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Household Air Pollution: Persistent Health Risks, Emerging Evidence and Priorities for Clean-Energy Transition

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Abstract: Background: Household air pollution remains a major but preventable environmental health risk, particularly in low- and middle-income countries where biomass, coal and kerosene are used for cooking, heating and lighting. Women, young children and disadvantaged rural populations experience the greatest exposure, although emissions also contribute substantially to outdoor air pollution and climate change. **Objective:** This narrative review critically examines the sources, exposure pathways and health consequences of household air pollution; evaluates recent intervention evidence; and considers current policy challenges and opportunities globally and in India. **Key findings:** Approximately 2.1 billion people continue to cook with polluting fuels and technologies. Household air pollution was associated with an estimated 2.9 million deaths and 95 million disability-adjusted life-years in 2021. Evidence strongly links exposure with childhood lower respiratory infection, chronic obstructive pulmonary disease, ischaemic heart disease, stroke and lung cancer, while associations with adverse pregnancy outcomes, impaired child development, tuberculosis and cataract remain important but variably quantified. Recent randomized trials demonstrate that free provision of liquefied petroleum gas can produce large reductions in personal particulate exposure. However, the Household Air Pollution Intervention Network trial did not show significant effects on birth weight, severe infant pneumonia or childhood stunting, highlighting the influence of exposure timing, background ambient pollution, residual exposure and outcome complexity. In India, the Pradhan Mantri Ujjwala Yojana has markedly expanded liquefied petroleum gas access, but affordability, refill continuity and fuel stacking remain barriers to sustained exclusive use. **Conclusion:** Household air pollution control requires more than distributing improved stoves or fuel connections. Policies must ensure affordable, reliable and sustained access to genuinely clean energy, prioritize complete displacement of polluting fuels, integrate household and ambient air-quality management, and monitor exposure and health outcomes rather than infrastructure coverage alone.

Keywords: Household air pollution; clean cooking; biomass fuel; liquefied petroleum gas; women's health; India

INTRODUCTION

Household air pollution is generated when fuels and technologies used for cooking, heating or lighting release health-damaging pollutants within and around the home. The principal sources in low-resource settings are open fires and inefficient stoves burning wood, crop residues, animal dung, charcoal, coal or kerosene. Tobacco smoke, incense, mosquito coils, waste burning, poorly vented heaters and emissions from generators also influence indoor air quality, but combustion of household fuels remains the dominant exposure for billions of people.

The term "household air pollution" is preferable to "indoor air pollution" because emissions do not remain confined indoors. Smoke escapes through windows, doors and roofs, enters neighbouring houses

and contributes to village- and city-level ambient particulate pollution. Conversely, outdoor pollution infiltrates homes. Household and ambient exposure therefore form a continuum rather than two independent environmental risks.

In 2021, approximately 2.1 billion people—around one-quarter of the global population—continued to cook with polluting fuels and technologies. Household air pollution was responsible for an estimated 2.9 million deaths, including more than 309,000 deaths among children younger than five years, and approximately 95 million disability-adjusted life-years.[1,2] Women and children experience disproportionate exposure because of their proximity to cooking and fuel-collection activities. At the present rate of progress, nearly 1.8 billion people may still lack access to clean cooking in 2030.[2]

Although the association between household smoke and disease has been recognized for decades, the intervention evidence is more complex than early observational findings suggested. Recent trials have shifted the debate from whether household air pollution is harmful to how much exposure must be reduced, how early in the life course intervention must occur and whether clean-energy programmes can achieve sustained displacement of polluting fuels under routine conditions.

Sources, Pollutants and Exposure Pathways

Traditional biomass combustion is chemically inefficient. Inadequate oxygen supply, wet fuel and low combustion temperatures generate high concentrations of fine particulate matter with an aerodynamic diameter of 2.5 μm or less, carbon monoxide, black carbon, nitrogen oxides, volatile organic compounds, formaldehyde, benzene and polycyclic aromatic hydrocarbons. Depending on the fuel, emissions may also contain silica, metals and other toxic constituents.

Fine particulate matter is of particular importance because it penetrates the terminal airways and alveoli, induces oxidative stress and inflammation, impairs pulmonary defence and may enter the systemic circulation. Carbon monoxide reduces oxygen delivery by binding to haemoglobin, while several organic combustion products are irritant, mutagenic or carcinogenic. Black carbon contributes to atmospheric warming, making cleaner household energy relevant to both health and climate policy.

Exposure intensity depends on more than the nominal fuel type. Stove design, kitchen location, ventilation, duration of cooking, fuel moisture, ignition practices, household crowding and the cook's position relative to the fire all influence inhaled dose. Peaks during ignition and fuel feeding may be extremely high even when daily average concentrations appear moderate. WHO notes that particulate concentrations in poorly ventilated homes can exceed acceptable levels by approximately 100-fold.[2]

Women commonly receive the highest cumulative exposure, but infants carried on their mothers' backs or kept near the hearth may experience intense exposure during critical periods of lung and immune development. Older children may participate in cooking or fuel collection. Men may be less exposed at home but can encounter the same pollutants through agricultural burning, occupational combustion and community-level ambient pollution.

The widespread practice of "fuel stacking" complicates exposure assessment. A household classified as an LPG user may continue using wood or dung for heating water, preparing animal feed, cooking foods perceived to taste better on a traditional stove, or managing large family gatherings. Classification according to the primary cooking fuel can therefore substantially overestimate the extent of clean-energy adoption.

Biological Mechanisms and Major Health Outcomes

Respiratory disease

The respiratory system is the most direct target of household combustion emissions. Fine particles and irritant gases damage airway epithelium, reduce mucociliary clearance, alter macrophage function and increase susceptibility to infection. In young children, exposure is associated with acute lower respiratory infection, including pneumonia, a major cause of mortality in low-resource settings.[1,2]

Long-term exposure contributes to chronic airway inflammation, impaired lung growth and accelerated decline in pulmonary function. The association with chronic obstructive pulmonary disease is particularly important among women who have never smoked but have cooked with biomass for decades. Biomass-associated chronic lung disease may differ phenotypically from tobacco-associated disease, with variable contributions of airway remodelling, small-airway disease and pulmonary vascular involvement.

Household air pollution has also been associated with tuberculosis. Plausible mechanisms include impaired pulmonary immune defence and increased vulnerability to infection or progression from infection to disease. However, observational studies are vulnerable to confounding by poverty,

malnutrition, crowding and limited access to health services. The strength and independence of the association therefore remain less certain than for pneumonia or chronic obstructive pulmonary disease.

Cardiovascular and cerebrovascular disease

Combustion-related particulate matter can trigger systemic inflammation, endothelial dysfunction, autonomic imbalance, vasoconstriction, thrombosis and changes in blood pressure. These pathways support observed associations with ischaemic heart disease and stroke.[1,2] Cardiovascular outcomes are important because much of the global household air-pollution burden occurs in adults rather than exclusively through childhood respiratory disease.

Nevertheless, the exposure–response relationship at the high concentrations encountered in biomass-using homes remains incompletely defined. Risk may not decline linearly with modest exposure reduction. Consequently, an intervention that reduces particulate concentrations by half may still leave exposure on a relatively flat, high-risk portion of the concentration–response curve.

Cancer and ocular disease

Combustion of coal in household settings is an established cause of lung cancer, while prolonged exposure to biomass smoke is also associated with increased lung-cancer risk. Polycyclic aromatic hydrocarbons, benzene, formaldehyde and other carcinogenic compounds provide biological plausibility. Evidence concerning cancers outside the respiratory tract remains less consistent.

Chronic smoke exposure has been associated with cataract, potentially through oxidative damage to lens proteins. Irritation, conjunctival symptoms and tearing are common among cooks, although these outcomes are frequently overlooked in burden estimates and intervention studies.

Maternal, fetal and child health

During pregnancy, particulate matter, carbon monoxide and systemic inflammation may affect placental perfusion, oxygen delivery and fetal growth. Observational studies have associated polluting-fuel use with low birth weight, preterm birth, stillbirth and impaired fetal growth. However, accurately separating household exposure from ambient pollution, nutrition, socioeconomic deprivation and maternal health is difficult.

Household air pollution may also influence childhood growth and neurodevelopment through recurrent infection, inflammation, hypoxia and adverse pregnancy outcomes. Yet growth and development are multifactorial. Cleaner cooking alone may be insufficient to produce measurable benefits where undernutrition, infection, poor sanitation and ambient pollution remain prevalent.

Recent Intervention Evidence: Lessons from the HAPIN Trial

Earlier clean-cooking interventions frequently focused on improved biomass stoves. Many reduced visible smoke or fuel consumption but did not lower personal exposure sufficiently to meet health-based targets. Chimneys could move pollution outdoors without eliminating it, and stove deterioration, incorrect operation and continued use of traditional fires reduced effectiveness.

The Household Air Pollution Intervention Network trial represented an important advance. This multicountry randomized trial enrolled approximately 3,200 pregnant women in Guatemala, India, Peru and Rwanda. Intervention households received an LPG stove, continuous fuel supply, behavioural support and maintenance, while control households continued biomass cooking. The intervention achieved high adherence and substantial separation in personal exposure between groups. Among pregnant women, average 24-hour particulate exposure was reduced by roughly two-thirds, demonstrating what can be achieved when fuel cost and supply barriers are removed.[3,4]

Despite this exposure reduction, the intervention did not significantly improve infant birth weight.[3] It also did not significantly reduce the incidence of severe infant pneumonia or improve linear growth and stunting outcomes during infancy.[5,6]

These neutral results should not be interpreted as evidence that household air pollution is harmless or that clean cooking lacks value. Several explanations are plausible. Women entered the trial during pregnancy, potentially after biologically important early gestational exposures had occurred. Infants remained exposed to ambient pollution, neighbourhood smoke and other household sources. Post-intervention particulate concentrations, although greatly reduced, were not always as low as WHO air-quality guideline levels. Pneumonia diagnosis is inherently difficult in field settings, and birth weight and linear growth are influenced by numerous nutritional, infectious and socioeconomic factors.

The trial nevertheless challenges the assumption that a large reduction from an extremely high baseline will automatically yield rapid improvements in every clinical outcome. It suggests that future interventions may need to begin before conception, continue throughout childhood and be implemented at community scale to reduce both household and neighbourhood pollution. Larger or longer studies may be required for cardiovascular and chronic respiratory outcomes.

Table 1. Household Air-Pollution Sources, Health Effects and Priority Interventions

Source or exposure context	Principal pollutants	Major health concerns	Current evidence and limitations	Priority interventions
Open fires and traditional biomass stoves	$PM_{2.5}$, carbon monoxide, black carbon, PAHs, volatile organic compounds	Childhood pneumonia, COPD, cardiovascular disease, adverse pregnancy outcomes and eye disease	Strong mechanistic and observational evidence; residual socioeconomic confounding remains possible	Complete transition to electricity, LPG, biogas, solar or other emission-compliant technologies
Household coal combustion	Particulate matter, sulphur compounds, metals, PAHs and carcinogenic organics	Lung cancer, COPD, cardiovascular disease and poisoning	Strong evidence for lung cancer in heavily exposed populations; fuel composition varies geographically	Eliminate household coal use and provide affordable clean heating and cooking
Kerosene stoves and lamps	$PM_{2.5}$, carbon monoxide, nitrogen oxides, sulphur compounds and black carbon	Respiratory and cardiovascular effects, burns, poisoning and childhood injury	Increasing evidence of harmful emissions; exposure data remain limited in some settings	Replace with electricity, solar lighting and clean cooking fuels
Improved biomass cookstoves	Lower but variable particulate and carbon-monoxide emissions	Residual respiratory and cardiovascular risk	Laboratory performance often exceeds real-world performance; stove deterioration and stacking are common	Use only technologies meeting WHO emission targets, with independent field verification
LPG cooking	Much lower particulate emissions than biomass; nitrogen dioxide may remain relevant	Major exposure reduction, but incomplete elimination of indoor pollution	HAPIN demonstrated large exposure reductions but no significant effect on several short-term primary outcomes	Ensure sustained affordability, ventilation, maintenance and exclusive use; monitor nitrogen dioxide
Electric and induction cooking	Minimal household combustion emissions	Lowest cooking-related combustion exposure; electrical and burn safety considerations	Health benefits are biologically plausible, but intervention evidence in low-resource populations is still developing	Reliable electricity, affordable appliances, suitable cookware and tariff support
Fuel stacking	Pollutants depend on retained traditional fuels	Persistent exposure despite nominal clean-fuel access	Commonly missed by surveys based only on "primary fuel"	Measure all stove and fuel use; design programmes for complete displacement
Community-wide biomass use	Household emissions add to outdoor particulate pollution	Population-wide respiratory and cardiovascular disease	Household and ambient exposures are difficult to separate	Combine household-energy policy with regional air-quality and climate action

Public Health Significance

Household air pollution is simultaneously an environmental, energy, gender, poverty and health-system issue. Its burden extends beyond disease caused directly by smoke. Women and girls may spend several hours collecting fuel, reducing time available for education, paid employment and rest. Fuel collection may expose them to musculoskeletal strain, injuries, violence or animal attacks. Open fires also cause burns, particularly among young children, while kerosene can cause poisoning and household fires.

Transitioning to clean energy can therefore produce benefits that are not fully captured by conventional disease endpoints. These include reduced drudgery, cleaner kitchens, shorter cooking times, improved thermal comfort, greater autonomy and lower pressure on local forests. Clean cooking can also reduce black-carbon emissions and contribute to climate mitigation.

Health services have an underused role. Antenatal clinics, child-health programmes, tuberculosis services and chronic respiratory clinics can identify households using polluting fuels, provide risk communication and connect families to energy-support programmes. However, counselling alone is unlikely to change behaviour when clean fuels are unaffordable or unreliable. Clinical advice must be linked to structural energy interventions.

Indian Perspective: Progress and Persistent Gaps

India has experienced a substantial transition towards cleaner household fuels. According to the National Family Health Survey 2019–2021, 58.6% of households used clean cooking fuel, compared with 43.8% in 2015–2016.[7] However, national averages conceal pronounced rural, socioeconomic and inter-state inequalities. Several populous northern, central and eastern states remained below the national average.

The health burden remains substantial. The India State-Level Disease Burden Initiative estimated that household air pollution contributed to approximately 0.61 million deaths and 20.9 million disability-adjusted life-years in India in 2019. Encouragingly, the crude death rate attributable to household air pollution fell by approximately 64% between 1990 and 2019, reflecting declining reliance on solid fuels and broader socioeconomic change.[8] These are modelled estimates with uncertainty intervals rather than directly counted deaths, but they demonstrate both major progress and a persisting preventable burden.

The Pradhan Mantri Ujjwala Yojana, launched in 2016, has transformed access to LPG by providing subsidized connections to women from socioeconomically disadvantaged households. As of March 1, 2025, approximately 103.3 million PMUY connections had been issued.[9] Most beneficiaries included in an earlier cohort had obtained at least one refill during the preceding two financial years, indicating continued engagement with LPG.[9]

Access, however, is not equivalent to sustained exclusive use. The recurring cost of cylinders, fluctuating household income, distance to distributors, refill delays, family size and cultural preferences influence consumption. Households may preserve LPG for quick meals while using freely collected biomass for prolonged cooking, water heating or livestock feed. Aggregate connection counts may therefore exaggerate actual exposure reduction.

Future Indian policy should shift from counting connections towards measuring affordability, refill frequency, exclusive use and personal exposure. Targeted subsidies may be more effective when linked to household vulnerability, family size and regional fuel needs. Smaller cylinders can reduce the immediate cash requirement, while dependable last-mile delivery is particularly important in remote, tribal and mountainous regions. Expanding reliable electricity also creates an opportunity for induction cooking, although appliance cost, tariff design, voltage stability and cooking preferences require attention.

Recent Advances

Affordable sensors and stove-use monitors increasingly permit repeated measurement of household particulate matter, carbon monoxide and cooking behaviour. These technologies can identify high-exposure periods and quantify fuel stacking more accurately than questionnaires. Their limitations include calibration drift, humidity effects, battery failure and the risk of confusing low-cost sensor outputs with reference-grade measurements.

Electric cooking is gaining policy attention as electricity access and renewable generation expand. Induction cooking avoids combustion at the point of use and can be highly energy efficient. However, health and climate benefits depend on electricity reliability, generation sources and affordability. LPG remains an important transitional or long-term clean-cooking option in many settings, especially where electrical infrastructure is weak.

Implementation research has also moved beyond stove performance to examine affordability, gender dynamics, supply chains, cultural acceptability and sustained adoption. This shift is essential because technologically effective devices produce little health benefit when they are unaffordable, inconvenient or incompatible with local cooking practices.

Challenges and Limitations

The evidence base faces important methodological constraints. Many studies classify exposure using the primary household fuel rather than personal monitoring, resulting in misclassification. Cross-sectional designs cannot establish temporality, and household fuel choice is strongly associated with income, housing quality, nutrition and health-care access. These factors can exaggerate or obscure associations.

Randomized trials provide stronger causal evidence but face different limitations. Blinding is generally impossible, clinical outcomes may be uncommon, and interventions lasting one or two years may be too short for chronic disease prevention. Trials providing free fuel under intensive supervision demonstrate efficacy under favourable conditions but may not predict effectiveness after subsidies or monitoring end.

A continuing controversy concerns improved biomass stoves. They may reduce fuel consumption, deforestation and some pollutants, but many do not achieve exposure levels considered protective of health. Presenting marginally improved combustion as "clean" risks locking disadvantaged households into residual exposure. Technologies should therefore be judged by verified emissions and exposure, not by labels such as "improved," "smokeless" or "efficient."

LPG also requires balanced appraisal. It produces markedly less particulate pollution than biomass but remains a fossil fuel and may emit nitrogen dioxide, particularly in poorly ventilated kitchens. Electrification offers a pathway towards near-zero household combustion but cannot be recommended without reliable supply and equitable tariffs. Policy should avoid a rigid fuel hierarchy divorced from local infrastructure while retaining the central objective of eliminating exposure to polluting combustion.

Future Directions

Research should prioritize longitudinal studies with repeated personal exposure measurement, objective clinical outcomes and adequate representation of women, children and marginalized populations. Interventions beginning before pregnancy could better evaluate effects on fetal development, while longer follow-up is needed for lung growth, chronic respiratory disease and cardiovascular outcomes.

Community-scale trials are especially important because household interventions cannot fully protect families when neighbouring homes continue emitting smoke. Future studies should integrate indoor and outdoor monitoring and assess whether widespread clean-energy adoption generates neighbourhood-level exposure reductions.

Programmes should report exclusive clean-fuel use, frequency of traditional-stove use, refill continuity and measured pollutant concentrations. Public dashboards based only on the number of connections or stoves distributed are insufficient. Health-impact evaluation should include respiratory symptoms, pneumonia, blood pressure, lung function, burns, time use, gender equity and household expenditure.

India could integrate clean-cooking surveillance with national family-health surveys, air-quality programmes and primary health-care systems. Geographic targeting should prioritize districts with high solid-fuel use, poverty, under-five mortality and chronic respiratory disease. Clean cooking should also be incorporated into climate-resilient health planning because floods, disasters and fuel-price shocks can force households to return to biomass.

CONCLUSION

Household air pollution remains one of the largest preventable environmental risks to health. The evidence linking polluting household combustion with respiratory, cardiovascular and malignant disease is compelling, although the magnitude of benefit achievable through individual interventions depends on the extent, timing and sustainability of exposure reduction.

Recent randomized evidence has refined rather than weakened the case for clean cooking. Large reductions in particulate exposure did not produce significant improvements in several short-term maternal and infant outcomes, emphasizing that partial exposure reduction, intervention during pregnancy alone and household-level action may be insufficient. Clean-energy transitions must begin early, remain affordable and displace rather than merely supplement polluting fuels.

India's expansion of LPG access represents a major public health achievement, but the next phase must focus on sustained exclusive use, equitable refill affordability and gradual expansion of reliable electric cooking. Household air-pollution control should be evaluated not by the number of technologies distributed, but by whether women, children and other household members actually breathe cleaner air.

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