Indoor Air Pollution in Developing Countries: Research and Implementation Needs for Improvements in Global Public Health

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Exposure to indoor air pollution (IAP) from the burning of solid fuels for cooking, heating, and lighting accounts for a significant portion of the global burden of death and disease, and disproportionately affects women and children in developing regions. Clean cookstove campaigns recently received more attention and investment, but their successes might hinge on greater integration of the public health community with a variety of other disciplines. To help guide public health research in alleviating this important global environmental health burden, we synthesized previous research on IAP in developing countries, summarized successes and challenges of previous cookstove implementation programs, and provided key research and implementation needs from structured discussions at a recent symposium. (*Am J Public Health.* 2013;103:e67–e72. doi:10.2105/AJPH.2012.300955)

Indoor air pollution (IAP) is responsible for many health, environmental, and social issues that disproportionately and adversely affect women and young children around the world.[1,2] Nearly half the world's population burns solid fuels (e.g., coal, biomass, and animal dung) as their principal household fuel for cooking, heating, and lighting.[3] IAP in these households was estimated to be responsible for almost 2 million premature deaths in 2001, and represented approximately 3% of the global burden of disease.[4] In addition to direct effects on IAP and health, carbon dioxide and black carbon emissions from burning solid fuels are also important contributors to global climate change.[5] In particularly vulnerable regions, women and young girls are subject to attacks by militia and rebels during extended periods of foraging for fuel to use in inefficient cookstoves.[6,7] Widespread improvements in cookstove and other combustion technologies could ensure greater safety for, and provide more time to, hundreds of millions of women to engage in other social and economic activities that improve their lives and the lives of their families and communities.

However, there are combined technical and social complexities associated with effective cookstove implementation in developing countries, and there remains a significant need for intervention studies and interdisciplinary research to reduce the effects of cookstoves and other devices as sources of IAP and agents of global climate change. To help guide the integration of public health and other disciplines in this field, we first provided a synthesis of previous research on IAP in developing countries and summarized successes and challenges from previous cookstove implementation programs. Subsequently, we provided recommendations for research and implementation needs from structured discussions among participants in a recent symposium on indoor air quality in developing countries at the international Indoor Air conference in Austin, Texas, on June 6–7, 2011.

PREVIOUS RESEARCH IN DEVELOPING COUNTRIES

Simple biomass cookstoves are widely used around the world and are frequently the most significant contributor to IAP in developing countries. They emit large amounts of pollutants, including particulate matter (PM), carbon monoxide (CO), metals, hydrocarbons, oxygenated organic compounds, and chlorinated organic compounds, depending on fuel and stove types.[8] In homes that use solid fuels for cooking, heating, and lighting, 24-hour mean indoor airborne concentrations of $PM_{2.5}$ and PM_{10} (particulate matter less than 2.5 and 10 μm, respectively) routinely reach several hundred micrograms per cubic meter and may peak as high as 10 000 micrograms per cubic meter during cooking.[9,10] In stark contrast, the World Health Organization (WHO) recommends that 24-hour mean $PM_{2.5}$ and PM_{10} concentrations outdoors should not exceed 25 and 50 micrograms per cubic meter, respectively.[11] Therefore, the typical inhaled dose of $PM_{2.5}$ from IAP in developing countries (and the associated health risks) likely lies between levels inhaled via secondhand smoke in developed countries and those inhaled by active smokers.[12]

Well-documented adverse health effects of exposure to pollutants from indoor solid fuel burning include acute respiratory infections (ARIs), chronic obstructive pulmonary disease, pulmonary tuberculosis, cataracts, low birth weight, perinatal and infant mortality, nasopharyngeal and laryngeal cancer, and lung cancer.[3,13] It is estimated that 4% to 5% of the global totals for both deaths and disability-adjusted life-years (DALYs) from ARIs, chronic obstructive pulmonary disease, tuberculosis, asthma, lung cancer, ischemic heart disease, and blindness is attributed to solid fuel use in developing countries.[14] These broad population estimates have provided great motivation for much of the previous research on IAP in developing countries, which can be differentiated into 5 general categories:

1. modeling studies,
2. health outcome studies,
3. exposure measurements,
4. health outcome studies combined with exposure measurements, and
5. testing of indoor combustion devices.

Although we cannot provide an exhaustive list here because of space constraints, we summarized some major findings in each of these subsets of research by highlighting several representative studies. Additionally, we presented some of the field's more recent findings, several of which were presented for the first time during the aforementioned symposium (which is described in more detail in Cookstove Implementation Efforts and Barriers to Widespread Adoption).

Modeling Studies

Modeling studies provide a useful method for screening possible impacts of interventions on human exposure to IAP and the associated impacts on health outcomes. In one of the first modeling studies in this field, Smith et al.[15] used a well-mixed reactor model to estimate indoor concentrations of total suspended particles (TSPs; or the mass of particles <100 μm) in homes in villages in Gujarat, India, using data on home volumes and TSP emission factors from studies of fireplaces in the United States. Their modeling effort showed that indoor concentrations of TSPs in these rural huts could be high (200–10 000 $\mu g/m^3$). More recently, Johnson et al.[16] performed a Monte-Carlo analysis of a single-zone box model of indoor $PM_{2.5}$ and CO concentrations from cookstove emissions using a range of measured and estimated cookstove emission rates, kitchen volumes, and air exchange rates. They predicted that only about 4% of homes using wood fuel in a rocket stove (a widely known cleaner and more efficient stove) would achieve WHO annual $PM_{2.5}$ guidelines, suggesting that although cleaner cookstoves can provide benefits, both fuels and stoves must drastically improve to meet WHO air quality guidelines.

Overall, modeling studies that evaluate IAP and cookstove performance in developing countries are thought to be underutilized and generally lag behind studies on outdoor and other indoor environments.[16] It is desirable to predict not only the concentrations of a small collection of traditional pollutants (e.g., CO and PM), but also other hazardous air pollutants of concern, such as nitric oxide, aldehydes, dioxins, polycyclic aromatic hydrocarbons, and others. Modeling efforts in this field would benefit from adopting more complex models of reaction chemistry similar to those used regularly to model outdoor air pollution. Furthermore, taking into consideration a more comprehensive range of environmental, household, and human behavioral conditions would improve the relevance of modeling results to proposed and sustained intervention strategies to reduce IAP in developing countries.

Health Outcome Studies

Epidemiological studies focusing only on longitudinal or cross-sectional health outcomes typically assessed health outcomes in populations without actual pollutant concentration or exposure measurements, although these studies often grouped populations into those that used different types of cookstoves or fuels. For example, Pérez-Padilla et al.[17] performed a case–control study of women in Mexico to evaluate the risk of cooking with traditional wood stoves for chronic bronchitis and chronic airway obstruction. Exposure to wood smoke was significantly higher in patients with chronic bronchitis or chronic airway obstruction than in controls.

In similarly designed studies, the use of biomass fuel sources was also associated with increased prevalence of partial and complete blindness,[18] lower birth weights,[19] ARIs,[20] and, more recently, birth defects[21] and lung cancer.[22] Studies of associations between health outcomes and IAP have frequently focused on a single health outcome relative to 1 or several cooking, cookstove, or fuel use variables; however, understanding of the adverse effects that IAP has on health should become more sophisticated as health-related research efforts continue to engage more academic disciplines.

Exposure Measurement Studies

Exposure measurement studies typically sought accurate quantification of the magnitude of pollutant concentrations to which occupants were exposed. They typically measured concentrations of airborne pollutants in and around homes or in persons living in households with indoor combustion devices. Location measurements were often combined with time-activity surveys to estimate personal exposures, although exposure assessments were sometimes estimated using surrogate measures. Many of these studies also differentiated between types of cookstoves, and although they varied in project location, they tended to center around regions of the world that were familiar to the individual researchers or research teams.

Smith et al.[15] published one of the first studies to investigate IAP from indoor biomass burning. Extremely high levels of TSPs and particle-bound benzo(a)pyrene were measured near women cooking on simple stoves using traditional biomass fuels in 4 Indian villages. Saksena et al.[23] measured similarly high personal and indoor TSP mass and CO concentrations indoors in villages in northern India. Particle measurements later became more refined to assess exposure to smaller respirable particles (i.e., $PM_{2.5}$ and PM_{10}), often before and after introducing stove interventions.[24] Additionally, Naeher et al.[25] and Bruce et al.[26] both demonstrated that CO concentrations, which are generally easier and more cost-effective to measure than PM, correlated well with PM concentrations, suggesting that CO measurements alone could be used to reduce costs during exposure assessments and make it possible to study increasingly larger sample sizes. More recently, Smith et al.[27] also supported this finding.

However, most exposure studies are limited in part by instrumentation. Only a few criteria pollutants were usually measured for a combination of reasons, including cost and availability of monitoring equipment, ease of measurement, and the role of pollutants as either the major pollutants of concern or as indicators of a number of pollutants of concern. Additionally, exposure studies were often limited by the time scale over which collected measurements were averaged. Continued development in instrumentation could increase the complexity and duration of exposure assessment studies.

Health Outcome Studies Combined With Exposure Measurements

In many cases, health outcome assessments were combined with exposure measurements, which can provide more direct links between stove use, indoor pollutant concentrations, and adverse health effects. For example, Ellegård[28] investigated the association between exposure to IAP from cooking fuels and several health outcomes in women in Mozambique. On average, wood users were exposed to PM_{10} levels during cooking times that were approximately twice that of charcoal users and 6 times that of liquefied petroleum gas users; wood users also had significantly more cough symptoms than the other groups. More recently, Smith-Sivertsen et al.[29] conducted a randomized trial of cookstove interventions in

Guatemala and observed significantly decreased incidences of pulmonary morbidity associated with decreased CO concentrations in those living in homes with improved cookstoves. Similarly, Baumgartner et al.[30] found that a 1-log increase in 24-hour integrated personal exposure to $PM_{2.5}$ was associated with higher systolic and diastolic blood pressure among women living in rural households using biomass fuels in Yunnan, China, suggesting that $PM_{2.5}$ exposure from biomass combustion might be a risk factor for elevated blood pressure, and thus for cardiovascular events. Most recently, Dix-Cooper et al.[31] found that chronic prenatal exposure to CO from wood smoke was associated with decreased neurodevelopment in children at age 6 years.

Despite current advances, some recent studies also highlighted difficulties in definitively identifying relationships between exposure and health outcomes, particularly in response to stove interventions. For example, Clark et al.[32] reported that the use of improved stoves was associated with lower personal and indoor $PM_{2.5}$ exposures; however, although women using traditional stoves reported respiratory symptoms more frequently than those using improved stoves, there was no significant association between cookstove type or air quality measures and pulmonary health indicators. Similarly, Clark et al.[33] observed a nonsignificant elevation in blood pressure with elevated 48-hour indoor $PM_{2.5}$ and indoor and personal CO concentrations across a sample of Nicaraguan households (although they did find a stronger relationship among obese participants). Finally, Smith et al.[34] reported on a randomized controlled trial in Guatemala of wood stove users with and without a chimney installed. In this study, infant pneumonia was not significantly reduced between exposure populations, but some reductions in pneumonia cases were observed at lower CO exposures. A lack of significant findings in these studies might be more representative of traditional study limitations, such as short survey periods or imperfect health or exposure metrics, or of the inability of many current "improved" cookstoves to reduce IAP exposures to levels as low as those observed in most developed countries.

Testing of Cookstoves and Other Indoor Combustion Devices

Combustion device performance was often tested independently of exposure and health effects studies, the results of which could be used to inform implementation programs of preferred higher efficiency, lower emission devices. Controlled stove and lamp tests were performed under laboratory conditions, simulated field conditions, and actual field conditions. These studies often quantified performance in terms of energy (e.g., thermal efficiency or rates of fuel consumption), pollutant emissions (e.g., mass of pollutants emitted per time, per mass of fuel burned, or per unit of energy delivered), or both. For example, McCracken and Smith[35] compared the thermal efficiency and emissions (of PM and CO) of traditional 3-stone fires to improved wood-burning planchas (a type of enclosed iron grill), both during a water boiling test and a standardized cooking test performed in kitchens in Guatemala. Although there was no difference in thermal efficiency, the plancha emitted 87% less $PM_{2.5}$ and 91% less CO per kilojoule of useful heat delivered during the water boiling test; emissions reductions were even higher for the standardized cooking test. However, in a study comparing laboratory-measured emissions from simulated cooking events to field-measured emissions from actual cooking events, Roden et al.[36] found field-measured emissions to be a mean of 3 times higher than laboratory-measured emissions. Emission factors were also highly dependent on the care and skill of the operator, which suggested that standardized cooking tests might not be entirely appropriate for accurately characterizing actual operation without adjusting for likely practices in the field.

Emissions and efficiency also varied greatly by stove type, which is an important issue given the rapid introduction of new technology into this sector. Jetter and Kariher[37] investigated 14 different stove and fuel combinations in a laboratory setting and identified significant differences in combustion performance and pollutant emissions during water boiling tests. They measured wide differences in emission rates of CO, carbon dioxide, total hydrocarbons, $PM_{2.5}$ mass, and size-resolved particles, and they noted the need for small stove components of acceptable cost and durability for use in the field. Apple et al.[38] characterized the need to consider other indoor combustion sources, including fuel-based lighting. They demonstrated that vendors in market kiosks in Kenya that used a single simple fuel-based wick lamp for lighting would likely be exposed to $PM_{2.5}$ concentrations an order of magnitude greater than WHO health guidelines. Kerosene lamps might be important, but too frequently overlooked, indoor combustion devices, because a recent study found higher risks for tuberculosis associated with their use than the risk associated with the use of biomass stoves or heaters and kerosene stoves.[39]

The technical complexity and variety of stoves and other combustion devices involved is growing. Previous research identified a need for standardized device tests, as well as better agreement with actual field performance. In response, some researchers proposed (1) simpler and more economical proxy methods for combustion efficiency that could be more representative of cooking cycles in the field,[40] (2) moving from mass-based particle dose parameters to those based on surface area concentrations that would deposit in the lungs,[41] (3) measuring a wider variety of pollutant emissions,[42] and (4) using computational methods to model heat transfer in and around cookstoves during development.[43] Tremendous opportunities still exist to improve field-testing methods and technologies and, ultimately, the development of cost-effective, clean, and efficient combustion devices for widespread use in developing regions of the world.

COOKSTOVE IMPLEMENTATION EFFORTS AND BARRIERS TO WIDESPREAD ADOPTION

There are currently more than 160 operating cookstove implementation programs in the world,[44] few of which go beyond dissemination of a few thousand stoves.[45] Manibog[46] reported that between 1977 and 1985, almost 43 million improved cookstoves were distributed in developing countries at a cost of at least $40 million USD, although 10% to 20% of stoves were not used and 20% to 30% were only used intermittently. Wallmo and Jacobson[47] encountered barriers to improved cookstove implementation in Uganda, including stove malfunctions, high costs, and no net changes in fuel consumption. Muneer and Mohamed[48] described the importance of gender roles in stove adoption in Sudan, showing that failing to include women in the household decision-making process led to decreased adoption of improved stoves. Cynthia et al.[9] reported substantial reductions in women's exposure to CO and PM in rural Mexican homes equipped with improved cookstoves, but also described the difficulty in adoption and reliance on multiple fuels and technologies for cooking needs. Cooks often did not want to give up their old stove because of tradition or cooking preference.[49] Ruiz-Mercado et al.[50] described challenges to the adoption and sustained use of improved cookstoves, noting that "stove stacking," or the use of several available stove and fuel types for different purposes, was common in many households with improved cookstoves. Most recently, Lewis and Pattanayak[51] reviewed cookstove adoption studies and reported that income, education, and urban location were most positively associated with the adoption of cleaner stoves, although the number of quantitative adoption studies remains low. These findings reflected the often mixed results and the combined technical and social complexities associated with effective cookstove implementation in developing countries, which if not addressed, could inadvertently prevent widespread reductions in exposures to IAP.[52]

Many research and implementation needs in this field have been outlined previously[3,53,54]; however, given the continued global health risks posed by IAP and the mixed successes of previous cookstove implementation programs, there remains a need to encourage and sustain new interdisciplinary research in the field and to improve adoption of clean stoves and fuels worldwide. To this end, we reported on the outcomes of a recent 2-day symposium on indoor air quality in developing countries that was held at the triennial Indoor Air conference, the official conference of the International Society of Indoor Air Quality and Climate (ISIAQ), in Austin, Texas in June 2011. Objectives of the 2-day symposium were to explore and discuss the state of the science of IAP in developing countries, to bring new researchers from a variety of disciplines in this field together, and to identify new avenues for integrating research, advocacy, and implementation efforts. The National Science Foundation's Integrative Graduate Education and Research Traineeship program supported the symposium, and with this support, 28 scholarships were awarded for students to attend, most of them graduate students actively conducting research on IAP in developing countries.

A full detailed report of the symposium, including its events, participants, and outcomes

Future Research and Implementation Needs for Indoor Air Pollution Reduction Efforts

Barriers to Widespread IAP Reductions	Research and Implementation Needs
The total costs of improved cookstove programs to date have been excessive.	Program costs must decrease. Governments, NGOs, private industry, and researchers should work to identify appropriate and cost-effective combinations of public and private funding for stove implementation programs.
Research and implementation efforts are frequently pursued independent of one another or with insufficient coordination, which, in some cases, has led to widespread implementation of "improved" stoves that have sometimes failed to deliver on their promise.	Researchers, donors, stove manufacturers, and funding agencies must work to achieve better integration of accurate laboratory and field testing before, or at least in conjunction with, widespread implementation programs.
Cookstove implementation efforts have often achieved mixed results because of the combined technical and social complexities associated with stove design and end-user preferences.	A wider array of researchers should work toward gaining a better understanding of factors that influence cookstove adoption, including practical and psychological user needs and preferences.
Although improved cookstoves often achieve substantial relative reductions in pollutant emissions, indoor concentrations are still typically much higher than those observed indoors in developed countries.	Engineers need to continue to develop cleaner and more efficient stoves that approach the cleanliness of those in the developed world, while working with other disciplines to address economic feasibility and user preferences.
Substantial variations in emissions and fuel consumption have been observed across ranges of cookstove designs and between laboratory and field test conditions.	Stove testing needs to advance toward standardized test methods that accurately incorporate variability in user practices.
Nomenclature in exposure, health, and stove testing studies is not always consistent, depending largely on the scientific discipline of the investigators.	Meetings and workshops comprising researchers and representatives from all stakeholders should be held to clarify and reach consensus on nomenclature, as is consistent with other well-established disciplines.
Health assessments, while increasing in number and variety, remain too limited to draw many robust connections to cookstove interventions and significant reductions in exposures to IAP and associated health outcomes.	Researchers should work to standardize IAP measurements and health metrics so governmental agencies can fund large epidemiological efforts similar to those conducted on outdoor air pollution in developed countries.
Instrumentation remains a significant barrier to accurate and widespread exposure studies.	Funding agencies should promote the development of low-cost, reliable sensors that would enable stronger health outcome studies.

Note. IAP = indoor air pollution; NGO = nongovernment organization.

can be found online in Carter et al.[55]; however, we have briefly summarized some major consensus findings from the symposium and subsequent discussion and review (see the Box on this page), which will hopefully help enable public health researchers to play a more meaningful role in improving the lives of those affected by indoor combustion in developing countries. The Box first lists several existing barriers to achieving widespread reductions in exposures to IAP in developing countries identified either during the symposium or during our review of previous literature. Key research and implementation needs are also summarized in Table 1 that, if addressed, could help overcome these barriers and allow stove implementation efforts to reach the scale necessary to have a lasting impact on global public health.

CONCLUSIONS

The previous research discussed in this report showcased the need for a wide variety of disciplines and organizations working in concert to address the substantial global public health burden of exposure to IAP in developing countries. As efforts to disseminate improved cookstoves accelerate, communication and collaboration across research fields and other sectors are critical to overcome some of the significant barriers to widespread reductions in the still remaining exposures to IAP. Importantly, strong desires for clarity and consensus on nomenclature and standardization of methods and metrics (including the introduction of metrics that incorporate the entire life-cycle of combustion devices) were identified at the 2-day symposium described herein as necessary precursors to successful collaboration between multiple sectors, organizations, and stakeholders. Other common themes that emerged during the symposium were that greater numbers of researchers from a variety of disciplines should be encouraged to address the many crucial research needs that still exist in the IAP field and that governments and nongovernmental organizations play critical roles in supporting efforts to achieve widespread improvements in public health in developing countries. Fortunately, some organizations are already working toward overcoming these barriers, such as the Global Alliance for Clean Cookstoves and the Partnership for Clean Indoor Air, but much work remains to be done.

Overall, continuing to provide a forum for researchers and field workers with varying backgrounds and experiences, including those in public health, can help address these questions as they evolve during this time of rapid change. Academic- and practitioner-oriented conferences offer the ideal environment to foster collaboration and establish partnerships between parties whose disciplines do not traditionally overlap. Continued use of the interdisciplinary approach supported by this symposium will help empower researchers to pursue the most critical efforts and support rapid reductions of the impacts of IAP on public health in developing nations. ■

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No participant protection was required because no human participants were involved in this study.

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