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Improving Indoor Air Quality for Poor Families:

A Controlled Experiment in Bangladesh

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Abstract

The World Health Organization's 2004 Global and Regional Burden of Disease Report estimates that acute respiratory infections from indoor air pollution (pollution from burning wood, animal dung, and other bio-fuels) kill a million children annually in developing countries, inflicting a particularly heavy toll on poor families in South Asia and Africa.

This paper reports on an experiment that studied the use of construction materials, space configurations, cooking locations, and household ventilation practices (use of doors and windows) as potentially-important determinants of indoor air pollution. Results from controlled experiments in Bangladesh are analyzed to test whether changes in these determinants can have significant effects on indoor air pollution. Analysis of the data shows, for example, that pollution from the cooking area diffuses into living spaces rapidly and completely. Furthermore, it is important to factor in the interaction between outdoor and indoor air pollution. Among fuels, seasonal conditions seem to affect the relative severity of pollution from wood, dung, and other biomass fuels. However, there is no ambiguity about their collective impact. All are far dirtier than clean fuels.

The analysis concludes that if cooking with clean fuels is not possible, then building the kitchen with porous construction material and providing proper ventilation in cooking areas will yield a better indoor health environment.

This paper—a product of the Sustainable Rural and Urban Development Team, Development Research Group—is part of a larger effort in the department to understand health risks from environment. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at sdasgupta@worldbank.org.

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Authors' names are in alphabetical order. We would like to express our appreciation to the Development Policy Group, for their excellent air-quality monitoring work under difficult conditions. We are grateful to Subrata Ghosh and his team for assisting us with architectural design and construction of the houses. Our sincere thanks to Ms. Polly Means for her help with the composition of graphics. Financial support for this study has been provided by the World Bank through Research Support Budget and Trust Funds administered by ESMAP. The findings, interpretations, and conclusions are entirely those of the authors. They do not necessarily represent the view of the World Bank, its Executive Directors, or the countries they represent.

1. Introduction

According to the WHO Global and Regional Burden of Disease Report, 2004 (http://www.who.int/publications/cra/en), acute respiratory infections from indoor air pollution (IAP - pollution from burning wood, animal dung and other biofuels) are estimated to kill a million children annually in developing countries. These infections inflict a particularly heavy toll on poor families in South Asia and Africa. This has prompted the World Bank and other international development institutions to identify reduction of IAP as a critical objective for the coming decades (World Bank, 2001).

Although IAP is a complex mixture of small and large particles, recent epidemiological studies have reported that exposure to particulates, particularly small particulates, is strongly associated with respiratory illness and death. Small particles are likely to be more dangerous, since they can be inhaled deeply into the lungs and settle in areas where natural clearance mechanisms, like coughing, cannot remove them. The current scientific consensus is that most respiratory health damage comes from the inhalation of respirable particles whose diameter is less than 10 microns (PM_{10}), with recent attention focusing on even finer particles ($PM_{2.5}$).

The design of cost-effective IAP reduction strategies has been hindered by lack of information about actual PM concentrations in poor households. Data have been scarce because monitoring in village environments is difficult and costly. Relatively small-scale studies of indoor PM_{10} exposure from wood-fuel combustion have been conducted in Kenya (Boleij, et al., 1989, 36 households), Guatemala (Smith, et al., 1993, 60 households), Mexico (Santos-Burgoa, et al., 1998, 52 households), and Gambia (Campbell, 1997, 12 households), and indoor PM_{10} exposure from coal combustion has been conducted in Mongolia (Cowlin et al., 2005, 65 *gers*[1]). In addition, Balakrishnan, et al., have studied a larger sample of houses in rural India (Balakrishnan, et al., 2002, 412 households; Parikh, et al., 2001, 436 households) and Baris et al. have studied a larger sample in China (Baris et al., 2006, 300 households). These studies have yielded two main conclusions: Natural gas and kerosene are far less pollution-intensive than biofuels such as wood and dung, and use of improved stove designs can significantly reduce indoor pollution from biofuels.

Unfortunately, nationwide energy surveys in many developing countries have revealed that poor households almost always use "dirty" biomass fuels, particularly in rural areas. This is often because clean fuels are not available. Even where a clean fuel is available, most poor households use dirty fuels because the relative price of the clean fuel is simply too high. Improved stoves for biomass combustion could help, but studies in Asia and Latin America have found almost no adoption of improved stoves, despite widespread promotional efforts. Households report non-adoption for a variety of reasons, including capital and maintenance costs, inconvenience, and incompatibility with food preparation traditions. Thus, neither clean fuels nor improved stoves offer strong prospects for reducing IAP in rural areas in the near future.

Some of the previous studies have alluded to construction materials, space configurations, cooking locations and household ventilation practices (use of doors and

[1] Traditional Mongolian dwellings.

windows) as potentially-important determinants of IAP (Brauer and Saxena, 2002, Moschandreas et al, 2002, Freeman and Sanez de Tajeda, 2002; ESMAP/World Bank, 2002; Heltberg, et al., 2003). In theory, many innovations in construction, space configuration and cooking practices could have significant effects on IAP. However, all systematic research on IAP seems to have focused on the use of clean fuels and improved stoves. We are not aware of any controlled, scientifically-monitored research on the relationships between structural arrangements and IAP in developing countries.

To promote better understanding of these relationships, we have conducted a controlled experiment in Bangladesh to test whether changes in construction materials, space configurations and cooking locations can have significant effects on IAP. This paper summarizes our results. The remainder of the paper is organized as follows. Section 2 discusses our controlled experiments, and describes how indoor air and the ambient environment have been monitored for this exercise. In Sections 3 and 4 we summarize our experimental results. Section 5 provides a summary and discussion of policy implications.

2. Controlled Experiments in Bangladesh

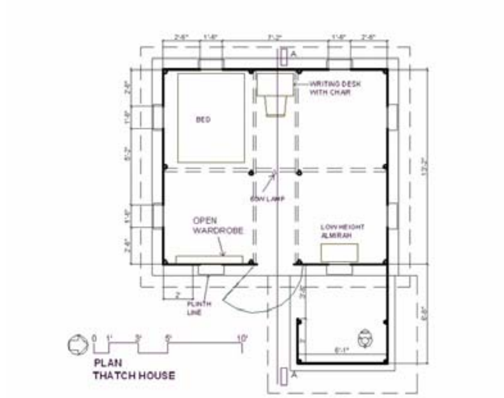
Previous World Bank research in Bangladesh, using the latest air monitoring technology and a national household survey, has found that IAP is dangerously high for many poor families. Concentrations of 300 ug/m^3 or greater for respirable airborne particulates (PM_{10}) are common in Bangladeshi households, implying widespread exposure to a serious health hazard (Dasgupta et al., 2006)[2]. The findings also suggest wide variation in indoor air quality based on fuels, cooking locations, construction materials and ventilation practices.

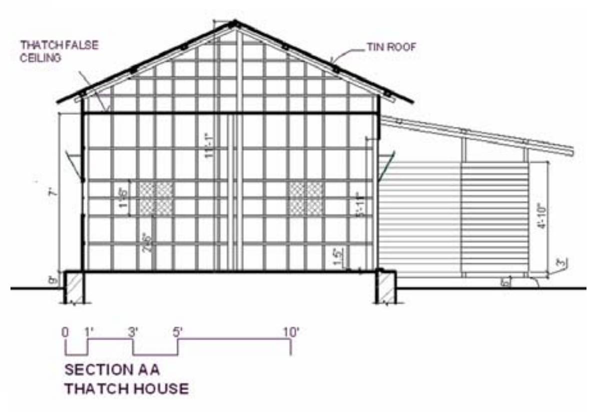
The potential importance of these factors prompted our follow-on program of direct experimentation, to overcome uncertainties about causation that are inevitably associated with cross-sectional survey analyses. The experiments focus on structural arrangements that are already common among poor households in Bangladesh, since the literature on interventions to promote clean fuels and improved stoves is replete with disappointments stemming from reluctance of poor families to adopt innovations that are unfamiliar, unsupported by existing services, and potentially costly to maintain.

The controlled experiments were conducted in Burumdi village of Narayanganj district. Village Burumdi is located approximately 27 km away from the center of Dhaka, the capital of Bangladesh in South-East direction. The distance of the village from the nearest secondary road is 3 km. At the time of the experiments, there were approximately 290 houses in the village with 1,600 inhabitants in total[3].

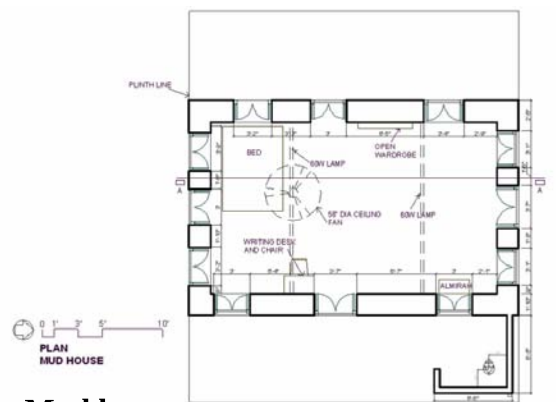
Architects familiar with climatic conditions and cultural constraints faced by Bangladeshi households studied building materials, housing configurations and constructiontechniques in different regions of the country, and developed an appropriate set of structural options.
Figure 1: Architectural Design: As-Built Drawings

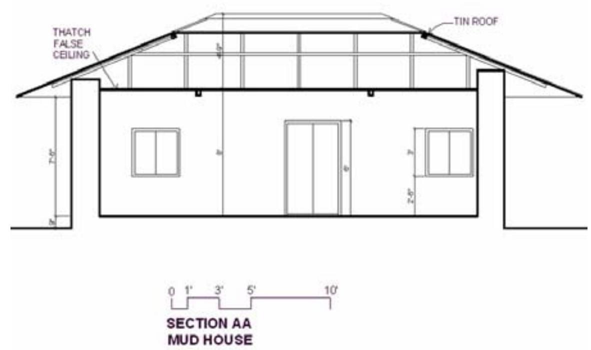
[2]By way of comparison, Galassi, Ostro, et al. (2000) find substantial health benefits for PM_{10} reduction in eight Italian cities whose annual concentrations are far lower: 45-55 ug/m^3.
[3] Most of the villagers are either self-employed in non-agricultural sectors (e.g., fisherman, rickshaw puller) or are service providers.



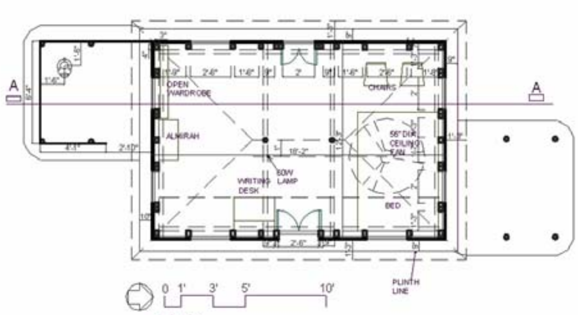


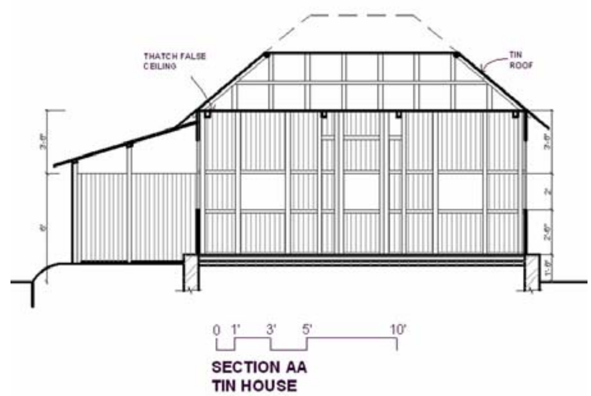
Thatch house





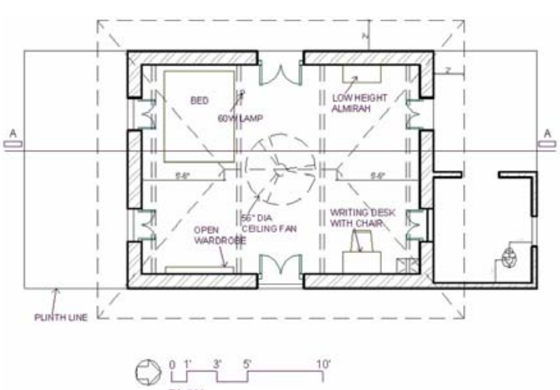
Mud house

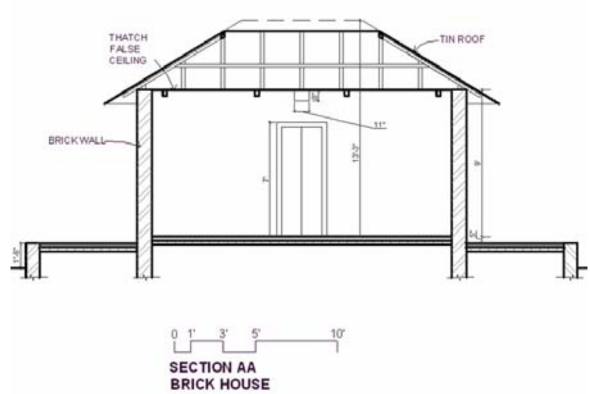




PLAN
TIN HOUSE

Tin house





PLAN
BRICK HOUSE

Brick house

Local workers at each site were hired to construct experimental houses that are indistinguishable from structures actually used by poor families in the area, using standard local building practices. The four sets of houses built had walls made of thatch, mud, corrugated iron (tin) and bricks (henceforth referred to as Thatch, Mud, Tin and Brick houses, respectively). The walls of each house were permanent, but roofing materials were altered to produce a variety of standard combinations. In the final experimental set, the Thatch house had tin and thatch roofs; the Mud, Tin and Brick houses had tin roofs, and in a later experimental stage the Brick house roof was changed to concrete. Prevailing winds in the region are from south to north in the summer and north to south in the winter, so the axes of the houses were aligned in the north-south direction to capture varying wind conditions. Houses were furnished to create life settings for the experiments.

Figure 2: Houses for Controlled Experiments

Provisions were made for cooking fuel combustion in four configurations that simulate common cooking arrangements: inside the house (within-dwelling); in a space attached to it (attached kitchen); in a space enclosed by walls and a roof at a little distance from the house (detached kitchen); and in the open air. The wall materials of attached and detached kitchens varied among thatch, mud, tin and brick, while the roofs varied among thatch, tin and concrete.[4] The experiments also allowed for turning on a ceiling fan in the living space. Experimental combustion used diverse energy sources: clean fuels (kerosene, LPG), wood, cow dung and other biomass fuels (rice husks, jute etc.). Table 1 summarizes the distribution of conducted experiments. Combinations of cooking arrangements, kitchen configurations and fuel were restricted to cases generally observed in Bangladesh[5].

Figure 3: Monitoring Indoor Air in Different Kitchens

[4] The designs of the houses were flexible enough to permit alterations in building materials and kitchen configurations from time to time, as the experimental program dictated, without much delay.
[5] For example, cooking with cow dung/rice husk/jute inside houses is not common in rural Bangladesh, and hence been excluded from our experiments.

Table 1: Experimental Configurations

Table 1a: By House Type

Wall	Roof	# of Experiments
Brick	Concrete	37
	Tin	63
Tin	Tin	112
	Thatch	0
Mud	Tin	117
	Thatch	0
Thatch	Tin	89
	Thatch	80

Table 1b: By Kitchen (Construction Material)

Kitchen Wall	Kitchen Roof	# of Experiments
Brick	Concrete	16
	Tin	34
Tin	Tin	134
	Thatch	33
Mud	Tin	46
	Thatch	34
Thatch	Tin	99
	Thatch	53

Table 1c: By Kitchen Type

Kitchen type	# of Experiments
Within Dwelling	59
Attached	165
Detached	225
Open	49

Table 1d: By Fuel

Fuel Type	# of Experiments
Clean	54
Firewood	186
Cow dung	100
Others	158

Cooking and indoor air quality monitoring were conducted during April 2005 – June 2006, with the exception of the monsoon period (July 2005-September 2005)[6]. The

[6] This monitoring period included the high-dust season (November- March, when humidity is low and rainfall is rare) and the low-dust season (April – June and October, when pre-monsoon thunderstorms and post-monsoon rainfall are frequent).

concentration of PM_{10} in ambient air near the houses was monitored at regular intervals during the period of controlled experiments.

Monitoring PM_{10} *Concentrations*

Our controlled experiments used two types of equipment: air samplers that measure 24-hour average PM_{10} concentrations, and real-time monitors that record PM_{10} at 2-minute intervals.

- The Airmetrics MiniVol Portable Air Sampler (Airmetrics, 2004) is a more conventional device that samples ambient air for 24 hours. While the MiniVol is not a reference method sampler, it gives results that closely approximate data from U.S. Federal Reference Method samplers. The MiniVols were programmed to draw air at 5 liters/minute through PM_{10} particle size separator (impactors) and then through filters. The particles were caught on the filters, and the filters were weighed pre- and post exposure with a microbalance.

- The other instrument used in the study is a real-time monitoring instrument: the Thermo Electric personal DataRAM (pDR-1000) (Thermo Electron, 2004). The pDR-1000 (pD-RAM) uses a light scattering photometer (nephelometer) to measure airborne particle concentrations.[7] At each location, the instrument operated continuously, without intervention, for a 24-hour period to record PM_{10} concentrations at 2-minute intervals.

The readings of the pD-RAM and MiniVol air samplers provided a detailed record of IAP concentration in each controlled experiment.

Table 2a: PM_{10} ($\mu g/m^3$) concentrations recorded by MiniVol Portable Air Samplers (24-hour average)

Season	Location of the Monitor	Mean	Median	Minimum	Maximum
High-Dust	Kitchen	221.63	212.92	38.75	472.5
High-Dust	Living Room	160.85	155.42	44.86	320.42
Low-Dust	Kitchen	128.97	124.72	30.42	310.83
Low-Dust	Living Room	69.33	63.88	21.53	183.61

Table 2b: PM_{10} ($\mu g/m^3$) concentrations recorded by pD-RAM (2-minute intervals)

Season	Location of the Monitor	Mean	Median	Minimum	Maximum
High-Dust	Kitchen	585.10	404	8	93900
High-Dust	Living Room	468.44	370	1	403200
Low-Dust	Kitchen	284.17	146	1	109900
Low-Dust	Living Room	843.00	132	1	195500

[7] The operative principle is real-time measurement of light scattered by aerosols, integrated over as wide a range of angles as possible.

In addition, ambient PM_{10} concentrations for 24 hours were monitored 76 times during the experiments with MiniVol air samplers. The readings (reference: Table 2c) revealed wide inter- as well as intra- season variation in PM_{10} in outdoor environment.

Table 2c: Ambient PM_{10} ($\mu g/m^3$) concentrations recorded by MiniVol Portable Air Samplers (24-hour average)

Season	# of readings	Mean	Minimum	Maximum
High-dust	41	171.158	82.083	274.167
Low-dust	35	54.21	15.278	125.278

3. Regression Analysis of Experimental Data

Kitchen Results

The regression analysis investigates the roles of several basic determinants of indoor air pollution: Kitchen configurations (within-dwelling, attached, detached or open), building materials (brick, mud, tin, thatch) and fuels (clean (kerosene, LPG), wood, dung, other biomass). As previously described, these elements have been varied under fixed experimental conditions, with prescribed burn times for fuels, in both low-dust and high-dust seasons.

We report regression results for houses in which kitchens and living rooms were concurrently monitored with MiniVol equipment. Systematic experimental variation has enabled us to avoid collinearity problems for construction materials. We control for seasonality, as well as variations in kitchen configurations that reflect seasonality. No one cooks outside during the low-dust season when rain is frequent, precluding measurement of pollution in open kitchen during that season. To ensure sample comparability, we include high-dust-season results for houses without open and detached kitchen arrangements, as well as full results that include open and detached configurations.

In Table 3, column (1) presents results for all experimental variables and housing configurations in the high-dust season. Column (2) retains the sample but drops the control for detached housing, which does not attain marginal significance in any of the regressions. Column (3) replicates column (2), but for a sample that drops open-kitchen configurations for direct comparability with the low-dust-season sample. Finally, column (4) provides results for the low-dust season.

All the results highlight the importance of seasonal conditions. The first three columns are for the high-dust season. The complete high-dust-season sample is 225 experimental results, which falls to 177 for experiments that are directly comparable to low-dust-season experiments (exclusion of detached and open kitchens). In the low-dust season, the sample is 250 experimental results. Regression standard errors are constructed from robust (Huber/White/Sandwich) variance estimates. Regression R^2's vary from .29 to .41, indicating substantial random variation in ambient conditions.

Table 3 Regression Results for Kitchen Pollution

Dependent Variable: Kitchen PM_{10} Concentration (ug/m^3, MINVOL, 24-hour)

	(1)	(2)	(3)	(4)
	High-Dust Season			Low-Dust Season
Kitchen Layout (Open Excluded)				
Within-dwelling	-187.314	-186.996	-187.067	6.085
	(7.65)**	(8.81)**	(8.60)**	(0.85)
Attached	-49.251	-48.931	-49.155	26.336
	(2.46)*	(3.03)**	(2.92)**	(4.12)**
Detached	-0.491			
	(0.03)			
Kitchen Wall Materials (Thatch Excluded)				
Brick	60.400	60.274	62.073	18.433
	(2.88)**	(2.93)**	(2.94)**	(1.83)
Mud	34.348	34.138	35.519	-41.444
	(2.40)*	(2.56)*	(2.47)*	(5.22)**
Tin	8.808	8.641	10.231	10.903
	(0.64)	(0.67)	(0.73)	(1.67)
Roof Materials (Thatch and Concrete Excluded)				
Tin	-23.395	-23.572	-22.945	-6.024
	(2.17)*	(2.30)*	(2.10)*	(0.87)
Fuels (Straw Excluded)				
Wood	70.593	70.573	71.139	61.995
	(4.61)**	(4.62)**	(4.61)**	(6.66)**
Dung	67.460	67.459	74.787	109.297
	(3.71)**	(3.71)**	(3.85)**	(9.71)**
Other	92.975	92.967	90.378	56.516
	(5.75)**	(5.77)**	(5.61)**	(5.78)**
Constant	156.079	155.898	153.886	55.398
	(8.03)**	(8.81)**	(7.78)**	(4.21)**
Observations	225	225	177	250
R-squared	0.29	0.29	0.36	0.41

Robust t statistics in parentheses
* significant at 5%; ** significant at 1%

The overall impact of seasonality is captured by the constant terms in the regressions. In all three high-dust-season regressions, the constant term is over 150 ug/m^3, while in the low-dust season it drops to about one-third of that level (55 ug/m^3). This seasonal difference of 100 ug/m^3 highlights the importance of seasonal variations in village ambient air quality in determining household-level IAP.

The results for kitchen configurations provide an interesting counterpoint to the conventional assumption that, controlling for fuels and building materials, IAP should be highest in the interior/ within-dwelling kitchen (because it is the most contained cooking space) and decline with progressive opening to the outside. However, this view reflects the implicit assumption that outdoor air is "clean". In reality, the high-dust-season reverses configuration effects because intervening structures filter the contaminated external air. Interior/ within-dwelling kitchens, furthest removed from the outdoors, have ambient concentrations 187 ug/m^3 lower than open or detached kitchens. Attached kitchens, next removed from the outdoors, have concentrations 49 ug/m^3 less than open or detached kitchens. In the low-dust season, the sign reverses for attached kitchens although interior/ within-dwelling kitchens exhibit no differential effect.

In the high-dust season, we find consistent differential effects for kitchen wall materials: Concentrations are significantly higher for brick and mud than for thatch and tin (whose difference is not significant). Brick accounts for the highest increment over thatch and tin – about 60 ug/m^3 – while mud has an increment of about 34 ug/m^3. Again, these results are significantly changed by conditions in the low-dust season: The increment for brick is small and insignificant, and the increment for mud retains it magnitude but changes signs. Tin remains insignificant. For roofing materials, tin accounts for a negative, significant increment from thatch during the high-dust season, but the significance disappears during the low-dust season.

Even the contaminating effects of fuels are affected by seasonal conditions, although the results retain the appropriate signs and high levels of significance in both seasons. In the high-dust season, both wood and dung account for increments of around 70 ug/m^3 relative to clean fuels. Other biomass fuels add an even greater increment – around 90 ug/m^3. The order of effects changes substantially during the low-dust season, with dung accounting for the greatest increment (109 ug/m^3) over clean fuels, followed by wood (62 ug/m^3) and other biomass fuels (57 ug/m^3).

Living Room Results

Table 4 reports regressions for living rooms that are monitored concurrently with kitchens using MiniVols. We introduce the kitchen PM_{10} concentration to control for diffusion of smoke from cooking. We estimate the kitchen concentration effect using both OLS and IV, the latter to correct for possible pollutant backflow from living spaces to kitchens.

Table 4 Regression Results for Living Room Pollution

Dependent Variable: Living Room PM_{10} Concentration (ug/m^3)

	(1)	(2)	(3)	(4)
	High-Dust Season		Low-Dust Season	
	OLS	IV	OLS	IV
Kitchen PM10 (ug/m^3)	0.610 (12.82)**	0.516 (7.11)**	0.107 (3.20)**	-0.114 (1.96)
Living Room Wall Materials (Thatch Excluded)				
Brick	6.531 (0.90)	1.570 (0.18)	-2.404 (0.39)	-9.590 (1.33)
Mud	-22.002 ((3.54)**	-23.942 (3.57)**	-15.390 (3.25)**	-20.568 (3.98)**
Tin	-46.856 (5.13)**	-41.781 (4.41)**	-11.883 (2.39)*	-11.217 (2.12)*
Living Room Roof Materials (Thatch Excluded)				
Tin	11.058 (2.29)*	11.266 (2.10)*	-15.207 (2.22)*	-13.454 (1.78)
Living Room Fan On	-22.543 (2.54)*	-19.087 (2.04)*	-0.701 (0.11)	-0.209 (0.03)
Constant	31.199 (2.82)**	52.077 (3.20)**	75.277 (10.71)**	104.777 (9.96)**
Observations	225	225	250	250
R-squared	0.60	0.59	0.15	

Robust t statistics in parentheses
* significant at 5%; ** significant at 1%

As before, our results indicate the importance of seasonality. Regression fits differ substantially between the two seasons, with R^2 near .60 during the high-dust season and .15 during the low-dust season.[8] The constant effects are again highly significant and very different, but for the living room their role is reversed. In the IV estimates, the high-dust-season constant is 52 ug/m^3, while during the low-dust season it doubles to 105 ug/m^3.

During the high-dust season, diffusion of kitchen pollution is a large, highly significant determinant of living-room pollution. Ceteris paribus, living room pollution increases by

[8] R^2 could not be computed for the low-dust-season IV equation.

.5-.6 ug/m^3 for each increase of 1 ug/m^3 in kitchen pollution. In the low-dust season, however, this effect essentially disappears. The OLS estimate is positive, small and significant, while the IV estimate is negative, small and marginally significant.

For building materials, inter-seasonal results are mixed. Relative to thatch, both mud and tin have negative increments that are significant in both seasons. They are roughly constant in magnitude across seasons for mud, while they are substantially greater in the high-dust season for tin. Brick-related increments are insignificant in both seasons. The effect of tin roofing relative to thatch is significant but contradictory across seasons. It is small in both seasons, but positive during the high-dust season and negative during the low-dust season.

The regressions also measure the effect of operating a fan in the living room. During the high-dust season, this has a modest but significant negative effect on IAP. During the low-dust season, however, the effect disappears.

4. Variations in Exposure Patterns: pD-RAM Results

Even if total particulate exposure is the same during a 24-hour period, brief, highly-concentrated exposures may affect health differently than sustained exposures. In this context, our experimental data provide useful information on the relationship between exposure patterns, building materials, fuels and kitchen configurations. Our MiniVols only record total 24-hour exposures, so they cannot track exposure variation. However, our pD-RAM samplers measure pollution at regular intervals over the 24-hour cycle. We use the pD-RAM data for a standardized assessment of kitchen exposure patterns during the mid-day meal preparation period. From each experiment, we draw 150 regular-interval pD-RAM observations covering five mid-day hours, centered on the hour of maximum IAP exposure. We draw inferences about distribution patterns from the mean, maximum, minimum, standard deviation and median for each experiment. Distributions with shorter but more extreme exposures have higher maxima, means (pulled upward by higher maxima), and standard deviations. Distributions with more uniform exposures have higher minima and medians.

Table 5 provides regression results for 101 experiments. Overall regression fits are reasonable, with R^2's around .26. The results suggest that building materials do not have significant effects on exposure patterns. However, wood and dung combustion seem to generate more intense exposures than other biofuels (the excluded fuel variable). Their particulate distributions have higher means, maxima and standard deviations; several estimated parameters are highly significant, and all are at least marginally significant. Attached Kitchen configuration also seems to promote more intense exposures. The means, maxima and standard deviations for Attached kitchen distributions are all much higher than those for the excluded configuration: inside-dwelling, and with very high significance. In the opposite vein, Detached Kitchen configuration seems to promote more sustained exposure. Minimum and median particulate concentrations for Detached Kitchens are significantly higher than those for the excluded (inside-dwelling) configuration.[9] The median result for the high-dust season is also worth noting here. It

[9] We found pD-RAMs hard to operate in the open due to high deposition and insect entry into the optical chamber.

suggests an overall increase of about 86 ug/m^3 during this season – a figure which is close to the MiniVol result for kitchens.

Table 5 Regression Results for Exposure Distribution Statistics

	Mean	Maximum	Minimum	St. Dev.	Median
Brick	249.683	5,765.622	24.741	642.883	27.575
	(1.78)	(1.94)	(1.10)	(1.83)	(0.48)
Mud	36.592	-635.003	-5.529	-85.740	41.120
	(0.27)	(0.22)	(0.25)	(0.25)	(0.74)
Thatch	201.391	2,405.807	31.963	339.155	46.685
	(1.50)	(0.84)	(1.48)	(1.01)	(0.85)
Wood	322.702	8,782.403	-14.011	1045.098	-9.783
	(2.45)*	(3.15)**	(0.66)	(3.17)**	(0.18)
Dung	203.429	4,407.647	-14.287	590.197	-28.595
	(1.70)	(1.74)	(0.74)	(1.97)*	(0.58)
Kitchen layout					
Attached	257.893	6,584.797	27.972	669.463	67.878
	(2.17)*	(2.62)**	(1.46)	(2.25)**	(1.40)
Detached	274.299	3,480.145	63.093	400.850	181.843
	(2.01)*	(1.20)	(2.87)**	(1.17)	(3.25)**
High Dust	88.887	498.348	22.689	42.903	85.526
	(0.86)	(0.23)	(1.36)	(0.17)	(2.02)*
Constant	49.277	-1847.06	46.929	-121.12	73.523
	(0.32)	(0.57)	(1.90)	(0.32)	(1.17)
Observations	101	101	101	101	101
R-squared	0.20	0.27	0.29	0.24	0.31

Absolute value of t statistics in parentheses

* significant at 5%; ** significant at 1%

5. Conclusions and Policy Implications

This study has identified several sources of IAP exposure risk that can be mitigated by Bangladeshi villagers at feasible cost. We believe that self-interest will motivate villagers to act, once they become convinced that the problem is serious, and that their actions will be cost-effective. Serious mitigation will require the approval of male household heads, who control many of the relevant resources, and one key to persuasion is provided by our findings on male exposure risk. Our experiments, as well as the survey and monitoring work reported in a previous paper, have undermined the conventional view that women face most of the IAP exposure risk. Men also face serious risk, for two principal reasons. First, dangerous particulates from kitchen fires spread immediately to living areas, so males' avoidance of cooking areas does not protect them.

Second, adult and adolescent males spend substantially more time outdoors than their female counterparts. This increases their exposure risk, since outdoor air pollution is also a serious problem.

Although elevated male exposure risk is unfortunate, it does provide an important motivation for men to support changes in two areas where male decisions play a decisive role -- at the household level, alteration of housing configurations and building materials; and at the village level, adoption of collective measures to reduce outdoor air pollution, particularly during the high-dust season.

Three of our results highlight household-level adjustments that can significantly mitigate IAP exposure. First, given the importance of outdoor air pollution, seasonality is very important in determining optimal cooking arrangements. During the polluted high-dust season, our results indicate that the air quality in interior kitchens is much better than outdoor or detached facilities. This is not true during the low-dust season (when rain is frequent), but then it is difficult to cook outside.

Second, building materials do make a significant difference for indoor pollution in the high-dust season. In kitchen areas, brick walls are significantly more air-trapping than mud walls, which are, in turn, significantly more air-trapping than thatch or tin walls. For kitchens, tin roofs provide better air quality than thatch roofs. In living rooms, tin walls provide better air quality than mud walls, which in turn are better than brick or thatch walls. In summary, tin seems to be the building material that contributes the most to healthy air quality, followed by thatch and mud; brick is the most dangerous material.

Third, our monitoring results show that operating a living room fan does provide significant benefits in the high-dust season.

At the village level, two results highlight the potential importance of collective mitigation measures. First, outdoor air pollution is a highly-significant determinant of indoor ambient pollution levels, particularly in the high-dust season. The importance of outdoor pollution implies a collective problem with small, private chimneys or vent-holes that expel cooking smoke at roof height. The use of chimneys or vent-holes may improve indoor air in individual households, or when dwellings are dispersed, but cooking smoke emerging from chimneys in a cluster of households is likely to aggravate outdoor air pollution. The polluted outdoor environment, in turn, will adversely affect indoor air quality for all households in the cluster. Second, our results support other research that has demonstrated the importance of clean fuels. Although seasonal conditions seem to affect the relative severity of pollution from wood, dung and other biomass fuels, they are all far dirtier than clean fuels If cooking with clean fuels is not possible, then building the kitchen with porous construction material and providing proper ventilation in cooking areas will yield a better indoor health environment.

Our results imply that several village-level measures could significantly reduce IAP exposure. All would require central cooking arrangements and the assent of male heads-of-household: negotiated bulk purchases of higher-cost, cleaner fuels; purchase of more fuel-efficient stoves; peripheral location of cooking facilities; rotation of women in cooking roles[10], to reduce their exposure; and ventilation of cooking smoke through a stack tall enough to reduce the village particulate concentration, by dispersing smoke over a relatively broad area.

Are Bangladeshi villagers likely to adopt such collective innovations or, for that matter, alter the private household arrangements to which they are accustomed[11]? We believe that village men and women will agree to these measures if they become convinced that IAP poses a severe risk to themselves and their children; that their actions will significantly improve their health because the sources of IAP risk have been correctly identified; and that central cooking can be organized and financed effectively. The keys to success are effective public education about the sources and risks of IAP, and financial and technical assistance for collective cooking arrangements. These services could be provided by the World Bank and the Government of Bangladesh in a collaborative program. We believe that this is well worth trying, because indoor air pollution ruins the health of many Bangladeshi villagers.

[10] In rural areas of Bangladesh, this can be tried where extended family members often live near one another within a cluster.

[11] Community-based sanitation approaches have proven to be successful in Bangladesh and other developing countries.

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