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Adoption and Use of Improved Stoves and Biogas Plants in Rural India

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Abstract

Household air pollution remains a dominant health risk, particularly in South Asia. Increasing international attention has focused on improved cookstoves (ICS) as a vehicle for reducing household air pollution, regional environmental and climate impacts. Biogas plants are a type of improved cooking technology. However, dissemination programs for ICS (including biogas) have met with mixed results, and biogas plants often suffer from operational and structural challenges. This analysis of ICS adoption adds to the limited literature informing cookstove dissemination programs. In a sample of households from Odisha, India, we find households with ICS have higher socioeconomic and educational status, while households with only a traditional stove spend more money on fuel and more time in hospitals treating respiratory disease. Hours of ICS use is significantly associated with less time spent collecting fuel and fewer days in the hospital for respiratory disease. We find that household receipt of higher subsidies for plant construction; livestock ownership and less time collecting wood are associated with ownership of biogas plants that remain functional. We also add to the scant field evidence of ICS impacts on fuel use and confirm that ownership of ICS including biogas stoves is associated with a significant decrease in fuelwood consumption.

Key words

Improved cookstove, biogas, adoption, household air pollution, fuelwood consumption, impact analysis

Adoption and Use of Improved Stoves and Biogas Plants in Rural India

1. Introduction

About 40% of the global population (amounting to 3 billion people) rely on solid biomass fuels including fuelwood, crop residues, charcoal, coal, and dung for cooking. India leads the world in number of people using traditional biomass for cooking; over two thirds of the national population (772 million) uses biomass as their main cooking fuel, accounting for 30% of the global total of biomass users (IEA 2012; Legros et al. 2009).

Inefficient combustion of solid fuels emits high concentrations of particulate matter (PM) and other harmful emissions (Smith et al. 2009). A strong association has been shown between household air pollution (HAP) and acute lower respiratory infections (ALRI) in children, and chronic obstructive lung disease (COPD) and lung cancer in adults (Smith et al. 2004; Bruce et al. 2006; Dherani et al. 2008; Kurmi et al. 2010).As a result of the magnitude of these adverse health impacts, household air pollution from burning solid fuels in primitive cookstoves is the primary environmental cause of death (Martin et al. 2011). The 2010 Global Burden of Disease Report found household air pollution to be the third most deadly global risk factor, accounting for about 3.5 million deaths annually (mainly due to cardiovascular and respiratory illnesses), and the second greatest risk factor in India (IHME 2013; Lim et al. 2012).

Inefficient, traditional cooking practices also adversely impact livelihoods, since women and children must spend time cooking and gathering fuel that could be spent on income generating activities, and can also affect local environmental conditions by exacerbating forest degradation (Hofstad et al. 2009). Residential biofuel cooking is the second greatest source of black carbon, a significant greenhouse pollutant that can lead to regional hotspots and the melting of Himalayan glaciers and snow (Bond et al. 2013; Ramanathan and Carmichael 2008).

The adverse health, livelihood, local environment, and climate impacts generated by household biomass burning have gained increased attention in the past few years. Improved cookstoves have been designed to alleviate these negative impacts through increased combustion efficiency that requires less fuel and reduces cooking time. A growing global consensus that improved cookstoves can produce this significant combination of beneficial impacts culminated in the creation of the Global Alliance for Clean Cookstoves (GACC) in 2011. With a similar aim, the Indian government developed the National Biomass Cookstove Initiative in 2009 to distribute 160 million ICS that will provide "the quality of energy services from cookstoves comparable to that from other clean energy sources, such as LPG" (MNRE 2009). Several "game changers" including new financing instruments designed to achieve climate change mitigation using ICS have made ICS distribution more feasible (World Bank 2011) and vaulted ICS onto the global policy stage.

ICS models differ substantially in efficiency, materials, ventilation, fuel types, and the number of burners (Jetter et al. 2012). In India, ICS include biogas, LPG, kerosene and electric stoves. Biogas plants produce a clean fuel from a local waste product – cow and buffalo dung – and thereby reduce household air pollution from dirtier traditional stoves while eliminating a source of greenhouse gas emissions.

However, the benefits of ICS are far from certain (Jeuland and Pattanayak 2012). The process of moving from traditional stoves and fuels to cleaner alternatives is complicated – households that use ICS or cleaner fuels often employ a "fuel stacking" strategy and maintain concurrent use of their traditional and improved cooking systems (Masera et al. 2000). In addition, studies of stove emissions and HAP exposure do not generally consider household-level confounders such as individual choices and behavior. The decisions made by households, such as the decision to adopt, frequency of ICS use, choice of fuel type, and correct or incorrect use moderate the potential benefits of ICS (Pattanayak and Pfaff 2009). Differences between households may result in non-random distribution of improved stoves such that health characteristics and individual preferences may differ between those with and without ICS (Mueller et al. 2011). For example, a family with a history of respiratory illness may be more likely to purchase ICS.

Adoption has been extensively modeled in other domains, including agroforestry (Pattanayak et al. 2003), and a similar approach was recently implemented for ICS: a systematic review of the determinants of ICS adoption highlighted the need for additional rigorous studies of ICS use to help keep pace with the growing effort to disseminate stoves – only 8 empirical studies conducted rigorous quantitative analyses of the determinants of ICS adoption. The authors find a positive association between adoption and income, education, and urban location. However, potentially significant drivers of adoption including fuel and credit availability were largely ignored in these studies (Lewis and Pattanayak 2012). Additional empirical research examining the connections between stove choice, household characteristics, and fuel use is needed. Some recent research highlights the challenges in increasing ICS uptake (Mobarak et al. 2012) and achieving sustained use and health benefits (Hanna et al. 2012), but novel, context-sensitive stove sale offers provide an encouraging counterpoint (Levine and Cotterman 2012).

Although the literature on adoption of improved cookstoves is slowly growing, the evidence base for what factors best encourage and promote adoption of cleaner technologies remains thin, particularly considering the tremendous health burdens currently borne by households using inefficient cooking technologies (Smith et al. 2013). Despite the support from the international community of clean technologies as a potential solution, the best path to speed the millions currently relying on solid fuel toward a cleaner future remains unclear. In particular, the literature on biogas fueled stoves as an alternative to traditional stoves is quite limited. To accurately describe and understand household decisions to use ICS or clean fuels, it is critical to consider factors underlying household choices.

In this paper, we examine household stove use in a cohort of rural Indian households in the coastal state of Odisha. Odisha is one of India's poorest states (OPHI 2011) where 85% of households rely on solid fuels as their primary cooking fuel, compared to the national average of 67% (Census of India, 2011a and 2011b). As one alternative to biomass fuels, the Odisha Renewable Energy Development Agency (OREDA) facilitated the installation of over 200,000 household biogas plants at subsidized rates throughout rural Odisha to promote renewable energy production (OREDA 2013).

In response to recent calls for additional empirical and quantitative ICS adoption analyses (Lewis and Pattanayak 2012) and more studies of biogas plant use (Bond and Templeton 2011), we analyze household use of ICS using a broad panel of socio-demographic data and a novel set of biogas-plant specific variables including level of subsidy. This ex-post study adds to the limited literature on ICS adoption, biogas plant use, sustainability, and the impacts of ICS use on fuelwood consumption. To our knowledge, only two rigorous analyses of biogas adoption have been conducted, both in Africa (Mwirigi et al. 2009; Walekhwa et al. 2009); two studies have considered what factors are associated with continued functioning of biogas plants (Chand and Murthy 1988; Mwigiri et al. 2009); and a single study to date has quantified whether biogas ownership results in a decrease in fuelwood consumption (Xiaohua and Jingfei 2005). We contribute to this limited literature by conducting a set of analyses, detailed below, to understand household ownership of stoves, household use of stoves, and the impacts on fuelwood use.

To address the knowledge gaps described above, we conduct a set of empirical analyses to understand households' decisions to adopt ICS, where adoption is defined as ownership of a stove. First, to understand which households adopt ICS, we identify factors significantly associated with households that own any cleaner stove (biogas, LPG, kerosene or electric stove). Second, we analyze factors that are significantly associated with household ownership of a biogas plant. Third, within the subsample of our study households that have biogas plants, we examine which households are more likely to have plants that are functional versus non functional. Fourth, we analyze hours of stove use for biogas, improved stoves, and traditional stoves separately, because household ownership of stoves is not necessarily equivalent to use of the stove. Finally, we consider how the amount of firewood consumed differs based on stove ownership.

We find significant differences between households that own an ICS (more likely to have higher expenditures and education) compared with households that only own a traditional stove (more likely to have higher fuel expenditure and spend more time treating respiratory illness). Of households with biogas plants, those that received higher subsidies for plant construction, own more livestock and spend less time collecting wood are more likely to own a currently functional plant. Household reduction in fuelwood consumption is also associated with ownership of ICS including biogas stoves.

2. Background on Biogas Plants

2.1 Biogas technology

Biogas plants capture gas (methane and carbon dioxide) released from animal manure for use as a household fuel for cooking and lighting. In biogas plants common in Odisha, dung is inserted through an inlet into a sealed mixing pit, where biogas is generated through anaerobic digestion. The gas is collected in an outlet pipe above the tank and piped to the household where it is burned in a gas burning stove, identical to an LPG stove. After digestion, the slurry released from the plant is often used as an agricultural fertilizer. Buffalo and cow dung is readily available in rural India, providing many households with a steady and accessible supply of this fuel (Bond and Templeton 2011; ISAT/GTZ 1999a).

Stoves powered by biogas plants (biogas stoves) can deliver numerous benefits over traditional cooking practices: 1) mitigation of fecal-borne and parasitic diseases through the removal of openly defecated dung; 2) reduction in household air pollution; 3) fuel substitution for firewood, reducing fuel collection time and easing strain on local forests; 4) combustion of methane reducing methane emissions, eliminating this greenhouse gas that has a global warming potential over 20 times greater than CO2; 5) generation of fertilizer (biogas slurry) that is more potent and of higher quality than conventional fertilizer, which can lead to increased yields (Bond and Templeton 2011; Brown 2006; De Alwis 2002; Chen et al. 2010; ISAT/GTZ 1999c; Jian 2009; Van Dyne 1994). A cost-benefit analysis of biogas plants in Ethiopia recently confirmed positive net benefits to households (Gwavuya et al. 2012).

2.2 Challenges to biogas plant suitability

Recognizing these potential benefits, almost four million biogas plants have been constructed across India through the Indian National Biogas and Manure Management Program (NBMMP)from 1982 through 2007 (MNRE 2007), and there is potential for up to 12 million (Abraham et al. 2007). As with other ICS technologies, there is substantial heterogeneity in plant structure and quality (Bond and Templeton 2011). Biogas stoves can achieve around 50% efficiency (Itodo et al. 2007; ISAT/GTZ 1999b; Sasse et al. 1991).

Many operational and structural problems may lead to early malfunctions and abandonment of biogas plants, although technical studies report that the expected life cycle of well-built and maintained biogas plants is around 25 years (Sasseet al. 1991). Rates of functionality of biogas plants range between 40% to 100% in India (Bhat et al. 2001; Bond and Templeton 2011; Chand and Murthy 1988; Tomar 1995) and 60% in China (Chen et al. 2010).

Operational problems include “accumulation of water in the pipeline; scum formation in the digester; clogging of the inlet and outlet; leakage of gas from the gas holder, etc.” (Quadir et. al 1995, p.1130).Biogas plants have laborious operation and maintenance (Bond and Templeton 2010); households must regularly add dung and water in specified proportions and stir the slurry at regular intervals (de Alwis 2002). Limited understanding of proper use and maintenance, or the inability to diagnose or resolve reasons for failure are also barriers to plant sustainability (Alwis 2001; Limmeechokchai and Chawana 2007; Mwigiri et al. 2009; Tomar 1995).

Structural problems usually pertain to constructional defects, such as a crack in a fixed dome plant or break in the pipe carrying gas to the house which will allow all captured biogas to escape, rendering cooking with a biogas stove impossible. Although construction requires engineering skills, many plants do not have precise design specifications and defective plants can readily develop cracks (Quadir et al. 1995).Inadequate supply for spare parts can prevent the resolution of structural problems (Alwis 2001; Tomar 1995).

Although there are many benefits of biogas stoves, there are also several constraints that limit the adoption of this technology. Biogas plants are only an option for households with access to a sufficient quantity of dung. Generation of enough biogas to cook food exclusively with a biogas stove for a family of five requires about five cows (Bond and Templeton 2011; ISAT 1999b). Biogas plants have a high construction cost relative to household income(Bond and Templeton 2011) which can be prohibitive for many households (e.g., Limmeechokchai and Chawana 2007; Mwigiri et al. 2009).To address these barriers, successful biogas programs often include provision of repair and maintenance, subsidy or financing (Alwis 2001; Bhat et al. 2001).

2.3 Studies of biogas dissemination and adoption

Few studies have rigorously examined reasons for adoption of biogas plants in South Asia, although biogas plants were first introduced in India in the 1950s (ISAT/GTD 1999a). Existing literature from China, Kenya, India and Sri Lanka suggests that households that adopt are more likely to receive a subsidy, be in the general caste, and have higher income, more education, greater land ownership, and more cattle than households without biogas plants (Bhat et al. 2001;Chand and Murthy 1988; Jian 2009; Mwigiri et al. 2009). All of the studies from India focus on partially-subsidized biogas plants.

Only a few quantitative studies have examined factors related to biogas plants remaining functional: studies in India (Chand and Murthy 1988) and Kenya (Mwigiri et al. 2009) find no correlation between biogas plant sustainability and socioeconomic status. One study in China found a decrease in fuelwood use with biogas stove use (Xiaohua and Jingfei 2005).

Focus group discussions we conducted within our sample districts in Odisha identified several issues of specific concern regarding biogas adoption:

No guarantee of high quality construction of biogas plants and no maintenance provision lead to durability and repair issues.

Investment cost of the plants is high for the rural poor in Odisha, even after a partial subsidy from OREDA.

The amount of biogas required to allow households to use biogas stove for all meals is generally more than a small household level plant produces – therefore, households continue to use their traditional stoves concurrently with the biogas plant.

Dung is not a valueless commodity for these households; alternative uses include production of organic fertilizer for crops or dung patties that are burned in a traditional stove – these alternatives do not require the significant investment of building a biogas plant.

3. Sampling and Data Collection Methods

Data were collected from households in rural Odisha in 2011 and 2012.Households were selected from 8 districts in Odisha that received household biogas plants as part of a previous campaign by the Odisha Renewable Energy Development Agency (OREDA). All OREDA biogas plants were subsidized with subsidy levels ranging from 17-100%.

Focus groups and survey pretesting were done in June and July 2011 in four districts - Cuttack, Jharsuguda, Koraput, Bolangir. A pilot was conducted in August-September 2011. The final extensive panel survey was administered from November 2011 through February 2012in 503 households from 8 districts and 42 total villages: Angul (60 households), Cuttack (84), Jagatsingpur (60), Jajpur (48), Jharsuguda (96), Keonghar (60), Sambalpur (84), Sundargarh (11). These districts were selected to capture the geographical and cultural diversity of the state. In an attempt to separate the impact of outdoor air pollution from indoor, blocks (district subdivisions) were stratified by the presence of major industrial areas, as identified by the Odisha State Pollution Control Board (OSPCB 2011). To ensure that the survey villages contained households who received biogas plants, blocks that received the greatest number of subsidized biogas plants villages within these districts were selected.

Household sampling was stratified by type of stove. After initial focus group visits revealed that a large number of biogas plants were nonfunctional, the sample was deliberately designed to include households with functional and broken biogas plants, other forms of ICS, and traditional stoves, to facilitate analysis between households using different stove types. Within each village, approximately twelve households were selected by counting every fifth house starting in the village center to meet pre-determined stove ownership categories: 6 households with a biogas plant (3 households with a working plant, 3 households with a non functional plant), 3 households with an improved stove other than biogas (kerosene, LPG, electric, or rocket stove), and 3 households with only a traditional mud stove were selected. Whenever possible, the interview was conducted with the head of the household with input from the primary cook. The survey collected data on household cooking and fuel use behavior, demographics, socioeconomic characteristics, and consumption.

4. Descriptive Statistics

Most households selected in the study own multiple stoves, which is common in these villages. This supports the theory of fuel stacking (Masera et al. 2000). The majority of households own a traditional stove (94%; Table 1). Seventy-one percent own an improved cookstove – the most commonly owned ICS are biogas (46%), kerosene (21%) and LPG (19%). Due to the purposive sampling design explained above, these figures are not representative of the population at large.

Only 29% of sample households own a single stove; 55% own two stoves, and the remainder own three or more. Of households with only one stove, almost all have a traditional stove, with only 6% having only biogas and a single household owning only LPG. Among households using two stoves, traditional chulhas are widely used (95%), followed by biogas (63%), and LPG (19%). Even among households using three stoves, traditional chulhas form the majority (94%), followed by kerosene (74%) and biogas (56%). Over half of households with a biogas or LPG stove have two stoves. Eighty-eight percent of households with functional biogas plants and 82% of households using LPG also own a traditional stove, illustrating the importance of considering fuelwood consumption in households that own ICS.

Descriptive statistics for the entire sample are provided in Table 2. Average household size of the sample is five people. Seventeen percent of the households surveyed are in general / open castes (government assigned category for people in India who do not qualify for positive discrimination schemes), and 40% of all households are below the poverty line. Almost the entire sample is Hindu. Nine percent of households have a female head of household, and the survey respondent was female in about one-third of the surveys. The average age of the head of household was about 54 years old and averaged 7.7 years of school, while primary cooks are younger (36 years of age on average), but have about the same schooling (8.1 years). About one third of households reported taking a loan in the previous year.

Every household surveyed with a biogas plant received a subsidy from OREDA. The average biogas plant cost was about 7,000 rupees (115 USD); the average subsidy covered about 50% of the plant cost. The vast majority (91%) of households with biogas plants report that the amount of dung available to them and possible reduction in fuelwood needed (85%) were positive factors when making the decision to build the plant. Fifty-four percent of households responded that the cost of the subsidized biogas plant was a positive factor.

A majority of the households surveyed (67%) have both some form of traditional and improved stove. On average, households with traditional mud stoves use them for 2.71 hours per day (Table 5), kerosene pump stoves are used 1.24 hours per day, LPG stoves for 1.9 hours per day, and biogas stoves for 2.22 hours per day. Households with improved stoves use them on average about half an hour less than households use traditional stoves. On average, households cook a total of 3.88 hours per day.

The expected coefficient sign for the adoption of an improved stove is also given in Table 2. We anticipate that older household heads and primary cooks often do not fully understand the negative impacts of household air pollution from solid fuels, and therefore may be resistant to adoption of clean fuel technologies. Educated household heads and primary cooks are expected to be better informed of the impacts of biomass fuels, and more likely to choose cleaner fuels for their household. Households with female heads are expected to be more likely to invest in biogas plants, since cooks are female in most households and are more exposed to the adverse effects of household air pollution. Since biogas alone may be insufficient to meet the daily cooking requirements of large households, we hypothesize that households with more members may rely on traditional fuels or incorporate fuel stacking.

Household consumption of firewood, time spent collecting traditional fuel, and traditional fuel expenditure is likely to be greater in households that have not adopted an improved stove.

Households that perceive significant negative impacts from cookstove smoke on health are expected to be more likely to adopt ICS. Households in industrial areas are expected to be subject to outdoor and indoor air pollution, but may be more constrained by income and lack of education. We theorize that these households are unlikely to use clean fuels, including biogas.

4.1 Tests for differences in means

Households that own an improved stove are significantly different from households without an ICS in substantial and diverse ways, as shown with simple tests for differences in means (Table 4). On average, households with an improved stove are significantly more likely to be in the government-assigned general/open caste, above the poverty line, and have higher education than households with only traditional stoves. Households that own ICS have higher average income or wealth than households with only traditional stoves, as measured by a range of variables including: monthly expenditure, number of rooms in their houses, land ownership, ownership or usage of toilets rather than open defecation, ownership of livestock, and use of electricity as their main source of lighting. ICS households are more likely on average to take risks and find it easier to take a loan than households without ICS. ICS households also use significantly less firewood in a week than households with only traditional stoves.

Households with a working biogas plant are substantially different from households with a nonfunctional biogas plant, as found with tests for differences in means (Table 5). Households with working biogas plant have significantly greater monthly expenditures and years of education for the head of household than those with broken plants, on average. Higher spending capacity and educational resources within the family could lead to these households paying for plant repairs or better understanding of how to use the biogas plants. These households also report that it is significantly easier to take out a loan than households with nonfunctional plants,, and self-identify as significantly more likely to take risks.

As expected, households with working biogas plants spend significantly fewer hours per day on fuel collection and use significantly less firewood in one week than households with a broken biogas plant. Working biogas plant households have significantly more livestock.

The total plant cost, cost borne by households, and subsidy was significantly greater for households with working biogas plants than for households with currently nonfunctional plants. However, the percent of the total plant cost that was subsidized was not significantly different for households with working and nonfunctional plants.

5. Conceptual Framework

Households face complex barriers to adoption of improved cooking technologies (GACC 2011).Although recent studies of ICS adoption offer a ray of hope that market- and demand-based ICS distribution programs may be attractive to households (e.g., Levine and Cotterman, 2012), only a handful of studies have considered the factors influencing the adoption of biogas stoves and continued plant functionality.

We consider three different sets of dependent variables: 1) stove ownership, 2) hours of stove use and 3) firewood consumption. At least two specifications are run for each model. Robust standard errors were clustered at the village level.

For the first model on stove ownership, binary analyses are run using different dependent variables for households owning: 1) any improved stove, 2) biogas stoves, and 3) only biogas stoves that are currently functional. The simplest specification estimates the following equation to examine what factors are significantly associated with stove ownership:

$$\textit{Stove Choice} = \beta_0 + \beta_1 \textit{household demographic characteristics} + \beta_2 \textit{household socioeconomic characteristics} + \beta_3 \textit{household health} + \beta_4 \textit{fuel use characteristics} + \varepsilon \quad (1)$$

Household demographic characteristics include gender of the head of the household (*femalehead*), age of the head of household (*headage_HH*), and household size (*hhsize*). Household socioeconomic characteristics include caste (*caste_general*), monthly expenditure (*lnmonth_exp*), location in an industrial area (*Industrial*), number of rooms (*rooms*), ownership of land (*own_land*), ownership or use of a toilet (*toilet*), ease of access to a 5,000 rupee loan (*loan_access*), and reliance on electricity as main source of lighting (*electricity*). Household health is represented by the number of days household members spent in the hospital due to their last episode of ARI (*hospARI_HH*). Fuel use characteristics include daily expenditure on traditional fuels (tradfuelcost) and fuel collection hours per day (*fuelcoll_HH*).

A second specification adds additional demographic variables including education of the head of household (*headedu_HH*), gap in ages between head of household and primary cookas an indicator for intra-household bargaining power (*agegap*), household status below the poverty line (*BPL*), and religion (*hindu*). We also include an indicator for household belief that household air pollution leads to negative health affects (*IAP_effect*).Households were asked questions as part of a thought experiment to assess their patience and preference for risk-taking.

Finally, we asked all respondents to answer a series of hypothetical questions designed to elicit risk and time preferences. In the time preference module, respondents answered two questions providing a tradeoff between less money (1000 Rs. or roughly $20) received immediately (tomorrow) and more money (2000 Rs.) received later (after 12 months). For those selecting the former, the amount received later was increased, to 2500 Rs. and the question was repeated. For those selecting the latter, the amount received later was instead decreased to 1500 Rs. In the risk module, respondents were presented with pairs of tradeoffs between a certain amount of 500 Rs. and a 50-50 chance of lesser and greater amounts with expected values of 600 Rs. first, 750 Rs. for those choosing the certain amount in the first question, and 500 Rs. for those choosing the uncertain amount in the first question. Based on survey responses to these questions, dummy variableswere included for households that were most willing to wait for a larger payment in the future rather than a smaller immediate payment (*mostpatient*) and households that prefer the chance of receiving a larger payment rather than a smaller certain payment (*mostrisk*). An additional variable for household illness is added – the number of people in the household who have had malaria in the past three years (*malaria*). In addition to self-reported ease of obtaining a loan, whether the household has received a loan in the past year (*loan*) was included.

Several additional stove-specific variables were included in the regressions examining adoption of biogas: the amount of the government subsidy (*biogcost_subs*), the total cost of building the biogas plant (*biogcost*), and whether a reduction in wood was a reason considered when building the biogas plant (*bg_wood*).

We conduct robustness checks for consistency in regression results, with the inclusion and exclusion of household health variables. Village-level fixed effects are also included in one specification for each model.

Ownership of improved stoves does not necessarily correlate with use. Therefore, the second model considers hours of stove use, separately modeling use of improved stove, any traditional stove or biogas stoves, using the specifications detailed for the previous model.

Similarly, ownership of an improved stove should not be assumed to generate substantial fuelwood reductions because of nonuse, partial use, or incorrect use of the stove. Our final model analyzes the amount of fuelwood consumed by households using the previously detailed specifications as well as whether the household owns a traditional cookstove (*tradstove*).

6. Results and Discussion

We run a series of regressions to examine 1) stove choice; 2) stove use (as defined by hours of cookstove use); and 3) fuelwood consumption.

6.1 ICS adoption

Households that own any form of improved stove (71% of the sample) are compared with households that do not own an improved stove with logit regression (Table 6). Many improved stove households also own a traditional stove, as discussed above in detail. As expected, socioeconomic variables (monthly expenditure, number of rooms, land ownership, electricity as a main source of lighting, and toilet ownership/use) are significantly associated with household ownership of an improved cookstove. The results are significant when village-level fixed effects are included.

6.2 Biogas adoption and sustainability

Using logit regression, we compare households that have a biogas plant (46% of sample) with those that do not (Table 7). Households that own land, and have a greater number of rooms in their houses are more likely to have a biogas plant. Lower traditional fuel expenditure and ownership of more livestock that produce dung are significantly associated with ownership of biogas plants, signaling that dung production may be an important constraint. Lower overall monthly household expenditures is also significantly associated with biogas plants ownership, but this is likely driven by the inclusion of households with broken plants, since households with working plants have significantly greater expenditure than those with broken plants.

Of households with a biogas plant, we next analyzed the factors associated with plants that were currently functional at the time of the study (Table 8). Higher income, lower rates of malaria, less patient households, and lower likelihood of a female head of household are all significantly associated with household ownership of a working biogas plant. A lower rate of electricity use (as the main source of lighting) is significantly and negatively associated with ownership of a working biogas plant, perhaps suggesting that a broken plant is not worth fixing to households with greater access to electricity. Lower expenditure on fuel and less time gathering traditional fuels are both significantly associated with households' ownership of a functional biogas plant. As expected, ownership of more livestock that produces dung is also significantly associated with working biogas plants. Households that considered the reduction in fuelwood consumption when building a biogas plant were more likely to have a biogas plant that remained functional. The overall cost of the plant was not significantly associated with plants that remained functional when controlling for other household level variables. However, the level of subsidy was highly significant, suggesting that greater subsidies are highly correlated with continued function of the plant.

We test the robustness of these results by considering the impact of household health variables using three alternative model specifications on two stove choice variables, ICS ownership and biogas ownership: (1) including both *hospARI_HH* and *malaria_HH*, (2) including only *malaria_HH* and (3) excluding both *hospARI_HH* and *malaria_HH*.

The results from our robustness checks remain unchanged; we find the same sign and significance of coefficients as in the other models. Monthly expenditure, total number of rooms in the house, household's ownership of land, use of toilets, and uses of electricity have a significant positive association with ownership of an improved stove or biogas plant. There is no significant association between improved stove choice or biogas ownership and number of days spent in the hospital due to ARI or number of household members reporting malaria in the past 3 years. Similarly, results are unchanged with the inclusion of village-level fixed effects. The results from our alternative specifications indicate that our results are consistent, irrespective of inclusion or exclusion of household health variables.

6.3 Stove use

Since 71% of households own more than one stove, ownership of a stove does not provide adequate information about the relative magnitude of stove use. To address this, we next consider explanatory factors behind the amount of hourly stove use, conducting separate OLS regressions considering use of improved stoves, traditional stoves, and biogas stoves (Table 9). Logically, household size is significantly associated with a greater number of hours of stove use regardless of stove type. Household expenditure has a positive significant association with hours of clean stove use (and the converse for traditional stove use), and other socioeconomic indicators (ownership of land, use of electricity as the main source of lighting) are negatively associated with hours of traditional stove use. The number of hours per day collecting traditional fuel is positively associated with use of traditional stoves, as expected. The number of days spent in a hospital for respiratory illness has a significantly negative association with hours of clean fuel use.

6.4 Fuelwood consumption

Reduction in fuelwood used is one of the main driving reasons for promotion of ICS – however, there is limited evidence demonstrating that ICS are associated with a reduction in fuelwood (Lewis and Pattanayak 2012; Nepal et al., 2011). We model fuelwood consumption with OLS regression (Table 10). The first analysis includes ownership of a traditional stove as a covariate, and finds that household ownership of traditional stoves is strongly significantly associated with an increase of about 25 kilograms of fuelwood consumption per week compared to households without a traditional stove. A second model specification also finds this effect in households that own biogas stoves – those with a working biogas plant consume about 5 kilograms of firewood less per week than households with a nonfunctional plant. As expected, both fuel expenditure and time spent collecting fuel are significantly correlated with firewood consumption.

Households' general caste status, and ownership or use of a toilet is significantly associated with higher fuelwood consumption. Total household expenditure is not significantly associated with fuelwood consumption, which may be because fuel consumption levels do not depend strongly on income. This relationship indicates that energy poverty is a problem for this population – households with the means to use cleaner fuels may not have the ability to do so (Pachauri et al. 2004). There is no significant relationship between days spent in a hospital for ARI and firewood consumption.

7. Conclusions

This research adds to the limited evidence base of rigorous household ICS adoption and use studies. Our analysis indicates that greater fuel expenditure and time spent in the hospital for respiratory disease are significantly associated with traditional stove use, while socioeconomic factors are significantly related with adoption of improved stoves.

There are high rates of biogas plants facing structural and operational problems in India. Our analysis of the factors associated with continued functionality of biogas plants finds that households with greater spending capacity and more biogas-producing livestock are more likely to own biogas plants that still work. Households that spent less time gathering and money purchasing traditional fuels, and those that received a greater subsidy during plant construction were significantly more likely to own working biogas plants. The latter suggests that the subsidy may indicate a higher plant quality or greater government oversight. Village location in an industrial area and access to loan facilities were not significantly associated with stove ownership.

Reduced fuelwood consumption is significantly associated with ICS ownership. Similarly, households with working biogas plants use significantly less fuelwood than households with biogas plants that are no longer functional – this suggests that although stove stacking may occur in households with biogas plants, some replacement occurs as well.

Our analysis suggests that biogas plants have the potential to reduce firewood use, time spent gathering fuel, and respiratory disease caused by household air pollution. Future policies encouraging the construction and maintenance of biogas plants have the potential to provide tremendous health and environmental gains.

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Tables

Table 1: Stove ownership

Stove type	All households (n=503)		Households using number of stoves					
			1 Stove (n=145)		2 stoves (n=279)		3 Stoves (n=62)	
Traditional Chulha	94%	(0.23)	94%	(0.24)	95%	(0.23)	94%	(0.25)
Biogas	46%	(0.5)	6%	(0.23)	63%	(0.48)	56%	(0.5)
Kerosene	21%	(0.41)	0%	(0)	15%	(0.36)	74%	(0.44)
LPG	19%	(0.4)	1%	(0.08)	19%	(0.39)	47%	(0.5)
Electric	8%	(0.27)	0%	(0)	5%	(0.22)	23%	(0.42)
Coal	3%	(0.17)	0%	(0)	3%	(0.16)	6%	(0.25)
Cast Iron Stove	0%	(0.06)	0%	(0)	0%	(0.06)	0%	(0)
Any Improved Cookstove	71%	(0.45)						
Any Improved Cookstove (other than Biogas)	37%	(0.48)						
Any Traditional Stove (Chulha, Coal, or Cast Iron)	94%	(0.23)						
*Seventeen households have more than 3 stoves.								

Table 2: Descriptive statistics

Description	N	Mean (s.d.)		Expected Coeff. sign with ICS adoption
Log of total monthly expenditure	503	8.13	(0.7)	+
Household is located in an Industrial Area	503	38%	(0.49)	+
# rooms in house	503	4.04	(1.69)	+
Household uses a community, neighbor's, or private toilet	503	31%	(0.46)	+
Household reports it is easy to borrow 5000Rs from lender or microfinance group for 1 month	503	30%	(0.46)	+
Household has taken a loan in the past year	503	33%	(0.47)	+
Household size (# people)	503	4.98	(1.71)	-
Survey Respondent was female	503	30%	(0.46)	-
Household has female head of household	502	10%	(0.3)	-
Age of Household Head (years)	502	53.7	(13.78)	-
Age of Primary Cook (years)	501	35.84	(10.4)	-
Age Difference (Household Head - Primary Cook; years)	500	17.78	(15.75)	-
Education of Household Head (years)	415	7.73	(3.68)	+
Education of Primary Cook (years)	435	8.09	(3.6)	+
Education Difference (Household Head - Primary Cook; years)	374	-0.28	(4)	-
Household is in open / general caste	503	17%	(0.38)	+
Household is Below Poverty Line	503	40%	(0.49)	-
Household is Hindu	503	98%	(0.15)	+
Daily expenditure on traditional fuel (Rs)	503	2.94	(4.22)	-
Fuel collection hours per day for household	503	1.84	(2.79)	-
Household perception of how smoke from cooking impacts health; scale 1 (low impact) to 5 (high impact)	503	2.19	(0.88)	+
Households take the most risks in time / risk game	497	16%	(0.36)	+
# days household members spent in hospital due to last ARI episode	503	0.79	(2.17)	-
# household members report malaria in past 3 yrs	503	0.56	(1.13)	-
Household owns land	503	88%	(0.33)	+
Electricity is main source of lighting	503	86%	(0.34)	+
# buffalo and milk cows (> 1yr old) household owns	503	1.21	(1.75)	+
Firewood consumed (kg) in past week	503	30.5	(15.88)	+
Household received subsidy to build biogas plant	253	100%	(0)	+
Total cost of building biogas plant (Rs.)	241	7020	(2522)	-
Household expenditure on biogas plant (Rs.)	239	3506	(1752)	-
Subsidy received for biogas plant (Rs.)	229	3730	(1444)	+
Percent of biogas plant cost that was subsidy	229	52%	(0.14)	+
Reduction in wood needed for traditional stoves was a positive factor during biogas construction decision	253	85%	(0.36)	+
Availability of dung was a positive factor during biogas construction decision	253	91% (0.29)		+
Cost of plant was a positive factor during biogas construction decision	253	54% (0.5)		+

Table 3: Hours of stove use

Stove type	Obs	Hrs of use per day: mean (S.D.)
Traditional Mud Chulha	445	2.71 (1.28)
Cast Iron	1	1
Coal	14	1.62 (1.12)
Kerosene- Pump	60	1.24 (0.91)
Kerosene – Wick	5	1.80 (1.1)
LPG	83	1.90 (0.79)
Electric	32	1.32 (0.84)
Biogas	199	2.22 (0.86)
Total for any Improved Cookstove	319	2.27 (1.02)
Total for any Traditional Stove (Chulha, Coal, or Cast Iron)	446	2.75 (1.28)
Total for all stoves	503	3.88 (1.31)

Table 4: Tests of difference in means by stove type

Variable	Obs		Mean		T-test	
	ICS	No ICS	ICS	No ICS	T-test	p>|t|
Log of total monthly expenditure	359	144	8.3	7.9	5.91	0.00
Household is located in an Industrial Area	359	144	36%	42%	-1.08	0.28
# rooms in house	359	144	4.3	3.	5.83	0.00
Household uses a community, neighbor's, or private toilet (not necessarily exclusive)	359	144	40%	10%	6.64	0.00
Household reports it is easy to borrow 5000Rs from lender or microfinance group for 1 month	359	144	35%	19%	3.53	0.00
Household has taken a loan in the past year	359	144	34%	31%	0.65	0.52
Household size (# people)	359	144	5.0	4.9	0.78	0.43
Survey Respondent was female	359	144	29%	33%	-0.81	0.42
Household has female head of household	359	143	11%	8%	0.74	0.46
Age of Household Head (years)	359	143	54.0	52.8	0.85	0.40
Age of Primary Cook (years)	357	144	36.1	35.3	0.74	0.46
Age Difference (Household Head - Primary Cook; years)	357	143	17.9	17.6	0.18	0.86
Education of Household Head (years)	309	106	8.2	6.4	4.5	0.00
Education of Primary Cook (years)	320	115	8.5	7.0	3.69	0.00
Household is in open / general caste	359	144	19%	11%	2.27	0.02
Household is Below Poverty Line	359	144	35%	51%	-3.2	0.00
Household is Hindu	359	144	99%	95%	2.61	0.01
Daily expenditure on traditional fuel (Rs)	359	144	2.8	3.2	-0.82	0.41
Fuel collection hours per day for household	359	144	1.7	2.1	-1.29	0.20
Household perception of how smoke from cooking impacts health; scale 1 (low impact) to 5 (high impact)	359	144	2.2	2.1	1.13	0.26
Households most patient in time / payment game	353	143	16%	12%	1.13	0.26
Households take the most risks in time / risk game	354	143	18%	10%	2.31	0.02
# days household members spent in hospital due to last ARI episode	359	144	0.87	0.59	1.33	0.18
# household members report malaria in past 3 yrs	359	144	55%	56%	-0.07	0.94
Household owns land	359	144	92%	78%	4.35	0.00
Electricity is main source of lighting	359	144	92%	72%	6.32	0.00
# buffalo and milk cows (> 1yr old) household owns	359	144	1.4	0.71	4.14	0.00
Firewood consumed (kg) in past week	359	144	29.1	33.9	-3.11	0.00

Table 5: Tests of differences in means by biogas functionality

Variable	Obs		Mean		T-test	
	Biogas working	Biogas not working	Biogas working	Biogas not working	T-test	p>|t|
Log of total monthly expenditure	133	120	8.16	7.99	2.3	0.02
Household is located in an Industrial Area	133	120	0.39	0.33	0.95	0.34
# rooms in house	133	120	4.21	4.33	-0.57	0.57
Household uses a community, neighbor's, or private toilet (not necessarily exclusive)	133	120	0.31	0.38	-1.25	0.21
Household reports it is easy to borrow 5000Rs from lender or microfinance group for 1 month	133	120	0.35	0.25	1.79	0.08
Household has taken a loan in the past year	133	120	0.32	0.30	0.27	0.79
Household size (# people)	133	120	5.09	5.05	0.18	0.86
Survey Respondent was female	133	120	0.34	0.25	1.54	0.13
Household has female head of household	133	120	0.07	0.13	-1.56	0.12
Age of Household Head (years)	133	120	52.38	55.16	-1.61	0.11
Age of Primary Cook (years)	132	119	34.87	36.37	-1.15	0.25
Age Difference (Household Head - Primary Cook; years)	132	119	17.40	18.58	-0.57	0.57
Education of Household Head (years)	112	104	8.42	7.62	1.75	0.08
Education of Primary Cook (years)	116	106	8.29	7.95	0.7	0.49
Household is in open / general caste	133	120	0.20	0.18	0.42	0.68
Household is Below Poverty Line	133	120	0.40	0.36	0.66	0.51
Household is Hindu	133	120	0.97	0.98	-0.24	0.81
Daily expenditure on traditional fuel (Rs)	133	120	1.70	2.22	-1.17	0.25
Fuel collection hours per day for household	133	120	1.51	2.14	-1.75	0.08
Household perception of how smoke from cooking impacts health; scale 1 (low impact) to 5 (high impact)	133	120	2.17	2.22	-0.41	0.68
Households most patient in time / payment game	131	118	0.11	0.09	0.36	0.72
Households take the most risks in time / risk game	131	118	0.15	0.07	2.13	0.03
# days household members spent in hospital due to last ARI episode	133	120	0.89	0.67	0.77	0.44
# household members report malaria in past 3 yrs	133	120	0.58	0.68	-0.63	0.53
Household owns land	133	120	0.92	0.95	-0.82	0.41
Electricity is main source of lighting	133	120	0.86	0.93	-1.55	0.12
# buffalo and milk cows (> 1yr old) household owns	133	120	2.14	1.36	2.96	0.00
Firewood consumed (kg) in past week	133	120	26.61	31.93	-2.53	0.01
Household received subsidy to build biogas plant	133	120	1.00	1.00		
Total cost of building biogas plant (Rs.)	129	120	7514	6451	3.33	0.00
Household expenditure on biogas plant (Rs.)	129	112	3690	3289	1.77	0.08
Subsidy received for biogas plant (Rs.)	123	110	40.11	34.03	3.24	0.00
Percent of biogas plant cost that was subsidy	123	106	0.52	0.52	0.32	0.75
Reduction in wood needed for traditional stoves was a positive factor during biogas construction decision	133	106	0.92	0.77	3.59	0.00
Availability of dung was a positive factor during biogas construction decision	133	120	0.91	0.90	0.26	0.79
Cost of plant was a positive factor during biogas construction decision	133	120	0.50	0.59	-1.52	0.13

Table 6: Logit regressions on stove ownership

	ICS ownership		
Variables	(1)	(2)	(3)1
Log of total monthly expenditure	0.76*** (0.21)	0.71*** (0.23)	0.69** (0.33)
Household is located in an Industrial Area	0.12 (0.24)	0.44 (0.28)	
Number of total rooms	0.27*** (0.09)	0.32*** (0.09)	0.20* (0.11)
Household owns land	0.86*** (0.26)	0.55 (0.37)	0.34 (0.53)
Household uses a community, neighbor's, or private toilet (not nec. exclusive)	0.91** (0.37)	0.93** (0.39)	1.10*** (0.41)
Main source of lighting in household is electricity	0.95** (0.39)	0.70* (0.40)	1.52*** (0.59)
HH says easy to borrow 5000Rs from lender or microfinance group for 1 month	-0.09 (0.27)	-0.40 (0.29)	-0.32 (0.38)
Household size	-0.11 (0.07)	-0.17 (0.11)	-0.05 (0.11)
Household has female head of household	0.56** (0.28)	0.81 (0.62)	0.94 (0.76)
Age of Household Head	-0.01 (0.01)	-0.01 (0.01)	-0.00 (0.01)
Household is in open/general caste	0.29 (0.33)	0.43 (0.46)	0.69 (0.47)
Daily expenditure on traditional fuel (Rs)	-0.02 (0.03)	0.00 (0.04)	0.00 (0.04)
Fuel collection hours per day for entire household	-0.03 (0.05)	-0.06 (0.06)	-0.11* (0.06)
Number of days household members spent in hospital due to last ARI episode2	-0.01 (0.06)	-0.05 (0.09)	-0.11 (0.09)
How badly does smoke from cooking impact health; scale 1 to 5		-0.05 (0.19)	-0.00 (0.19)
Most patient household		-0.70 (0.51)	-0.70 (0.59)
Most risk-taking household		0.91* (0.50)	0.97 (0.72)
Household has taken a loan in the past year		-0.30 (0.28)	-0.26 (0.35)
Survey Respondent was female		-0.68** (0.29)	-0.68** (0.34)
Number of household members reporting malaria in past 3 yrs		0.20 (0.14)	0.19 (0.16)
Number of years of education of household head		0.09 (0.06)	0.12** (0.05)
Household is below poverty line		-0.14 (0.31)	0.02 (0.33)
Household is Hindu		0.75** (0.38)	13.78 (1,098.77)
Constant	-6.87*** (1.71)	-7.08*** (1.71)	
Observations	502	406	370
Pseudo R-squared	0.172	0.200	0.274
Number of villages			37

Robust standard errors in parentheses, clustered by village

*** p<0.01, ** p<0.05, * p<0.1

[1] Fixed effects logit model at the village level

[2] Logit regressions on ownership of traditional stoves showed a significant relationship with the number of days household members spent in the hospital due to the last ARI episode.

Table 7: Logit regressions on ownership of all biogas plants

	Biogas ownership1			
Variables	**(1)**	**(2)**	**(3)**	**(4) 2**
Log of total monthly expenditure	-0.42**	-0.44**	-0.46**	-0.40*
	(0.18)	(0.20)	(0.22)	(0.23)
Household is located in an Industrial Area	0.03	0.31	0.09	
	(0.16)	(0.19)	(0.25)	
Number of rooms in house	0.13*	0.13*	0.07	0.00
	(0.08)	(0.07)	(0.07)	(0.09)
Household owns land	1.14***	0.92**	0.59	0.30
	(0.35)	(0.44)	(0.43)	(0.47)
Household uses a community, neighbor's, or private toilet (not nec. exclusive)	0.27	0.25	0.20	0.13
	(0.28)	(0.31)	(0.34)	(0.32)
Main source of lighting in household is electricity	0.36	0.28	0.39	0.69
	(0.38)	(0.39)	(0.36)	(0.51)
HH says easy to borrow 5000Rs from lender or microfinance group for 1 month	-0.12	-0.22	-0.06	0.11
	(0.21)	(0.24)	(0.27)	(0.30)
Household size	0.11*	0.05	-0.04	-0.03
	(0.07)	(0.07)	(0.07)	(0.09)
Household has female head of household	-0.04	-0.09	0.21	0.37
	(0.32)	(0.50)	(0.54)	(0.51)
Age of Household Head	-0.01	-0.00	0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)
Household is in open/general caste	0.01	0.20	0.07	0.22
	(0.26)	(0.33)	(0.34)	(0.38)
Daily expenditure on traditional fuel (Rs)	-0.12***	-0.10***	-0.08***	-0.09***
	(0.03)	(0.03)	(0.03)	(0.03)
Fuel collection hours per day for entire household	-0.02	-0.02	0.02	-0.01
	(0.04)	(0.05)	(0.05)	(0.05)
Number of days household members spent in hospital due to last ARI episode	0.05	0.04	0.06	0.07
	(0.04)	(0.05)	(0.05)	(0.07)
How badly does smoke from cooking impact health; scale 1 to 5		-0.17	-0.11	-0.05
		(0.12)	(0.13)	(0.16)
Households most patient in time / payment game		-0.62	-0.40	-0.25
		(0.42)	(0.42)	(0.45)
Households take the most risks in time / risk game		-0.16	-0.27	-0.41
		(0.29)	(0.31)	(0.45)
Household has taken a loan in the past year		-0.28	-0.58**	-0.65**
		(0.23)	(0.28)	(0.30)
Survey respondent was female		-0.37	-0.29	-0.33
		(0.23)	(0.22)	(0.28)
Number of household members reporting malaria in past 3 yrs		0.12	0.13	0.10
		(0.11)	(0.11)	(0.13)
Number of years of education of household head		0.05	0.04	0.04
		(0.03)	(0.03)	(0.04)
Household is below poverty line		0.05	0.05	0.03
		(0.26)	(0.27)	(0.29)
Household is Hindu		0.50	0.89**	13.10
		(0.45)	(0.45)	(732.71)
Number of milk buffalo and milk cows (> 1yr old) household owns			0.65***	0.69***
			(0.12)	(0.12)
Log of total monthly expenditure	-0.42**	-0.44**	-0.46**	-0.40*
	(0.18)	(0.20)	(0.22)	(0.23)
Constant	1.53	1.55	1.27	
	(1.37)	(1.53)	(1.67)	
Observations	253	201	241	229
Pseudo R-squared	0.0934	0.135	0.143	0.170
Number of villages				42

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
[1] Households owning a biogas plant are compared to those without a biogas plant. 2 Model includes fixed effects at village level.whwth sdfsd

Table 8: Logit regression on ownership of only working biogas plants

	Biogas (currently working) ownership[1]						
Variables	**(1)**	**(2)**	**(3)**	**(4)[2]**	**(5)**	**(6)**	**(7)[2]**
Log of total monthly expenditure	0.85** (0.35)	0.70* (0.37)	0.72** (0.36)	0.20 (0.55)	0.61* (0.33)	0.75** (0.33)	0.99** (0.44)
Household is located in an Industrial Area	0.09 (0.26)	-0.20 (0.38)	-0.35 (0.40)		-0.06 (0.27)	-0.16 (0.29)	
Number of rooms in house	-0.11 (0.12)	-0.23* (0.13)	-0.24* (0.14)	-0.27* (0.16)	-0.11 (0.11)	-0.10 (0.12)	-0.23* (0.13)
Household owns land	-0.15 (0.51)	-0.20 (0.54)	-0.29 (0.58)	-0.18 (1.08)	-0.11 (0.43)	-0.26 (0.47)	0.05 (0.76)
Household uses a community, neighbor's, or private toilet (not nec. exclusive)	-0.57* (0.30)	-0.46 (0.35)	-0.55 (0.36)	-0.32 (0.64)	-0.37 (0.31)	-0.17 (0.32)	-0.00 (0.50)
Main source of lighting in household is electricity	-1.28*** (0.45)	-1.04 (0.81)	-0.89 (0.83)	0.01 (1.03)	-1.41*** (0.54)	-1.52** (0.68)	-0.88 (0.84)
HH says easy to borrow 5000Rs from lender or microfinance group for 1 month	0.57 (0.38)	0.76 (0.51)	0.89* (0.52)	1.25** (0.59)	0.52 (0.41)	0.46 (0.44)	1.00** (0.48)
Household size	0.06 (0.09)	0.21 (0.14)	0.18 (0.14)	0.30* (0.17)	0.00 (0.09)	0.03 (0.11)	0.05 (0.12)
Household has female head of household	-0.84* (0.51)			-24.43 (60,057.5)	-0.62 (0.56)	-0.78 (0.53)	-0.77 (0.58)
Age of Household Head	-0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)	-0.02 (0.02)	-0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)
Household is in open/general caste	0.01 (0.46)	0.18 (0.54)	0.02 (0.53)	-0.13 (0.65)	0.04 (0.46)	0.21 (0.50)	-0.29 (0.58)
Daily expenditure on traditional fuel (Rs)	-0.05* (0.03)	-0.08** (0.04)	-0.07* (0.04)	-0.18** (0.08)	-0.02 (0.03)	-0.01 (0.04)	-0.05 (0.06)
Fuel collection hours per day for entire household	-0.14*** (0.06)	-0.18** (0.09)	-0.16* (0.09)	-0.27** (0.13)	-0.12** (0.05)	-0.15*** (0.05)	-0.20** (0.08)
Number of days household members spent in hospital due to last ARI episode	0.04 (0.12)	0.10 (0.15)	0.10 (0.16)	0.10 (0.11)	0.04 (0.12)	0.04 (0.12)	0.07 (0.08)
How badly does smoke from cooking impact health; scale 1 to 5		-0.10 (0.26)	-0.06 (0.26)	0.21 (0.29)			
Households most patient in time / payment game		-1.07 (0.67)	-0.98 (0.73)	0.21 (0.85)			
Households take the most risks in time / risk game		2.08*** (0.64)	2.06*** (0.67)	2.91*** (1.08)			
Household has taken a loan in the past year		-0.11 (0.28)	-0.19 (0.30)	0.02 (0.50)			
Survey Respondent was female		0.15 (0.27)	0.19 (0.27)	-0.11 (0.53)			
# of household members reporting malaria in past 3 yrs		-0.35* (0.18)	-0.37* (0.20)	-0.70** (0.32)			
Number of years of education of household head		0.02 (0.05)	0.02 (0.05)	0.04 (0.08)			
Household is below poverty line		0.34 (0.40)	0.43 (0.40)	0.37 (0.53)			
Household is Hindu		-0.41 (0.86)	-0.59 (0.89)	22.52 (162,496)			
# buffalo and milk cows (> 1yr old) household owns			0.18** (0.09)	0.22* (0.13)	0.17** (0.08)	0.17** (0.08)	0.21* (0.11)
Total cost of building biogas plant (Rs.)					0.00 (0.00)		
Reduction in wood needed for trade. stoves was a positive factor during biogas construction decision					1.15** (0.48)	1.50*** (0.55)	1.80*** (0.63)
Subsidy received for biogas plant (Rs.)						0.00*** (0.00)	0.00 (0.00)
Constant	-4.29* (2.50)	-2.84 (2.59)	-3.12 (2.62)		-4.41* (2.44)	-6.04** (2.42)	
Observations	253	201	201	180	241	229	203
Pseudo R-squared	0.0934	0.135	0.149	0.356	0.143	0.170	0.243
Number of villages				34			35

Robust standard errors in parentheses, clustered by village

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

[1] Households owning a working biogas plant are compared to those owning a nonfunctional biogas plant.
[2] Model includes fixed effects at village level.

Table 9: OLS regression of hours of stove use

	Traditional stove			Improved stove			Biogas stove		
Variables	(1)	(2)	(3)[1]	(1)	(2)	(3)[1]	(1)	(2)	(3)[1]
Log of total monthly expenditure	-0.53***	-0.47***	-0.53***	0.27***	0.35***	0.40***	0.10	0.10	-0.11
	(0.10)	(0.10)	(0.13)	(0.09)	(0.11)	(0.12)	(0.12)	(0.15)	(0.15)
Household is located in an Industrial Area	0.01	0.03		-0.00	0.00		-0.02	0.09	
	(0.14)	(0.19)		(0.10)	(0.12)		(0.15)	(0.14)	
Number of rooms in house	-0.05	-0.05	-0.05	0.03	-0.01	-0.05	-0.02	-0.01	0.03
	(0.04)	(0.05)	(0.05)	(0.04)	(0.05)	(0.05)	(0.04)	(0.04)	(0.05)
Household owns land	-0.27*	-0.27	-0.14	0.15	0.26	0.33	-0.29	-0.18	-0.07
	(0.14)	(0.21)	(0.25)	(0.23)	(0.29)	(0.25)	(0.31)	(0.36)	(0.33)
Household uses a community, neighbor's, or private toilet (not nec. exclusive)	0.02	-0.05	-0.20	0.19	0.19	0.20	0.07	0.06	0.18
	(0.17)	(0.19)	(0.18)	(0.16)	(0.16)	(0.17)	(0.16)	(0.17)	(0.20)
Main source of lighting in household is electricity	-0.28*	-0.19	-0.24	0.08	-0.26	-0.48	0.08	-0.10	-0.27
	(0.16)	(0.19)	(0.26)	(0.19)	(0.32)	(0.37)	(0.20)	(0.26)	(0.36)
HH says easy to borrow 5000Rs from lender or microfinance group for 1 month	-0.24	-0.13	-0.04	0.05	0.07	0.13	0.04	0.03	-0.21
	(0.14)	(0.17)	(0.17)	(0.15)	(0.19)	(0.16)	(0.17)	(0.19)	(0.18)
Household size	0.23***	0.18***	0.18***	0.07	0.11*	0.11**	0.11***	0.10***	0.08
	(0.05)	(0.05)	(0.05)	(0.05)	(0.06)	(0.05)	(0.04)	(0.04)	(0.05)
Household has female head of household	0.08	0.06	0.07	-0.03	0.02	-0.23	-0.18	-0.74**	-0.45
	(0.19)	(0.28)	(0.30)	(0.19)	(0.25)	(0.31)	(0.28)	(0.32)	(0.39)
Age of Household Head	0.00	0.00	0.00	-0.01	-0.00	0.00	-0.01	-0.00	-0.00
	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Household is in open/general caste	0.08	0.07	-0.02	-0.07	-0.19	-0.50**	-0.19	-0.16	-0.43*
	(0.17)	(0.20)	(0.22)	(0.15)	(0.19)	(0.20)	(0.14)	(0.16)	(0.23)
Daily expenditure on traditional fuel (Rs)	0.00	0.00	0.01	-0.03	-0.01	-0.02	-0.03	-0.02	-0.01
	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Fuel collection hours per day for entire household	0.04*	0.06**	0.05*	-0.02	-0.03	-0.04	-0.03	-0.02	0.01
	(0.02)	(0.03)	(0.03)	(0.02)	(0.03)	(0.03)	(0.02)	(0.03)	(0.04)
Number of days household members spent in hospital due to last ARI episode	0.02	0.05	0.05	-0.04	-0.09**	-0.11**	0.01	-0.01	0.02
	(0.03)	(0.03)	(0.04)	(0.03)	(0.04)	(0.05)	(0.03)	(0.05)	(0.06)
How badly does smoke from cooking impact health; scale 1 to 5		0.06	0.04		0.11	0.09		0.05	0.04
		(0.10)	(0.09)		(0.08)	(0.09)		(0.08)	(0.10)
Households most patient in time/payment game		0.22	0.15		-0.29	-0.24		-0.11	-0.12
		(0.29)	(0.23)		(0.22)	(0.22)		(0.21)	(0.27)
Households take the most risks in time/risk game		-0.39*	-0.35		0.11	0.13		-0.10	-0.05
		(0.21)	(0.24)		(0.21)	(0.21)		(0.20)	(0.25)
Househld has taken a loan in the past year		-0.03	-0.09		-0.02	-0.03		0.15	0.25
		(0.15)	(0.16)		(0.16)	(0.16)		(0.16)	(0.17)
Survey Respondent was female		0.08	-0.04		-0.05	0.04		-0.09	0.08
		(0.13)	(0.16)		(0.10)	(0.16)		(0.13)	(0.17)
Number of household members reporting malaria in past 3 yrs		-0.06	-0.04		-0.12**	-0.04		-0.16***	-0.12
		(0.07)	(0.07)		(0.06)	(0.07)		(0.06)	(0.09)
Number of years of education of household head		-0.03	-0.03		0.04**	0.03		0.01	-0.00
		(0.02)	(0.02)		(0.02)	(0.02)		(0.02)	(0.02)
Household is below poverty line		0.09	0.01		0.14	-0.09		0.40***	0.36**
		(0.14)	(0.16)		(0.13)	(0.17)		(0.14)	(0.18)
Household is Hindu		0.01	-1.04		0.96**	1.53		0.93***	1.00
		(0.22)	(1.31)		(0.38)	(1.26)		(0.30)	(1.03)
Constant	6.42***	6.02***	7.75***	-0.24	-2.44**	-2.89*	1.60	0.31	1.98
	(0.84)	(0.86)	(1.65)	(0.81)	(0.95)	(1.60)	(0.96)	(1.15)	(1.59)
Observations	445	354	354	319	269	269	199	167	167
R-squared	0.18	0.19	0.32	0.09	0.18	0.32	0.09	0.22	0.50

Robust standard errors in parentheses, clustered by village

*** p<0.01, ** p<0.05, * p<0.1

[1] Fixed effects at village level

Table 10: OLS regression of firewood consumption (kg) per week

	Firewood consumption		
Variables	**(1)**	**(2)**	**(3)**[1]
Household has traditional stove - chulha, cast iron biomass, or coal	25.55***		
	(2.08)		
Log of total monthly expenditure	0.22	-1.15	-5.12**
	(0.92)	(1.79)	(2.25)
Household is located in an Industrial Area	-0.80	-0.42	
	(1.54)	(1.92)	
Number of rooms in house	0.76*	1.09	1.01
	(0.42)	(0.75)	(0.76)
Household owns land	-0.35	1.62	0.06
	(1.84)	(3.03)	(4.48)
Household uses a community, neighbor's, or private toilet (not nec. exclusive)	-3.09*	-7.92***	-3.53
	(1.80)	(2.82)	(2.90)
Main source of lighting in household is electricity	-0.16	0.51	6.80
	(1.38)	(2.37)	(4.99)
HH says easy to borrow 5000Rs from lender or microfinance group for 1 month	0.55	2.85	3.70
	(1.12)	(2.15)	(2.54)
Household size	0.61	0.72	0.57
	(0.41)	(0.58)	(0.74)
Household has female head of household	-0.97	-1.02	-3.29
	(1.99)	(3.03)	(3.52)
Age of Household Head	0.06	0.02	0.02
	(0.05)	(0.09)	(0.08)
Household is in open/general caste	-3.15*	-4.44	0.60
	(1.63)	(2.95)	(3.26)
Daily expenditure on traditional fuel (Rs)	0.48***	1.23***	1.15***
	(0.16)	(0.39)	(0.32)
Fuel collection hours per day for entire household	0.82***	0.98**	0.60
	(0.25)	(0.38)	(0.42)
Number of days household members spent in hospital due to last ARI episode	0.10	0.22	-0.17
	(0.22)	(0.31)	(0.51)
Household biogas plant is working		-4.52*	-4.66**
		(2.65)	(2.21)
Constant	-5.56	28.06**	55.90***
	(7.86)	(13.83)	(17.70)
Observations	502	253	253
R-squared	0.27	0.23	0.41
Robust standard errors in parentheses, clustered by village			

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

[1] Fixed effects at village level

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