REVIEW ARTICLE

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Air pollution from household solid fuel combustion in India: an overview of exposure and health related information to inform health research priorities

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Environmental and occupational risk factors contribute to nearly 40% of the national burden of disease in India, with air pollution in the indoor and outdoor environment ranking amongst leading risk factors. It is now recognized that the health burden from air pollution exposures that primarily occur in the rural indoors, from pollutants released during the incomplete combustion of solid fuels in households, may rival or even exceed the burden attributable to urban outdoor exposures. Few environmental epidemiological efforts have been devoted to this setting, however. We provide an overview of important available information on exposures and health effects related to household solid fuel use in India, with a view to inform health research priorities for household air pollution and facilitate being able to address air pollution within an integrated rural–urban framework in the future.

Keywords: *Household air pollution*; *solid fuels*; *exposure assessment*; *India*

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Approximately three billion people worldwide use biomass (wood, charcoal, crop residues, and dung) and coal as their primary source of energy for cooking and heating (coal is common in China and biomass in all nations including India where solid fuels are used). A majority of these households are located in poor rural communities and burn such solid fuels in inefficient devices, often in kitchens that are poorly ventilated, resulting in very high exposures to multiple toxic products of incomplete combustion (1). Concentrations of particulate matter, gases, and, in some settings, toxic metals such as arsenic and fluorine (from use of coal) have been shown to be up to 10–20 times higher than commonly used health guidelines (2, 3). The comparative risk assessment (CRA) exercise conducted by the World Health Organization (WHO) in 2002 estimates that exposure to indoor smoke from solid fuels may be annually responsible for about 1.6 million premature deaths in developing countries and 2.6% of the global burden of disease (4).

According to the Indian National Census (2001), 75% of households use solid fuels (primarily firewood and cow dung), with the prevalence of solid fuel use as high as 90% in rural areas. Currently about 70% of India's population lives in rural areas (estimated to decline to 55% by 2030). In India, an estimated 400,000 deaths from acute lower respiratory infection (ALRI) in children younger than five and 34,000 deaths from chronic obstructive pulmonary disease (COPD) in women are attributed annually to household solid fuel use, making

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this the third leading risk factor amongst all risk factors contributing to the national burden of disease and exceeding the burden attributable to outdoor air pollution (5, 6).

Following the initial recognition of the scale of the problem provided by the WHO-CRA exercises, several researchers have reviewed the available global evidence and also identified important research directions specifically for developing countries (7–10). Considerable efforts are also underway at the national and global levels to identify alternative interventions to reduce this burden, but such efforts are often hampered by lack of high-resolution information on exposures and health effects (11).

In India, over the last three decades, several studies have reported results from epidemiological investigations and air quality measurements in solid fuel using rural households. However, to our knowledge, a comprehensive consolidation of the available information at the national level has not been attempted. Based on this rationale, we undertook a review exercise aimed at summarizing the results reported in a large range of research studies conducted in India, to identify research gaps and inform health research priorities. Information from published literature was retrieved using a simple search strategy that while being systematic would, however, not qualify to be labeled as a formal systematic review. Despite this limitation, the search provided important insights from major studies and allowed a synthesis of specific research recommendations that may be useful for researchers/organizations interested in framing/funding collaborative research initiatives.

Methods

We initiated a search for articles indexed in PubMed, Web of Science (Science, Social Science, and Arts and Humanities Citation Indexes), and Bioscience (Article indexes), and a few thesis citations that were frequently cross-referenced in published articles were included using the following criteria. Studies were included if written in English, conducted in India, and reported results on either area concentrations/exposures (for one or more pollutants) or health outcomes or both in solid fuel using households. Studies that only provided general information on solid fuel use and/or information on emissions were excluded. Keywords for abstraction of exposure information included IAP/Indoor Pollution; Indoor Air Quality; Exposure/Exposure Assessment/Personal Exposure; Environmental Exposure; Rural Health; Developing Countries; Less Developed Countries; India; Biomass/Biomass Combustion/Fuels; Woodstove/Cookstove; Biofuel Smoke Exposure; Volatile Organic Compounds; Particulate Matter, PM; Particles; Solid Fuels; Sulfur Dioxide; Nitrogen Dioxide; and Carbon Monoxide. To identify the range of health outcomes to be included, we used the health endpoints that were identified as part of the WHO-CRA exercise (4) regardless of the strength of evidence. Accordingly we used the following keywords in addition to the ones cited above for abstraction of health effects related information – COPD, ALRI, lung cancer, cataracts, asthma, tuberculosis (TB), low birth weight, and still birth (it may be noted that the only outcomes with a strong strength of evidence, namely, COPD in women, ALRI in children younger than five, and lung cancer among coal users were used in the CRA and the burden of disease estimations cited earlier).

Results

Studies providing data from measurement of pollutants in solid fuel using households in India

The search for exposure studies produced 18 studies that are summarized in Table 1. Most measurements have been performed in wood-using households. However, many earlier studies did not specify the type of solid fuel. A substantial number of measurements from gas using households are also included in many studies. Although a great majority of studies have performed single pollutant measurements on a cross-sectional sample of households, some studies have examined temporal, spatial, or multipollutant patterns, in addition to day-to-day or seasonal variability in concentrations and exposures (12, 13). A few have also developed models to examine the differential contributions of household-level determinants and validate the use of simpler household-level indicators (that are relatively easy to collect) as a proxy for household-level exposures (14).

Reported kitchen and living area concentrations were significantly different across fuel types. Use of dung typically resulted in the highest concentrations, followed by wood, and then gas. Concentrations in kerosene-using houses, although lower than solid fuel-using households, were often more than twice the average levels found in gas-using households. However, these households while reporting kerosene as their primary fuel also frequently switch to cooking with wood, (within the monitoring period) thus sometimes resulting in high concentrations. Kitchen configuration was an important determinant of concentrations in solid fuel but not in gas-using households. Kitchen area concentrations were significantly higher in enclosed kitchens as compared to outdoor kitchens. Through quantitative estimates, these studies have confirmed that women cooks are exposed to far higher concentrations than most other household members, and adult men experience the least exposure. Further, even for households that cook outdoors, the 24-hour concentrations and exposures could be significant both in the cooking place and indoors, and well

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Table 1. Listing of exposure studies related to solid fuel combustion in India

SNO	Reference, location	Region/season	Fuel	Stove type	Sampling duration	Levels of pollutants reported
1	Aggarwal et al (26), Ahmedabad, Gujarat, Urban	West/NS	Wood/dung/charcoal	Traditional	Half-an-hour during cooking	TSP: 7203–26147 (μg/m^3) PAH (BaP): 1270–8248 (ng/m^3)
2	Smith et al (16), Anand, Gujarat, Rural	West/winter	Wood	Traditional	Meal duration	TSP: 6400 (μg/m^3) BaP: 4100 (ng/m^3)
				Improved	Meal duration	TSP: 4600 (g/m^3) BaP: 2400 (ng/m^3)
3	Ramakrishna (27), Kerala, Karnataka, Haryana, Rural	North/NS	Wood	Traditional	Meal duration	TSP: 3200–3300 (g/m^3) CO: 7–19 (mg/m^3)
				Improved	Meal duration	TSP: 1700– 2900 (g/m^3) CO: 5.7–8.9 (mg/m^3)
4	Menon et al (28), Islamnagar, Padaria, Ariyur, Perambia, Adampur villages, Rural	North/NS	Wood	Traditional	NA	TSP: 2000–5000 (g/m^3) CO: 30.9–74.4 (mg/m^3)
5	Norboo et al (29), Chuchot Sharma village, Ladakh District, Jammu & Kashmir State, Rural	North/winter, summer	Wood	Traditional	Meal duration	CO: 12–29.8 (mg/m^3)
6	Saksena et al (12), Pauri District, Uttar Pradesh, Rural	North/winter, summer	Wood	Traditional	Meal duration	TSP: 5600 (μg/m^3) CO: 21 (mg/m^3)
7	Raiyani et al (30), Ahmedabad, Gujarat, Urban	West/NS	Wood/dung/charcoal	Traditional	Meal duration	TSP: 1190–3470 (μg/m^3) BaP: 38–410 (ng/m^3)
8	Smith et al (31), Pune, Maharashtra, Urban	West/NS	Crop residue, wood	Traditional	Meal duration	PM10: 900–1100 (μg/m^3)
9	TERI (32), Tehri District, Uttar Pradesh	North/NS	Wood	Traditional	Meal duration	PM5: 850–1460 (μg/m^3)
10	Mandal et al (33), Delhi, Urban	North; NS	Wood	Traditional	4 hours	TSP: 646 (μg/m^3)
11	Balakrishnan et al (13), four districts in Tamil Nadu, Rural	South/summer	Wood/crop residue/ wood chips	Traditional	1–2 hours during cooking 24 hours	PM4: 1307–1535 (g/m^3) PM4: 847–1327 (g/m^3)
12	Saksena et al (34), New Delhi, Urban	North/winter	Wood	Traditional	Meal duration	PM5: 1204 (μg/m^3) CO: 13.7 (mg/m^3)
13	Balakrishnan et al (14), Nizamabad, Warangal, Rengareddy Districts, Andhra Pradesh, Rural	South/summer	Wood/dung/crop residues	Traditional	22–24 hours	PM4: 431–467 (μg/m^3) PM4: 297–666 (μg/m^3) PM4: 215–357 (μg/m^3)
14	Bhargava et al (35), (2004), Malihabad, Lucknow, Uttar Pradesh, Rural	North/winter, summer	Wood/cow dung	Traditional	1-hour during cooking	BaP: 0.5–1.86 (%)
15	Sinha et al (36), Gujarat, Rural	West/NS	Wood, dung	NS	45 min to 1-hour during cooking	Benzene: 45–114.3 (μg/m^3) Toluene: 2–8.5 (μg/m^3)
16	Smith et al (15), Maharashtra, Madhya Pradesh, Rural	Central/monsoon, winter, summer	Wood	Traditional	48 hours	PM2.5: 520–1250 (g/m^3) CO: 9.02–12.4 (mg/m^3)
		Central/Monsoon, winter, summer	Wood	Improved	48 hours	PM2.5: 330–940 (g/m^3) CO: 6.17–7.6 (mg/m^3)

above levels considered acceptable by the WHO air quality guidelines (15).

Limited evaluations of interventions through the use of improved biomass stoves have shown that the levels of exposure reduction achieved are still insufficient (with levels of PM_{10} and $PM_{2.5}$ much higher than even the first interim target levels recommended by the WHO air quality guidelines and remaining uncertainties on feasibility of sustained use) (15).

The available exposure studies thus collectively provide measurement results for short- term and 24-hour concentrations and exposure estimates for a wide cross-section of *rural* homes using a variety of household fuels under a range of exposure conditions across multiple states. While most of solid fuel use related exposures occur in the rural indoors, the use and accompanying high exposures is not uncommon among the urban poor who may be receiving double burdens from polluted outdoor and indoor air. Very limited information data are currently available, however, to assess the scale and levels of such exposures.

Studies reporting health effects associated with solid fuel smoke exposure in India

Some of the earliest human evidence linking indoor air pollution from biomass combustion with respiratory health came from studies carried out in Nepal and India in the mid-1980s (16, 17). Since then, there have been a modest number of new studies, especially on women who cook with these fuels and young children. The WHO-CRA exercise in 2002 used estimates of relative risk obtained from meta-analyses of epidemiological studies for only three disease end-points for which there is strong evidence of an association with use of solid fuels, namely, ALRI in children aged <5 years, COPD, and lung cancer (only for use of coal). With coal use being relatively uncommon in India, most Indian studies only reported associations with biomass use. More recently, systematic reviews and meta-analyses (that include Indian studies) of the available epidemiological evidence have been completed for ALRI (18), low birth weight (19), COPD (20), and lung cancer (21); and new studies for TB and cataracts have also become available. Table 2 summarizes the results of the search for solid fuel use related health studies in India.

Discussion

A detailed review of the available literature in India on exposure and health effects related to household solid fuel use enabled a synthesis of suggested research priorities as described in the subsequent section.

Table 1 (Continued)

SNO	Reference, location	Region/season	Fuel	Stove type	Sampling duration	Levels of pollutants reported
17	Kumar et al (37), Dallupura, Nizamuddin, Ashok Vihar, Shahdara, ITO, Janakpuri, Siri Fort, Shahzada Bagh, Jagatpur – Delhi, Urban	North/all seasons	Coal, wood, kerosene, cow dung	NS	6 hours	SPM: 290–1200 (μg/m^3)
18	Kumar et al (38), Ashok Vihar, Delhi, Urban	North/summer	Wood, dung, gas	NS	6–8 hours	SPM: 960 (μg/m^3)

Note: NS, Not specified; GM, Geometric mean; TSP, Total suspended particulates; PM, Particulate matter; SPM, Suspended particulate matter; BaP, Benzo(a)pyrene.

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Suggested health research priorities

Strengthening evidence for association for a wider range of outcomes through integration with exposure assessments

The health studies related to solid fuel use have a long history in India. Globally, increased risks have been reported for several health outcomes in women and children exposed to cooking smoke. While strength of evidence is strong for COPD and ALRI in children younger than five, evidence for other outcomes including TB, cataracts, and asthma is considered weak. New but persuasive evidence for adverse pregnancy-related and perinatal outcomes related to solid fuel use are also beginning to emerge. Evidence for lung cancer is strong (resulting in the classification of coal smoke as a Class I carcinogen by the International Agency for Research on Cancer) while insufficient evidence is currently available for carcinogenicity of biomass smoke (22).

However, owing to the paucity of quantitative measurements virtually none of the health studies for burden of disease estimations could use quantitative exposure metrics. The burden of disease has thus been estimated, using odds ratios of adverse health outcomes in solid fuel users with respect to 'clean fuel' users. 'Liquified petroleum gas' (LPG) use is commonly used as an indicator of a 'clean fuel using household' but the definitions of such 'counterfactual' levels of exposure are yet to be resolved. Further, in the absence of continuous exposure information, it has also not been possible to generate exposure-response functions to estimate incremental risks per unit increase in pollutant exposure similar to what has been possible in urban outdoor air-related health studies.

There is a large base of quantitative exposure information that has recently become available across multiple states in India, but they are yet to be applied in health studies. While exposure assessment may add substantial costs limiting feasibility, future health studies, which use a combination of measurements in a nested subset of health assessment households together with exposure models, are needed to minimize exposure misclassification, thereby strengthening the evidence for association while providing relevant exposure-response information.

Integration of exposure and health assessments in planned or ongoing intervention studies

The use of LPG (or other gaseous fuels), which is known to result in the lowest pollution levels within households, remains a nonfeasible proposition for bulk of India's population as a result of prices, limited supply, and access. Little information on exposure reduction potential is available for other alternative interventions, such as improved stoves and ventilation. Behavioral aspects such as frequency and nature of use of interventions may decide the 'dose of the therapy' but remain poorly captured with respect to exposure reduction. Thus, while the available exposure information provides convincing evidence for the need for interventions, the health benefits from incremental reductions cannot be reliably estimated, and this in turn has handicapped assessment of intervention effectiveness. Availability of exposure information in tandem with health effects especially in intervention studies are needed to assess and evaluate intervention effectiveness.

Longitudinal studies of childhood health outcomes with respect to prenatal and early infant exposure to biomass smoke

Very few studies have focused on birth and children's health outcomes. Since air pollution is independently associated with birth outcomes and children's health outcomes, it is crucial to examine them in longitudinal studies to delineate the relative contributions of air pollution and birth outcomes to children's health. Furthermore, many chronic diseases including heart disease and diabetes are now thought to have strong prenatal determinants, and any adverse effects of air pollution during the prenatal period thus could have enormous implications for both children's and adult health. Against a backdrop of competing risk factors for high prevalence of low birth weight and ALRI, such studies would be enormously useful in India, as few such parallels exist anywhere in the world.

Examination of cardiovascular disease-related implications for solid fuel use related exposures in integrated urban–rural and indoor–outdoor frameworks

The evidence for association of urban outdoor air pollution (in particular fine particulates) with cardiovascular outcomes has been available from nearly all regions of the world. As could be expected, emissions from solid fuels can cause exposures not just in the rural indoors but in the rural outdoors with similar implications for urban households. Little information is available for how such an attribution may be made for estimates of air pollution-related cardiovascular disease (CVD) burdens that currently rely on urban outdoor studies, mostly from developed country settings. The rural outdoors in India may thus not be as 'clean' as popularly perceived, and health effects studies for chronic outcomes including CVD would need to be designed in ways that are sensitive to the primary and secondary data collection challenges in this setting. Given the high prevalence of CVD in India, even slightly elevated (attributable) risks from air pollution related to solid fuel use would have huge implications for population disease burdens.

Table 2. Listing of major health studies related to solid fuel combustion in India

Outcome	Study reference	Outcome details	Exposure	Reported range of OR/RR
Low birth weight	Mavalankar et al (39), Case–control	Hospital births; birth weight measure not reported; term and preterm estimates	Cooking with solid fuels	1.23 (1.01–1.5)
	Tielsch et al (40), Cohort	Trained FWs – scales within 72 hours; term and preterm estimates	Cooking with wood/dung versus gas/kerosene	1.7 (0.92–3.10)
	Pope et al (19), Meta-analysis	Five studies were included in the meta-analysis for generation of the overall pooled odds ratio	Cooking with solid fuels	1.38 (1.25–1.52)
Still birth	Mavalankar et al (41), Case–control	Hospital still birth ($n=451$). Early neonatal death ($n=160$) (within 1 week). Controls: surviving >7 days – same hospital	Cooking with solid fuels	1.5 (1.04–2.17)
	Mishra et al (42), Cross-sectional survey	'Dead baby after 28th week of pregnancy.' Complete birth histories from Nationally representative sample	Cooking with wood/dung versus gas/electricity	1.44 (1.05–1.98)
	Tielsch et al (40), Cohort	Delivery after 28 weeks in which fetus born dead. Excluded early neonatal deaths	Cooking with wood/dung versus gas/kerosene	1.34 (0.76–2.36)
ALRI	Mishra et al (42), Cross-sectional	Self-reported symptoms/DHS surveys	Cooking with solid fuels and exposure to tobacco smoke	1.58 (1.28–1.95)
	Dherani et al (18), Meta-analysis	24 studies included in the meta-analysis for generation of the overall pooled odds ratio for ALRI in children under five years	Cooking with solid fuels and exposure to tobacco smoke	1.78 (1.45–2.18)
Lung cancer	Gupta et al (43), Case–Control	Cancer of the lung, trachea, bronchus as confirmed by histology; clinical diagnosis with radiology	Cooking with solid fuels	1.52 (0.33–6.98)
	Sapkota et al (21), Case–Control			3.76 (1.64–8.63)
	Hosgood et al (44), Meta-analysis	25 studies included in the meta-analysis for generation of the overall pooled OR for Lung cancer	Coal use	2.15 (1.61–2.89)
COPD	Behera et al (45), Descriptive study	COPD as defined clinically	Cooking with solid fuels	3.04 (2.15–4.31)
	Qureshi et al (46), Case–Control	COPD as defined clinically		2.10 (1.50–2.94)
	Kurmi et al (20), Systematic review and Meta-analysis	12 studies were included in the meta-analysis for generation of the overall pooled OR		2.80 (1.85–4.0)
Cataract	Mohan et al (47), Case–Control	1441 patients with age-related cataracts and 549 controls	Cooking with solid fuels	1.61 (1.02–2.50)
	Zodpey et al (48), Case–control	223 clinically diagnosed cataract women and equal number of age-matched controls		2.37 (1.44–4.13)
	Pokhrel et al (49), Case–control	Cases ($n=206$) were women patients, aged 35–75 years with confirmed cataracts. Controls ($n=203$), frequency matched by age, were patients attending the refractive error clinic at the same hospital		1.90 (1.00–3.61)

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Table 2 (Continued)

Outcome	Study reference	Outcome details	Exposure	Reported range of OR/RR
Blindness	Mishra et al (50), Cross-sectional	National Family Health Survey (NFHS) questionnaire data	Cooking with solid fuels	1.32 (1.16–1.50)
Tuberculosis	Gupta et al (51), Case–control	Tuberculosis	Cooking with solid fuels	2.54 (1.07–6.04)
	Mishra et al (52), Cross-sectional	National Family Health Survey (NFHS) questionnaire data		2.58 (1.98–3.37)
	Shetty et al (53), Case–control	Cases – new diagnoses of pulmonary TB. Age- and sex-matched controls, one for each case ($n = 189$)		0.90 (0.46–1.76)
	Kolappan et al (54), Case–control	Definition of cases either by sputum smear or culture examination. Five age-sex matched controls per case		1.7 (1–2.9)
	Lakshmi et al (55), Case–control	Physician-diagnosed cases of sputum positive pulmonary tuberculosis and matched controls per case		3.14 (1.15–8.56)
	Behera et al (56), Case–control	Sputum positive tuberculosis (TB) and 109 healthy controls		0.60 (0.22–1.63)

Adding/integrating biomarker assessments in ongoing genetic studies

The role of gene–environment interactions is in the nascent stage for all air pollution-related health effects. While some candidate biomarkers of exposure and early biological effect (in response to carcinogenic insults) have been identified in laboratory studies, they have not been widely applied in epidemiological studies. The role of some air toxics in carcinogenicity and single nucleotide polymorphisms in susceptibility remains largely unexplored in exposure settings commonly encountered in India. Although it is difficult to specify candidate biomarkers, there is an urgent need to add exposure and biomarker assessments to ongoing genetic studies in India so as to elucidate the role of gene–environment interactions for air pollution-related health effects well beyond solid fuel use.

Conclusions

The review of available literature captures some of the most important pieces of information that are available on the issue of air pollution related to solid fuel use in India. While it is very likely that a few studies and/or publications may have been missed, the available information could perhaps be deemed sufficient to guide the scoping of future research efforts. While most of the implications of suggested research priorities concern the health sector, it would be important to recognize that overarching benefits may accrue from improved understanding of health impacts for the energy (including climate and housing), environment, and education sectors. For example, globally, household solid fuel combustion is responsible for as much as half of all black carbon emissions from human sources, a few percent of methane and carbon dioxide emissions, and significant amounts of total carbon monoxide and volatile organic chemical emissions (23, 24). Integrating emissions and exposure reductions in interventions would not only be efficient but may even be necessary to justify cost-effectiveness of planned efforts (such as the launch of the new National cookstove initiative of the Ministry of New and Renewable Energy of the Government of India) on grounds of co-benefits for health and climate (25).

It is hoped that the preceding description of studies in India will spur the creation of new international networks to undertake studies that would have the ability to provide tangible evidence, duly address multiple confounders, assist in intervention design/evaluation, and create baselines for future follow-up. With a combination of measurement and modeling methods, it may also be possible to undertake multicentric studies across multiple developing countries and even perhaps 'retro-fit' ongoing studies. The issue of solid fuel use related smoke exposures is now well recognized as an important risk factor for the global and national burden of disease amongst researchers in the discipline but begs serious consideration by funding agencies and policy makers. Such a synergy is imminently needed to ensure that research facilitates the closure of key scientific gaps and brings intervention packages to the most vulnerable communities without further delays.

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