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A Bridge to Clean Cooking? The Cost-Effectiveness of Energy-Efficient Biomass Stoves in Rural Senegal

Abstract

Rural areas of sub-Saharan Africa have experienced limited progress towards the sustainable development goal of universal access to clean cooking. Energy-efficient biomass cookstoves (EEBCs) are considered a potential bridge technology, but EEBC models vary widely, and there is a lack of understanding about their real-world use implications. We conduct a randomized controlled trial in rural Senegal to compare a low-cost, locally produced stove designed to achieve fuel savings and an expensive, imported stove shown to be more efficient and emissions-reducing in the laboratory. We find that the two EEBCs perform similarly: both reduce fuel consumption but have no significant impact on cooking time and fuel collection, emissions, or objective health measures. We conclude that the technically advanced option is not cost effective for most of our sample, while the low-cost EEBC can be seen as a stop-gap solution that primarily reduces fuel use. The findings underpin the importance of customizing EEBC dissemination to local context and baseline cooking patterns.

JEL-Code: C93, D12, O12, O13, Q51, Q53

Keywords: Cookstoves; energy access; biomass burning; energy efficiency; technology choice

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1. Introduction

Traditional cooking with solid fuels remains widespread in much of rural sub-Saharan Africa. Despite considerable efforts by governments and international development partners, limited progress has been made in the region towards the cooking energy-related dimensions of Sustainable Development Goal 7, which aim for universal access to clean cooking fuels such as electricity and liquefied petroleum gas (LPG) (Stoner et al. 2021; Rose et al. 2022).

Energy-efficient biomass cookstoves (EEBCs) are therefore promoted as intermediate technologies that would alleviate the environmental, socio-economic and health burdens of traditional cooking (Köhlin et al. 2011; Shindell et al. 2012; Bailis et al. 2015). While EEBCs are not emissions-free, they are typically much less expensive to use than clean-fuel stoves and do not require reliable new fuel delivery infrastructure. Overall, EEBCs are expected to reduce biomass consumption and, thus, the time or money spent on fuel collection, but mostly not to produce health improvements (Bensch and Peters 2015; Hanna et al. 2016; Mortimer et al. 2017). Yet, prices and efficiency levels vary substantively across a wide range of EEBC technologies promoted in the Global South. In addition to technical differences, the impacts of such improved stoves critically depend on, first, the extent by which they are used alongside polluting stoves, known as fuel or stove stacking (Ruiz-Mercado and Masera 2015; Muller and Yan 2018), and second, on how well these new technologies are adapted to local cooking behaviours and practises (Yu 2011; Langbein et al. 2017; Bensch and Peters 2020). Accordingly, the relative merits, and costs and benefits, of various stove options remain poorly understood (Jeuland et al. 2018).

This paper examines the impacts of two differentiated types of EEBCs, comparing a low-cost locally produced stove designed to achieve fuel savings with a more advanced, but more expensive, imported stove that is expected to also substantially reduce health-harming emissions. We implement a randomized controlled trial (RCT) among 525 households living in 15 rural Senegalese villages. Both EEBCs were provided free of charge to 175 household each, with a third group serving as controls. Key outcomes measured ten months after stove dissemination are fuel consumption, time use, and health effects, as well as key intermediate outcomes such as airborne particulate matter ($PM_{2.5}$) emissions and exposures. To further our understanding of the impacts, we make use of time-series emissions data, evaluate treatment effects among those adopting the EEBCs ('treatment on the treated'), and assess heterogeneity by baseline ventilation levels. We then perform a cost-benefit analysis that compares the two stove options. In the study locations in rural Senegal, challenges related to inefficient cooking are particularly severe. In 2021, 94 percent of the rural population relied on solid cooking fuels (primarily fuelwood) burned in inefficient, traditional stoves (IEA et al. 2023).

We find that the two EEBCs perform similarly. About 70 percent of the treated households adopt the EEBCs, and fully or partially replace their cooking on open fires – more so for the simple EEBCs. We also observe a diversification of household fuel use and a reduction in fuel consumption for both stove types, which varies by region, highlighting the importance of careful targeting in EEBC programs. Cooking and fuel collection times, and emissions, are unaffected, as are objective health measures, though there are modest effects on self-reported proxy measures of respiratory distress or thoracic pressures.

Understanding the null effects on most downstream outcomes is highly relevant for current developments in the health and environmental policy scene. The total cost of our small-scale intervention – including logistics – is USD 39 and USD 105 per household for the two types of EEBC, respectively. In the present study setup, the cost-effectiveness of the technically more advanced option thus appears to be low, as the stove did not deliver on the expected reductions in $PM_{2.5}$ emissions despite its higher cost. The low-cost EEBC produced results that are consistent with previous findings, and its cost effectiveness ultimately depends on the value placed on its local production and reduced fuelwood use, which is substantial relative to traditional cooking. This stove appears to be a viable bridging technology given the extreme fuel scarcity in semi-arid regions such as northern and central Senegal. In the medium term, however, such entry-level improved stoves will need to be replaced by fully clean technologies, if a wider range of benefits (including pollution reduction and health, in particular) are to be realised.

2. The intervention stoves

The two biomass stoves studied in this paper are the Jambar and the Zama (Table 1). The Jambar stove is a simple biomass stove designed primarily to reduce fuel consumption. It consists of a fired clay liner that is bound to a metal casing using a mixture of cement and ash. Owing to simple design improvements over traditional stoves, the wood fuel burns more efficiently, and the heat is better conserved and transferred to the cooking pot. The Jambar is locally produced and can be found in other African countries, mostly under the name Jiko (see e.g. Jetter et al. 2012). In urban Senegal, more than one million charcoal Jambars have been disseminated, primarily by the programme *Foyers Améliorés au Senegal*, making it one of the most widely adopted EEBCs in sub-Saharan Africa. The firewood version of the Jambar is sold for about USD 13 in urban Senegal, but has only achieved limited reach in rural areas, where cooking with firewood in three-stone open fires is much more prevalent.

The Zama stove is manufactured in South Africa and retailed for USD 73 at the time of the study. It is a more complex, sophisticated stove that can be fed with both firewood and charcoal and that aims to reduce both fuel consumption and smoke emissions. The Zama is a rocket stove made of heat-resistant stainless steel with a vertical air duct and an insulating heat shield. At the time of the study in 2018 and 2019, the Zama was not available in Senegal. Growing interest in the cookstove sector has also led to further recent advances beyond the Zama's rocket stove technology in terms of design, materials and fuels, including forced-air stoves with small fans that reduce fuel consumption and emissions (Yunusa et al. 2023).

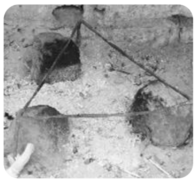
Before assessing the performance of the two stoves in the field, we tested them against a three-stone fire in a controlled laboratory environment.[1] We followed protocols of the International Workshop Agreement (IWA) to determine stove efficiency – measured as the fraction of heat that is transferred to a pot of water – and carbon monoxide and $PM_{2.5}$ emissions for a simulated cooking process. $PM_{2.5}$ is fine particulate matter of less than 2.5 micrometres in diameter; this by-product of combustion may cause health damages given its low likelihood of getting filtered by the upper respiratory tract, and hence, its ability to penetrate deep into small body airways, lungs, and bloodstreams (Pope and Dockery 2006). Carbon monoxide and $PM_{2.5}$ are the main pollutants of concern for human health from incomplete combustion of biomass fuels (WHO 2008).

Results of these tests allow categorisation into IWA performance levels, ranging from 0 to 5 (ISO 2018). The EEBCs showed higher efficiencies than an open fire, though both are classified into efficiency tier level 2. The results furthermore suggest a reduction in emissions only when

[1] Related stove tests were carried out by García López (2017) who conducted a lab test study with the Zama Zama, the predecessor version of the Zama, and by Wathore et al. (2017) who performed in-field emission tests with the Zama stove in rural Malawi. Zhang and Adams (2015) reported on a pilot study with the Zama Zama but did not present any findings on stove adoption or performance.

cooking with the Zama (Tier 2 to 5). From these laboratory results, relative to three stone fires, we would expect a moderate reduction in wood consumption, of a similar magnitude for both treatment stoves, and for the Zama, a sizable reduction in emissions, especially of $PM_{2.5}$.

Table 1: Stove characteristics and performance

		Energy-efficient biomass cookstoves		**Traditional stove**
Metric	**Unit**	Jambar	Zama	Three-stone Fire
				
Material	-	metal, clay inlay	stainless steel	stones
Fuel type	-	wood	wood, charcoal	wood
Approximate price	USD	13 (urban Senegal)	70 (South Africa)	0
Approximate lifetime‡	Years	2	2	-
ISO efficiency and emission metrics	*(Tier 0-5)*			
Thermal efficiency	%	27.09 *(2)*	28.68 *(2)*	20.00 *(2)*
Emissions: carbon monoxide	g/MJ delivered	11.81 *(1)*	7.65 *(2)*	11.77 *(1)*
Emissions: $PM_{2.5}$	mg/MJ delivered	1288.19 *(0)*	54.27 *(5)*	1527.79 *(0)*

Note: MJ refers to megajoules, the standard measurement unit of energy. Efficiency and emission values are averages of three tests for the Three Stone Fire and the Jambar and of five tests for the Zama stove. ‡ See CCA (2020)

3. Methods

3.1. Identification strategy

To assess the impacts of these EEBCs, our empirical analysis uses data from a randomized controlled trial (RCT) implemented at the household level, with two treatment arms and a control group.[2] Since we are interested in the impacts of making the stoves available to households, we analyse the intent-to-treat (ITT) impacts that assess impacts on treatment households irrespective of treatment uptake. We thus estimate the following Ordinary Least Squares (OLS) regression:

$$Y_{ijt=2} = \beta_0 + \beta_1 EEBC\_a_{ij} + \beta_2 EEBC\_b_{ij} + \mathbf{X}'_{ijt=0}\beta_3 + \gamma_j + \epsilon_{ij} \quad [1].$$

[2] We opted for randomization at household instead of village level given the costly measurements conducted that resulted in a moderate sample size and number of clusters. A key concern with this approach is the potential for spillovers between treatment and control households. We expected such spillovers to be modest for most of the stove impact dimensions and for the bias – if any – to be downwards.

This equation determines the impact of receiving the advanced Zama EEBC, $EEBC\_a$, or the basic Jambar EEBC, $EEBC\_b$, on the endline ($t = 2$) level of the outcome indicator for household i from community j, $Y_{ijt=2}$. Primary outcome variables presented in the results section were defined in the pre-analysis plan of this study (Peters and Jeuland 2017).[3] The key impact estimates are the coefficients β_1 and β_2. γ_j represents a vector of village fixed effects, and ϵ_{ij} the unobserved household-specific residual. As an additional precaution to protect against confounding, and to enhance precision of the estimates, we include $\mathbf{X}'_{ijt=0}$, a vector of baseline household demographics and socio-economic variables, such as participants' educational attainment, household size and assets. For health outcomes, $\mathbf{X}'_{ijt=0}$ additionally includes a set of health-related variables, namely ventilation conditions in the household, the number of cooks in the household, whether the household has health insurance, and whether the participant has red eyes sometimes or more often as a health status proxy.

We also conduct several pre-specified robustness tests. First, to test the consequentiality of the set of controls, we estimate equation [1] without $\mathbf{X}'_{ijt=0}$. Second, we test the robustness of results from the above equation by estimating a standard difference-in-differences (DiD) model to control for time-invariant unobserved differences between groups. Third, we use data from a midline survey shortly after the treatment ($t = 1$) to extend the DiD estimation equation and thereby to assess how quickly the uptake of the treatment stoves unfolded. Fourth, we test for heterogeneity in health outcomes across low- and high-ventilation strata, i.e. among more and less pollution-exposed households as identified by baseline ventilation conditions.[4] For that purpose, we additionally include a dummy for high cooking ventilation status, $H_{ijt=0}$, and an interaction term with this dummy: $\beta_4 H_{ijt=0} + \beta_5(H_{ijt=0} \times EEBC\_a_{ij}) + \beta_6(H_{ijt=0} \times EEBC\_b_{ij})$.

[3] In comparison to the pre-analysis plan, we reduced the set of primary outcome variables in two ways: first, we focus on objective measures where we initially proposed objective and subjective measures for the same indicator, namely firewood use and stove use duration. Second, in the self-reported variables, we focus on primary cooks and abstain from looking at household members aged below 10 or above 59 years. Also note that we followed the pre-analysis plan in the procedure to deal with the few cases of missing covariate information following Lin et al. (2016), recoding the missing values to the village means, but abstained from imputing missing values for dependent variables.

[4] Baseline data for seven variables was used to determine whether a household was above or below median kitchen ventilation as generated using Principal Component Analysis (see, e.g., Filmer and Pritchett 2001): kitchen volume, kitchen openings, cooking location, the number of primary cooks, the number of stoves used for cooking, daily cooking time, and main fuel type.

Lastly, we use two-stage least squares Instrumental Variable (IV) estimations instead of OLS to explore impacts on stove-adopting households only. Here, the random assignment into the treatment group is used as an instrument for use of the EEBCs – more specifically, a variable indicating whether the EEBC was used during the day of measurement.

3.2. Data

The household data used in our estimation framework were collected in 15 rural Senegalese villages during surveys conducted between early 2018 and early 2019. The study sample covered two regions in northern and central Senegal, Saint-Louis and Kaffrine, which are characterized by typical Sahelian vegetation and scarce firewood. Villages in these regions were eligible if they complied with two inclusion criteria. First, village population was within the range of 600 to 1,600, which is typical of rural communities in the region, and second, they had not previously seen significant EEBC promotion, ensuring low initial penetration of improved biomass cooking technologies. Thirty-five households per community were randomly sampled from household lists. With 15 communities, this yielded a sample of 525 households evenly distributed across the two treatment arms and one control arm, in line with power calculations carried out during the preparatory phase of the study (Peters and Jeuland 2017).

To answer our research questions, we exploit a range of objective and self-reported measures obtained from surveys and other field measurements. The design of all instruments was informed by intensive interaction with local sector experts and focus group discussions in the field prior to data collection. Beyond demographic and socio-economic survey measures, the survey elicited multiple outcome measures. For fuel use, we asked households to set aside slightly more than a day's worth of fuel during the first survey day, and weighed this fuel stock using weighing scales. Households were asked to consume only from this measured stock; we then re-weighed any remaining fuel 24 hours later. Stove use was recorded using Stove Use Monitors (SUMs) and we developed an algorithm that identifies the start (and end) of a cooking event on the basis of positive (negative) temperature changes occurring over short monitoring periods. Both these measures were also elicited using detailed self-reporting. Objective health measures were taken from households' primary cooks by certified nurses – these included oxygen saturation and blood pressure measurements as well as dried blood spots. Lastly, measures of particulate matter ($PM_{2.5}$) concentrations in kitchens and exposure of households' primary cooks during 24 hours were taken using state-of-the-art measurement devices.[5]

Data collection started with two rounds of baseline surveys, deployed between March and May 2018, during the dry season in Senegal. We invited households' primary cooks to participate in the interview if they were above age 15; in case this individual was unavailable, a secondary cook was enrolled instead. The assigned EEBCs were next provided free of charge to treatment households, shortly after baseline data collection, whereas control group households received a wax printed textile. The field team explained that the EEBCs and wax prints were compensations for survey participation, and that the nature of the gift had been determined randomly. The primary cooks furthermore received a short introduction to the EEBCs and their usage. Ethical approval for all study components was obtained from Duke University's Institutional Review Board.

In September 2018, a midline survey was conducted to elicit key information on fuelwood consumption and cooking practices in the rainy season, and this was followed by an intensive endline survey in March and April 2019 that repeated all measures obtained at baseline. A total of 518 households were interviewed during both baseline and endline. Of the seven attritor households at endline, four belonged to the Jambar treatment group and three to the Zama group. In all cases, the reason for attrition was absence of household cooks during the survey visit. In addition, not all stove use and particulate matter measurements could be retaken at endline given technical malfunctions of some SUMs and emission measurement devices (this is not uncommon in similar studies, for example, see Bluffstone et al. 2020). Similarly, the intended protocol for objective fuel use measurement could not be followed with all households, since households did not always have fuel at home. Dropout analyses show that the data loss in the particulate matter measurements is partly correlated with household characteristics, which makes controlling for household characteristics in the robustness analyses particularly important.[6]

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[5] For budgetary reasons, emission and exposure data was collected only from subsamples of our study sample. We applied stratified random sampling to maintain representativeness in the subsamples selected for these measurements, using the same categorization into low and high levels of baseline ventilation as for the heterogeneity analyses described in Section 3.1. See Lenz et al. (2023) for details on data collection of emission and exposure data.

[6] Dropouts occured also for SUM-based indicators, as we considered only those households for whom data could be retrieved for all SUMs installed in the respective household.

4. Results

4.1. Descriptive statistics and balancing

The 15 sampled communities are medium-sized villages with about 200 households each. All villages had a primary school, and roughly a third had a secondary school. Eight of the villages had access to grid electricity and another village had a mini-grid fed by a diesel generator at the time of the survey. Table 2 presents baseline household data. We show those variables selected as control variables, the $\mathbf{X}'_{ijt=0}$ introduced in equation [1] above. The first three columns include mean values for the three randomized groups – Control, Jambar, and Zama. Column (4) provides test statistics on the joint significance of the randomized group variable coefficients using ANOVA. This test indicates whether our randomization process was successful in creating balanced groups in terms of socio-economic characteristics.

Table 2: Baseline sample characteristics

	Baseline mean			Control vs. Jambar vs. Zama *p-value*
	Control	Jambar	Zama	
	(1)	(2)	(3)	(4)
Household characteristics				
Participant is homemaker	0.53	0.54	0.52	0.88
Participant is literate	0.21	0.19	0.19	0.90
Female head of household	0.11	0.07	0.09	0.36
Household size	12.21	11.67	11.87	0.72
	(7.10)	(5.82)	(5.82)	
Household has a private tap	0.64	0.71	0.69	0.32
Household has electricity	0.58	0.58	0.58	1.00
Normalized wealth index§	-0.06	0.06	0.00	0.51
	(1.01)	(0.99)	(1.01)	
Share of cooking on open fire in 24h measurement	0.79	0.76	0.78	0.75
	(0.38)	(0.42)	(0.40)	
Monthly cooking fuel expenditures (USD)	9.13	10.91	10.38	0.34
	(11.39)	(11.42)	(11.84)	
Health-related characteristics				
High-ventilation PC stratum	0.47	0.51	0.51	0.73
	(0.50)	(0.50)	(0.50)	
Number of cooks	1.17	1.15	1.17	0.86
	(0.45)	(0.52)	(0.45)	
Household with health insurance	0.32	0.37	0.33	0.53
Participant has red eyes at least sometimes	0.23	0.24	0.25	0.94
Number of observations	175	171	172	518

Note: Standard deviation in brackets. *p*-values refer to *F*-tests on the joint significance of the randomized group variable coefficients in an ANOVA with the respective pre-survey characteristic on the left-hand-side. § The wealth index is a single index constructed based on different wealth indicators such as land holding and device and livestock ownership calculated with Principal Component (PC) Analysis (see, e.g., Filmer and Pritchett 2001).

Households in this rural Senegalese sample are relatively large, with an average of 12 household members. Almost 80 percent of meals were cooked on open fires at baseline. The RCT created balanced and comparable groups, as none of the variables shows significant differences – a conclusion that also holds when running separate pairwise *t*-tests for each of the pairs of randomized groups. Relevant heterogeneity can be observed within the sampled groups, notably between households from the northern and central region. For example, the use of Liquefied Petroleum Gas (LPG), the predominant modern cooking fuel in the sample, is entirely driven by households from the northern region: here, the baseline share of modern fuel use is 39 percent, whereas it is zero percent in the central region (see also Table A1 in Appendix). Even though the majority of households have electricity access, electricity is not used for cooking in our study population, which is in line with evidence from other African countries (Rahut et al. 2017).

4.2. Stove use

The use of the disseminated EEBCs is a key intermediate outcome in the causal chain leading to downstream intervention impacts. Table 3 shows estimates of equation [1], i.e. the impacts of having received a Jambar or Zama ten months earlier, both at the extensive and intensive margin of stove use. Treatment stove adoption is lower for the advanced Zama EBBC (58 percentage points) than for the simpler Jambar EEBC (69 percentage points), a difference that is statistically significant (see *p*-value Jambar = Zama at the bottom of the table rejecting equality of the mean coefficients). These impact estimates imply that about a fourth of households did not fully adopt the new stoves, given that ten percent of households owned EEBCs at baseline. Treatment stoves mainly crowd out the use of open fire stoves, which decreases by 35 percentage points. The other two stove types, basic metal stoves and modern stoves (primarily LPG), are typically used to prepare hot drinks only, mainly tea and coffee. Treatment did not significantly alter the use of either of these two stove types at the extensive margin.

We assess the intensive margin through stove use monitor (SUM) data for a 24-hour period. According to this monitoring, the time of open fire stove usage declined by about 1.3 hours per day on average, while EEBC usage increased by double this amount (+ 2.9 hrs. for the Jambar and +2.4 hrs. for the Zama), to become the dominant stove type among treatment households. The usage intensity of basic metal stoves decreased in treatment households as well, but this effect corresponds to a relatively scant reduction of about 20 minutes per day.

The total usage duration of all stoves increased in the treatment group by about 0.8 hrs, an increase that is statistically significant only for the households who received the Zama. While treatment households may have opted for splitting their meal preparation over multiple stoves for convenience, this increase may also be indicative of a partial rebound: households with more efficient EEBCs may decide to cook more, rather than simply substituting cooking preparations one for one.

Table 3: Stove use impacts

	Stove use for food preparation on day preceding the interview				24-hour usage duration (hours)				
	open fire	basic metal stove	EEBC	modern stove	open fire	basic metal stove	EEBC	modern stove	total
Treatment Jambar	-0.35*** (0.06)	-0.08 (0.06)	0.69*** (0.06)	0.02 (0.02)	-1.41*** (0.36)	-0.45** (0.21)	2.86*** (0.40)	-0.21 (0.25)	0.80 (0.49)
Treatment Zama	-0.34*** (0.07)	-0.07 (0.05)	0.58*** (0.07)	0.04 (0.03)	-1.13*** (0.33)	-0.36* (0.19)	2.42*** (0.32)	-0.06 (0.16)	0.85* (0.45)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control group mean	0.77	0.18	0.08	0.09	3.67	0.68	0.20	0.63	5.21
p-value Jambar = Zama	0.91	0.91	0.02	0.28	0.42	0.47	0.41	0.60	0.93
R-squared	0.33	0.07	0.42	0.29	0.26	0.11	0.23	0.13	0.11
Number of observations	518	518	518	518	460	460	460	460	460

Note: Standard errors clustered at the village level in brackets. *** p<0.01, ** p<0.05, * p<0.1.

We take a closer look at potential rebound and downstream impact channels in Table 4. Regarding rebound, the results indicate that households did not increase the number of meals or hot drinks prepared. It was already common at baseline for this population to cook more than two full meals. It is therefore not surprising that the more efficient stoves did not induce a significant increase in the quantity of food prepared, and this is also in line with previous findings from Bensch and Peters (2015). The table furthermore reports on stove stacking, i.e. the contemporaneous use of different stove types. Households may benefit from having an additional stove in that they can cook multiple dishes at the same time, which may affect cooking duration and time use in general. In addition, stove stacking may affect smoke exposure, limiting emission reductions, if households use treatment stoves in tandem with more polluting stoves rather than simply replacing them. We see that the use of multiple stoves for a single meal increased with Jambar households, whereas stove type stacking over a day increased significantly for both treatment groups. Hence, the new EEBCs did not completely replace previously used stove types. We acknowledge that the higher efficiency of the EEBCs may have induced households who had partially transitioned to cleaner LPG stoves to revert back to biomass stoves. The treatment effect on the indicator for whether households used a wood-burning stove for meal preparation during the prior 24-hour measurement period is close to zero for both EEBC stove groups, however, suggesting that this channel does not play a major role in this setting. This is also supported by data on the intensive margin of stove use presented in Table 3 above.

Results on stove use impacts are not qualitatively different when we exclude controls or estimate impacts in a DiD setup; similarly, midline results do not differ from endline results. Thus, it appears that the EEBCs were used to a similar extent four and ten months after distribution, that is, during the rainy and dry season (see Table B1 and Table B2 in Appendix).

Table 4: Impacts on stove use patterns

	Meals prepared per day	Hot drinks prepared per day	Stove type stacking		Any wood stove used for meal preparation over 24-hour measurement period
			per meal cooking event	over 24-hour measurement period	
Treatment Jambar	0.01	-0.05	0.12*	0.25***	0.00
	(0.12)	(0.08)	(0.07)	(0.07)	(0.05)
Treatment Zama	-0.07	-0.06	-0.02	0.21***	-0.05
	(0.10)	(0.07)	(0.05)	(0.07)	(0.05)
Controls	Yes	Yes	Yes	Yes	Yes
Control group mean	2.66	0.65	0.12	0.18	0.87
p-value Jambar = Zama	0.56	0.89	0.02	0.42	0.32
R-squared	0.10	0.09	0.03	0.07	0.34
Number of observations	507	513	507	513	513

Note: Standard errors clustered at the village level in brackets. *** p<0.01, ** p<0.05, * p<0.1.

In Table 5, we take a closer look at self-reported EEBC adoption. Presence of the EEBCs at the time of endline data collection and the main perceived advantages of the treatment stoves are very similar across the two EEBC types. Other perceived advantages such as the safety of the stove are mentioned by at most six percent of households. We also see strong regional differences in the level of EEBC adoption. As supported by complementary econometric analyses, these differences are driven by the socio-economic status of households in the two regions and, relatedly, by baseline clean cooking diffusion, which is considerably higher in the northern study region. On the right of Table 5, we summarize self-reported reasons for infrequent EEBC use, acknowledging that sub-sample sizes are relatively low. The main reason is inconvenience of fuel use. More than half of the households naming this reason were primary or exclusive users of modern LPG stoves, but convenience of solid fuel loading is also mentioned. Some households prefer to cook with charcoal or do not want to cook with a biomass EEBC, partly because access to wood is difficult in some areas or because the EEBC requires chopped wood. In a few cases, the Zama stove also appears to be preferred for its ability to use charcoal, but only for irregular occasions like gatherings.

Table 5: Treatment stove adoption

	Jambar *mean*	Zama *mean*
Still in the household	0.96	0.98
Perceived advantages of EEBC[#]		
amount of fuel needed	0.67	0.60
smoke emitted by stove	0.53	0.58
cooking time	0.53	0.55
Infrequent EEBC use[‡]	0.16	0.18
in northern study region	0.24	0.26
in central study region	0.06	0.08
Number of observations	171	172

	Jambar *mean*	Zama *mean*
Reason for infrequent use [‡]		
fuel inconvenience	0.41	0.52
[main stove type is modern]	[0.22]	[0.29]
other stove characteristics (size, cooking duration)	0.22	0.16
don't know how to use	0.00	0.10
cooking person absent or ill	0.11	0.03
sold or given away	0.19	0.00
stove broken	0.07	0.19
Number of observations	27	31

Note: All figures refer to endline data; [#] two answers possible; [‡] infrequent use refers to treatment households not using the EEBC in the week before survey.

4.3. Fuel consumption

We next examine firewood consumption, at both the extensive and intensive margin. Table 6 shows that significantly fewer Jambar households used firewood exclusively at endline relative to control households, rather stacking it alongside other fuels. Importantly, the share of treated households using modern fuels exclusively did not decrease. This confirms the lack of crowding out of modern fuels by the EEBCs. Households instead seem to slightly diversify their household fuel use after the introduction of the EEBC. In terms of quantity consumed, we find that the average amount of wood used per 24 hours decreased by about 15 percent to around 9 kg for both stove types (Table 6). Instrumental Variable (IV) regressions, which approximate the effect on treatment households who actually use the randomized EEBC, suggest a treatment effect on the treated of around 25 percent, with a slightly higher estimate for the Zama stove. Exploring the fuel consumption data further by adding interactions with the two regions in our estimations, we see that Jambar savings are more precisely estimated for the central region, whereas the data for the Zama stove suggests that effects are negligible in the central region and clearly stronger in the North, the region where cleaner cooking is more commonplace. These findings confirm our expectations for fuel consumption savings based on the laboratory tests presented in Section 2, and they are further corroborated by the robustness checks presented in Table B3 in the Appendix. Nonetheless, they hint at considerable treatment heterogeneity according to baseline fuel use patterns, qualifying the previous findings by Bensch and Peters (2015) that were obtained from a more homogeneous sample from a neighbouring region in central Senegal.

Table 6: Fuel use impacts

	24-hour fuel use			24-hour wood consumption (kg)		Self-reported daily charcoal consumption‡ (kg)
	wood only	charcoal only	modern fuel only			
	OLS	OLS	OLS	OLS	IV	OLS
Treatment Jambar	-0.10**	-0.03	0.00	-1.71*	-2.22**	-0.31
	(0.05)	(0.02)	(0.02)	(0.90)	(1.12)	(0.54)
Treatment Zama	-0.06	-0.03	0.01	-1.75*	-2.73**	0.11
	(0.06)	(0.02)	(0.02)	(0.87)	(1.33)	(0.58)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Control group mean	0.52	0.04	0.03	10.97	10.97	1.62
p-value Jambar = Zama	0.42	0.95	0.76	0.96	0.69	0.49
R-squared	0.33	0.04	0.26	0.24	0.22	0.04
First-stage *F*-Stat	–	–	–	–	73.1	–
Number of observations	518	518	518	439	439	497

Note: Standard errors clustered at the village level in brackets. ‡ Too few measurements could be conducted for charcoal, which is why the charcoal consumption figure refers to self-reported consumption. ** p<0.05, * p<0.1 abbreviate statistical significance.

4.4. Time use

Fuel consumption effects may translate to lower fuel collection requirements, though there are also substantial fixed time costs of firewood collection (see, for example, Bošković et al. 2023). Cooking time is another time-use impact dimension, which tends to be less impacted by the adoption of EEBCs than fuel collection (Krishnapriya et al. 2021).

We do not find consistent time use impacts in this study, in either the main analyses, the IV regressions, or the robustness checks presented in Table B4 in the Appendix.[7] This is in spite

[7] Along with the null effect on fuel collection, we do not find effects on the additionally pre-specified indicator of money spent on fuel.

of the fuel consumption impacts and the fact that around half the treatment households perceive shorter cooking time as an advantage of the new EEBC. The lack of significant results may indicate that fixed costs of fuel collection dominate, but may also be due to insufficient statistical power for these relatively noisy indicators, or imperfect measures of time use.

Table 7: Time use impacts

	Household collects firewood	Weekly time spent on firewood collection (min)		Self-reported daily time to cook food		
				total time (min)		total time staying adjacent to stove (min)
	OLS	OLS	IV	OLS	IV	OLS
Treatment Jambar	-0.01	-8.12	-11.57	-2.50	-3.35	0.51
	(0.06)	(10.92)	(14.31)	(7.78)	(10.01)	(4.79)
Treatment Zama	-0.04	12.25	18.89	-2.41	-3.62	6.42
	(0.05)	(11.50)	(16.33)	(7.69)	(11.15)	(7.27)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Control group mean	0.70	122.66	122.66	279.17	279.17	188.09
p-value Jambar = Zama	0.47	0.05	0.03	0.99	0.99	0.52
R-squared	0.27	0.24	0.22	0.10	0.10	0.00
First-stage *F*-Stat	–	–	83.5	–	83.4	–
Number of observations	518	518	518	517	517	517

Note: Standard errors clustered at the village level in brackets. *** p<0.01, ** p<0.05, * p<0.1.

4.5. Smoke emissions and exposure

Apart from fuel efficiency, biomass-dependent households value reduced smoke as the main benefit of improved cookstoves (Jeuland et al. 2015; Talevi et al. 2022). In Table 8, we show two indicators for $PM_{2.5}$ kitchen concentration (KC) and primary cooks' personal exposure (PE) to $PM_{2.5}$, namely mean pollution levels measured over the 24-hour observation period, and peak pollution levels. The latter are measured at the 95th cumulative percentile $PM_{2.5}$ levels, which means that this value is exceeded during 5% of the monitoring day, equal to the 1.2 hours with the highest exposure. Emission and exposure levels are extremely high, clearly exceeding concentration levels considered as safe by the WHO. Mean personal exposure in our sample is more than 20 times higher than the WHO guideline value for mean annual concentration of 5 $\mu g/m^3$ (WHO 2021). This provides further field evidence on the high pollution levels faced almost exclusively by female cooks (Abera et al. 2021).

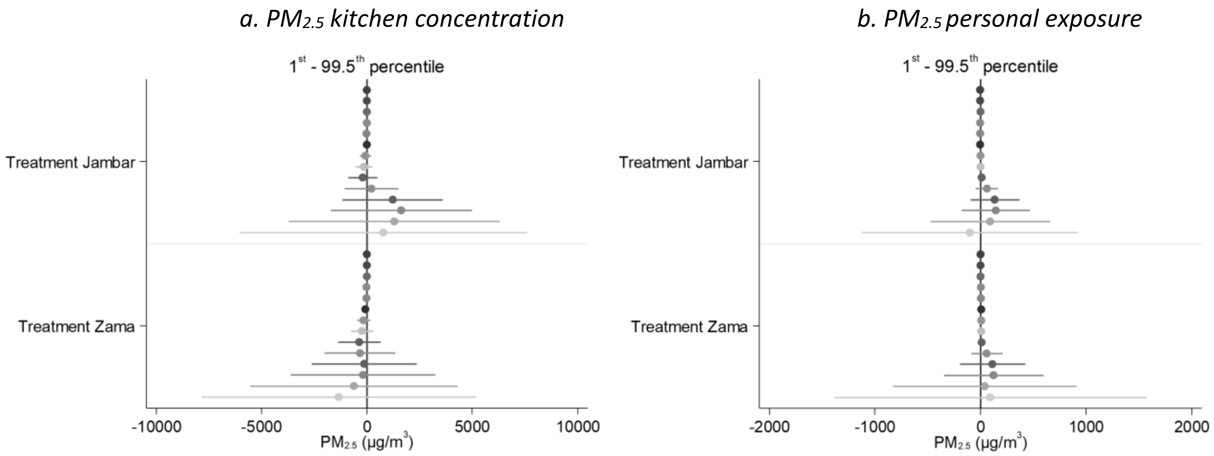
The table shows no impact from the disseminated stoves. We find sizable, but imprecisely estimated point estimates for the kitchen concentration indicator among the treatment households with the advanced stove, the Zama. This might be interpreted as tentative evidence of emission reductions that cannot be identified due to insufficient sample size. At the same time, we see that the estimates for the more critical personal exposure indicators are much smaller. These discrepancies are most likely driven by cooking behaviour that leads to avoidance of smoke exposure; indeed, Lenz et al. (2023) find tentative supporting evidence of this in their examination of proxies for cooking behaviour. More generally, other studies such as Hanna et al. (2016) and Mortimer et al. (2017) have shown that technical cleanliness does not necessarily imply cleanliness under regular household use.

Table 8: Impacts on smoke emissions and exposure

	$PM_{2.5}$ kitchen concentration (log, µg/m^3)		$PM_{2.5}$ personal exposure (log, µg/m^3)	
	24-hour mean	95th percentile	24-hour mean	95th percentile
Treatment Jambar	0.04	0.06	-0.04	0.08
	(0.34)	(0.39)	(0.10)	(0.12)
Treatment Zama	-0.14	-0.29	0.01	0.06
	(0.27)	(0.50)	(0.12)	(0.16)
Controls	Yes	Yes	Yes	Yes
Control group mean	398	2064	119	298
p-value Jambar = Zama	0.61	0.48	0.73	0.94
R-squared	0.23	0.27	0.14	0.12
Number of observations	93	74	179	173

Note: Standard errors clustered at the village level in brackets. See also the robustness checks presented in Table B5 in the Appendix. *** p<0.01, ** p<0.05, * p<0.1.

Figure 1: Impacts on smoke emissions and exposure by percentiles



Note: Graphs show coefficients and their 95% confidence intervals retrieved from our default OLS regression for the following percentiles, from top to bottom: P1, P10, P25, P40, P60, P75, P80, P84, P90, P95, P97, P98, P99, and P99.5.

Figure 1 underpins that pollution levels are not differentiated relative to the control group, even when looking at other percentiles. We only see non-zero (but partly positive and always insignificant) estimates for very high percentiles of 95 and above at the lower part of the graphs, which reflect peak concentrations of a day. In contrast, background concentrations reflected in the lower percentiles presented in the upper part of the graph do not differ at all.

4.6. Health outcomes

We finally consider health impacts, acknowledging that the rather muted impacts on personal exposure reduce the likelihood of such impacts. We focus on proxy health outcomes that can be expected to manifest within ten months of gaining access to the new stoves, owing to cumulative differences over time, or due to changes in cooking behaviour that are not apparent from the air pollution measurements alone. We first discuss objective measures that include oxygen saturation, pulse rate, blood pressure and a biomarker of inflammation, C-Reactive Protein.

We see only very weak evidence for improvement in any of these measures (Table 9). Several indicators appear to change consistently among the treated households but all of the effects are statistically imprecise, including the robustness checks in Appendix Table B6 where we additionally account for ventilation strata in line with the estimations outlined in Section 3.1.

Table 9: Impacts on objectively measured health of primary cooks

	Oxygen saturation (%)	Pulse rate	Elevated blood pressure	Biomarker of inflammation (C-reactive protein)
Treatment Jambar	0.27	-0.93	-0.02	-0.54
	(0.24)	(1.22)	(0.02)	(0.78)
Treatment Zama	0.26	0.04	-0.01	-1.03
	(0.28)	(1.28)	(0.02)	(0.64)
Controls	Yes	Yes	Yes	Yes
Control group mean	98.23	81.93	0.03	5.87
p-value Jambar = Zama	0.93	0.49	0.58	0.58
R-squared	0.01	0.01	0.01	0.05
Number of observations	518	518	518	502

Note: Standard errors clustered at the village level in brackets. C-Reactive Protein concentrations were normalized by haemoglobin concentration to correct for differences in the volume of blood in the blood spot samples. *** p<0.01, ** p<0.05, * p<0.1.

Lastly, we consider self-reported health indicators tracked in our study. Though many of these indicators also improve in the treatment group (Table 10), most of these estimates are imprecise. The only statistically meaningful improvement is a reduction in respiratory difficulties for the Zama group and a borderline significant effect on thoracic pressure in the past two weeks in both groups (*p*-values of 0.10 and 0.12). It is possible that these patterns reflect social desirability bias among households who received an EEBC for free. Still, these selective improvements do appear consistent with the similarly modest improvements in objective outcomes described previously and may reflect the fact that these indicators react more quickly than the objective measures. Results are largely similar in our robustness analyses, both for the objective and subjective health measures (Table B6 and Table B7).

Table 10: Impacts on self-reported health of primary cooks

	Number of medical visits, last twelve months	Respondent experienced in last two weeks …		Respondent diagnosed w/…		Experience eye pain regularly
		respiratory difficulties	thoracic pressure	asthma	cardio-vascular illness	
Treatment Jambar	0.39	-0.05	-0.08	0.00	0.02	-0.05
	(0.28)	(0.04)	(0.05)	(0.02)	(0.02)	(0.04)
Treatment Zama	0.46	-0.09**	-0.08	0.02	0.03	0.01
	(0.31)	(0.03)	(0.05)	(0.02)	(0.02)	(0.04)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Control group mean	1.64	0.18	0.23	0.02	0.02	0.15
p-value Jambar = Zama	0.84	0.43	0.89	0.25	0.44	0.09
R-squared	0.01	0.02	0.02	0.01	0.00	0.01
Number of observations	493	491	491	491	491	493

Note: Standard errors clustered at the village level in brackets. *** p<0.01, ** p<0.05, * p<0.1.

5. Cost-effectiveness of the two stove options

To compare the two EEBC stove options, we now weigh their benefits observed in our study against their costs. The benefits are cumulative over the time that the stove is in use and functioning, i.e. over its two-year expected lifetime, while the main costs are one-off monetary costs of stove distribution.

Table 11 summarizes our intervention costs following J-PAL (2018), where the scale of the intervention is defined by the number of stoves distributed (350) and the number of communities (15). The unit cost of stove distribution could be substantially reduced by targeting more nearby communities or more households within a community, and once high-volume distribution chains are in place. In addition, both costs and impacts are likely to be quite different in urban contexts or outside of Senegal.

The total cost of our small-scale intervention is approximately USD 25,000, or USD 72 per stove distributed. These costs vary considerably depending on the type of stove: The cost of providing the 350 Jambar stoves was USD 39 per targeted household, and provision of 350 Zama stoves cost USD 105 per household.

Table 11: Cost of intervention with 350 stoves disseminated across 15 communities

	Cost type I	Cost type II	Quantity	Days	Unit Cost (USD)	Total Cost (USD)
3-month junior staff	ongoing	fixed				
Recruiting of stove distributors, organizing logistics, beneficiary management, and quality control			1	63	31	1,950
Stove distribution	one-off	variable				
Jambar stoves (medium-sized)			175		13	2,283
Zama stoves			175		73	12,798
Distributors: per diems, food, lodging, insurance			2	18	43	1,565
Warehouse rental			2		783	1,565
Security guard for stove stocks			1	18	9	157
Car rental and fuel			1	18	144	2,598
Communication			5		5	26
Subtotal						22,942
10 % Overhead						2,294
Total			*350*		*72*	*25,236*
Total unit cost per Jambar					*39*	
Total unit cost per Zama					*105*	

Regarding the benefits of the EEBCs, we observe a relatively high rate (about two thirds) of stove adoption among treated households. Additionally, we observe a reduction in fuel consumption that differs across regions but not across stove types. However, we find no statistically significant improvements or deteriorations in a wide range of downstream indicators. We only observe limited evidence of improvements in proxy health indicators, which lack support from objective health condition indicators. The benefits of the Jambar and Zama stoves are thus very similar, despite their drastically different costs.

Given these muted downstream impacts, the benefits of the Zama stove are unlikely to outweigh the cost of over 100 USD per distributed stove, even if the per-stove dissemination costs can be reduced. For the Jambar, a cost-benefit analysis is less straightforward given the much lower cost of the stove and its distribution – approximately USD 13 and 39, respectively, which must be weighed against the monetary value of the reduction in fuel consumption over the stove's lifetime. In addition, the value assigned to other non-monetary benefits, such as stove satisfaction and potentially unobservable benefits, will also affect the outcome, or at least the households' willingness to pay for the stove which is indicative of what households may we willing and able to afford for the stove (cf. Bensch et al. 2015 and Levine et al. 2018). It is noteworthy from a national policy perspective that the two stoves generate added value and employment opportunities in distinct areas (cf. Bensch et al. 2021). The value chain of the Zama stove largely remains outside of Senegal, while that of the Jambar stove primarily remains within the country.

6. Conclusions and recommendations

Governments and the international community have been promoting cleaner cooking across the developing world. Promotion efforts are at odds, however, over whether and which types of energy-efficient stoves are worthy of support. Evidence on the costs and benefits of different EEBCs is inconclusive, partly because impacts are context-specific and sensitive to socio-cultural, technological, economic, and environmental aspects. This study assessed the effects of two highly differentiated biomass EEBCs ten months after providing households with the stoves on a large range of impact dimensions under real-life in two rural regions of Senegal – an important low-income context, where solid fuel use is nearly ubiquitous, and fuelwood is scarce.

Overall, our results do not lend support for disseminating the more advanced stove in Senegal, considering that it is relatively costly and did not deliver on expected reductions in particulate matter emissions, even as it performed quite similarly to the simpler EEBC in other impact dimensions. Factors such as stove stacking and avoidance behaviour, as well as background levels of ambient air pollution, likely contributed to the discrepancies between laboratory and in-the-field stove performances and thereby prevented the more advanced stove from generating meaningful reductions in emission exposure. The simpler EEBC, for its part, yielded results that corroborate previous evidence. Specifically, while it did not appear to substantially alter time use patterns, it did allow sizable woodfuel savings compared to traditional cooking, and its local production brings added value to the country. For environmental – not health – reasons, it can thus be considered a stop-gap technology that helps to reduce fuelwood consumption, which is of particular relevance in semi-arid regions like central and northern Senegal.

Based on the findings, we recommend tailoring EEBC dissemination activities to the local context and baseline cooking patterns. Stoves, especially when costly, need to be assessed by their in-the-field performance and their acceptability among target beneficiaries. Improved ventilation and low-cost EEBCs may play an important role on the path towards cleaner cooking, and can potentially be integrated into a portfolio of stove options that cater to households' heterogeneous preferences and needs (Jeuland et al. 2020, Gill-Wiehl et al. 2021). Ideally, promotion of such cost-effective and relatively simple intermediate solutions will be harmonized and integrated into the longer-term strategy of promotion of truly clean cooking, mainly via LPG and electricity, to achieve SDG 7 and finally deliver universal access to modern energy.

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Appendices

Appendix A. Additional descriptive statistics

Table A1: Baseline sample characteristics, by region

	Baseline mean		Saint-Louis vs. Kaffrine
	Saint-Louis (North)	Kaffrine (central)	*p-value*
	(1)	(2)	(3)
Household characteristics			
Participant is homemaker	0.49	0.58	0.03
Participant is literate	0.25	0.14	0.00
Female head of household	0.13	0.04	0.00
Household size	11.34 (6.19)	12.57 (6.32)	0.03
Household has a private tap	0.71	0.64	0.09
Household has electricity	0.74	0.39	0.00
Normalized wealth index§	0.36 (1.09)	-0.41 (0.70)	0.00
Share of cooking on open fire in 24h measurement	0.63 (0.46)	0.94 (0.23)	0.00
Monthly cooking fuel expenditures (USD)	14.39 (12.25)	5.33 (8.45)	0.00
Health-related characteristics			
High-ventilation PC stratum	0.58 (0.49)	0.40 (0.49)	0.00
Number of cooks	1.17 (0.50)	1.15 (0.43)	0.67
Household with health insurance	0.21	0.48	0.00
Participant has red eyes sometimes or more often	0.24	0.25	0.74
Number of observations	276	242	518

Note: Standard deviation in brackets. *p*-values refer to *F*-tests on the joint significance of the randomized group variable coefficients in an ANOVA with the respective pre-survey characteristic on the left-hand-side. § The wealth index is a single index constructed based on information on different wealth indicators such as land holding and device and livestock ownership calculated with Principal Component (PC) Analysis (see, e.g., Filmer and Pritchett 2001).

Appendix B: Robustness checks

Table B1: Stove use impacts

	Stove use for food preparation on day preceding the interview				24-hour usage duration (hours)				
	open fire	basic metal stove	EEBC	modern stove	open fire	basic metal stove	EEBC	modern stove	total
Panel A: OLS, without controls									
Treatment Jambar	-0.36***	-0.07	0.68***	0.04	-1.41***	-0.40*	2.78***	-0.12	0.84
	(0.06)	(0.06)	(0.06)	(0.03)	(0.39)	(0.19)	(0.41)	(0.24)	(0.51)
Treatment Zama	-0.35***	-0.07	0.57***	0.05	-1.11**	-0.34	2.37***	0.00	0.91*
	(0.07)	(0.06)	(0.07)	(0.04)	(0.41)	(0.20)	(0.33)	(0.18)	(0.51)
Controls	No	No	No	No	No	No	No	No	No
Control group mean	0.77	0.18	0.08	0.09	3.67	0.68	0.2	0.63	5.21
p-value Jambar = Zama	0.88	0.98	0.03	0.59	0.39	0.63	0.45	0.67	0.92
R-squared	0.29	0.06	0.42	0.22	0.22	0.07	0.24	0.08	0.10
Number of observations	518	518	518	518	460	460	460	460	460
Panel B: DiD									
Treatment Jambar	-0.27***	-0.04	0.60***	0.03	-0.91*	-0.22	2.74***	-0.15	1.50**
	(0.05)	(0.05)	(0.05)	(0.04)	(0.47)	(0.17)	(0.31)	(0.26)	(0.58)
Treatment Zama	-0.34***	-0.05	0.55***	0.06	-1.18**	-0.30*	2.45***	-0.05	0.96
	(0.05)	(0.05)	(0.05)	(0.04)	(0.49)	(0.18)	(0.32)	(0.27)	(0.60)
Controls	No	No	No	No	No	No	No	No	No
Control group mean	0.77	0.18	0.08	0.09	3.7	0.74	0.17	0.65	5.26
p-value Jambar = Zama	0.21	0.91	0.26	0.39	0.57	0.65	0.37	0.71	0.37
R-squared	0.43	0.23	0.49	0.34	0.38	0.38	0.34	0.16	0.25
Number of observations	1036	1036	1036	1036	808	808	808	808	808
Panel C: three-wave DiD, midline estimates									
Treatment Jambar at midline	-0.26***	-0.04	0.59***	0.08*					
	(0.06)	(0.05)	(0.05)	(0.04)					
Treatment Zama at midline	-0.31***	-0.09*	0.55***	0.08*					
	(0.05)	(0.05)	(0.05)	(0.04)					
Controls	No	No	No	No					
Control group mean	0.77	0.21	0.05	0.13					
p-value Jambar = Zama	0.42	0.32	0.44	0.99					
R-squared	0.44	0.29	0.51	0.34					
Number of observations	1554	1554	1554	1554					

Note: Standard errors clustered at the village level in brackets under estimation coefficients. *** p<0.01, ** p<0.05, * p<0.1

Table B2: Impacts on stove use patterns

	Meals prepared per day	Drinks prepared per day	Stove type stacking: per meal cooking event	Stove type stacking: over 24-hour measurement period	Any wood stove used for meal preparation over 24-hour measurement period
Panel A: OLS, without controls					
Treatment Jambar	0.00	-0.03	0.13*	0.25***	-0.02
	(0.12)	(0.07)	(0.06)	(0.07)	(0.05)
Treatment Zama	-0.07	-0.05	-0.01	0.21***	-0.06
	(0.10)	(0.07)	(0.05)	(0.07)	(0.05)
Controls	No	No	No	No	No
Control group mean	2.66	0.65	0.12	0.18	0.87
p-value Jambar = Zama	0.57	0.82	0.01	0.36	0.41
R-squared	0.11	0.07	0.03	0.07	0.31
Number of observations	507	513	507	513	513
Panel B: DiD					
Treatment Jambar	0.06	-0.03	0.11***	0.27***	0.00
	(0.12)	(0.09)	(0.04)	(0.06)	(0.04)
Treatment Zama	-0.12	-0.05	-0.02	0.25***	-0.02
	(0.12)	(0.09)	(0.04)	(0.06)	(0.04)
Controls	No	No	No	No	No
Control group mean	2.67	0.65	0.12	0.19	0.88
p-value Jambar = Zama	0.15	0.89	0.00	0.69	0.63
R-squared	0.20	0.12	0.07	0.15	0.50
Number of observations	996	1014	996	1014	1014

Note: Standard errors clustered at the village level in brackets under estimation coefficients. *** p<0.01, ** p<0.05, * p<0.1

Table B3: Fuel use impacts

	24-hour fuel use			24-hour wood consumption (kg)		Self-reported daily charcoal consumption‡ (kg)
	wood only	charcoal only	modern fuel only			
Panel A: OLS & IV, without controls						
	OLS	OLS	OLS	OLS	IV	OLS
Treatment Jambar	-0.12**	-0.03	0.01	-2.30**	-3.06**	-0.28
	(0.04)	(0.02)	(0.02)	(1.00)	(1.27)	(0.51)
Treatment Zama	-0.07	-0.03	0.02	-1.97*	-3.07**	0.11
	(0.06)	(0.02)	(0.02)	(0.97)	(1.52)	(0.58)
Controls	No	No	No	No	No	No
Control group mean	0.52	0.04	0.03	10.97	10.97	1.62
p-value Jambar = Zama	0.32	0.78	0.87	0.69	0.99	0.53
R-squared	0.31	0.02	0.22	0.19	0.16	0.05
First-stage *F*-Stat	–	–	–	–	61.0	–
Number of observations	518	518	518	439	439	497
Panel B: DID						
	DID	DID	DID	DID		DID
Treatment Jambar	-0.12**	-0.03	0.01	-1.55		-0.41
	(0.06)	(0.02)	(0.02)	(1.61)		(0.58)
Treatment Zama	-0.05	-0.02	0.01	-0.32		0.17
	(0.06)	(0.02)	(0.02)	(1.57)		(0.58)
Controls	No	No	No	No		No
Control group mean	0.52	0.04	0.03	10.51		1.53
p-value Jambar = Zama	0.24	0.76	1.00	0.45		0.31
R-squared	0.39	0.30	0.38	0.16		0.05
Number of observations	1036	1036	1036	654		878

Note: Standard errors clustered at the village level in brackets. DiD estimates on wood consumption have to be treated with particular caution since the measurement protocol could not be applied in 25 percent of baseline and 15 percent of endline observations, which leads to many missing panel observations. ‡ Too few measurements could be conducted for charcoal, which is why the charcoal consumption figure refers to self-reported consumption. *** p<0.01, ** p<0.05, * p<0.1.

Table B4: Time use impacts

	Household collects firewood	Weekly time spent on firewood collection (min)		Self-reported daily time to cook food		
				total time (min)		total time staying adjacent to stove (min)
Panel A: OLS & IV, without controls						
	OLS	OLS	IV	OLS	IV	OLS
Treatment Jambar	-0.04	-16.10	-22.20	-2.46	-3.34	-1.21
	(0.06)	(11.18)	(15.21)	(8.63)	(11.15)	(5.50)
Treatment Zama	-0.05	7.58	12.22	-2.92	-4.44	5.05
	(0.05)	(11.99)	(17.43)	(7.48)	(11.09)	(7.64)
Controls	No	No	No	No	No	No
Control group mean	0.70	122.66	122.66	279.17	279.17	188.09
p-value Jambar = Zama	0.79	0.03	0.01	0.97	0.95	0.51
R-squared	0.19	0.18	0.17	0.05	0.05	0.00
First-stage *F*-Stat	–	–	76.1	–	75.9	–
Number of observations	518	518	518	517	517	517

Panel B: DID

	Household collects firewood	Weekly time spent on firewood collection (min)	Self-reported daily time to cook food: total time (min)	Self-reported daily time to cook food: total time staying adjacent to stove (min)
	DID	DID	DID	DID
Treatment Jambar	0.07	-22.26	17.63	-1.90
	(0.06)	(17.01)	(17.11)	(13.46)
Treatment Zama	-0.03	11.45	17.95	-0.36
	(0.06)	(16.98)	(17.06)	(13.42)
Controls	No	No	No	No
Control group mean	0.70	122.66	279.17	188.09
p-value Jambar = Zama	0.08	0.05	0.99	0.91
R-squared	0.33	0.23	0.04	0.06
Number of observations	1036	1036	1034	1034

Note: Standard errors clustered at the village level in brackets under estimation coefficients. *** p<0.01, ** p<0.05, * p<0.1

Table B5: Impacts on smoke emissions and exposure

	$PM_{2.5}$ kitchen concentration (log, µg/m^3)		$PM_{2.5}$ personal exposure (log, µg/m^3)	
	24-hour mean	95th percentile	24-hour mean	95th percentile
Panel A: OLS, without controls				
Treatment Jambar	0.16	0.33	-0.04	0.07
	(0.41)	(0.54)	(0.09)	(0.11)
Treatment Zama	-0.10	-0.03	0.01	0.04
	(0.35)	(0.49)	(0.11)	(0.15)
Controls	No	No	No	No
Control group mean	398	2064	119	298
p-value Jambar = Zama	0.39	0.45	0.70	0.86
R-squared	0.05	0.24	0.16	0.14
Number of observations	93	74	179	173
Panel B: DID				
Treatment Jambar	0.09	0.19	-0.14	-0.45*
	(0.35)	(0.67)	(0.16)	(0.26)
Treatment Zama	0.13	0.07	0.03	-0.09
	(0.34)	(0.65)	(0.15)	(0.24)
Controls	No	No	No	No
Control group mean	315	1144	121	272
p-value Jambar = Zama	0.91	0.85	0.28	0.15
R-squared	0.33	0.20	0.00	0.00
Number of observations	174	92	352	234

Table B6: Impacts on objectively measured health of primary cooks

	Oxygen saturation (%)	Pulse rate	Elevated blood pressure	Biomarker of inflammation (C-reactive protein)
Panel A: OLS, without controls				
Treatment Jambar	0.33	-0.77	-0.01	-0.24
	(0.23)	(1.28)	(0.01)	(0.74)
Treatment Zama	0.29	0.13	-0.01	-0.82
	(0.28)	(1.25)	(0.01)	(0.75)
Controls	No	No	No	No
Control group mean	98.23	81.93	0.03	5.87
p-value Jambar = Zama	0.82	0.50	0.56	0.55
R-squared	0.01	0.02	0.02	0.04
Number of observations	518	518	518	502
Panel B: DID				
Treatment Jambar	-0.16	-2.31	0.02	1.33
	(0.33)	(1.47)	(0.03)	(1.60)
Treatment Zama	-0.04	-1.05	0.03	0.71
	(0.33)	(1.46)	(0.03)	(1.65)
Controls	No	No	No	No
Control group mean	98.22	81.89	0.03	5.42
p-value Jambar = Zama	0.70	0.39	0.58	0.70
R-squared	0.00	0.32	0.05	0.10
Number of observations	1030	1028	1028	936
Panel C: OLS, with ventilation strata				
Treatment Jambar	0.15	-1.45	-0.04	-1.53
	(0.41)	(1.65)	(0.03)	(1.22)
Treatment Zama	0.10	0.29	-0.02	-0.28
	(0.40)	(1.63)	(0.03)	(1.46)
High-ventilation PC stratum	0.11	-1.55	-0.02	0.44
	(0.54)	(1.44)	(0.02)	(1.27)
Treatment Jambar x high-ventilation PC stratum	0.25	1.06	0.04	1.86
	(0.57)	(1.89)	(0.03)	(1.99)
Treatment Zama x high-ventilation PC stratum	0.32	-0.43	0.03	-1.54
	(0.65)	(2.53)	(0.04)	(2.18)
Controls	Yes	Yes	Yes	Yes
Control group mean	98.23	81.93	0.03	5.87
R-squared	0.01	0.01	0.00	0.05
Number of observations	518	518	518	502

Table B7: Impacts on self-reported health of primary cooks

	Number of medical visits, last twelve months	Respondent experienced in last two weeks …		Respondent diagnosed w/…		Experience eye pain regularly
		respiratory difficulties	thoracic pressure	asthma	cardio-vascular illness	
Panel A: OLS, without controls						
Treatment Jambar	0.42	-0.04	-0.07	0.00	0.01	-0.05
	(0.30)	(0.04)	(0.05)	(0.02)	(0.02)	(0.04)
Treatment Zama	0.48	-0.08**	-0.07	0.02	0.03	0.02
	(0.31)	(0.04)	(0.05)	(0.02)	(0.02)	(0.04)
Controls	No	No	No	No	No	No
Control group mean	1.64	0.18	0.23	0.02	0.02	0.15
p-value Jambar = Zama	0.87	0.36	0.92	0.18	0.32	0.09
R-squared	0.01	0.02	0.01	0.00	0.00	0.00
Number of observations	493	491	491	491	491	493
Panel B: DID						
Treatment Jambar	0.53	-0.02	-0.09	0.00	0.01	-0.01
	(0.36)	(0.05)	(0.06)	(0.02)	(0.04)	(0.06)
Treatment Zama	0.15	-0.06	-0.10	0.00	0.01	0.07
	(0.36)	(0.05)	(0.06)	(0.02)	(0.04)	(0.06)
Controls	No	No	No	No	No	No
Control group mean	1.62	0.18	0.24	0.02	0.01	0.15
p-value Jambar = Zama	0.31	0.44	0.88	0.99	0.93	0.13
R-squared	0.27	0.18	0.10	0.36	0.05	0.21
Number of observations	942	938	938	938	938	942
Panel C: OLS, with ventilation strata						
Treatment Jambar	0.36	-0.04	-0.08	-0.01	0.02	-0.08*
	(0.44)	(0.07)	(0.05)	(0.01)	(0.04)	(0.04)
Treatment Zama	0.60	-0.06	-0.06	-0.02	0.01	0.00
	(0.49)	(0.05)	(0.06)	(0.01)	(0.03)	(0.04)
High-ventilation PC stratum	-0.17	0.09	0.09	-0.01	-0.03	-0.01
	(0.39)	(0.08)	(0.06)	(0.02)	(0.03)	(0.05)
Treatment Jambar x high-ventilation PC stratum	0.04	-0.02	0.00	0.03	0.00	0.07
	(0.55)	(0.10)	(0.09)	(0.03)	(0.04)	(0.06)
Treatment Zama x high-ventilation PC stratum	-0.28	-0.06	-0.03	0.06*	0.06	0.02
	(0.58)	(0.09)	(0.11)	(0.03)	(0.04)	(0.06)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Control group mean	1.64	0.18	0.23	0.02	0.02	0.15
R-squared	0.01	0.02	0.02	0.01	0.00	0.01
Number of observations	493	491	491	491	491	493