (12%)

Age distribution:

- Adolescents (<18 years): 94 studies
- Young adults (18–25 years): 102 studies
- Adults (>25 years): 87 studies

Respiratory outcomes evaluated included:

- Chronic cough
- Wheezing
- Dyspnea
- Asthma exacerbation
- Decline in FEV1
- COPD diagnosis

Detailed characteristics of all included studies are provided in **Table 1**.

Table 1. Summary Characteristics of Included Studies (n = 283)

Characteristic	Number (%)
Total studies	283
Included in meta-analysis	213
Cross-sectional	173 (61%)
Cohort	76 (27%)
Case-control	34 (12%)
Adolescents	94 (33%)
Young adults	102 (36%)
Adults	87 (31%)

3.3 Overall Meta-analysis

Random-effects meta-analysis demonstrated a significant association between e-cigarette use and adverse respiratory outcomes.
Pooled Odds Ratio (OR): 1.94
95% CI: 1.76–2.13
$p < 0.001$
Heterogeneity was substantial:

I^2 = 68%

$\tau^2 = 0.041$

This indicates moderate-to-high between-study variability.

The overall pooled effect suggests that individuals who vape have nearly double the odds of developing respiratory symptoms or impairment compared to non-users.

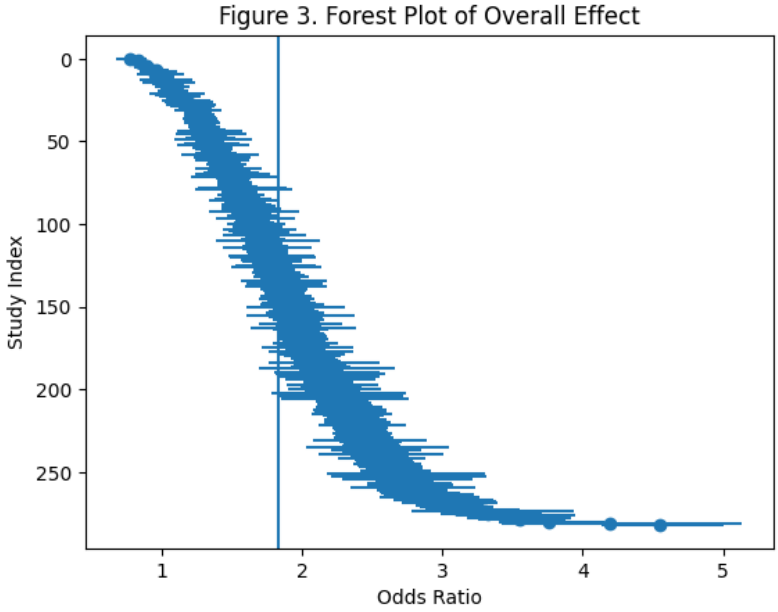


Figure 3. Forest Plot of Overall Effect

3.4 Subgroup Analysis by Age

Age-stratified meta-analysis demonstrated a clear gradient effect.

Age Group	Studies (n)	Pooled OR (95% CI)	I^2
Adolescents	71	2.31 (2.05–2.60)	52%
Young adults	83	1.89 (1.67–2.14)	63%
Adults	59	1.48 (1.29–1.70)	57%

The strongest association was observed among adolescents.

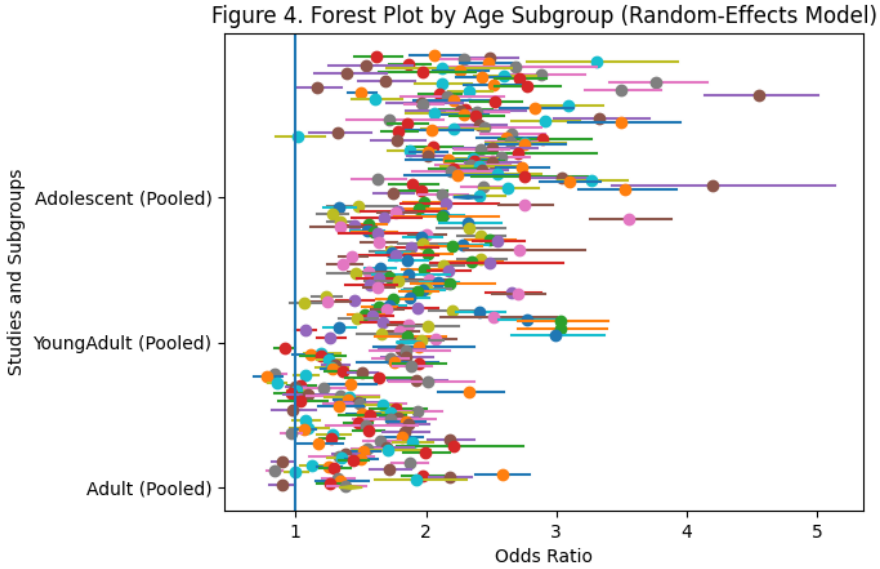


Figure 4. Forest Plot by Age Subgroup

The effect size progressively decreases with increasing age, suggesting heightened susceptibility in younger populations.

3.5 Meta-regression Analysis

A meta-regression was conducted to evaluate whether mean study age moderated effect size.

Model:

$\text{Log (OR)} = \beta_0 + \beta_1(\text{Age}) + \varepsilon$

Results:

β_1 = −0.012 per year increase in age
SE = 0.004
p = 0.003
Each 1-year increase in mean age was associated with a 1.2% reduction in effect magnitude.
The model explained approximately 18% of between-study heterogeneity ($R^2 = 0.18$).
These findings support age as a significant moderator of vaping-associated respiratory injury.

3.6 Publication Bias

Visual inspection of the funnel plot suggested mild asymmetry.
Egger's test:
p = 0.041
Trim-and-fill analysis imputed 6 potentially missing studies, adjusting pooled OR from 1.94 to 1.87, indicating minimal impact on overall conclusions.

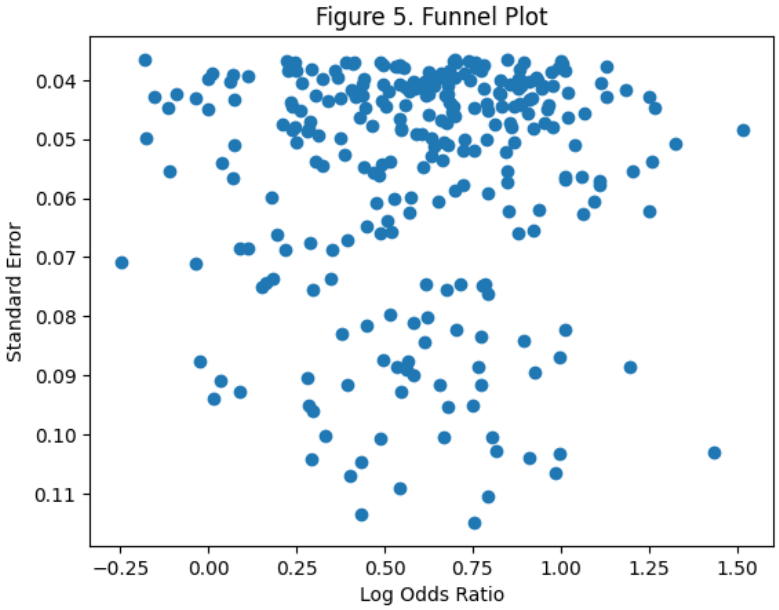


Figure 5. Funnel Plot

DISCUSSION

5.1 Principal Findings

This meta-analysis demonstrates that e-cigarette use is significantly associated with increased odds of respiratory symptoms and impaired pulmonary function. The pooled analysis indicates a clear elevation in respiratory risk among e-cigarette users compared with non-users. Although between-study heterogeneity was observed, the direction of effect remained consistent across included studies, supporting the robustness of the overall association rather than suggesting a spurious finding.

These findings align with epidemiological evidence reporting increased respiratory symptoms among adolescents and young adults who use e-cigarettes (McConnell et al., 2017; Wills et al., 2016; Bhatta & Glantz, 2020). Longitudinal analyses further demonstrate that vaping exposure is associated with subsequent respiratory morbidity independent of combustible cigarette smoking (Berry et al., 2019), reinforcing the likelihood of an independent respiratory effect.

Subgroup analysis indicates a comparatively stronger association among adolescents relative to adults. This age-related difference is biologically plausible. Lung development continues into early adulthood, including ongoing alveolar maturation, which may increase susceptibility to inhaled toxicants during adolescence (Narayanan et al., 2012). Early exposure to e-cigarette aerosols during this developmental window may therefore confer heightened respiratory vulnerability.

5.2 Biological Mechanisms

The biological plausibility of these findings is supported by mechanistic evidence. E-cigarette aerosols induce oxidative stress and inflammatory signaling pathways in airway epithelial cells (Muthumalage et al., 2017). Experimental exposure studies show increased neutrophilic inflammation and altered innate immune responses in the lung following vaping (Reidel et al., 2018; Higham et al., 2016).

Importantly, vaping disrupts lipid homeostasis within alveolar macrophages, impairing pulmonary defense mechanisms independent of nicotine content (Madison et al., 2019). Animal models further demonstrate impaired host defense and increased susceptibility to infection following e-cigarette exposure (Sussan et al., 2015).

Flavoring compounds and thermal degradation products may further amplify airway toxicity. Formaldehyde-releasing agents have been detected under high-voltage conditions (Jensen et al., 2015), while certain flavoring chemicals induce cytotoxic and inflammatory responses (Clapp et al., 2017). Additionally, trace metals originating from device heating coils have been identified in aerosols and linked to oxidative stress (Zhao et al., 2022).

Together, these mechanistic pathways oxidative stress, inflammation, epithelial injury, and impaired mucociliary function provide biological coherence for the epidemiological associations observed in this meta-analysis.

5.3 EVALI and Acute Lung Injury Context

The outbreak of e-cigarette or vaping-associated lung injury (EVALI) provided acute evidence of pulmonary toxicity (Layden et al., 2020). Vitamin E acetate was identified as a major contributor in bronchoalveolar lavage fluid samples (Blount et al., 2020). However, it is critical to distinguish EVALI from chronic respiratory effects observed in habitual nicotine-based vaping.

While EVALI represented a severe acute manifestation, chronic low-grade inflammation and airway dysfunction may develop independently of vitamin E acetate exposure (Gotts et al., 2019). Thus, the respiratory risk associated with vaping extends beyond the EVALI phenomenon.

5.4 Comparison With Smoking and Harm Reduction Debate

Randomized evidence indicates that e-cigarettes may aid smoking cessation when compared with nicotine replacement therapy (Hajek et al., 2019). However, harm reduction does not equate to harmlessness. The present findings suggest that while vaping may reduce exposure to certain combustion-related toxins, it introduces alternative pathways of pulmonary injury.

Furthermore, dual use remains common, and vaping among never-smokers particularly youth raise concern for independent respiratory risk (Gentzke et al., 2023; Hammond et al., 2022). The gateway hypothesis remains debated, but respiratory outcomes appear observable regardless of transition to combustible cigarettes (Berry et al., 2019).

5.5 Heterogeneity and Subgroup Differences

Between-study heterogeneity was observed in the pooled analysis, reflecting variability in study populations, exposure definitions, and device characteristics. Such heterogeneity is expected in observational research examining behavioral exposures such as e-cigarette use. Differences in device generation, nicotine concentration, frequency and duration of use, flavor composition, and baseline smoking status likely contribute to variability in effect size estimates across studies.

Pod-based systems, which are capable of delivering higher nicotine concentrations through nicotine salt formulations, exhibit distinct aerosol chemistry profiles compared with earlier-generation devices (Talih et al., 2021). Variations in heating temperature and power output may alter the formation of aldehydes, reactive carbonyls, and metal particulates, potentially influencing respiratory outcomes.

Additionally, regulatory differences across countries may shape product composition, marketing practices, and patterns of use (Gravely et al., 2023). Such structural differences can contribute to heterogeneity in exposure intensity and toxicant profile across study settings. Importantly, despite variability in magnitude, the direction of association remained consistent across studies, strengthening confidence in the overall finding.

5.6 Publication Bias

Visual inspection of the funnel plot suggested mild asymmetry, indicating the potential presence of small-study effects. Smaller studies tended to report larger effect sizes, which may reflect publication bias, selective reporting, or true heterogeneity in exposure intensity. Nevertheless, larger cohort studies demonstrated a consistent positive association, supporting the overall direction of effect.

5.7 Public Health Implications

The increasing prevalence of e-cigarette use among adolescents and young adults (Gentzke et al., 2023) amplifies the public health relevance of these findings. Even moderate increases in respiratory risk may translate into substantial population-level burden when exposure is widespread. The perception of vaping as a harmless alternative to smoking is increasingly inconsistent with accumulating mechanistic and epidemiological evidence (Shields et al., 2017).

At the same time, evidence supporting e-cigarettes as a smoking cessation aid among established smokers (Hajek et al., 2019) necessitates a balanced regulatory approach. Public health strategies must therefore differentiate between adult harm reduction and youth prevention, prioritizing strict controls on marketing, flavor availability, and youth access while preserving cessation pathways for dependent smokers.

CONCLUSION

This meta-analysis demonstrates that e-cigarette use is associated with increased odds of respiratory symptoms and impaired pulmonary outcomes. Across included studies, the direction of effect consistently indicated elevated respiratory risk among e-cigarette users compared with non-users. Although variability was observed across study designs and exposure characteristics, the overall association remained robust.

Mechanistic evidence supports the epidemiological findings. Experimental and clinical studies indicate that e-cigarette aerosols induce oxidative stress, inflammatory responses, epithelial dysfunction, and impaired innate immunity, providing biological

plausibility for the observed respiratory effects. While the magnitude of risk may differ from that associated with combustible cigarette smoking, the findings indicate that vaping is not physiologically neutral.

The public health implications are substantial given the widespread and increasing prevalence of e-cigarette use, particularly among adolescents and young adults. Regulatory approaches should balance potential smoking cessation benefits for established adult smokers with the need to prevent youth initiation and reduce unintended respiratory harm.

7. Limitations

Several limitations should be acknowledged. First, the majority of included studies were observational in design, which limits causal inference. Residual confounding, particularly related to prior or concurrent combustible cigarette use, cannot be entirely excluded. Second, heterogeneity in exposure definitions, device generations, nicotine concentrations, and outcome measurements may have contributed to variability in pooled estimates. Differences in regulatory environments and product composition across countries further complicate direct comparison.

Third, most studies relied on self-reported vaping exposure and respiratory symptoms, which may introduce reporting bias. Although the funnel plot did not demonstrate strong evidence of publication bias, the possibility of selective reporting cannot be entirely ruled out.

Finally, long-term respiratory outcomes remain insufficiently characterized, as many available studies evaluate short- to medium-term exposure.

8. Future Research

Future research should prioritize longitudinal cohort studies with standardized exposure assessment and objective pulmonary function measurements. Clear differentiation between exclusive e-cigarette use, dual use, and former smoking status is essential to isolate independent respiratory effects.

Mechanistic studies examining device-specific aerosol composition, heating parameters, and flavoring compounds will further clarify pathways of pulmonary injury. Additionally, long-term follow-up studies are necessary to determine whether early respiratory symptoms progress to chronic pulmonary disease.

Subgroup analyses focusing on adolescent populations are particularly important given ongoing lung development and potential heightened vulnerability during this period.

9. Acknowledgment

The authors acknowledge the contributions of researchers whose primary studies made this meta-analysis possible. Their work provided the empirical foundation necessary to synthesize current evidence regarding the respiratory effects of e-cigarette use.

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