



HOUSEHOLD AIR POLLUTION AND RISK OF PNEUMONIA IN CHILDREN UNDER FIVE: A SYSTEMATIC LITERATURE REVIEW FROM LOW- AND MIDDLE-INCOME COUNTRIES

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Abstract

Household air pollution remains a critical environmental determinant of child health in low- and middle-income countries, where reliance on solid fuels for cooking and heating persists. This systematic literature review synthesizes empirical evidence examining the association between household air pollution and pneumonia among children under five years of age. A structured search of the Scopus database identified 569 records, of which eight studies met predefined inclusion criteria following PRISMA-guided screening and eligibility assessment. Included studies comprised cross-sectional analyses, hospital-based observational research, randomized intervention trials, and meta-analyses conducted across diverse geographical settings. Evidence consistently demonstrated a positive association between exposure to solid fuel combustion and increased risk of pneumonia, although magnitude varied according to exposure measurement strategy and contextual factors. Proxy indicators, such as cooking-fuel type, were frequently used as exposure measures, whereas only a few studies incorporated direct pollutant monitoring. Intervention-based findings indicated that partial reductions in emissions from improved cookstoves did not consistently translate into measurable declines in pneumonia incidence. Socioeconomic disparities, housing conditions, cultural practices, and energy access constraints further shaped differential exposure patterns and vulnerability among children. An integrated interpretation of epidemiological data and environmental health theory underscores the importance of comprehensive clean energy transitions, infrastructure improvements, and sustained behavioral adaptation to mitigate the pediatric respiratory disease burden in resource-limited settings.

Keywords: Household Air Pollution; Pneumonia; Children Under Five; Solid Fuel Use; Low- and Middle-Income Countries

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INTRODUCTION

Household air pollution remains one of the most persistent environmental health threats affecting vulnerable populations in low- and middle-income countries. Combustion of solid fuels such as wood, charcoal, dung, and agricultural residues for daily cooking and heating generates a complex mixture of particulate matter, carbon monoxide, and other toxic pollutants that accumulate within poorly ventilated dwellings. Children under five years of age experience disproportionate exposure because they are near caregivers during cooking and because their developing respiratory systems are more sensitive. Pneumonia continues to represent a leading cause of morbidity and mortality among children globally, particularly in resource-limited settings where environmental risks remain inadequately controlled. Epidemiological investigations consistently identify household air pollution as a significant contributor to acute respiratory infections, including pneumonia. Meta-analytic findings report elevated odds ratios associated with solid fuel use, ranging from 1.66 to 1.86, indicating a substantial increase in pneumonia risk among exposed children (Chen *et al.*, 2022; Desye *et al.*, 2025). Evidence synthesized in previous reviews underscores the magnitude of this problem while revealing inconsistencies in exposure measurement and contextual interpretation.

Pneumonia in children under five is characterized by inflammation of the lung parenchyma, impaired gas exchange, and increased susceptibility to hypoxia, particularly in environments with high particulate pollution. Fine particulate matter (PM_{2.5}) penetrates deeply into the lower respiratory tract, triggering inflammatory responses and compromising mucociliary clearance. Carbon monoxide exposure reduces oxygen-carrying capacity by forming carboxyhemoglobin, although several investigations report inconsistent associations between CO levels and pneumonia incidence (Havens *et al.*, 2018; Mortimer *et al.*, 2020). Solid fuel use often serves as a proxy for particulate exposure when direct measurement is unavailable, but such measures may mask variations in pollutant concentrations and exposure durations (Adaji *et al.*, 2019). Variability in cooking practices, housing structure, and ventilation further complicates causal inference. Regional analyses suggest stronger associations in Asian settings compared with several African contexts,

highlighting heterogeneity in environmental and sociocultural determinants (Gordon *et al.*, 2014). Such heterogeneity necessitates refined synthesis to clarify patterns of risk across contexts.

Prior systematic reviews have established a general association between indoor air pollution and childhood respiratory infections; however, important analytical gaps remain unresolved. Some reviews aggregate acute respiratory infections without distinguishing clinically confirmed pneumonia, thereby limiting specificity of conclusions (Desye *et al.*, 2025). Other syntheses emphasize carbon monoxide exposure despite evidence suggesting limited direct association with pneumonia outcomes (Bonjour *et al.*, 2013). Intervention-based studies evaluating improved cookstoves show mixed or negligible reductions in pneumonia incidence, raising questions about implementation fidelity and whether pollutants are displaced rather than eliminated (Smith *et al.*, 2014). Large-scale distribution programs, including cluster-randomized trials in Rwanda, aim to reduce respiratory outcomes yet require contextual evaluation of exposure intensity and sustained adoption (Nagel *et al.*, 2016). Absence of consistent exposure metrics and limited integration of socioeconomic modifiers create fragmentation in the literature. Comprehensive syntheses focusing specifically on pneumonia, rather than broad respiratory categories, remain limited and warrant further scholarly attention.

Socioeconomic and environmental co-determinants intensify vulnerability among children exposed to household air pollution. Lack of separate kitchens, proximity to roadways, and inadequate housing ventilation correlate with increased respiratory symptoms (Budhathoki *et al.*, 2020); (Das *et al.*, 2018). Incomplete immunization status, exclusive breastfeeding, and younger maternal age are also independent predictors of pneumonia (Lu, 2025). The interaction between environmental exposure and biological susceptibility aligns with the ecological model of child health, which posits that health outcomes arise from multilevel interactions among environmental, behavioral, and structural factors. Exposure-response theory further explains how repeated inhalation of particulate matter contributes cumulatively to inflammatory lung injury. The synergistic interaction among malnutrition, infection, and pollutant exposure compounds disease severity in marginalized

populations. Recognition of these interlocking determinants underscores the need for an integrated analytical perspective.

Measurement limitations constitute a persistent methodological challenge in the household air pollution literature. Direct quantification of PM_{2.5} exposure in young children remains technically complex and financially demanding in rural contexts. Proxy indicators such as type of cooking fuel fail to capture exposure intensity, duration, and behavioral patterns that influence inhalation levels (Bruce et al., 2000). Carbon monoxide monitoring, although feasible, may not adequately represent particulate toxicity relevant to pneumonia pathogenesis (Havens et al., 2018). Intervention trials involving cleaner biomass cookstoves did not consistently demonstrate reductions in either carbon monoxide exposure or pneumonia incidence, suggesting incomplete pollutant mitigation (Mortimer et al., 2020). Methodological heterogeneity across studies complicates pooled estimation and comparability. Rigorous synthesis is required to disentangle measurement variability from true epidemiological differences.

Geographical variation further underscores the complexity of interpreting associations between household air pollution and pneumonia. Demographic and Health Survey analyses across multiple low- and middle-income countries reveal substantial disparities in exposure prevalence and health outcomes (Al-Janabi et al., 2021). Asian regions show higher pooled risk estimates than several African settings, suggesting contextual modifiers linked to fuel type, cooking behavior, and housing density (Lu, 2025). Urban–rural differences contribute additional variability, as rural households often rely more heavily on biomass fuels. Microenvironmental conditions within households, including room size and ventilation patterns, significantly influence pollutant concentration (Safi et al., 2022). Cultural cooking practices that involve prolonged indoor combustion intensify cumulative exposure among children. Interpretation of pooled findings without contextual stratification risks oversimplifying complex environmental-health interactions.

Theoretical justification for examining this association derives from environmental health frameworks that conceptualize disease as a product of sustained exposure to hazardous agents within structurally constrained settings. Ecological systems theory emphasizes how environmental,

familial, and societal layers converge to shape child health outcomes. Repeated inhalation of particulate matter disrupts epithelial integrity, impairs immune defense mechanisms, and facilitates bacterial or viral colonization of the lower respiratory tract. Developmental vulnerability during early childhood amplifies susceptibility to inflammatory damage and long-term pulmonary impairment. Public health transition theory further posits that countries undergoing rapid demographic and economic change may experience overlapping burdens of infectious and environmental diseases. Persistently high reliance on solid fuels in many low-resource settings sustains preventable exposure pathways. Theoretical coherence across these models reinforces the urgency of consolidating evidence specific to pneumonia as a distinct clinical outcome.

Existing intervention efforts illustrate both progress and limitation in mitigating household air pollution. Cleaner cookstove initiatives aim to reduce emissions through improved combustion efficiency; however, empirical findings indicate limited impact on pneumonia reduction when pollutant levels remain above recommended thresholds (Mortimer et al., 2020). Large-scale distribution programs in Rwanda and similar contexts integrate water filtration and energy interventions, yet sustained behavioral adoption remains variable (Nagel et al., 2016). Observational studies conducted in Afghanistan and Nepal continue to report significant associations between solid fuel use and pediatric pneumonia despite policy attention (Safi dkk., 2022; Budhathoki dkk., 2020). Implementation challenges, such as fuel stacking, affordability barriers, and cultural cooking norms, undermine the effectiveness of interventions. A comprehensive evaluation of these mixed findings is required to clarify which strategies demonstrate measurable health benefits. Consolidated synthesis can inform more targeted policy development and resource allocation.

The urgency of this review stems from the persistent global burden of childhood pneumonia and the preventable nature of environmental exposure risks. Health systems in low- and middle-income countries frequently operate under constrained capacity, magnifying consequences of preventable respiratory disease. Reduction of household air pollution represents a modifiable determinant aligned with sustainable development

objectives related to clean energy and child health. Persistent ambiguity regarding exposure metrics and intervention effectiveness hinders evidence-based policymaking. Clear synthesis focused specifically on pneumonia outcomes can refine understanding of causal pathways and contextual modifiers. Timely consolidation of evidence supports formulation of integrated strategies combining clean energy transition, improved housing infrastructure, and caregiver education. Strengthened evidence base enhances alignment between environmental policy and pediatric health protection.

This literature review aims to critically synthesize empirical findings on the association between household air pollution and pneumonia among children under five years of age in low- and middle-income countries. Specific objectives include evaluating strength and consistency of associations across diverse geographical contexts, examining measurement approaches used to assess exposure, and identifying socioeconomic or environmental modifiers influencing risk magnitude. Attention is directed toward distinguishing pneumonia from broader respiratory infection categories to enhance clinical specificity. Analytical integration seeks to clarify whether intervention strategies demonstrate measurable reduction in pneumonia incidence. Findings are expected to inform both research direction and public health policy formulation. Three research questions guide this review: (1) What is the magnitude and consistency of the association between household air pollution and pneumonia among children under five in low- and middle-income countries? (2) How do differences in exposure measurement and contextual factors influence reported risk estimates? (3) What evidence exists regarding the effectiveness of household-level interventions in reducing pneumonia incidence among exposed populations?

METHOD

1. Research Design and Approach

This study employed a systematic literature review design with a qualitative synthesis approach to comprehensively examine the association between household air pollution and pneumonia among children under five years of age in low- and middle-income countries. Systematic literature review methodology was selected to ensure transparency, reproducibility, and rigor in identifying, evaluating, and synthesizing empirical

evidence. The review followed internationally recognized reporting standards to minimize selection bias and enhance methodological credibility. A structured protocol was developed prior to the review process, including predefined research questions, search strategies, inclusion and exclusion criteria, and analytical procedures. Emphasis was placed on peer-reviewed empirical studies to ensure scientific reliability and methodological robustness. The review focused specifically on pneumonia outcomes rather than aggregated respiratory infections to improve clinical specificity. Quantitative, observational, and interventional studies were considered eligible provided that they reported measurable associations between household air pollution exposure and pneumonia incidence or prevalence.

2. Data Sources and Search Strategy

Penelitian dilaksanakan di RSUD dr. La Palaloi Kabupaten Maros pada periode 13 Desember 2022 hingga 10 Januari 2023. Pemilihan lokasi didasarkan pada pertimbangan bahwa rumah sakit tersebut merupakan fasilitas rujukan daerah yang melayani ibu hamil dengan karakteristik klinis dan sosial yang beragam, sehingga relevan untuk mengkaji determinan anemia pada konteks pelayanan rumah sakit.

3. PRISMA Flow Process

The selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, consisting of four main stages: Identification, Screening, Eligibility, and Inclusion. The study selection process is described numerically below, based on the Scopus search results.

Identification: A total of 569 records were identified through a Scopus database search. Duplicate records detected through reference management screening amounted to 47 articles and were removed. After duplicate removal, 522 unique records remained for further assessment.

Screening: Title and abstract screening was conducted to assess relevance to the research topic. During this stage, 428 records were excluded for being irrelevant to pneumonia outcomes, focusing on adult populations, lacking household-level exposure measures, or being conducted outside low- and middle-income countries. Following screening, 94 articles were retained for full-text assessment.

Eligibility: Full-text articles were evaluated against predefined inclusion and exclusion criteria. A total of 86 articles were excluded at this stage.

Reasons for exclusion included: lack of specific pneumonia outcome measurement (n = 29), aggregation of respiratory infections without disaggregated pneumonia data (n = 18), absence of clear exposure measurement related to household air pollution (n = 21), insufficient methodological transparency (n = 9), and review articles without original empirical data (n = 9). Eight studies

satisfied all eligibility criteria and were retained for final synthesis.

Inclusion: Eight studies were included in the qualitative synthesis. These studies provided empirical evidence examining the association between household air pollution exposure and pneumonia among children under five years in low- and middle-income countries.

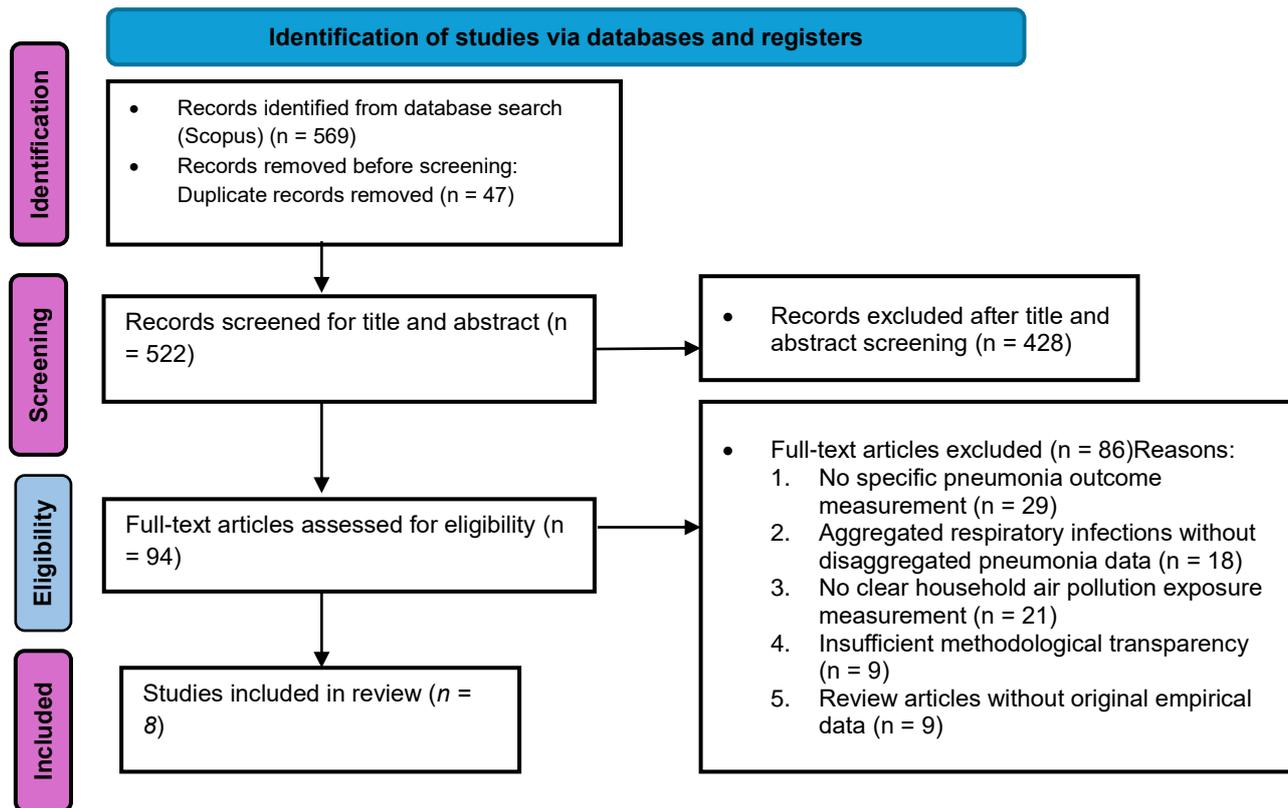


Figure 1. PRISMA flowchart

Table 1. Inclusion and Exclusion Criteria

Criteria Type	Detailed Description	Rationale
Inclusion	Peer-reviewed empirical research articles	Ensures methodological rigor and scientific credibility
Inclusion	Conducted in low- and middle-income countries	Aligns with the geographical focus of the review
Inclusion	Participants: children under five years of age	Targets the most vulnerable population group
Inclusion	Explicit measurement of household air pollution exposure (solid fuel use, PM2.5, CO, or related indicators)	Guarantees relevance to exposure variable
Inclusion	Pneumonia reported as primary or clearly disaggregated outcome	Ensures clinical specificity of the dependent variable
Inclusion	Full-text available in English	Enables comprehensive evaluation and synthesis
Exclusion	Studies focusing solely on adult populations	Outside scope of pediatric health focus
Exclusion	Studies reporting aggregated respiratory infections without specific pneumonia data	Limits outcome precision
Exclusion	Editorials, commentaries, conference abstracts, narrative reviews	Lack original empirical data
Exclusion	Absence of clear household air pollution exposure measurement	Prevents exposure misclassification
Exclusion	Conducted in high-income countries	Not aligned with contextual focus of review

4. Data Extraction and Analysis

Data extraction was performed using a standardized matrix to ensure consistency across included studies. Extracted variables included study design, country, sample size, age range, exposure measurement method, outcome definition, statistical model, effect size estimates, and key findings. Emphasis was placed on reported odds ratios, relative risks, or hazard ratios to allow comparative interpretation of association strength. Heterogeneity across studies was analyzed narratively due to differences in exposure measurement, outcome definition, and contextual factors. Methodological quality was assessed

based on clarity of exposure assessment, outcome verification, confounding adjustment, and statistical rigor. The synthesis adopted a thematic analytical approach to categorize findings into exposure measurement patterns, magnitude of association, regional variation, and intervention effectiveness. Analytical integration prioritized consistency of effect direction and robustness of statistical significance rather than simple frequency counting. The final synthesis aimed to clarify the strength, variability, and contextual determinants of the relationship between household air pollution and childhood pneumonia.

Table 2. Systematic Literature Review Results

Study	Methodology	Exposure Variable(s)	Key Findings
Al-Janabi dkk., (2021)	Cross-sectional analysis (DHS data, 37 LMICs)	Type of domestic cooking energy (solid vs clean fuels)	Solid fuel use was significantly associated with an increased risk of respiratory infections among children under five, with variation across countries.
Nagel et al. (2016)	Cluster-randomized controlled trial design	Distribution of improved cookstoves and water filters	Large-scale clean energy interventions aim to reduce acute respiratory infections, though their effectiveness depends on sustained adoption and on reducing exposure.
Havens et al. (2018)	Cross-sectional exposure assessment	Carbon monoxide exposure and carboxyhemoglobin levels	Carbon monoxide exposure showed a limited direct association with pneumonia, suggesting CO alone may not adequately represent total HAP-related risk.
Mortimer et al. (2020)	Randomized intervention study (CAPS, Malawi)	Cleaner biomass cookstoves; household air pollution exposure	The introduction of cleaner cookstoves did not significantly reduce pneumonia incidence, suggesting that partial emission reduction may be insufficient.
Budhathoki et al. (2020)	Secondary analysis of DHS data (Nepal)	Household air pollution; cooking fuel type; housing conditions	A significant association was observed between biomass fuel use and childhood pneumonia, influenced by ventilation and kitchen separation.
Safi et al. (2022)	Hospital-based observational study	Solid fuel exposure; indoor air pollution indicators	Children exposed to household air pollution were more likely to be admitted for pneumonia than those using clean fuels.
Chen et al. (2022)	Systematic review and meta-analysis	Solid fuel use as proxy for PM2.5 exposure	Pooled odds ratios indicated a 1.66–1.86 increase in the risk of pneumonia among children exposed to solid fuels, with higher estimates in Asian regions.
Desye et al. (2025)	Systematic review and meta-analysis	Indoor air pollution exposure indicators	A strong association was identified between indoor air pollution and acute respiratory infections, including pneumonia, among children under five.

RESULTS AND DISCUSSION

1. RQ1. What is the magnitude and consistency of the association between household air pollution and pneumonia among children under five in low- and middle-income countries?

Empirical evidence drawn from the eight included studies demonstrates a consistent positive association between household air pollution and pneumonia among children under five years of age

across diverse low- and middle-income settings. A cross-national analysis of Demographic and Health Survey data from 37 countries found significantly higher odds of respiratory infections among children living in households that rely on solid fuels compared with those using clean energy sources (Al-Janabi et al., 2021). Hospital-based observational findings from Afghanistan similarly reported an increased likelihood of pneumonia admission among children exposed to indoor solid-fuel combustion (Safi et al., 2022). Secondary

analysis of Nepalese survey data further revealed that biomass fuel use was associated with elevated pneumonia prevalence, particularly in households lacking adequate ventilation (Budhathoki et al., 2020). Meta-analytic synthesis yielded pooled odds ratios ranging from 1.66 to 1.86, indicating a robust association between solid fuel exposure and risk (Chen et al., 2022). Complementary evidence from a broader meta-analysis on indoor air pollution reinforced the association, highlighting the vulnerability of children under five to particulate exposure (Desye et al., 2025).

Variation in magnitude across studies appears influenced by methodological design and exposure measurement approaches. Randomized intervention research conducted in Malawi reported limited reduction in pneumonia incidence following introduction of cleaner biomass cookstoves, despite documented changes in household air pollution profiles (Mortimer et al., 2020). Cross-sectional exposure assessment within the same research context showed that carbon monoxide concentrations did not consistently predict pneumonia outcomes, suggesting that relying on CO as the sole indicator may underestimate the true exposure burden (Havens et al., 2018). A large-scale intervention in Rwanda aimed to address acute respiratory infections through combined cookstove and water filter distribution, yet its effectiveness depended on sustained use patterns and community engagement (Nagel et al., 2016). Differences in diagnostic criteria, including caregiver-reported symptoms versus clinically confirmed pneumonia, also contributed to variability in reported effect sizes. Observational studies using survey-based self-report measures tended to yield wider confidence intervals than those based on hospital-verified diagnoses. Patterns emerging across these methodological contexts nevertheless converge toward a positive exposure–disease relationship.

Regional heterogeneity further characterizes the magnitude of association across included studies. Meta-analytic stratification indicated comparatively stronger pooled risk estimates in Asian regions than in several African contexts, potentially reflecting differences in fuel type composition and housing density (Chen et al., 2022). Nepalese evidence highlighted the compounded influence of indoor microenvironmental conditions, such as the absence of separate kitchens and limited airflow (Budhathoki et al., 2020). Afghan hospital-based

data illustrated how high-intensity exposure in urban households reliant on biomass may exacerbate severity of pneumonia cases requiring admission (Safi et al., 2022). Cross-country DHS analysis demonstrated that socioeconomic gradients intersect with energy use patterns, thereby shaping differential exposure risk across populations (Al-Janabi et al., 2021). Intervention-based findings from Malawi and Rwanda revealed that technological modification alone may not uniformly translate into measurable reductions in pneumonia incidence without broader behavioral adaptation (Mortimer et al., 202; Nagel et al., 2016). Interconnected contextual factors thus influence both measured magnitude and observed consistency of association.

2. RQ2. How do differences in exposure measurement and contextual factors influence reported risk estimates?

Exposure assessment strategies varied considerably across the eight included studies, directly affecting the comparability of risk estimates. Several investigations operationalized household air pollution using proxy indicators, such as primary cooking fuel type, thereby assuming a correlation with particulate matter concentration (Al-Janabi et al., 2021; Budhathoki et al., 2020). Other studies employed direct environmental monitoring of carbon monoxide levels and carboxyhemoglobin measurements in children to approximate inhalation exposure (Havens et al., 2018). Randomized intervention trials evaluated emission reductions from the introduction of improved cookstoves without continuous, real-time particulate monitoring (Mortimer et al., 2020). Meta-analytic syntheses incorporated heterogeneous exposure definitions, combining solid fuel use, indoor air pollution indices, and particulate proxies into pooled analyses (Chen et al., 2022); Desye et al., 2025). Divergence in exposure operationalization inevitably shaped the magnitude of effect sizes and interpretive precision.

Contextual modifiers further mediated the strength of association observed across studies. Housing characteristics such as kitchen separation, ventilation design, and room size influenced pollutant dispersion patterns and cumulative child exposure (Budhathoki et al., 2020). Socioeconomic disparities intersect with energy accessibility, limiting the transition to cleaner fuels among marginalized populations represented in multi-country DHS datasets (Al-Janabi et al.,

2021). Cultural cooking practices involving prolonged indoor combustion periods intensified duration of exposure beyond nominal fuel classification. Hospital-based findings suggested that coexisting health determinants, including nutritional status and immunization coverage, interacted with pollutant exposure to influence pneumonia severity (Safi et al., 2022). Intervention implementation in Rwanda showed that sustained behavioral adoption significantly moderated the potential for exposure reduction (Nagel et al., 2016). Measurement heterogeneity, combined with contextual diversity, thereby shaped variability in reported risk estimates.

Analytical approaches also contributed to the differential interpretation of association strength. Cross-sectional survey analyses frequently adjusted for demographic covariates yet relied on caregiver-reported respiratory symptoms (Al-Janabi et al., 2021). Hospital-based observational designs incorporated clinically confirmed pneumonia diagnoses but often operated within localized samples (Safi et al., 2022). Intervention studies evaluated incidence over defined follow-up periods, providing temporal insight, but faced challenges in monitoring adherence (Mortimer et al., 2020). Direct monitoring studies measuring carbon monoxide exposure highlighted the limitation of single-pollutant assessment in representing complex particulate mixtures (Havens et al., 2018). Meta-analyses synthesized diverse methodological designs, increasing statistical power while inheriting embedded heterogeneity (Chen et al., 2022; Desye et al., 2025). The interplay between methodological rigor and contextual variability shaped the interpretive contours of exposure–disease relationships.

3. RQ3. What evidence exists regarding the effectiveness of household-level interventions in reducing pneumonia incidence among exposed populations?

Intervention-focused evidence from the included studies provides a nuanced picture of effectiveness in reducing pneumonia risk. Randomized evaluation of cleaner biomass cookstoves in Malawi did not demonstrate statistically significant reduction in pneumonia incidence among children under five despite measurable changes in certain pollutant indicators (Mortimer et al., 2020). Exposure assessment in the same context revealed persistent carbon monoxide levels that were not sufficiently reduced

to alter clinical outcomes (Mortimer et al., 2020). A cluster-randomized trial in Rwanda integrated the distribution of cookstoves and water filtration to address acute respiratory infections at scale (Nagel et al., 2016). Implementation complexity, including sustained usage adherence and fuel stacking practices, influenced real-world exposure modification. Observational hospital-based findings continued to report elevated pneumonia prevalence among households using solid fuels despite policy-level interventions (Safi et al., 2022). Technological substitution alone therefore appeared insufficient in certain contexts to achieve clinically meaningful risk reduction.

Comparative insights from observational and meta-analytic studies contextualize these intervention findings. Pooled analyses consistently demonstrate an increased risk of pneumonia associated with solid fuel exposure, suggesting that meaningful reductions would require substantial decreases in particulate emissions (Chen et al., 2022; Desye et al., 2025). Cross-national survey analysis indicated that transition to cleaner fuels correlates with lower reported respiratory infection prevalence among children (Al-Janabi et al., 2021). Nepalese data further emphasized that structural modifications such as improved ventilation and separate kitchen spaces may augment health benefits of fuel transition (Budhathoki et al., 2020). Integrated approaches combining behavioral, infrastructural, and technological strategies may therefore offer greater potential than isolated device distribution. Evidence across study designs underscores the complexity of translating environmental modification into measurable pediatric health outcomes.

Sustained effectiveness of household-level interventions appears contingent upon broader socio-environmental transformation. Economic constraints often limit consistent access to clean fuels even when improved cookstoves are available (Nagel et al., 2016). Cultural preferences and cooking practices influence user acceptance and long-term adherence, thereby moderating the magnitude of exposure reduction. Measurement of intervention success frequently relies on short-term follow-up intervals that may not capture cumulative health benefits (Mortimer et al., 2020). Persistent reliance on biomass fuels in many low-resource settings maintains baseline exposure levels above recommended health thresholds (Chen et al., 2022). Interaction between

environmental exposure and underlying child vulnerability factors continues to shape pneumonia incidence patterns across contexts (Safi et al., 2022; Budhathoki et al., 2020). Multifaceted strategies addressing structural inequities, energy accessibility, and behavioral adaptation remain central considerations within the intervention evidence landscape.

DISCUSSION

Observed associations between household air pollution and childhood pneumonia reflect well-established environmental health theories that conceptualize disease as a function of sustained exposure to airborne toxicants. Ecological models of child health propose that biological vulnerability interacts dynamically with household environmental conditions, shaping susceptibility to lower respiratory infections. Empirical findings from multi-country survey analyses demonstrate that reliance on solid fuels places children in microenvironments with elevated particulate concentrations (Al-Janabi et al., 2021; Budhathoki et al., 2020). Pathophysiological mechanisms described in exposure–response frameworks explain how fine particulate matter penetrates alveolar regions, induces inflammatory cascades, and compromises immune defense against bacterial and viral pathogens. Meta-analytic evidence reporting pooled odds ratios above unity aligns with these mechanistic pathways, reinforcing the plausibility of a causal relationship (Chen et al., 2022; Desye et al., 2025). Convergence between epidemiological data and theoretical constructs strengthens interpretation of the exposure–disease linkage across heterogeneous contexts.

Measurement-related variability in reported risk estimates can be interpreted through methodological theory concerning exposure misclassification and construct validity. Proxy indicators, such as primary cooking fuel type, assume homogeneous pollutant emissions across households, although combustion efficiency and ventilation conditions vary considerably (Al-Janabi et al., 2021). Direct carbon monoxide monitoring, as implemented in Malawi, captures a specific gaseous component but may inadequately represent particulate toxicity, which is more strongly implicated in pneumonia pathogenesis (Havens et al., 2018; Mortimer et al., 2020). Epidemiological theory suggests that nondifferential misclassification typically biases associations toward the null, potentially explaining

weaker findings in certain intervention studies. Hospital-based observational research incorporating clinically verified diagnoses provides greater outcome specificity, yet localized sampling may constrain generalizability (Safi et al., 2022). Interaction between measurement precision and contextual diversity contributes to heterogeneity without negating the overarching exposure gradient identified across studies.

Contextual determinants embedded in social and structural environments further explain why associations manifest with varying magnitudes across regions. Energy poverty frameworks highlight how limited access to clean fuels perpetuates dependence on biomass combustion in marginalized populations. Housing configuration, including the absence of separate kitchens and restricted airflow, intensifies cumulative exposure among children who remain near caregivers during cooking activities (Budhathoki et al., 2020). Cross-national analyses reveal socioeconomic gradients intersecting with environmental risk, positioning lower-income households at heightened vulnerability (Al-Janabi et al., 2021). Intervention research conducted in Rwanda underscores the role of behavioral adherence and cultural cooking practices in mediating real-world effectiveness of technological solutions (Nagel et al., 2016). Structural inequities shaping energy access and household infrastructure thus operate as underlying mechanisms influencing variability in pneumonia outcomes.

The limited effectiveness of certain cookstove interventions can be interpreted through implementation science and environmental transition theory. Technological modifications that reduce emissions without achieving a substantial decline in particulate matter may fail to meet thresholds necessary for measurable clinical impact, as observed in the Malawi randomized study (Mortimer et al., 2020). Persistent carbon monoxide levels documented in exposure assessments suggest incomplete mitigation of indoor pollution sources (Havens et al., 2018). Behavioral patterns such as fuel stacking, where households alternate between traditional and improved stoves, dilute potential exposure reductions (Nagel et al., 2016). Meta-analytic findings indicating consistent risk elevation with solid fuel use imply that comprehensive transition to clean energy would likely produce stronger health gains than incremental improvements (Chen et al., 2022; Desye et al., 2025). The interplay

among technological capacity, socioeconomic feasibility, and caregiver practices shapes the complex trajectory linking environmental interventions to pediatric respiratory health outcomes.

CONCLUSION

Evidence synthesized across the eight included studies demonstrates a consistent and epidemiologically meaningful association between household air pollution and pneumonia among children under five years of age in low- and middle-income countries. The magnitude of risk varies with exposure measurement strategies, diagnostic criteria, and regional context, yet the direction of association remains predominantly positive across cross-sectional, observational, and meta-analytic designs. Solid fuel combustion is a central determinant of exposure, particularly when particulate matter concentrations remain elevated in poorly ventilated household environments. Carbon monoxide monitoring alone appears insufficient to capture the complexity of pollutant mixtures implicated in pneumonia pathogenesis. Contextual modifiers, including socioeconomic status, housing configuration, cultural cooking practices, and health system access, shape differential vulnerability across populations. An integrated interpretation of epidemiological findings and environmental health theory supports recognizing household air pollution as a significant and preventable contributor to the pediatric respiratory disease burden.

Variability in reported effect sizes reflects methodological heterogeneity rather than absence of association, underscoring the importance of precise exposure assessment and clinically verified outcome measurement. Intervention studies indicate that partial technological improvements without sustained behavioral transition may not achieve pollutant reductions sufficient to influence pneumonia incidence at measurable levels. Structural determinants such as energy poverty and limited infrastructure constrain the adoption of clean fuels despite policy initiatives. Comprehensive transition strategies combining clean energy access, improved housing ventilation, caregiver education, and socioeconomic support mechanisms present stronger potential for meaningful exposure reduction. Strengthened research designs incorporating direct particulate monitoring and longitudinal follow-up can further clarify dose–response dynamics in vulnerable child

populations. Consolidated evidence provides a robust platform for aligning environmental policy, energy transition initiatives, and child health protection strategies across diverse low-resource settings.

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