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Releasing the killer from the kitchen? Ventilation and air pollution from biomass cooking[☆]

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ABSTRACT

Household air pollution from biomass cooking is the most significant environmental health risk in the Global South. Interventions to address this risk mostly promote less-polluting stoves and clean fuels, but their diffusion has proven difficult. This paper assesses the potentially complementary role of ventilation in reducing household air pollution. Using state-of-the-art measurements of kitchen concentrations of particulate matter (PM_{2.5}) and personal exposure from around 250 households in rural Senegal, we show that higher ventilation is strongly related to lower kitchen concentration, though absolute pollution levels remain high. This association is robust to controlling for a comprehensive set of potential confounders. Yet, these reductions in concentration do not clearly translate into lower pollution exposure among cooks, probably due to avoidance behaviour. Our findings indicate that ventilation interventions may reduce smoke concentration nearly as much as many real-world clean stove interventions and can hence be an important complement to existing strategies. However, a more holistic approach is needed in order to reduce personal exposure in line with international health standards.

1. Introduction

One third of humanity primarily cooks with biomass, mostly wood and charcoal (IEA et al. 2022). The household air pollution resulting from combustion of such fuels is the leading environmental cause of mortality, inducing an estimated 3.8 million premature deaths per year

globally (WHO 2016). Since the 2000s, policy interventions have promoted clean stoves and fuels such as gas and electricity, in order to combat household air pollution and forest degradation, and relieve firewood collection burdens (Köhlin et al., 2011; Shindell et al., 2012; Bailis et al., 2015; Bensch et al., 2021a). Yet, many countries are well off track of meeting Sustainable Development Goal 7, which requires

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universal access to clean cooking by 2030. The main transitional alternative to clean stoves and fuels are energy-efficient biomass cookstoves (EEBCs), which are not emission-free, but reduce biomass consumption and, hence, time or monetary expenditures for fuel acquisition. Such EEBCs are more affordable than clean technologies, but supply and demand side challenges also slow their adoption and sustained use.¹ In rural Senegal for example, the site of this study, 96% of the population still use solid cooking fuels in 2020 (IEA et al. 2022), and poorer urban strata often use biomass fuels as well (Rose et al., 2022).

This paper studies the role of improved kitchen ventilation in reducing household air pollution levels and exposures. Such a solution has recently emerged in policy and academic discussions as a potentially complementary approach to the predominant strategy of disseminating cleaner stoves and fuels (see Fullerton et al., 2008; Langbein 2017; ESMAP 2020; Simon et al., 2014). Rather than reducing the generation of kitchen pollution at its source, the cooking spot, ventilation may lower kitchen pollution levels by directing harmful emissions away from people, for example through improved kitchen air exchange. We examine the relationship between kitchen ventilation features and kitchen concentration, as well as cooks' personal exposure to particulate matter of a diameter less than $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), which is the most harmful component of air pollution from firewood combustion (WHO 2008).

The analysis relies on pooled data from two waves of state-of-the-art emission measurements and in-depth household surveys. The data were collected in the dry seasons of 2018 and 2019 in rural Senegalese communities, where traditional cooking is predominant and ventilation conditions vary substantially. As such, our sample is plausibly representative of rural and poor households in arid and dusty regions of West Africa, while external validity caveats apply for other regions and the rainy season. Our identification strategy based on a cross-sectional comparison of ventilation types is prone to typical concerns about selection bias. The strength of our approach, though, is in combining high-accuracy measurements with a comprehensive set of socio-economic and cooking-specific control variables in pre-specified regression analyses, that reduce measurement error and mitigate the risk of unobservables and data mining.

Given the lack of consensus on how to measure ventilation in the existing literature (Lenz et al., 2022), we present a conceptual framework that defines four different dimensions of kitchen ventilation and their operationalisation, which we then carry to the data: (i) kitchen air exchange (wall structure, roofing structure, kitchen openings), (ii) kitchen volume, (iii) kitchen separation and (iv) ventilation behaviour. Additionally, we generate two composite indicators of ventilation: a simple additive indicator, and an indicator constructed using a data-driven classification method, namely principal component analysis. We add to a thin literature on ventilation and household air pollution that mostly includes small samples and limited data to control for behavioural and other household-related confounders (see again Lenz et al., 2022).

We find that improved ventilation is associated with substantially lower kitchen concentration. These household air pollution reduction potentials are not substantially different from those associated with moving from traditional cooking to clean fuels, since clean stove interventions usually fail to fully displace all dirty stoves in a household (so-called stove stacking, see e.g. Pope et al., 2021 or Ruiz-Mercado and Masera 2015). It is important to note, though, that our measurements also show that the average kitchen concentration of $474 \mu\text{g}/\text{m}^3 \text{PM}_{2.5}$

exceeds even the least stringent WHO (2021) interim air quality target of $35 \mu\text{g}/\text{m}^3 \text{PM}_{2.5}$ by an order of magnitude. Average 24-h personal exposure is substantially lower, but remains high ($136 \mu\text{g}/\text{m}^3 \text{PM}_{2.5}$) even during non-cooking periods. Moreover, personal exposure is not significantly associated with kitchen concentration and is lower – as a fraction of kitchen concentration – than the levels that are commonly assumed in the literature. These discrepancies are most likely driven by cooking behaviour to avoid smoke exposure, and we find tentative supporting evidence of this using proxies for cooking behaviour.

Our findings can inform the design of potential transitional measures that would complement clean cooking access policies. First, policy might encourage greater ventilation in homes as a stand-alone intervention in settings where more open kitchens are climatically and culturally appropriate. Second, ventilation improvements could be tested as a complement to clean stove and EEBC interventions in an effort to improve their health effects and hence cost-effectiveness. Third, our finding that kitchen concentration is an inaccurate proxy for exposure in biomass-using households suggests that the interaction of stoves, fuels, housing conditions and cooking behaviours must not be ignored when tracking the success of clean cooking policies.

2. Conceptual framework

2.1. Ventilation as a cleaner-cooking intervention

The ultimate public health objective of clean cooking interventions is a reduction of health burdens related to cooking-induced pollution. Fig. 1 illustrates a stylized causal chain linking cooking stove use to health outcomes, and locates a spectrum of techno-economic and behavioural interventions aiming to influence different elements in that causal chain. Traditional stoves combust solid fuels inefficiently and thereby emit pollutants, such as fine particulates, carbon monoxide, nitrogen oxides, and volatile organic compounds. These all contribute to elevated kitchen concentration of pollutants, which is dispersed across the kitchen and beyond. The pollution to which a person is exposed, and hence inhales, defines personal exposure, which then affects health. The main pollutant of concern from incomplete combustion of biomass fuels is $\text{PM}_{2.5}$ (WHO 2008). Due to its small size, $\text{PM}_{2.5}$ has a low likelihood of getting filtered by the upper respiratory tract and can hence penetrate deep into small body airways, lungs, and bloodstreams (Pope and Dockery 2006). A second important toxin is carbon monoxide (CO), which cannot be assumed to be proxied by $\text{PM}_{2.5}$ (Klasen et al., 2015).

The specific hypothesis examined in this paper is that kitchen ventilation – represented by the four dimensions of ventilation in Fig. 1 – can also alter kitchen concentrations and personal exposures, leading to an interference in the links III-IV and IV-V in the figure. Early efforts to show correlations between proxies of ventilation, such as roof type or air circulation in the kitchen, date back to the 1980s (Dary et al., 1981; Menon 1988; Ramakrishna 1988). Smith et al. (1983) integrated ventilation conditions and cooking behaviour into a holistic model on cooking-induced pollution, that was further developed in policy papers, such as Ballard-Tremeeer and Mathee (2000), but these efforts were mostly of a conceptual nature and were applied in empirical studies only in limited and inconsistent ways (cf. also Lenz et al., 2022).

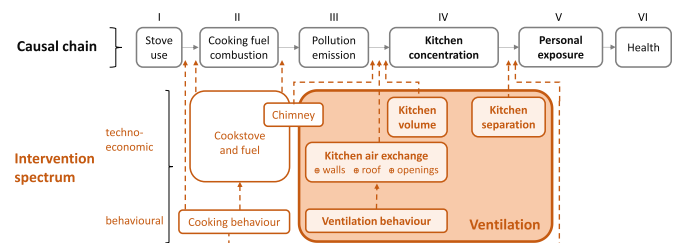


Fig. 1. Stylized causal chain and intervention spectrum.

¹ These challenges include underdeveloped supply chains (Lewis et al., 2015; Pattanayak et al., 2019), barriers to commercialization for stove developers (Bailis et al., 2009; Bensch et al., 2021b), misalignment of consumer preferences with available improved technologies, low valuation of these solutions (Mobarak et al., 2012; Jeuland et al., 2015; 2020; Jeuland and Pattanayak 2012), liquidity constraints or affordability (Levine et al., 2018; Bensch and Peters 2020; Bensch et al., 2015), and poor durability (Hanna et al., 2016).

The ventilation dimensions may affect the causal chain in Fig. 1 as follows: Keeping emissions constant, pollution will be lower in a space with more kitchen air exchange, because particles move towards openings (Patel et al., 2017). More specifically, we consider the three kitchen air exchange sub-dimensions *wall structure*, *roof structure* and *kitchen openings*. A second dimension of kitchen ventilation is *kitchen volume*, i.e. the volume over which emissions can dilute. A third dimension is *ventilation behaviour*, which mainly refers to people's inclination to keep doors and windows open. Lastly, *kitchen separation* affects pollution dilution to parts of the house beyond the kitchen. Kitchen separation is therefore relevant for personal exposure only and, in contexts like ours, where pollution exposure is measured with cooks only, it is just relevant when pollution persists during non-cooking times. All these dimensions may interact with *cookstove and fuel choices* and *cooking behaviour*, which includes the choice of dishes cooked, the use of dry wood, and contact time, among others.² Fig. 1 also identifies chimneys as technologies that pair a stove intervention with a significant ventilation intervention, venting emissions directly to the outside.

Our empirical analysis does not consider health outcomes and hence ends at link IV-V. Importantly, existing evidence indicates that the concentration-response relationship between household air pollution and health impacts differs across diseases and may be highly nonlinear, implying that only very low pollution levels induce substantial health improvements (Ezzati and Kammen 2002; Burnett et al., 2014; Apte et al., 2015).³

Multiple contextual factors can alter the impact of kitchen ventilation on kitchen concentration and personal exposure. These include household wealth and cultural aspects. The installation of windows, for example, can be compromised by privacy or security concerns (Muindi et al., 2016; Lueker et al., 2020). The health status of household members is also important as it may determine whose and how much time is spent in the kitchen. In addition to these individual factors, for which we seek to control in our empirical analyses, the effectiveness of ventilation is conditioned on the quality of ambient air. Studies from urban areas have indeed shown that ventilation can worsen indoor air quality, if ambient air pollution or neighbours' emissions are high (Mönkkönen et al., 2005; Shibata et al., 2014). Finally, weather – including rain, winds and dust storms – can impact air quality via changes in ventilation behaviour (Kulshreshtha and Khare 2011; Nayek and Padhy 2017).

2.2. Kitchen ventilation indicators

The range of kitchen designs in rural Senegal covers many kitchen structures found in other developing countries. Kitchen volume is the only kitchen ventilation dimension that can be characterized using a continuous measure, which is m^3 . For each kitchen ventilation dimension, we therefore create categorical indicators, using the following four categories: *no*, *poor*, *substantial*, and *full* ventilation (Table 1). These categories build on the Cooking Energy System concept proposed by the global Energising Development programme (GIZ 2017). With open-air kitchens included in the *full* ventilation category for all

² For example, Bensch and Peters (2015) present exploratory evidence that the dissemination of a portable EEBC (stove intervention) increased the likelihood of outdoor cooking (a ventilation-enhancing behaviour) and reduced the time that primary cooks spent near their stoves (an exposure-mitigating cooking behaviour). Jeuland et al. (2021) present a recent systematic review of the impact of cookstove interventions across impact dimensions.

³ The small number of studies that address this link furthermore suggest that better ventilation can reduce the incidence of acute lower respiratory infections among children (Rehfuess et al., 2009; Buchner and Rehfuess 2015; Langbein 2017), reduce bronchitis (in Bolivia) and other respiratory problems (in Ghana) (Albalak et al., 1999; Boadi and Kuitunen 2006), and increases the rate of depressive symptoms (Zhang et al., 2017).

non-behavioural ventilation dimensions, *open air* is included as additional binary indicator in the analytical framework. The open-air indicator also has the advantage that it is included in some cross-country secondary datasets such as the Demographic Health Survey (DHS).

We further create composite indicators based on the single, one-dimensional ventilation indicators that refer to non-behavioural ventilation dimensions and that are relevant for both kitchen concentration and personal exposure. These are the first four single indicators in Table 1 – walls, roof, openings, and volume. We consider two approaches from the literature on how to condense the information from multiple single indicators in a composite indicator. We call the first such composite indicator *aggregated ventilation*, as it simply sums up the four single indicators and implicitly applies an equal weighting to all four of them. Our second composite indicator abstains from imposing weights and instead leverages the correlation structure between the indicators using Principal Component Analysis (PCA, see Filmer and Pritchett 2001). To determine our *PCA ventilation* indicator, we combine the first two components derived by PCA, each weighted by the extent to which it explains the variation in the PCA. Both indicators are analysed as continuous measures ranging from 0 to 1 and as categorical measures, where the continuous score is split into quartiles. We tested a second data-driven composite indicator based on recursive partitioning techniques, where the categorization itself is informed by the data instead of adopting equal sample splits. Yet, this approach faces several challenges owing to the relatively small sample size of our study, problems in finding logical splits in the data, and a potential for overfitting, which is why we only discuss it in Appendix A.

3. Empirical approach

3.1. Identification strategy and estimation framework

Our empirical work focuses on the relationship between ventilation variables and two outcome measures, kitchen concentration of $PM_{2.5}$, and personal exposure to that pollutant. To isolate the causal impact of ventilation on these measures, one would ideally vary ventilation randomly. In the absence of such a randomization, we use detailed individual-level data that allows controlling for many potential confounders, acknowledging that further confounders may remain uncontrolled. For example, households particularly vulnerable to household air pollution may preferentially invest in ventilation technology. The specification of variables used in the analysis is discussed in a pre-analysis plan for the larger impact evaluation study of which the present analysis is a part; this evaluation also contained a field experiment with two treatment groups receiving either a simple or an advanced EEBC (Peters and Jeuland 2017).





To test the association between kitchen ventilation and air pollution measures, we conduct Ordinary Least Squares (OLS) estimations with the following specification:

$$\log(Y_{ijt}) = \alpha + \beta_1 \text{Ventilation}_{ijt} + \mathbf{X}'_{ijt} \boldsymbol{\beta}_2 + \delta W_t + \gamma_j + \varepsilon_{ijt} \quad (1)$$

where α is the intercept term, W is an indicator that is equal to 1 if the survey took place in $t = 2019$ (and otherwise 0 for $t = 2018$), γ_j are village fixed effects, and ε_{ijt} represents an error term specific to household i from village j for survey wave t . In the following, we explain in more detail the other three components of equation (1), the outcome $\log(Y_{ijt})$, the ventilation indicators Ventilation_{ijt} , and the set of control variables, \mathbf{X}'_{ijt} .

$\log(Y_{ijt})$ represents either of the two logged outcome measures of interest for household ij and survey wave t : mean 24-h $PM_{2.5}$ kitchen concentration and mean 24-h cooks' personal exposure to $PM_{2.5}$. We log-transform pollution because its bivariate relationship with ventilation is not linear and to reduce the influence of extreme values. Kitchen concentration was measured at an approximate 1-m vertical and horizontal

Table 1
Categorization of kitchen ventilation dimensions.

	No ventilation	Poor ventilation	Substantial ventilation	Full ventilation
Wall structure	 fully closed: impermeable with/without openings	 fully closed: permeable with/without openings	 semi- enclosed: one to three walls to the roof	 no walls
Roof structure	 solid roof	 permeable	 permeable with openings significant openings	 no roof no walls, no roof or open air
Kitchen openings	no opening except for the door	small or medium-sized openings	with openings significant openings	roof no walls, no roof or open air
Kitchen volume	less than 12.5m ³	12.5 to 25 m ³	more than 25 m ³	open air
Kitchen separation	inside main building	attached to main building	separated from main building	open air
Ventilation behaviour	frequency of opening doors and windows while cooking: never	rarely	often	always
Open air		non-open air		open air

Note: Impermeable materials include e.g. concrete, bricks, and mud; permeable materials include e.g. bamboo, grass, and boards. Kitchen openings include hoods. Photographs taken during field work.

distance from households' main stoves. For this measurement, we used one of two types of meters, gravimetric Micro Personal Exposure Monitors (MicroPEMs, RTI International, USA) and optical Indoor Air Pollution Meters (IAP Meters, Aprovecho, USA). For measurement of personal exposure, women agreed to wear the lightweight MicroPEMs at chest level to measure the fine particles they inhale from their breathing zone (see Appendix B for a depiction of the in-field measurement setup and details on the calibration of the measurement devices). Additionally, the MicroPEMs provide real-time pollution data, by registering PM_{2.5} inflow in 30-s intervals via a light-scattering particle detector built into the devices. We order the real-time pollution measurements into percentiles of 24-h pollution, from most polluting to least polluting, and use these as outcome variables in a robustness test.

In equation (1), $Ventilation_{ijt}$ describes an indicator for a household's kitchen ventilation, for which we evaluate the single and composite ventilation indicators introduced in Section 2 and listed in Table 2. Note that the present study does not test the indicator *ventilation behaviour*

Table 2
Definition of ventilation indicators.

Indicator type	Indicator	Type of classification
Single	Kitchen walls	Categorical 1-4
	Kitchen roof	Categorical 1-4
	Kitchen openings	Categorical 1-4
	Kitchen volume	Continuous/Categorical 1-4
	Kitchen separation	Categorical 1-4
	Open air	Categorical 0-1
Composite (walls + roof + openings + volume)	Aggregated ventilation	Continuous 0-1/Categorical 1-4 (quartiles)
	PCA ventilation	Continuous 0-1/Categorical 1-4 (quartiles)

Note: See Section 2.2 for the categorizations.

given that only around 25% of households have closable doors and virtually none have closable windows. Hence, this indicator is not applicable and can thus not be tested for the large majority of households in our sample.⁴

The last component of equation (1), X'_{ijt} , represents a set of household, participant and measurement characteristics to control for potential confounders of the relationship between ventilation and pollution or exposure, the full list of which is presented in Appendix Table C.1. In brief, we first control for socio-demographic household and participant characteristics, such as household size and whether the participant is literate. Second, we control for measures of wealth, including the occupation of the main cook, a wealth index derived from asset ownership, and access to water and electricity infrastructure. Third, we add cooking variables, such as aspects of cooking behaviour (e.g., total cooking time and whether the participant reports avoiding kitchen smoke), and the two EEBC types that were randomized as part of the impact evaluation of which the analysis is a part. Fourth, we test whether our findings are robust to the inclusion of health status, which we exclude from our main specification due to concerns about reverse causality. Finally, we control for technical factors specific to the kitchen concentration and personal exposure measurements.⁵

We lack measurements to control for biomass moisture content but expect this to be less of a concern in our dry-season context. Indeed, 99% of enumerators recorded that the firewood encountered in the sampled

⁴ Similarly, chimneys as a stove-ventilation combination are not found in the survey regions and therefore not included in our analysis.

⁵ Two factors only included in the control set for kitchen concentration are the meter type and the share of cooking events next to monitored stove. Meanwhile, the personal exposure set includes three factors that are only relevant to exposure: the number of persons cooking during the measurement period, whether participants were secondary or main cooks during measurement, or neither, and the share of daytime hours spent wearing the MicroPEM.

households was dry. Wind and dust storms likely affect cooking-related pollution concentrations heterogeneously across villages, even in our relatively homogeneous sample. Lacking the relevant data, we cannot control for this in our estimations. Therefore, the estimated coefficient reflects the relationship between ventilation and the combination of cooking-related emissions and other such air fouling constituents.

Given that our controls may not cover all relevant potential confounders, we investigate the role of unobservables and omitted variable bias in our estimates based on Oster (2019). The Oster method formalizes a well-known link, namely that smaller changes in coefficients paired with larger changes in R-squared after inclusion of controls eases concerns about omitted variable bias. The method estimates the ratio of selection on unobservables to selection on observables which would make the coefficient of interest equal to zero (δ). A δ higher than one signals that unobservables are more important than observables in explaining selection into ventilation. It is commonly interpreted as support for the model specification. The method requires definition of a maximum R-squared R_{\max} , which Oster (2019) suggests setting to 1.3 times the observed R-squared. We apply this approach to specifications where it is technically possible, i.e., those that estimate a single coefficient for the ventilation indicator, which is the case for the three categorical and continuous indicators on a scale from zero to one.

3.2. Data collection

The household data used in our estimation framework was collected in 15 rural Senegalese villages during surveys conducted in the dry season in early 2018 and early 2019. The study sample comprised two regions in northern and central Senegal characterized by typical Sahelian vegetation and scarce fuelwood. Villages located in these regions were eligible if they complied with two inclusion criteria. First, their total population was within the range of 600 to 1600 typical for rural communities in the region, and second, they had not previously seen significant EEBC promotion to ensure low initial penetration of improved biomass cooking technologies. The sample for the personal exposure measurements included 16 to 17 households per community, randomly sampled from household lists, among which around half were also selected for the kitchen concentration measurements. We applied stratified random sampling to maintain representativeness in the sub-sample selected for this measurement. The stratification variable was an indicator variable for whether the household was above or below median kitchen ventilation as generated using PCA.⁶ The household data was collected during two survey visits made on two consecutive days including household interviews, and the 24-h pollution measurement occurred between these two visits. We invited households' primary cooks above age 15 to participate in the interview; in case this individual was unavailable, a secondary cook was enrolled instead. Only three households attrited due to absence of all household cooks at the time of the second round of interviews and measurements. In addition, measurements could not be performed in all households in 2019 due to technical issues with a few measurement devices. As a consequence, the number of households sampled per community in 2019 ranged between 10 and 15 households.

The pooled sample used in this paper includes 418 household-year observations with cooks' personal exposure measurements, and 220 household-year observations with kitchen concentration measurements, where the combination of household and survey year uniquely identifies individual observations. The samples are different, albeit with a good overlap ($n = 202$, see Appendix Table C.2), and use data from a total of 244 households, of whom 192 households were visited twice. Note that,

⁶ The PCA used seven variables: kitchen volume and kitchen openings, cooking location, the number of primary cooks, a dummy for stove stacking, daily cooking time, and main fuel type. The PCA indicator used for stratification loads most strongly on kitchen location and openings.

due to problems with data storage in the field, percentile pollution data used in our robustness analyses is available for only a subset of 344 personal exposure and 140 kitchen concentration measurements. Dropout analyses using probit estimations show that the data loss is partly correlated with household characteristics, which makes controlling for household characteristics in the robustness analyses particularly important.

4. Summary statistics

4.1. Control variables

Survey participants were on average 32 years old, and spent about 5.5 h cooking per day. Eighty-three percent used a traditional or basic metal stove at the time of the surveys, with the remainder having an EEBC (13%) or LPG stove (4%) as their dirtiest stove. The average share of meals cooked on the respective stove type was 89%, indicating that stove type stacking is uncommon in our sample. There were 1.4 primary cooks among an average of 12 household members; in households with multiple cooks, the cooks typically take turns. Seventy-three percent of study participants identified as the primary cook, while 13% identified as a secondary cook. Households used a stove that was located next to our meter during roughly 90% of all cooking events. The MicroPEMs' built-in accelerometers suggest that cooks wore the device for personal exposure measurement on average during 70% of daytime hours (assuming 8 h of sleep). Ninety-four percent of participants categorized the day of measurement as a typical day. The kitchen concentration and personal exposure subsamples are very similar in terms of control variable statistics (Appendix Table C.1), which is in line with expectation from the stratified randomization of measurements outlined in Section 3.2.

4.2. Ventilation indicators

The different kitchen ventilation categories are well represented across ventilation indicators in our sample (Fig. 2). One exception is kitchen separation, with around 80% of households cooking in a detached kitchen. With around 12% of households cooking in open air, open-air cooking in our sample corresponds to what Langbein et al. (2017) find for entire rural Senegal using DHS data, which is lower than in rural areas of other developing countries (see again Langbein et al., 2017). Fig. 2 furthermore shows that the two sub-samples with kitchen concentration and personal exposure measurements are similar with regards to their ventilation categorization. High variability is found in kitchen structures within our two study regions, underscoring the need to consider ventilation heterogeneities.

Correlations among single ventilation indicators range from $\rho = 0.4$ to $\rho = 0.5$, with lower Spearman correlation coefficients of around 0.2 for kitchen volume, which is reassuring since a high correlation would suggest redundant indicators. Given their common variable base, the two composite ventilation indicators show a higher correlation of $\rho = 0.8$ (see Appendix Table C.3). In our case, the first two components identified by PCA, which together form the basis of the PCA ventilation indicator, explain 58% and 21% of the variation in the PCA, respectively.

4.3. Kitchen concentration and personal exposures

Fig. 3 plots the cumulative distribution of the 24-h air pollution measurements. The first result to note is that kitchen concentration surpasses the standards set by the WHO (2021) by a great deal, as does personal exposure. The five red lines represent the WHO guideline value for mean annual concentration of $5 \mu\text{g}/\text{m}^3$ and four less stringent interim target levels ranging from 10 to $35 \mu\text{g}/\text{m}^3$. The WHO's least demanding interim target 1, with mean annual concentration of $35 \mu\text{g}/\text{m}^3$, is met by only two percent of households for kitchen concentration and four

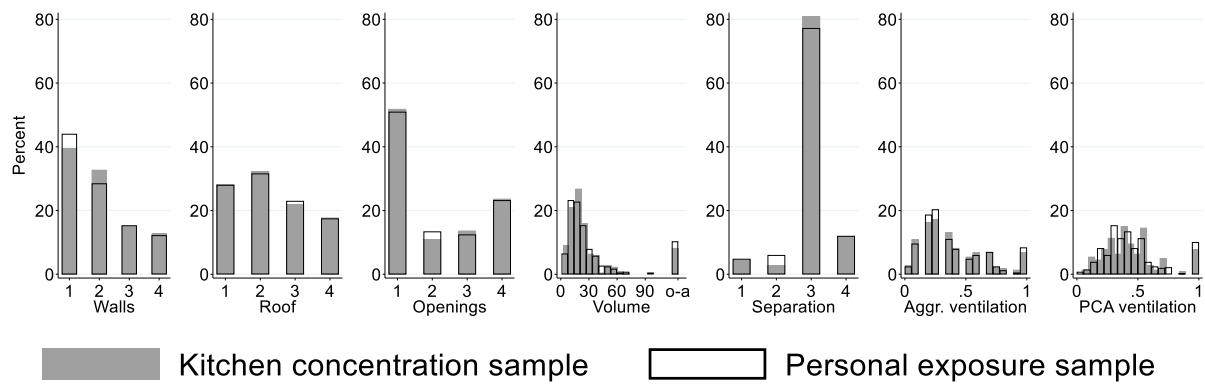


Fig. 2. Distribution of households across ventilation indicators.

Note: The values for the categorical ventilation variables refer to: 1 = No ventilation, 2 = Poor ventilation, 3 = Substantial ventilation, 4 = full ventilation. o-a refers to open air, which corresponds to the binary open-air indicator. The three continuous indicators are all as well transformed to categorical quantile indicators.

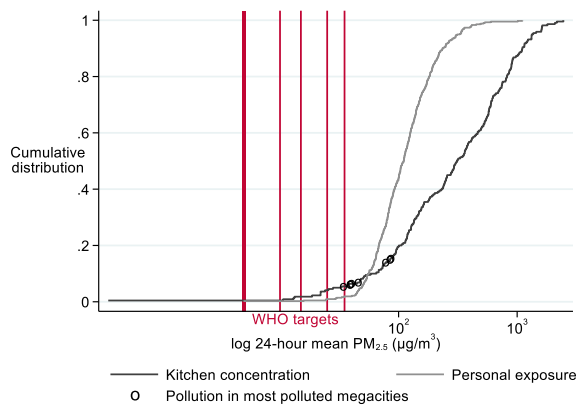


Fig. 3. Cumulative distribution of 24-h mean $PM_{2.5}$ kitchen concentration and personal exposure.

Note: Red lines indicate the WHO guideline value and interim targets 4, 3, 2, and 1. Dots represent annual average $PM_{2.5}$ air quality values for the eight most polluted mega-cities with more than 10 million inhabitants, from Lahore, Pakistan to Beijing, China (IQAir, 2022; UN, 2022).

percent for personal exposure when considering our 24-h measurement results.⁷ Even median exposure in our sample is more than 20 times higher than the WHO guideline value. Fig. 3 also illustrates that in at least 80 percent of households’ kitchen concentration surpasses annual averages of ambient pollution levels measured in the world’s most polluted mega-cities (Krzyzanowski et al., 2014; IQAir 2022). Second, kitchen concentration is much higher than exposure, namely 312 versus 110 $\mu\text{g}/\text{m}^3$ at the median. Third, both kitchen concentration and exposure vary greatly across households.

The non-linear concentration-response functions discussed in Section 2 suggest that daily peak pollution within a household also plays an important role in health outcomes. Table 3 shows mean pollution and pollution levels at two extreme points in the 24-h pollution distribution, the 95th and 25th percentiles. The 95th percentile value reveals extremely elevated peak pollution that corresponds to the highest 5% of levels recorded during the day, i.e. the worst 1.2 h. The 25th percentile, in contrast, can be interpreted as the background pollution level experienced during times without any cooking, given that cooking hours are limited during the day. Even this value surpasses the WHO interim target values in our setting with mostly detached kitchens, suggesting that

⁷ This interim target 1 is associated with a mortality that the WHO projects to be 24% higher than under the WHO guideline value (WHO 2021).

Table 3
Summary statistics of kitchen concentration and personal exposure.

	Kitchen concentration		Personal exposure	
	mean (sd)	median	mean (sd)	median
$PM_{2.5}$: mean, in $\mu\text{g}/\text{m}^3$	474 (455)	312	136 (107)	110
$PM_{2.5}$: 95 percentile, in $\mu\text{g}/\text{m}^3$	1839 (2204)	780	379 (556)	234
$PM_{2.5}$: 25 percentile, in $\mu\text{g}/\text{m}^3$	30 (21)	25	33 (19)	29

Note: See Appendix Figure C.1 for various percentile medians.

secondary or ambient pollution sources contaminate the indoor and outdoor environment. Note that none of the survey areas were in heavy traffic areas or located close to industrial point sources of pollution, but that they do experience regular storms that can carry Saharan dust, especially in the dry season (Heft-Neal et al., 2020). Moreover, the burning of waste and agricultural residues is common in these communities, adding to the cooking smoke from neighbours that regularly permeates the air. The figures in the table also demonstrate the considerable heterogeneity in pollution levels across households, which is consistent with the wide ranges of pollution variation commonly observed in similar studies.⁸

5. Relationship between ventilation and air pollution measures

5.1. Ventilation and kitchen concentration

5.1.1. Main results

Fig. 4 graphically displays the coefficients for all single and composite ventilation indicators, both absolute and percentage changes, when switching from unventilated kitchens as the reference case to poorly, substantially, and fully ventilated kitchens. The coefficients are based on the model specification in equation (1). Across the different indicators, we find considerably lower kitchen concentrations in fully and substantially ventilated kitchens than in unventilated ones. Note that the no ventilation reference categories, which are presented by dashed vertical lines in the figure, are not the same across indicators. Percentage changes therefore cannot necessarily be directly compared across indicators and need to be considered in combination with the respective absolute level of the reference category.

Switching from no to fully ventilated kitchens is associated with a reduction of kitchen concentration by between 63 and 76%, depending on the indicator. This corresponds to absolute reductions in kitchen

⁸ Pope et al. (2021) compile kitchen pollution measurements from 75 studies, and the ratio between standard deviation and mean is larger in 37 of these studies.

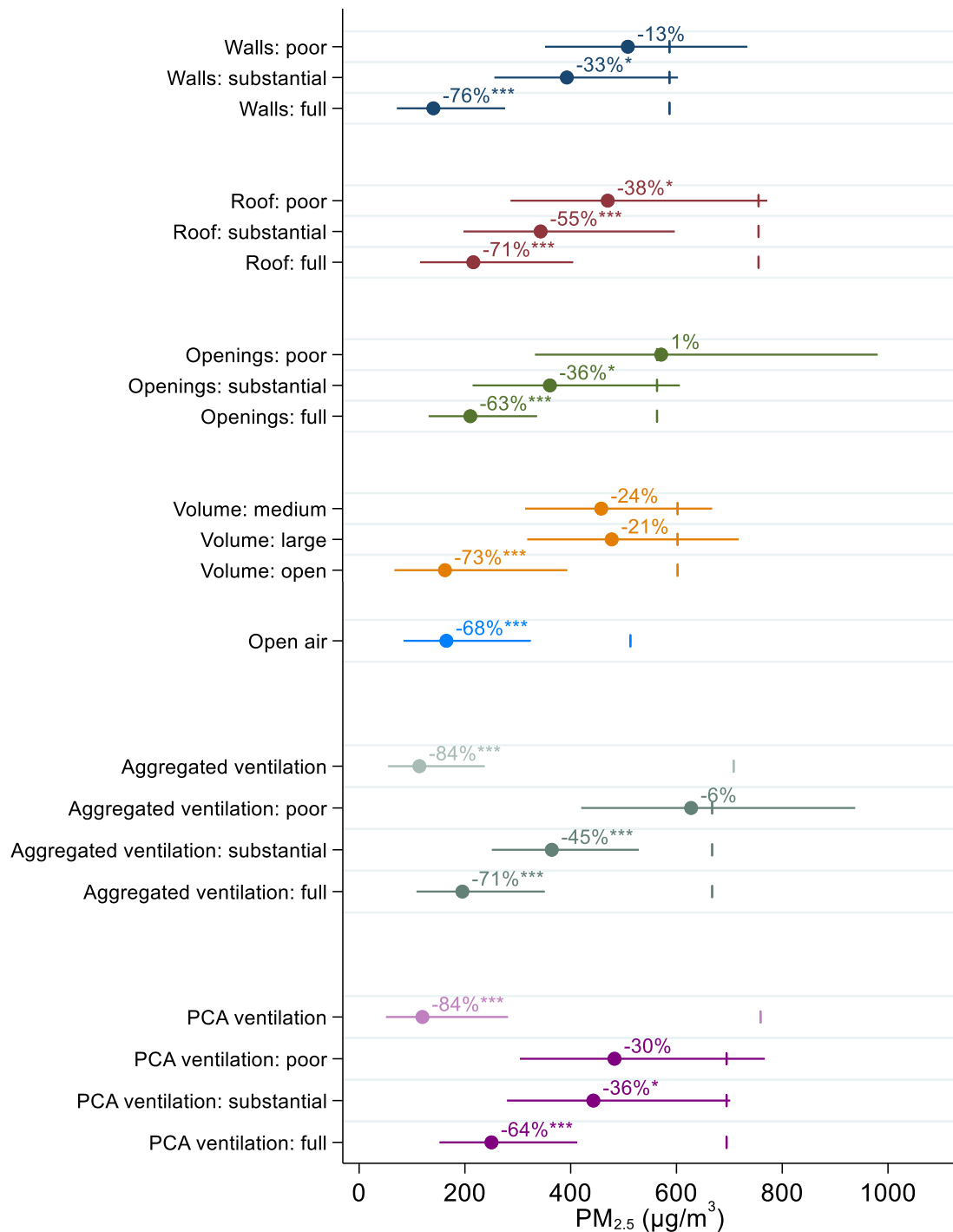


Fig. 4. Associations between kitchen concentration and ventilation indicators.

Note: The coefficient plot displays estimates for each ventilation indicator in the specifications where we regress the log of 24-h average $PM_{2.5}$ kitchen concentration on the full set of control variables. The reference category, which is presented by dashed vertical lines, is the lowest category according to each indicator, i.e. most unventilated, closed, or smallest kitchen. Horizontal lines indicate the 95% confidence intervals. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; $N = 211$ in all estimations.

concentrations from 560 to $750 \mu g/m^3$ to between 140 and $250 \mu g/m^3$. The coefficient of switching from *no* to *poor* ventilation varies between +1% and -38%, and that of switching to *substantial* ventilation between -21% and -55%. These relationships are qualitatively robust across specifications. R-squared values of the OLS estimations suggest that at least 42% of variance across indicators can be explained by the full set of controls. The binary *open air* indicator as well captures important variation in ventilation and the continuously defined composite indicators

for *aggregated ventilation* and *PCA ventilation* suggest a reduction of around 84% when switching from the extremes of *no* to *fully* ventilated kitchens. Regarding the categorical versions of the two composite indicators, the coefficients for the individual categories of *aggregated ventilation* are more differentiated than those for *PCA ventilation*. *PCA ventilation* exhibits the more precise estimates.

Further insight can be obtained from the covariate coefficients in the full specifications that underlie Fig. 4 (Appendix Table D.1). Pollution

levels are consistently and significantly lower when the dirtiest stove (within 3 m distance to the meter) is an LPG stove, when study participants are illiterate, cook for fewer people, or report that they smell neighbours' smoke relatively infrequently (less than weekly).⁹ The latter may indicate that diffusion of secondary pollution into households' kitchens is higher among people with higher kitchen concentration. Somewhat unexpectedly, the simple and advanced EEBCs assigned randomly as part of the impact evaluation this analysis is a part (see Section 3.1) did not significantly affect air pollution.¹⁰

5.1.2. Sensitivity analyses

Fig. 4 presented results separately for each ventilation indicator. We also estimated several models with multiple indicators, focusing especially on combinations that included kitchen volume as a continuous variable. Controlling for volume does add explanatory power to the models that include other ventilation indicators and some of the association between ventilation and pollution migrates to volume, but the association itself is not significant (Appendix Table D.1).¹¹ Moreover, one would expect that the role of volume for kitchen concentration increases as kitchens become less ventilated. Interacting volume and ventilation is suggestive of such a relationship, but the coefficients are imprecisely estimated. Overall, we tentatively conclude that increased kitchen volume is negatively related to kitchen concentration, and that this variable may be more important in less ventilated kitchens.

Our main analysis examined average 24-h pollution. This measure masks considerable variation during the day as pollution levels drop at night, and peak episodes coincide with periods of cooking. We therefore also regress PM_{2.5} percentiles on the composite indicators, and find that ventilation is significantly associated with lower kitchen concentration during periods of high pollution (e.g., above the 80th percentile concentrations), but not during periods with medium or low pollution levels (Figure D.1 in Appendix). This is in line with expectations and increases confidence in our results.

In addition, we investigate the role of unobservables using the Oster method. Specifically, we compute Oster's delta for the three ventilation indicators to which it can be applied: the continuous *aggregated* and *PCA ventilation* indicators and the *open air* indicator. We find the delta to be extremely high for all indicators (Appendix Table D.1). To make the ventilation coefficient equal to zero, unobservables in our model would need to be at least 7 times more important, respectively, than what the other observables in our model explain. This seems unlikely, and further increases confidence in the results.

Next, to test whether the observed association is driven by households with *open air* kitchens, we estimate the model on a reduced sample that excludes these households, who comprise eight percent of the kitchen concentration sub-sample. *Aggregated* and *PCA ventilation* indicators decrease slightly in size, but remain large and significant, suggesting that the identified coefficient is not driven exclusively by households cooking outdoors (Appendix Table D.3).

⁹ Another significant difference is observed between the two measurement devices: the MicroPEM measured systematically higher concentrations than the IAP meters. This may be explained by the fact that the gravimetric data collection method captures smaller particles than the light-scattering nephelometer in the IAP meters and is considered a more precise measurement approach. In any case, we expect the difference to be in levels and hence not to bias our estimates.

¹⁰ The most plausible explanation for this finding seems that the simple EEBC is not designed to reduce emissions and – in contrast to the findings from Bensch and Peters (2015) – does not achieve pollution reductions via substantial changes in cooking duration. In contrast, the advanced EEBC was designed to reduce emissions, but uptake was lower and performance of this stove in the field did not meet expectations.

¹¹ Alternatively, Appendix Table D.2 excludes open-air cooking households and looks at the association between continuous volume and air pollution. The volume coefficient is marginally significant only in some specifications.

Finally, we did not control for the health of the primary cook in our main analysis, as health status is likely endogenous to air pollution in kitchens. In a separate estimation, we include a subjective indicator (self-reports of suffering from red or irritated eyes) and an objective indicator (normal blood pressure), to see whether our results hold if we include these potentially endogenous variables. Coefficient sizes of some ventilation indicators increase slightly but are otherwise robust to these changes. Self-reported experience of red or irritated eyes is significantly related to kitchen concentration, likely due to reverse causality (see Appendix Table D.4).

5.2. Ventilation and cooks' personal exposures

In Fig. 5, we observe no clear relationship between kitchen ventilation and cooks' personal exposure. Overall, coefficient sizes are small, significance is marginal at best, and statistically significant coefficients are not robust to different specifications and indicators. Several other factors are significantly associated with personal exposures (Appendix Table E.1), most prominently whether those who wore the MicroPEMs were the households' primary cooks.

Similarly to the analysis of kitchen concentration percentiles, we regress PM_{2.5} personal exposure percentiles on the composite indicators to test for associations during periods with higher pollution (which more clearly indicate that cooking is underway). In fact, our composite ventilation indicators do suggest such an association, but only with the highest percentiles of concentrations (above the 97th percentile, in contrast to the 75th to 80th percentile for kitchen concentrations), and with substantial variation (Figure E.1 in Appendix).

The much lower variance share explained by our multivariate analyses of cooks' exposure also indicates that unobserved context-specific factors likely play a larger role for personal exposures than for kitchen concentration. While these factors also include the pollution that cooks face during non-cooking activities and exposures during periods when the MicroPEM was not worn, behaviour likely drives personal exposure more strongly, and also more than kitchen concentration. Selective smoke avoidance could, for example, occur if cooks are more inclined to leave a smoky cooking space, thus delivering benefits in less ventilated places and cancelling out the effect of poorer ventilation on exposures. Cooks may also have been sensitized to engage in smoke avoidance by our interviews and the very act of wearing devices.

We observe such behavioural responses only imperfectly and thus cannot rigorously test for them, but three additional pieces of evidence suggest that they may be at play. First, and consistent with selective responses, median personal-to-kitchen pollution ratios increase with kitchen ventilation: households with increasingly open kitchens, as measured from poor to full for *aggregated ventilation*, have median ratios of 0.25, 0.24, 0.38, and 0.62, respectively. Second, we find mixed evidence when assessing the relationship between two proxies for behavioural smoke avoidance and other relevant variables. In particular, the relationship between better ventilated kitchens and self-reports of avoidance behaviour as well as the share of cooking time spent off the stove is mostly insignificant, but rather negative when including the full set of control variables (Appendix Table E.2). Third, Fig. 5 suggests that some of our ventilation indicators, most notably wall ventilation, are non-linearly related to personal exposure, which either reflects large confidence intervals, or selective smoke avoidance behaviour. Similarly, cooks may respond differently depending on their baseline health. Introducing health proxies to the estimation, does not confirm this hypothesis, however (Appendix Table E.3). Lastly, we check whether controlling for kitchen concentration affects personal exposure results (Appendix Table E.1). We see a positive kitchen concentration coefficient that is robust across indicators, but the coefficients of the ventilation indicators are neither strongly nor systematically affected by addition of this control.

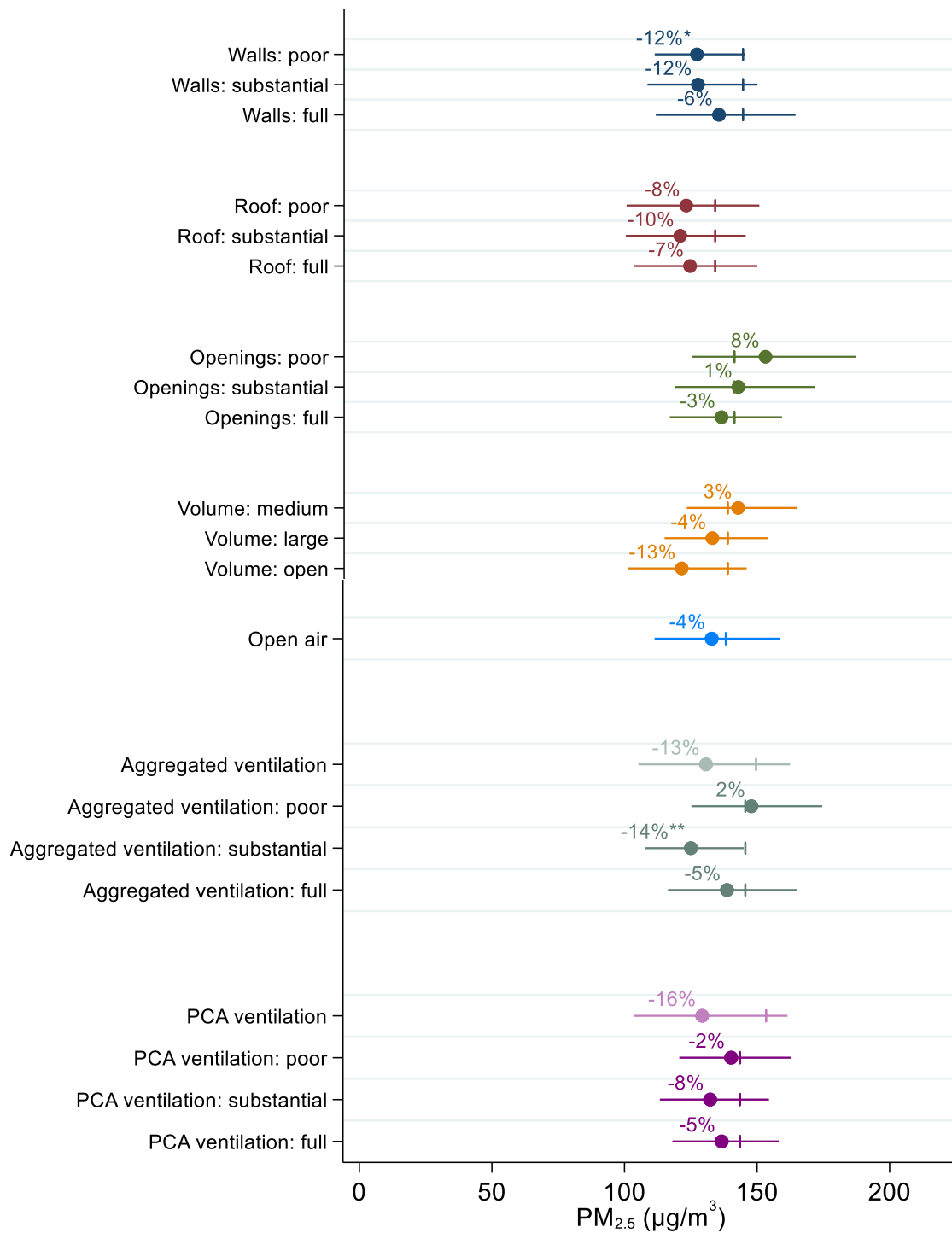


Fig. 5. Associations between personal exposure and ventilation indicators.

Note: The coefficient plot displays estimates for each ventilation indicator in the specifications where we regress the log of 24-h average personal exposure to PM_{2.5} on the full set of control variables. The reference category, which is presented by dashed vertical lines, is the lowest category according to each indicator, i.e. most unventilated, closed, or smallest kitchen. Horizontal lines indicate the 95% confidence interval. We do not show estimates for kitchen separation given that very few households cook inside or in a space attached to the main building (see Fig. 2). ***p < 0.01, **p < 0.05, *p < 0.1; N = 414 in all estimations.

5.3. Contextualization of results

To put the pollution reduction potentials found in this study in perspective, we first compare kitchen concentration reduction estimates to those of stove and fuel interventions as determined in a recent meta-analysis (Pope et al., 2021). In that analysis of evidence from 39 studies on EEBCs, EEBCs without and with chimneys lowered PM_{2.5} kitchen concentration compared to traditional stoves by 52% and 63%, respectively. The same meta-analysis used 18 studies to estimate a decrease in PM_{2.5} kitchen concentration of 83–86% from the adoption of clean fuel stoves (LPG, electricity and ethanol) among samples of households where the baseline technology was a traditional stove. This finding is in line with previous research that shows that stacking of more and less polluting fuels and stoves is often prevalent among poor households (Ruiz-Mercado and Masera 2015). Panel A of Fig. 6 provides a graphical comparison of those results and our results for *substantial* and *full* ventilation across the different indicators. Both relative and absolute changes again have to be considered to make meaningful comparisons.

Effect sizes for EEBCs correspond roughly to the coefficient estimates we find in switching from *no* kitchen ventilation to *substantial* ventilation, and the effect sizes for clean fuels are only slightly higher than what we find for *fully* ventilated kitchens. One could also interpret our coefficient sizes for *substantial* and *full* ventilation as equivalent to doing 20%–56% and 62%–77% of cooking on a fully *clean* stove with zero emissions, keeping everything else constant. Other research suggests that stove stacking in similar populations that use clean stoves is indeed prevalent, with 20%–80% of cooking being done on cleaner stoves among households who own them (Jeuland et al., 2018).

Panel B of Fig. 6 makes obvious that there is a considerable discrepancy between our estimates and those of the – relatively fewer – studies that look at personal exposure. The figure suggests that the difference is partly driven by the reference pollution level. For example, the reference pollution level for the studies on EEBC with chimneys covered by Pope et al. (2021), which all come from Latin America and South Asia, is five times higher than the reference pollution levels of *no* ventilation households in our sample. At the same time, half the studies find reference pollution levels similar to those in our study.

The results on kitchen concentration and personal exposure furthermore imply a low correlation between the two outcomes. One measure to express this relationship is the median ratio between the two, that is, the personal-to-kitchen PM_{2.5} pollution ratio. We find a ratio of 0.37 in our sub-sample of households that participated in both measurements ($n = 202$). This is much lower than the spatially uniform value of 0.74 applied for women by the leading epidemiological research program on global health risks, the Global Burden of Disease Study (Shupler et al., 2020). The multi-country study by Shupler et al. (2020) helps to contextualize this discrepancy: these authors find similar levels with median ratios between 0.33 and 0.44 in countries with similar cooking conditions to those in Senegal, namely Bangladesh, Pakistan, and Zimbabwe. Countries studied by Shupler et al. (2020) with clearly different shares of clean fuel and/or chimney woodfuel stove usage – China, India, Chile, and Columbia – have considerably higher ratios, ranging between 0.88 and 1.33. The same picture emerges when looking at correlation coefficient between kitchen concentration and personal exposure, which we find to amount to 0.26 (Pearson's r), or alternatively 0.34 (Spearman's ρ).¹² In the countries studied by Shupler et al. (2020), Spearman correlation coefficients range between 0.15 and 0.36 for those countries with similar cooking conditions and

¹² The ratio is only somewhat higher for peak pollution, while the correlation tends to be lower (for example, the values are 0.48 and 0.16/0.24 at the 90th percentile, respectively, reflecting the 2.4 most polluted hours).

between 0.31 and 0.79 for countries with different shares of clean fuel and/or chimney woodfuel stove usage.¹³

6. Conclusion and policy implication

This paper has demonstrated that kitchen concentration of PM_{2.5} greatly exceed the WHO guideline value in rural Senegal. This holds true even outside of cooking hours, indicating that ambient air pollution is already above WHO standards. Our results also show that average kitchen concentration has a large, highly significant, and robust inverse relationship with kitchen ventilation, but not for average personal exposure. A significant association can only be detected at the very highest (above 97th) percentile concentrations of the PM_{2.5} distribution. This provides tentative evidence that cooking behaviour is important for the relationship between pollution levels and exposures: cooks seem to evade all but the highest concentrations of smoke, perhaps by leaving the kitchen during some portion of peak emission events. In combination, our findings suggest that the crucial question of people's exposure to harmful smoke is co-determined by cooking fuels, stoves, cooking behaviour and kitchen ventilation, echoing arguments that have already been made long ago by Smith et al. (1983). The narrow focus in the policy debate on cooking fuels and stoves seems partly misleading.

This observation leads us to a number of conclusions and recommendations regarding pollution and ventilation measurement and potential policy responses to household air pollution. Regarding measurement, our study provides a blueprint for how to conceptualize and operationalize ventilation as part of the cooking environment, both using one- and multi-dimensional indicators for ventilation. More can be done to systematize aspects of ventilation and cooking behaviour, and to understand the influence of ambient air pollution, which is well above the WHO guideline value in our setting. Some of the discrepancies between our findings and those of previous studies may be driven by different procedures, protocols, and measurement devices, which calls for more standardized approaches. At the same time, the variation across studies also hints at the context dependence of cooking-related emissions. In line with studies from similar contexts, we find much lower personal-to-kitchen pollution ratios than the global default applied by the Global Burden of Disease Study to estimate the burden of disease from traditional cooking. We therefore recommend replacing this global default with a differentiated set of default values that account, at a minimum, for fuels and the cleanliness of the stoves. In addition, we caution against overinterpreting any such default values and, likewise, technology-based cookstove classifications, since such factors and classifications fail to incorporate the important roles of both ventilation and cooking behaviour.

A more holistic view of cooking environments that explicitly considers kitchen ventilation could also improve intervention planning and policy-making. This begins with the design of cookstove interventions,

¹³ This is also consistent with data from Pope et al. (2021) who find higher ratios for households with clean stoves (around 0.7–0.8) than with traditional stoves (around 0.5). Higher ventilation through chimneys installed in the kitchens would likely show lower personal-to-kitchen ratios, as also evidenced in a study from Sri Lanka (Chartier et al., 2017). For an eighth country studied by Shupler et al. (2020), Tanzania, the authors provide no values due to low sample size. We further screened the *Global database of household air pollution measurements* (WHO 2018) to retrieve additional values for comparison. However, merely four studies report either a ratio or correlation for PM, which are all hardly comparable, as one studies children (and finds a lower correlation coefficient) and three are from samples with chimney stoves (and find somewhat higher ratios or correlations ranging between 0.4 and 0.6). Lastly, it is worth noting that the discrepancy in the personal-to-kitchen ratio may also be linked to a lack of uniformity in the distribution of pollutant emissions within the cooking space (cf. MacCarty et al., 2020). This could result in cooks' exposures being from zones with pollution levels diverging from measured kitchen concentrations.

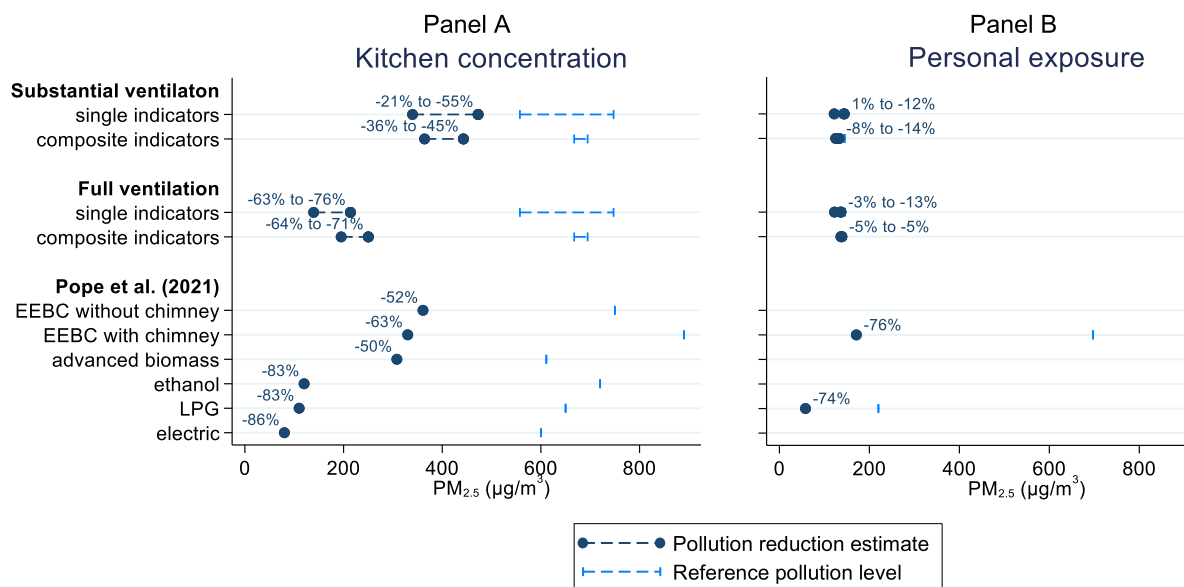


Fig. 6. Reduction potentials compared to those from stove and fuel interventions.

Note: Advanced biomass stoves refer to stoves fuelled with biomass and with fans to aid combustion or to stoves that use gasification.

where currently a number of EEBC models are being promoted that are bricked into the kitchen and, hence, non-portable. Such technologies may push households to cook in spaces with lower ventilation (see Hanna et al., 2016; Grimm and Peters 2012). Ventilation can also be integrated into transitional interventions that complement clean cooking access policies, for example information campaigns that sensitize biomass users to the many ways they might reduce exposure to harmful smoke, including cooking outdoors, leaving windows and doors open, minimizing time spent in close proximity of the cooking fire, using fans, or installing more advanced solutions such as kitchen retrofits with chimneys and exhaust hoods. Some ventilation improvements are cheap and may be cost-effective if adapted to the local context, such as simple housing modifications to add openings. Others will be more expensive and may require subsidies to achieve substantial uptake. Furthermore, low-cost EEBCs combined with, or targeted to, households with highly ventilated kitchens may be particularly effective as a transitional solution towards cleaner cooking. Such a strategy may also be more cost-effective than clean technology promotion, especially in remote rural areas where the supply chain for clean options is interrupted (for similar claims see Langbein et al., 2017 and Teune et al., 2020).

As alluded to in the comments above, this study has several important limitations. Chief among these are issues that relate to its limited context: we only cover one region in rural Senegal during a single (dry) season, over a short time period (24 h), and from a relatively small sample. Ambient pollution concentrations and the complexity of exposures vary substantially across the low- and middle-income contexts where clean cooking remains elusive, and our findings may not generalize. A related issue is that while this paper does a great deal to systematize the analysis of ventilation conditions observed in developing country kitchens, a more challenging task awaits regarding characterization of cooking behaviours, which are highly varied, private, and

difficult to observe. More detailed direct observations of such behaviours would clearly raise concerns about Hawthorne effects. Purely anthropological long-term research, meanwhile, better suited to avoiding the problem of outsiders influencing observations, may not easily scale to the degree needed for quantitative studies and tests. Finally, our study stops at pollution levels and exposures, and does not consider health outcomes.

Indeed, the absence of evidence on reductions in personal exposure from improved ventilation cautions against asserting that ventilation alone will trigger reductions in personal exposure that are sufficient to mitigate the negative health impacts of household air pollution. It remains true that only exclusive use of clean stoves has the potential to fully eliminate this pollution. Still, there is room (and need) for experimentation with a number of interventions – information campaigns, combined technology-ventilation promotion, and subsidies for larger investments – to shed light on their potential role in improving the cooking environment. In light of substantial challenges with providing universal access to clean stoves, we therefore recommend that the effects of kitchen ventilation and behavioural interventions and conditions be considered and tested more systematically by researchers, and results from such studies be shared with policy-makers seeking to understand and overcome the myriad burdens of traditional cooking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and replication code for the analysis presented in this paper can be accessed online: Bensch, G., Jeuland, M., & Lenz, L. (2023):

Replication files for "Releasing the killer from the kitchen? Ventilation and air pollution from biomass cooking". RWI-REPLICATION-FILES. Version: 1. RWI – Leibniz Institute for Economic Research. Dataset. doi.org/10.7807/sn:lenzetal:deveng:2023:v1.

Appendix

Appendix A. The composite CHAID ventilation indicator

We also tested a third composite indicator that differs in two further ways from the two presented in the main text: first, it brings in outcome and control variable information, and, second, the categorization is not based on equal sample splits but is rather informed by the data. It relies on an algorithm that recursively searches through alternative potential splits of the four single ventilation indicators to uncover an optimal “decision tree” that explains the dependent variable. For the dependent variable, we use predicted kitchen concentration, such that the categorization explains the outcome variable conditional on the control variables. We call this indicator *CHAID ventilation* according to the name of the recursive partitioning technique Chi-square automated interaction detection (CHAID) on which it is based, which was originally proposed by Kass (1980).

We set the CHAID algorithm to create a four-category indicator for the data to make it comparable to the other composite indicators. The CHAID algorithm requires to categorize the outcome variable into quantiles (nq) and allows to set two minimum requirements, the minimum number of observations allowed in a terminal cluster or “node” (mn) and the minimum number of observations across all levels of an optimally merged splitting variable (ms). With our sample, CHAID splits the data into four categories when setting these three values to $nq = 5$, $mn = 30$ and $ms = 50$. The resulting four categories of *CHAID ventilation* are depicted in Figure A.1 and include the following categories of the single kitchen ventilation indicators: *category 1 (no ventilation)*: walls{ no }, roof{ no }, openings{ no to substantial }; *category 2 (poor ventilation)*: like category 1, but with roof{ poor to full }; *category 3 (substantial ventilation)*: walls{ poor to full }, openings{ no to substantial }; *category 4 (full ventilation)*: openings{ full }.

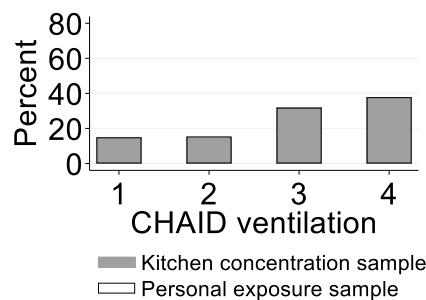


Fig. A.1. Distribution of households across indicator categories

However, this indicator comes with a number of shortcomings in our study context. First, since we fit the CHAID indicator to kitchen concentration, for which we have data only from a sub-sample, this indicator is available for this sub-sample only. Second, the study sample is anyway rather small for the data-driven nature of the underlying algorithm. This affected our methodology in that we did not split the sample into training data and validation data but used the entire available sample for both training and validation. Furthermore, the algorithm could only find splits in the data when not using the entire set of control variables, but excluding the measurement controls. Third, we also find indications that the indicator suffers from overfitting: in the analysis where we regress $PM_{2.5}$ percentiles on the composite indicators, we find a reverse relationship for poorly ventilated households according to *CHAID ventilation* (Appendix D; Figure D.1). Hence, while *CHAID ventilation* is fitted to the households’ mean kitchen concentration, this comes at the cost of it being unfit for disaggregated pollution data.

These shortcomings may be overcome with even larger study samples so that the *CHAID ventilation* indicator may be an option for multi-dimensional ventilation measurement in other settings. However, in light of these shortcomings we abstain from showing results for this indicator in the present study.

Appendix B. Calibration and in-field use of measurement devices

Most measurement devices used were gravimetric Micro Personal Exposure Monitors (MicroPEMs, RTI International, USA). Prior to the beginning of the study, all MicroPEMs were tested against a laboratory reference (TSI DustTrak 8530) with a well-characterized challenge aerosol (0–2.5 μm Arizona Test Dust) to confirm performance and functionality. The MicroPEMs do not undergo calibration per se as the MicroPEM collects a gravimetric sample filter during each deployment (gold standard). The corresponding real-time $PM_{2.5}$ data were then post-corrected to match the gravimetrically

determined mean PM_{2.5} concentration. All filters were pre- and post-weighed in an environmentally controlled weighing facility (21 °C, 35% relative humidity) at RTI (Research Triangle Park, NC) using an ultra-microbalance (Mettler Toledo UMX2). We collected approximately 4% field blanks. These are pre-weighed filters that travel to the field and are handled in the same manner as the sample filters, but are never deployed for collection of samples. As such, they function as a measure of potential contamination during filter handling. All gravimetric filter data were post corrected by subtracting the mean net mass of the field blank filters.

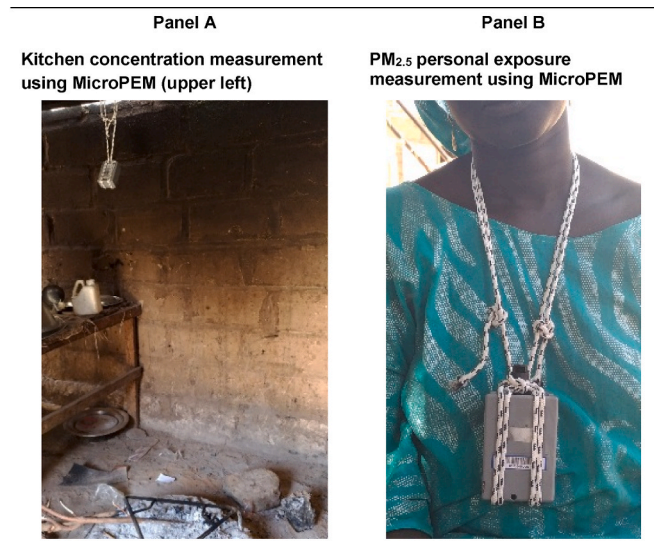


Fig. B.1. In-field use of measurement devices of kitchen concentration and personal exposure

The additionally deployed optical Indoor Air Pollution Meters (IAP Meters, Aprovecho, USA) were always cleaned before installation and a simple algorithm was applied to post-correct the baseline drift.

In the field, Kitchen concentration was measured at an approximate 1-m vertical and horizontal distance from households’ main stoves, and personal exposure was measured at chest level of the person responsible for cooking (see Figure B.1).

Appendix C. Descriptives

Table C.1

Household, cooking, and measurement controls, by measurement sub-sample

	Kitchen concentration mean (sd)	Personal exposure mean (sd)
(i) Socio-demographic and wealth characteristics		
Age of Participant	32.43 (11.40)	32.62 (10.55)
Participant is homemaker	0.59	0.57
Participant is literate	0.17	0.19
Participant is Wolof	0.72	0.72
HH size	11.87 (5.90)	12.14 (6.44)
HH has a private tap	0.68	0.66
HH has an electricity source	0.58	0.57
HH’s normalized wealth index	-0.04 (1.05)	0.02 (1.07)
(ii) Cooking variables		
Dirtiest stove = traditional wood stove, exclusively	0.50	0.48
Dirtiest stove = traditional wood stove + other fuel(s)	0.25	0.27
Dirtiest stove = basic metal stove	0.09	0.08
Dirtiest stove = fuelwood EEBC	0.14	0.13
Dirtiest stove = LPG stove	0.03	0.04
Share of meals cooked on an open-fire stove	0.67	0.68
Total cooking duration per day	332.57 (126.44)	337.55 (122.71)
Person-caterings per day	31.94 (20.16)	34.25 (24.16)

(continued on next page)

Table C.1 (continued)

	Kitchen concentration	Personal exposure
	mean (sd)	mean (sd)
Treatment group: control	0.70	0.71
Treatment group: simple EEBC	0.14	0.14
Treatment group: advanced EEBC	0.16	0.16
(iii) Cooking behaviour		
Household regularly burns agricultural waste at home	0.33	0.34
Participant reports to avoid kitchen smoke	0.84	0.80
Participant smells neighbours' smoke at least weekly (secondary exposure to air pollution)	0.35	0.31
(iv) Health status		
Participant has normal blood pressure	0.45	0.41
Participant has red eyes at least sometimes	0.19	0.18
(v) Measurement controls		
Meter is MicroPEM	0.80	
Share of cooking events with meter installed	0.90	
Number of main cooks		1.39 (0.72)
Participant was main cook		0.73
Participant was secondary cook		0.14
Meter daytime wearing (in %)		0.70 (0.19)
Endline	0.42	0.43
Observations	220	418

Note: sd = standard deviation. We control for (Wolof) ethnicity because cooking practises differ across ethnic groups in Senegal. The wealth index is generated via Principal Component Analysis using 19 variables, among others land holding, device ownership and livestock ownership. The index is normalized to a mean of zero and a standard deviation of 1. The dirtiest stove refers to stoves observed to be located close (<3m) to the meter for kitchen concentration measurement, and to the self-reported dirtiest stove used for personal exposure measurement. Normal blood pressure is defined as (SYS<120 and DIA<80), as opposed to elevated pressure or hypertension stages, following the definition of the American Heart Association from 2017.

Table C.2

Sample sizes, by measurement and year

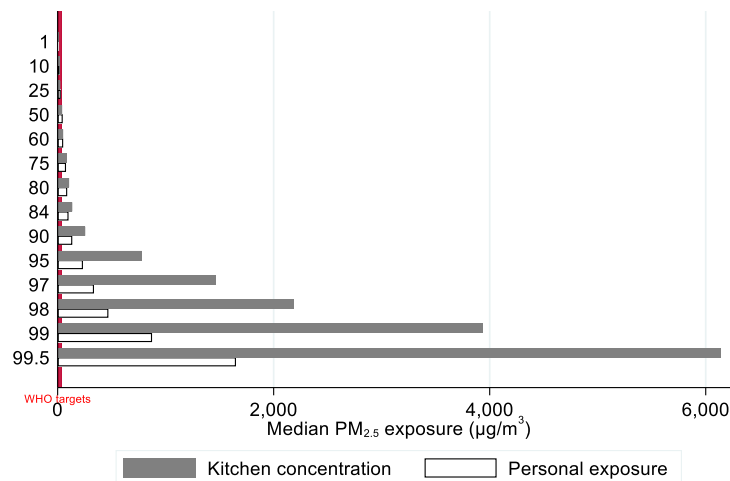
	Year 1	Year 2	Total
Kitchen concentration only	2	16	18
Personal exposure only	114	102	216
Kitchen concentration and personal exposure	125	77	202
Total	241	195	436

Note: We have a slightly larger sample from year 1, due to malfunctioning meters in year 2.

Table C.3
Spearman monotone dependence between ventilation indicators

	Kitchen walls	Kitchen roof	Kitchen openings	Kitchen volume	Kitchen separation	Aggregated ventilation	PCA ventilation
Kitchen roof	0.45	1.00					
Kitchen openings	0.44	0.53	1.00				
Kitchen volume	0.24	0.17	0.23	1.00			
Kitchen separation	0.39	0.52	0.42	0.34	1.00		
Aggregated ventilation	0.71	0.76	0.79	0.49	0.49	1.00	
PCA ventilation	0.62	0.55	0.46	0.72	0.45	0.80	1.00
CHAID ventilation	0.66	0.63	0.78	0.21	0.35	0.87	0.56

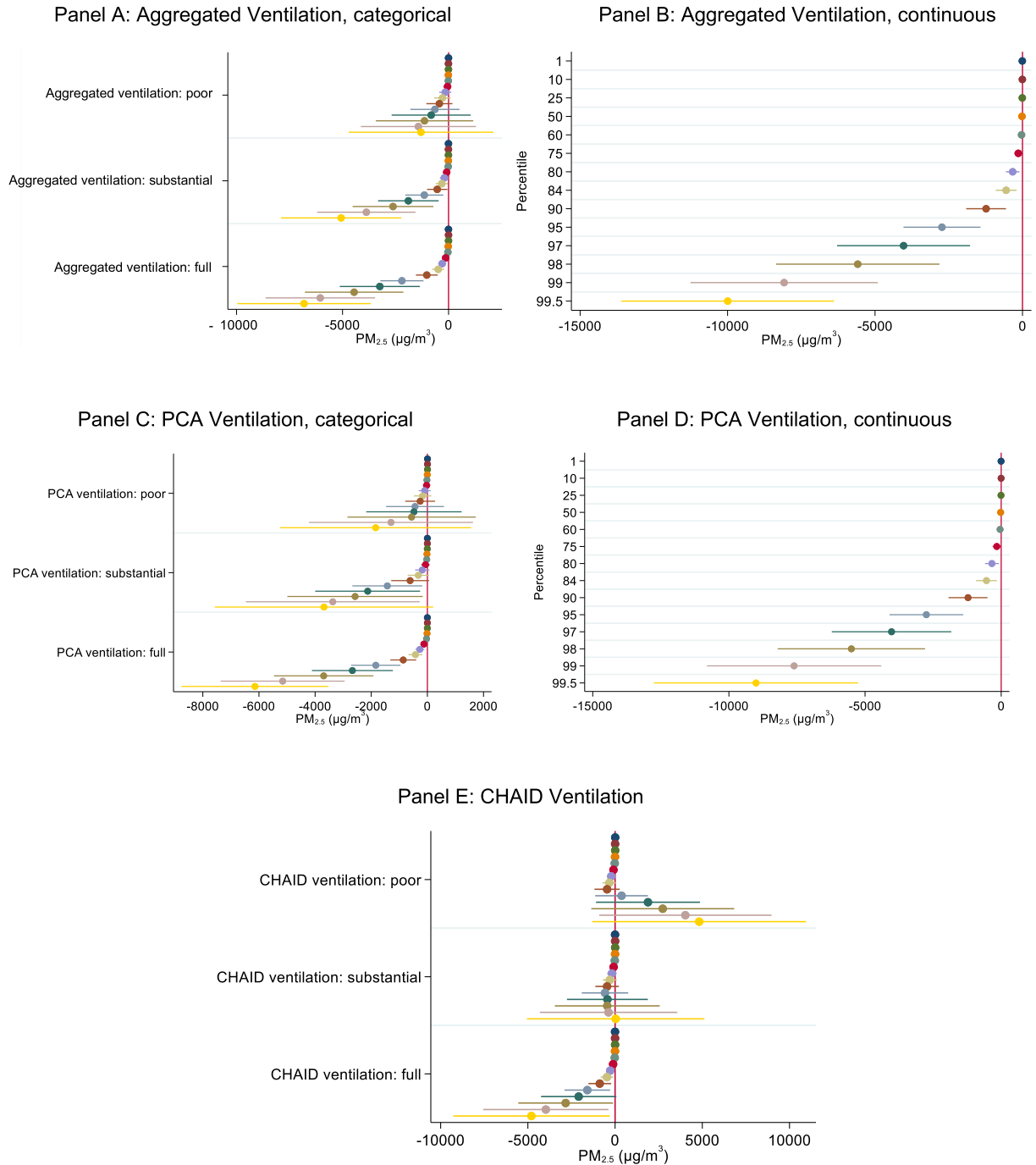
Note: Light-shaded cells refer to correlations among single ventilation indicators and darker-shaded cells to correlations among composite ventilation indicators. Medium-shaded cells represent correlations between single and composite ventilation indicators. The composite indicator CHAID ventilation is discussed in Appendix A.



Note: Percentiles on the y-axis, with smaller intervals at higher pollution levels. The 95th percentile value, for example, states that during 95 percent of the day or 22.8 hours, pollution is below that value.

Fig. C.1. Median kitchen concentration and personal exposure, by percentiles

Appendix D. Estimation results on kitchen concentration



Note: Graphs show coefficients and their 95% confidence intervals retrieved from our default OLS regression with the full set of controls, where each panel presents a different composite ventilation indicator.

Fig. D.1. Ventilation and percentile absolute kitchen concentration

Table D.1
Ventilation and kitchen concentration (PM_{2.5})

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL A: Single ventilation indicators										
Walls: poor	-0.21 (0.20)	-0.22 (0.20)	-0.18 (0.17)	-0.17 (0.18)	-0.14 (0.19)					
Walls: substantial	-0.58*** (0.21)	-0.57** (0.22)	-0.64*** (0.22)	-0.45** (0.21)	-0.40* (0.22)					
Walls: full	-1.24*** (0.35)	-0.87** (0.37)	-1.28*** (0.34)	-1.27*** (0.33)	-1.43*** (0.34)					
Roof: poor						-0.30 (0.25)	-0.26 (0.25)	-0.35 (0.23)	-0.39 (0.25)	-0.47* (0.25)
Roof: substantial						-0.46 (0.30)	-0.45 (0.30)	-0.56** (0.26)	-0.62** (0.28)	-0.79*** (0.28)
Roof: full						-1.10*** (0.32)	-0.78*** (0.29)	-1.19*** (0.31)	-1.06*** (0.33)	-1.25*** (0.32)
Endline	-0.19 (0.13)	-0.22* (0.13)	-0.24* (0.13)	-0.17 (0.18)	-0.04 (0.22)	-0.22 (0.13)	-0.25* (0.13)	-0.25* (0.13)	-0.21 (0.13)	0.04 (0.22)
Volume: medium		-0.19 (0.21)					-0.19 (0.22)			
Volume: large		-0.17 (0.23)					-0.16 (0.24)			
Volume: open		-0.68 (0.53)					-0.85* (0.46)			
Share of cooking events with measurement			0.22 (0.26)	0.40 (0.26)	0.47 (0.34)			0.25 (0.28)	0.46 (0.30)	0.72** (0.34)
MicroPEM			0.88*** (0.22)	0.91*** (0.20)	0.86*** (0.18)			0.89*** (0.21)	0.93*** (0.20)	0.94*** (0.19)
Participant's age				-0.00 (0.01)	-0.00 (0.01)				0.00 (0.01)	0.00 (0.01)
Participant is homemaker				0.35* (0.19)	0.20 (0.18)				0.37* (0.19)	0.24 (0.17)
Participant is literate				0.47** (0.22)	0.49*** (0.19)				0.54** (0.21)	0.55*** (0.17)
HH is primarily Wolof (d)				0.07 (0.23)	0.12 (0.22)				0.04 (0.22)	0.06 (0.21)
HH size (#)				0.04* (0.02)	0.03 (0.02)				0.04** (0.02)	0.03 (0.02)
HH has a private tap (d)				0.27 (0.19)	0.35* (0.19)				0.16 (0.18)	0.22 (0.17)
HH has modern electricity (d)				0.03 (0.31)	-0.08 (0.30)				0.06 (0.31)	-0.06 (0.29)
HH's normalized wealth index				0.06 (0.12)	0.11 (0.11)				0.01 (0.13)	0.07 (0.12)
Traditional wood stove + other fuel(s)					0.20 (0.22)					0.20 (0.23)
Basic metal stove					0.58 (0.44)					0.38 (0.50)
Improved woodfuel stove					0.00 (0.33)					0.03 (0.35)
LPG stove					-1.08** (0.49)					-1.37** (0.56)
Share of cooking on OFS					0.22 (0.31)					0.17 (0.30)
Total cooking duration					-0.00 (0.00)					-0.00** (0.00)
Simple treatment stove					0.21 (0.32)					0.09 (0.30)
Advanced treatment stove					0.10 (0.29)					0.04 (0.28)
Person-caterings per day					0.01** (0.00)					0.01*** (0.00)
Burn agricultural waste at home (d)					-0.28* (0.15)					-0.19 (0.14)
Participant avoids kitchen smoke					0.10 (0.24)					-0.05 (0.24)
Smell neighbours' smoke weekly (d)					0.46*** (0.16)					0.49*** (0.16)
Constant	5.79*** (0.27)	5.88*** (0.28)	4.95*** (0.42)	3.55*** (0.64)	3.32*** (0.74)	5.86*** (0.35)	5.96*** (0.37)	5.04*** (0.43)	3.49*** (0.57)	3.41*** (0.67)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat	582.7	582.7	582.7	586.9	586.9	637.8	637.8	638.3	641.7	641.7

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Table D.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
R-squared	0.21	0.22	0.29	0.37	0.46	0.19	0.21	0.28	0.35	0.44
	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)
PANEL B: Single ventilation indicators										
Openings: poor	0.50** (0.23)	0.52** (0.24)	0.41* (0.23)	0.12 (0.26)	0.01 (0.27)					
Openings: substantial	-0.18 (0.27)	-0.15 (0.27)	-0.31 (0.28)	-0.36 (0.25)	-0.45* (0.26)					
Openings: full	-0.93*** (0.25)	-0.72*** (0.21)	-1.02*** (0.24)	-0.94*** (0.24)	-0.98*** (0.24)					
Volume: medium		-0.20 (0.22)				-0.23 (0.22)	-0.23 (0.20)	-0.38* (0.20)	-0.27 (0.19)	
Volume: large		-0.13 (0.23)				-0.20 (0.23)	-0.10 (0.22)	-0.24 (0.21)	-0.23 (0.21)	
Volume: open		-0.73 (0.44)				-1.29*** (0.47)	-1.29*** (0.47)	-1.23*** (0.46)	-1.31*** (0.45)	
Endline	-0.12 (0.14)	-0.16 (0.14)	-0.15 (0.14)	-0.14 (0.15)	0.08 (0.24)	-0.27** (0.13)	-0.31** (0.13)	-0.26* (0.14)	-0.09 (0.23)	
Share of cooking events with measurement			0.28 (0.27)	0.45 (0.29)	0.70** (0.33)		0.16 (0.27)	0.43 (0.30)	0.54 (0.37)	
MicroPEM			0.88*** (0.21)	0.92*** (0.20)	0.91*** (0.20)		0.86*** (0.22)	0.90*** (0.20)	0.86*** (0.19)	
Participant's age				0.00 (0.01)	0.00 (0.01)			0.00 (0.01)	0.00 (0.01)	
Participant is homemaker				0.36** (0.18)	0.23 (0.17)			0.35* (0.18)	0.20 (0.17)	
Participant is literate				0.51** (0.21)	0.55*** (0.19)			0.61*** (0.22)	0.65*** (0.19)	
HH is primarily Wolof (d)				0.19 (0.21)	0.24 (0.21)			0.14 (0.24)	0.15 (0.23)	
HH size (#)				0.04* (0.02)	0.02 (0.02)			0.04* (0.02)	0.02 (0.03)	
HH has a private tap (d)				0.14 (0.17)	0.21 (0.17)			0.22 (0.19)	0.31 (0.19)	
HH has modern electricity (d)				0.08 (0.31)	-0.06 (0.31)			-0.03 (0.33)	-0.14 (0.32)	
HH's normalized wealth index				0.06 (0.12)	0.14 (0.11)			0.09 (0.13)	0.16 (0.12)	
Traditional wood stove + other fuel(s)					0.28 (0.23)				0.22 (0.21)	
Basic metal stove					0.40 (0.44)				0.60 (0.47)	
Improved woodfuel stove					-0.02 (0.33)				0.16 (0.37)	
LPG stove					-1.29** (0.50)				-1.09** (0.51)	
Share of cooking on OFS					0.13 (0.29)				0.28 (0.33)	
Total cooking duration					-0.00* (0.00)				-0.00 (0.00)	
Simple treatment stove					0.06 (0.31)				0.15 (0.33)	
Advanced treatment stove					0.01 (0.27)				0.10 (0.28)	
Person-caterings per day					0.01* (0.00)				0.01** (0.00)	
Burn agricultural waste at home (d)					-0.18 (0.14)				-0.20 (0.14)	
Participant avoids kitchen smoke					-0.02 (0.23)				0.08 (0.23)	
Smell neighbours' smoke weekly (d)					0.41** (0.16)				0.47*** (0.16)	
Constant	5.77*** (0.37)	5.84*** (0.35)	4.93*** (0.48)	3.56*** (0.64)	3.38*** (0.73)	5.54*** (0.27)	4.74*** (0.41)	3.28*** (0.59)	2.95*** (0.70)	
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Observations	220	220	219	212	211	220	219	212	211	
Mean(Y) reference cat.	543.2	543.2	542.7	543.2	543.2	507.2	507.2	515.2	515.2	
R-squared	0.23	0.25	0.31	0.37	0.44	0.18	0.26	0.34	0.42	

PANEL C: Single ventilation indicators

(continued on next page)

Table D.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)				
Open air	-0.99*** (0.33)	-0.58* (0.33)	-1.03*** (0.33)	-1.03*** (0.33)	-1.13*** (0.34)				
Volume: medium		-0.20 (0.22)							
Volume: large		-0.19 (0.23)							
Volume: open		-0.77 (0.53)							
Endline	-0.20 (0.14)	-0.24* (0.13)	-0.24* (0.14)	-0.21 (0.14)	-0.10 (0.21)				
Share of cooking events with measurement			0.14 (0.27)	0.36 (0.28)	0.50 (0.35)				
MicroPEM			0.86*** (0.22)	0.89*** (0.20)	0.85*** (0.19)				
Participant's age				-0.00 (0.01)	-0.00 (0.01)				
Participant is homemaker				0.37** (0.19)	0.22 (0.17)				
Participant is literate				0.56** (0.23)	0.59*** (0.20)				
HH is primarily Wolof (d)				0.11 (0.23)	0.15 (0.22)				
HH size (#)				0.04 (0.02)	0.02 (0.02)				
HH has a private tap (d)				0.29 (0.20)	0.36* (0.19)				
HH has modern electricity (d)				-0.02 (0.33)	-0.11 (0.31)				
HH's normalized wealth index				0.09 (0.12)	0.15 (0.11)				
Traditional wood stove + other fuel(s)					0.23 (0.22)				
Basic metal stove					0.62 (0.44)				
Improved woodfuel stove					0.08 (0.35)				
LPG stove					-1.00* (0.53)				
Share of cooking on OFS					0.23 (0.32)				
Total cooking duration					-0.00* (0.00)				
Simple treatment stove					0.29 (0.32)				
Advanced treatment stove					0.18 (0.27)				
Person-caterings per day					0.01** (0.00)				
Burn agricultural waste at home (d)					-0.26* (0.14)				
Participant avoids kitchen smoke					0.07 (0.22)				
Smell neighbours' smoke weekly (d)					0.44*** (0.16)				
Constant	5.46*** (0.29)	5.57*** (0.29)	4.69*** (0.45)	3.32*** (0.62)	3.11*** (0.73)				
Community and year	Yes	Yes	Yes	Yes	Yes				
Observations	220	220	219	212	211				
Mean(Y) reference cat.	503.5	503.5	503.0	505.6	505.6				
R-squared delta	0.18	0.19	0.26	0.35	0.43 15.56				
	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PANEL D: composite ventilation indicators									
Aggregated ventilation	-1.70*** (0.41)	-1.67*** (0.47)	-1.81*** (0.38)	-1.65*** (0.37)	-1.83*** (0.37)				
Aggregated ventilation: poor						0.12 (0.25)	0.08 (0.25)	0.00 (0.21)	0.05 (0.21)
Aggregated ventilation: substantial						-0.47** (0.21)	-0.52** (0.24)	-0.56*** (0.19)	-0.53*** (0.19)
Aggregated ventilation: full						-1.14*** (0.30)	-0.93*** (0.26)	-1.22*** (0.28)	-1.11*** (0.29)
									-1.23*** (0.30)

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Table D.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Endline	-0.19 (0.13)	-0.19 (0.13)	-0.23* (0.13)	-0.20 (0.13)	0.08 (0.22)	-0.17 (0.13)	-0.20 (0.13)	-0.21 (0.13)	-0.17 (0.13)	0.09 (0.23)
Volume: medium		-0.03 (0.21)					-0.10 (0.21)			
Volume: large		0.16 (0.24)					0.10 (0.24)			
Volume: open		-0.10 (0.53)					-0.57 (0.45)			
Share of cooking events with measurement			0.19 (0.25)	0.40 (0.26)	0.58* (0.31)			0.24 (0.26)	0.45* (0.27)	0.62* (0.32)
MicroPEM			0.91*** (0.21)	0.94*** (0.20)	0.93*** (0.18)			0.87*** (0.21)	0.91*** (0.19)	0.89*** (0.19)
Participant's age				-0.00 (0.01)	0.00 (0.01)				-0.00 (0.01)	-0.00 (0.01)
Participant is homemaker				0.35* (0.18)	0.20 (0.16)				0.38** (0.19)	0.25 (0.18)
Participant is literate				0.52** (0.21)	0.51*** (0.17)				0.54** (0.21)	0.53*** (0.18)
HH is primarily Wolof (d)				0.08 (0.22)	0.10 (0.20)				0.06 (0.22)	0.09 (0.21)
HH size (#)				0.04* (0.02)	0.03 (0.02)				0.04* (0.02)	0.03 (0.02)
HH has a private tap (d)				0.18 (0.17)	0.26 (0.16)				0.18 (0.18)	0.25 (0.17)
HH has modern electricity (d)				0.05 (0.30)	-0.09 (0.28)				0.06 (0.31)	-0.08 (0.29)
HH's normalized wealth index				0.05 (0.11)	0.12 (0.10)				0.07 (0.12)	0.14 (0.11)
Traditional wood stove + other fuel(s)					0.24 (0.21)					0.24 (0.21)
Basic metal stove					0.40 (0.43)					0.36 (0.43)
Improved woodfuel stove					0.02 (0.33)					-0.04 (0.33)
LPG stove					-1.36*** (0.50)					-1.37*** (0.51)
Share of cooking on OFS					0.24 (0.29)					0.16 (0.29)
Total cooking duration					-0.00* (0.00)					-0.00* (0.00)
Simple treatment stove					0.08 (0.30)					0.11 (0.29)
Advanced treatment stove					0.01 (0.27)					-0.04 (0.28)
Person-caterings per day					0.01** (0.00)					0.01** (0.00)
Burn agricultural waste at home (d)					-0.19 (0.13)					-0.16 (0.13)
Participant avoids kitchen smoke					-0.06 (0.23)					-0.10 (0.23)
Smell neighbours' smoke weekly (d)					0.50*** (0.15)					0.45*** (0.15)
Constant	6.22*** (0.36)	6.21*** (0.36)	5.42*** (0.46)	3.92*** (0.61)	3.74*** (0.71)	5.92*** (0.32)	5.97*** (0.32)	5.12*** (0.44)	3.63*** (0.61)	3.61*** (0.70)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat.	.	.	.	.	.	617.0	617.0	617.0	625.5	625.5
R-squared	0.23	0.23	0.32	0.39	0.48	0.23	0.24	0.31	0.39	0.47
delta					7.3					
	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL E: Composite ventilation indicators										
PCA ventilation	-1.72*** (0.48)	-1.99** (0.76)	-1.75*** (0.46)	-1.67*** (0.46)	-1.85*** (0.43)					
Quartile PCA ventilation: poor						-0.29 (0.25)	-0.41 (0.27)	-0.24 (0.23)	-0.32 (0.24)	-0.36 (0.23)
Quartile PCA ventilation: substantial						-0.36 (0.27)	-0.62* (0.35)	-0.24 (0.26)	-0.46* (0.23)	-0.45* (0.23)
Quartile PCA ventilation: full						-0.97*** (0.27)	-0.97*** (0.32)	-1.02*** (0.25)	-0.96*** (0.26)	-1.02*** (0.25)
Endline	-0.23* (0.13)	-0.23* (0.13)	-0.27** (0.13)	-0.23* (0.14)	-0.03 (0.22)	-0.20 (0.14)	-0.24* (0.13)	-0.25* (0.14)	-0.21 (0.14)	-0.00 (0.22)

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Table D.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Volume: medium		0.17 (0.24)					0.16 (0.24)			
Volume: large		0.39 (0.32)					0.40 (0.34)			
Volume: open		0.18 (0.71)					-0.48 (0.52)			
Share of cooking events with measurement			0.17 (0.26)	0.39 (0.28)	0.50 (0.34)			0.18 (0.28)	0.44 (0.30)	0.59 (0.37)
MicroPEM			0.85*** (0.22)	0.90*** (0.20)	0.88*** (0.18)			0.91*** (0.22)	0.93*** (0.21)	0.90*** (0.19)
Participant's age				0.00 (0.01)	0.00 (0.01)				0.00 (0.01)	-0.00 (0.01)
Participant is homemaker				0.35* (0.18)	0.20 (0.17)				0.33* (0.19)	0.19 (0.17)
Participant is literate				0.58*** (0.21)	0.58*** (0.18)				0.53*** (0.22)	0.53*** (0.18)
HH is primarily Wolof (d)				0.02 (0.23)	0.03 (0.21)				0.03 (0.22)	0.06 (0.21)
HH size (#)				0.04* (0.02)	0.03 (0.02)				0.04* (0.02)	0.02 (0.02)
HH has a private tap (d)				0.21 (0.18)	0.28* (0.17)				0.15 (0.18)	0.21 (0.18)
HH has modern electricity (d)				0.00 (0.30)	-0.10 (0.29)				0.05 (0.31)	-0.05 (0.30)
HH's normalized wealth index				0.09 (0.11)	0.16 (0.10)				0.11 (0.11)	0.17* (0.10)
Traditional wood stove + other fuel(s)					0.17 (0.21)					0.21 (0.23)
Basic metal stove					0.49 (0.44)					0.41 (0.44)
Improved woodfuel stove					0.00 (0.34)					-0.06 (0.36)
LPG stove					-1.26** (0.53)					-1.26** (0.52)
Share of cooking on OFS					0.28 (0.32)					0.19 (0.33)
Total cooking duration					-0.00* (0.00)					-0.00 (0.00)
Simple treatment stove					0.19 (0.31)					0.14 (0.31)
Advanced treatment stove					0.13 (0.27)					0.08 (0.28)
Person-caterings per day					0.01** (0.00)					0.01** (0.00)
Burn agricultural waste at home (d)					-0.20 (0.14)					-0.18 (0.15)
Participant avoids kitchen smoke					0.03 (0.22)					0.06 (0.23)
Smell neighbours' smoke weekly (d)					0.48*** (0.15)					0.44*** (0.15)
Constant	6.13*** (0.35)	6.16*** (0.37)	5.35*** (0.47)	3.91*** (0.61)	3.70*** (0.70)	5.80*** (0.28)	5.83*** (0.27)	4.96*** (0.43)	3.59*** (0.59)	3.37*** (0.69)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat.	.	.	.	.	.	571.4	571.4	571.4	573.2	573.2
R-squared	0.21	0.21	0.28	0.37	0.45	0.19	0.22	0.28	0.35	0.43
delta					166.1					

	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)
PANEL F: Composite ventilation indicators				
CHAID ventilation: poor	0.05 (0.32)		0.02 (0.32)	-0.05 (0.29)
CHAID ventilation: substantial	-0.39 (0.30)		-0.41 (0.31)	-0.47* (0.28)
CHAID ventilation: full	-0.89*** (0.29)		-0.73** (0.28)	-1.05*** (0.27)
Endline	-0.09 (0.14)		-0.15 (0.14)	-0.13 (0.14)
Volume: medium			-0.24 (0.22)	
Volume: large			-0.13 (0.23)	

(continued on next page)

Table D.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)
Volume: open		-0.94** (0.47)			
Share of cooking events with measurement			0.34 (0.29)	0.49 (0.30)	0.75** (0.33)
MicroPEM			0.89*** (0.22)	0.96*** (0.19)	0.98*** (0.18)
Participant's age				-0.00 (0.01)	-0.00 (0.01)
Participant is homemaker				0.34* (0.19)	0.20 (0.18)
Participant is literate				0.53** (0.21)	0.53*** (0.18)
HH is primarily Wolof (d)				0.12 (0.22)	0.12 (0.21)
HH size (#)				0.04* (0.02)	0.03 (0.02)
HH has a private tap (d)				0.15 (0.18)	0.20 (0.17)
HH has modern electricity (d)				0.08 (0.30)	-0.06 (0.28)
HH's normalized wealth index				0.03 (0.13)	0.11 (0.12)
Traditional wood stove + other fuel(s)					0.27 (0.23)
Basic metal stove					0.35 (0.47)
Improved woodfuel stove					-0.04 (0.33)
LPG stove					-1.42*** (0.50)
Share of cooking on OFS					0.14 (0.29)
Total cooking duration					-0.00* (0.00)
Simple treatment stove					0.02 (0.30)
Advanced treatment stove					-0.10 (0.28)
Person-caterings per day					0.01* (0.00)
Burn agricultural waste at home (d)					-0.26* (0.14)
Participant avoids kitchen smoke					-0.16 (0.24)
Smell neighbours' smoke weekly (d)					0.47*** (0.16)
Constant	5.89*** (0.43)	6.05*** (0.44)	5.09*** (0.48)	3.69*** (0.66)	3.74*** (0.76)
Community	Yes	Yes	Yes	Yes	Yes
Observations	212	212	212	212	211
Mean(Y) reference cat.	679.1	679.1	679.1	679.1	679.1
R-squared	0.19	0.22	0.28	0.36	0.44

Notes: The dependent variable is log of 24-h average PM_{2.5} kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. In order to derive percentage changes presented in the main text, coefficients are transformed with the formula $(\exp(\text{coef})-1)*100$. ***p < 0.01, **p < 0.05, *p < 0.1.

Table D.2
Kitchen volume and kitchen concentration (PM_{2.5}), closed-kitchen subsample and continuous kitchen volume definition

	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)
Kitchen volume (#)	-0.01 (0.01)	-0.00 (0.00)	-0.01 (0.00)	-0.01 (0.00)	0.00 (0.01)
Aggregated ventilation: poor					-0.03 (0.21)
Aggregated ventilation: substantial					-0.63*** (0.20)
Aggregated ventilation: full					-0.70*** (0.26)
Constant	5.54*** (0.34)	4.64*** (0.49)	3.22*** (0.59)	3.00*** (0.68)	3.36*** (0.67)
Community and year	Yes	Yes	Yes	Yes	Yes
Measurement	No	Yes	Yes	Yes	Yes
Cook and household	No	No	Yes	Yes	Yes
Cooking behaviour	No	No	No	Yes	Yes
Observations	192	191	185	184	184
R-squared	0.17	0.26	0.36	0.45	0.50

Notes: The dependent variable is log of 24-h average PM_{2.5} kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen; ***p < 0.01, **p < 0.05, *p < 0.1.

Table D.3
Ventilation and kitchen concentration (PM_{2.5}), closed-kitchen subsample

	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Aggregated ventilation: poor	0.14 (0.25)	0.13 (0.26)	0.02 (0.21)	0.07 (0.22)	-0.02 (0.20)					
Aggregated ventilation: substantial	-0.48** (0.21)	-0.50** (0.24)	-0.55*** (0.19)	-0.55*** (0.19)	-0.61*** (0.19)					
Aggregated ventilation: full	-0.77*** (0.23)	-0.79*** (0.26)	-0.86*** (0.21)	-0.61*** (0.23)	-0.71*** (0.25)					
Quartile PCA ventilation: poor						-0.34 (0.25)	-0.43 (0.27)	-0.30 (0.23)	-0.34 (0.23)	-0.38 (0.23)
Quartile PCA ventilation: substantial						-0.49* (0.26)	-0.70* (0.36)	-0.37 (0.24)	-0.58** (0.24)	-0.57** (0.23)
Quartile PCA ventilation: full						-0.68*** (0.24)	-0.89*** (0.33)	-0.76*** (0.21)	-0.61*** (0.23)	-0.63*** (0.23)
Constant	5.81*** (0.35)	5.86*** (0.35)	4.94*** (0.46)	3.43*** (0.53)	3.42*** (0.67)	5.70*** (0.31)	5.73*** (0.30)	4.84*** (0.45)	3.37*** (0.56)	3.16*** (0.68)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Kitchen volume	No	Yes	No	No	No	No	Yes	No	No	No
Measurement	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Cook and household	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Cooking behaviour	No	No	No	No	Yes	No	No	No	No	Yes
Observations	193	193	192	186	185	193	193	192	186	185
Mean(Y) reference cat.	617.0	617.0	617.0	625.5	625.5	571.4	571.4	571.4	573.2	573.2
R-squared	0.23	0.23	0.32	0.41	0.50	0.20	0.20	0.29	0.39	0.48

Notes: The dependent variable is log of 24-h average PM_{2.5} kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. ***p < 0.01, **p < 0.05, *p < 0.1.

Table D.4
Ventilation and kitchen concentration (PM_{2.5}), with health covariates

	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Walls: poor	-0.20 (0.18)									
Walls: substantial	-0.48** (0.21)									
Walls: full	-1.37*** (0.34)									
Roof: poor		-0.45* (0.25)								

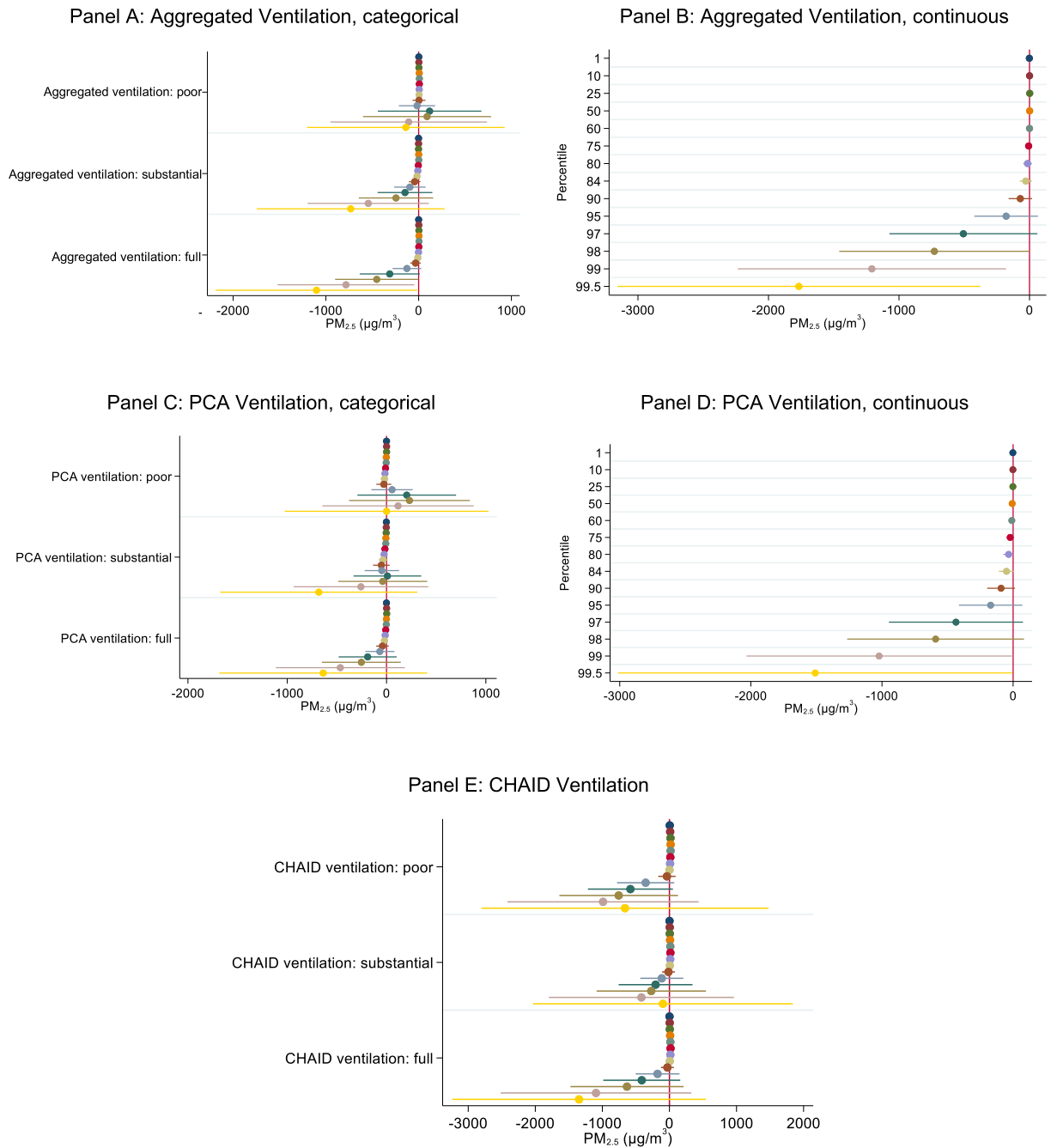
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Table D.4 (continued)

	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>	<u>coeff (se)</u>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Roof: substantial		-0.72** (0.28)								
Roof: full		-1.17*** (0.32)								
Openings: poor			0.04 (0.27)							
Openings: substantial			-0.49* (0.26)							
Openings: full			-0.93*** (0.23)							
Volume: medium				-0.28 (0.19)						
Volume: large				-0.26 (0.20)						
Volume: open				-1.25*** (0.44)						
Open air					-1.07*** (0.34)					
Aggregated ventilation						-1.77*** (0.37)				
Aggregated ventilation: poor							-0.07 (0.21)			
Aggregated ventilation: substantial							-0.64*** (0.19)			
Aggregated ventilation: full							-1.17*** (0.30)			
PCA ventilation								-1.79*** (0.44)		
Quartile PCA ventilation: poor									-0.37 (0.23)	
Quartile PCA ventilation: substantial									-0.46* (0.23)	
Quartile PCA ventilation: full									-0.97*** (0.25)	
CHAID ventilation: poor										-0.10 (0.31)
CHAID ventilation: substantial										-0.57* (0.32)
CHAID ventilation: full										-1.12*** (0.31)
Participant has normal blood pressure	0.14 (0.16)	0.18 (0.15)	0.17 (0.16)	0.17 (0.17)	0.15 (0.16)	0.11 (0.15)	0.13 (0.17)	0.11 (0.16)	0.13 (0.17)	0.17 (0.16)
Participant has red eyes at least sometimes	0.40** (0.16)	0.30* (0.18)	0.40** (0.16)	0.41** (0.17)	0.37** (0.17)	0.40** (0.16)	0.40** (0.17)	0.42** (0.17)	0.39** (0.17)	0.52*** (0.17)
Constant	3.23*** (0.75)	3.23*** (0.69)	3.25*** (0.73)	2.83*** (0.72)	2.98*** (0.74)	3.63*** (0.73)	3.48*** (0.73)	3.58*** (0.73)	3.23*** (0.72)	3.66*** (0.76)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Measurement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	211	211	211	211	211	211	211	211	211	211
Mean(Y) reference cat.	586.9	641.7	543.2	515.2	508.1	945.7	625.5	.	573.2	679.1
R-squared	0.47	0.46	0.46	0.44	0.45	0.49	0.48	0.47	0.45	0.47

Notes: The dependent variable is log of 24-h average PM_{2.5} kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. ***p < 0.01, **p < 0.05, *p < 0.1.

Appendix E. Estimation results on cooks' personal exposure



Note: Graphs show coefficients and their 95% confidence intervals retrieved from our default OLS regression with the full set of controls, where each panel presents a different composite ventilation indicator.

Fig. E.1. Ventilation and percentile absolute personal exposure

Table E.1
Ventilation and personal exposure (PM_{2.5}).

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL A: Single ventilation indicators										
Walls: poor	-0.09 (0.06)	-0.12* (0.06)	-0.12* (0.07)	-0.13* (0.07)	-0.10 (0.10)					
Walls: substantial	-0.10 (0.08)	-0.07 (0.08)	-0.10 (0.08)	-0.13 (0.08)	-0.10 (0.14)					
Walls: full	-0.15 (0.10)	-0.10 (0.09)	-0.06 (0.09)	-0.06 (0.10)	0.03 (0.19)					
Roof: poor						-0.07 (0.11)	-0.07 (0.10)	-0.06 (0.10)	-0.09 (0.10)	-0.15 (0.16)
Roof: substantial						-0.03 (0.09)	-0.05 (0.09)	-0.05 (0.09)	-0.10 (0.09)	-0.11 (0.15)
Roof: full						-0.08 (0.10)	-0.08 (0.09)	-0.05 (0.09)	-0.07 (0.09)	-0.06 (0.18)
24-h mean KC (log)					0.08** (0.04)					0.08** (0.03)
Endline	-0.16** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13* (0.08)	-0.05 (0.12)	-0.16*** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13 (0.08)	-0.06 (0.13)
Primary cook		0.48*** (0.07)	0.49*** (0.07)	0.51*** (0.07)	0.49*** (0.10)		0.48*** (0.07)	0.49*** (0.08)	0.52*** (0.08)	0.47*** (0.10)
Secondary cook		0.08 (0.08)	0.07 (0.09)	0.10 (0.09)	0.07 (0.15)		0.09 (0.09)	0.08 (0.09)	0.10 (0.09)	0.08 (0.15)
Main cooks (#)		-0.02 (0.04)	-0.03 (0.04)	-0.05 (0.04)	-0.01 (0.07)		-0.01 (0.04)	-0.03 (0.04)	-0.05 (0.04)	0.01 (0.07)
PE daytime wearing compliance (#)		0.47*** (0.14)	0.51*** (0.15)	0.45*** (0.16)	0.59** (0.26)		0.47*** (0.14)	0.50*** (0.15)	0.44*** (0.16)	0.58** (0.26)
Participant's age			-0.01** (0.00)	-0.00* (0.00)	-0.01 (0.00)			-0.00* (0.00)	-0.00* (0.00)	-0.01 (0.00)
Participant is homemaker			-0.03 (0.06)	-0.05 (0.06)	-0.11 (0.10)			-0.03 (0.06)	-0.05 (0.06)	-0.08 (0.10)
Participant is literate			0.06 (0.08)	0.06 (0.08)	-0.05 (0.11)			0.07 (0.08)	0.07 (0.08)	-0.04 (0.11)
HH is primarily Wolof (d)			-0.09 (0.07)	-0.07 (0.08)	0.06 (0.10)			-0.08 (0.07)	-0.07 (0.08)	0.07 (0.10)
HH size (#)			0.01* (0.00)	0.00 (0.01)	0.01 (0.01)			0.01* (0.00)	0.00 (0.01)	0.01 (0.01)
HH has a private tap (d)			-0.07 (0.07)	-0.05 (0.07)	-0.19* (0.11)			-0.06 (0.07)	-0.05 (0.07)	-0.19* (0.11)
HH has modern electricity (d)			0.14 (0.10)	0.10 (0.10)	0.12 (0.17)			0.14 (0.10)	0.09 (0.09)	0.11 (0.17)
HH's normalized wealth index			-0.02 (0.04)	-0.01 (0.04)	-0.07 (0.06)			-0.01 (0.05)	-0.00 (0.05)	-0.08 (0.06)
Traditional wood stove + other fuel(s)				0.03 (0.07)	0.11 (0.12)				0.03 (0.07)	0.09 (0.12)
Basic metal stove				0.03 (0.14)	0.14 (0.20)				0.04 (0.14)	0.15 (0.21)
Improved woodfuel stove				-0.06 (0.15)	-0.08 (0.19)				-0.06 (0.15)	-0.09 (0.19)
LPG stove				-0.18 (0.17)	0.16 (0.19)				-0.19 (0.17)	0.12 (0.20)
Share of cooking on OFS				0.11 (0.11)	0.13 (0.13)				0.11 (0.11)	0.13 (0.13)
Total cooking duration				0.00 (0.00)	-0.00 (0.00)				0.00 (0.00)	-0.00* (0.00)
Simple treatment stove				-0.05 (0.11)	-0.21 (0.19)				-0.07 (0.11)	-0.23 (0.19)
Advanced treatment stove				0.02 (0.10)	-0.10 (0.18)				0.02 (0.10)	-0.08 (0.18)
Person-caterings per day				0.00 (0.00)	0.00 (0.00)				0.00 (0.00)	0.00 (0.00)
Burn agricultural waste at home (d)				0.03 (0.06)	0.15* (0.09)				0.03 (0.05)	0.12 (0.09)
Participant avoids kitchen smoke				0.01 (0.07)	-0.03 (0.10)				0.01 (0.07)	-0.02 (0.10)
Smell neighbours' smoke weekly (d)				0.07 (0.06)	0.15 (0.09)				0.07 (0.06)	0.15 (0.09)
Constant	4.89*** (0.17)	4.26*** (0.18)	4.24*** (0.23)	4.12*** (0.28)	3.68*** (0.42)	4.86*** (0.18)	4.24*** (0.19)	4.20*** (0.23)	4.12*** (0.28)	3.71*** (0.41)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	146.2	146.2	147.1	147.1	153.7	129.6	129.6	130.6	130.6	139.6
R-squared	0.10	0.22	0.24	0.26	0.40	0.10	0.21	0.24	0.26	0.40

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL B: Single ventilation indicators										
Openings: poor	0.05 (0.11)	0.08 (0.10)	0.09 (0.10)	0.08 (0.10)	0.32* (0.17)					
Openings: substantial	0.09 (0.09)	0.04 (0.09)	0.03 (0.09)	0.01 (0.09)	0.09 (0.15)					
Openings: full	-0.04 (0.08)	-0.03 (0.08)	-0.02 (0.08)	-0.03 (0.08)	0.01 (0.11)					
Volume: medium						0.04 (0.08)	0.06 (0.07)	0.04 (0.07)	0.03 (0.07)	0.16 (0.11)
Volume: large						-0.01 (0.08)	0.02 (0.07)	-0.03 (0.07)	-0.04 (0.07)	0.05 (0.12)
Volume: open						-0.18* (0.09)	-0.14 (0.09)	-0.13 (0.09)	-0.13 (0.09)	-0.15 (0.17)
24-h mean KC (log)					0.07** (0.03)					0.06* (0.03)
Endline	-0.16** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13* (0.08)	-0.08 (0.13)	-0.16** (0.06)	-0.22*** (0.06)	-0.22*** (0.06)	-0.14* (0.08)	-0.09 (0.11)
Primary cook		0.47*** (0.07)	0.48*** (0.08)	0.51*** (0.08)	0.44*** (0.11)		0.48*** (0.06)	0.48*** (0.07)	0.51*** (0.07)	0.47*** (0.10)
Secondary cook		0.07 (0.08)	0.06 (0.09)	0.08 (0.09)	0.00 (0.15)		0.10 (0.08)	0.08 (0.09)	0.10 (0.09)	0.05 (0.15)
Main cooks (#)		-0.01 (0.04)	-0.03 (0.04)	-0.04 (0.04)	0.03 (0.07)		-0.01 (0.04)	-0.03 (0.04)	-0.04 (0.04)	0.01 (0.06)
PE daytime wearing compliance (#)		0.47*** (0.14)	0.50*** (0.16)	0.44*** (0.16)	0.53** (0.26)		0.47*** (0.14)	0.51*** (0.15)	0.45*** (0.16)	0.62** (0.25)
Participant's age			-0.00* (0.00)	-0.00 (0.00)	-0.01 (0.00)			-0.01** (0.00)	-0.00* (0.00)	-0.01 (0.00)
Participant is homemaker			-0.03 (0.06)	-0.05 (0.06)	-0.09 (0.10)			-0.03 (0.06)	-0.05 (0.06)	-0.12 (0.10)
Participant is literate			0.07 (0.08)	0.07 (0.08)	-0.04 (0.10)			0.07 (0.08)	0.07 (0.08)	-0.03 (0.11)
HH is primarily Wolof (d)			-0.08 (0.07)	-0.06 (0.08)	0.09 (0.09)			-0.08 (0.07)	-0.06 (0.08)	0.09 (0.10)
HH size (#)			0.01 (0.00)	0.00 (0.01)	-0.00 (0.01)			0.01 (0.00)	0.00 (0.01)	-0.00 (0.01)
HH has a private tap (d)			-0.06 (0.07)	-0.04 (0.07)	-0.18 (0.11)			-0.05 (0.07)	-0.03 (0.07)	-0.15 (0.10)
HH has modern electricity (d)			0.14 (0.10)	0.10 (0.10)	0.12 (0.16)			0.13 (0.10)	0.09 (0.10)	0.08 (0.17)
HH's normalized wealth index			-0.01 (0.04)	0.00 (0.05)	-0.07 (0.06)			-0.00 (0.04)	0.01 (0.04)	-0.06 (0.05)
Traditional wood stove + other fuel(s)				0.04 (0.08)	0.09 (0.12)				0.04 (0.07)	0.13 (0.12)
Basic metal stove				0.05 (0.14)	0.21 (0.20)				0.05 (0.14)	0.16 (0.21)
Improved woodfuel stove				-0.05 (0.15)	-0.07 (0.19)				-0.03 (0.15)	-0.09 (0.20)
LPG stove				-0.15 (0.17)	0.19 (0.22)				-0.15 (0.17)	0.08 (0.21)
Share of cooking on OFS				0.10 (0.11)	0.14 (0.13)				0.12 (0.11)	0.13 (0.13)
Total cooking duration				0.00 (0.00)	-0.00* (0.00)				0.00 (0.00)	-0.00* (0.00)
Simple treatment stove				-0.06 (0.11)	-0.21 (0.19)				-0.06 (0.11)	-0.18 (0.18)
Advanced treatment stove				0.02 (0.10)	-0.10 (0.18)				0.02 (0.10)	-0.05 (0.18)
Person-caterings per day				0.00 (0.00)	0.00 (0.00)				0.00 (0.00)	0.00* (0.00)
Burn agricultural waste at home (d)				0.03 (0.06)	0.12 (0.08)				0.04 (0.06)	0.10 (0.09)
Participant avoids kitchen smoke				0.01 (0.07)	-0.01 (0.10)				-0.00 (0.07)	-0.02 (0.10)
Smell neighbours' smoke weekly (d)				0.05 (0.06)	0.11 (0.09)				0.06 (0.06)	0.17* (0.09)
Constant	4.82*** (0.18)	4.19*** (0.19)	4.18*** (0.23)	4.07*** (0.28)	3.80*** (0.39)	4.85*** (0.16)	4.18*** (0.18)	4.19*** (0.23)	4.08*** (0.28)	3.72*** (0.39)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	140.3	140.3	140.8	140.8	136.5	135.9	135.9	138.0	138.0	130.2
R-squared	0.10	0.22	0.24	0.26	0.41	0.11	0.22	0.24	0.26	0.41

PANEL C: Single ventilation indicators

(continued on next page)

Table E.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Separation: attached	0.30** (0.15)	0.38*** (0.13)	0.37*** (0.13)	0.33** (0.13)	0.39* (0.23)					
Separation: detached	0.06 (0.09)	0.13 (0.10)	0.14 (0.09)	0.11 (0.09)	0.08 (0.17)					
Separation: open air	-0.02 (0.12)	0.09 (0.13)	0.12 (0.12)	0.10 (0.13)	0.11 (0.21)					
Open air						-0.13 (0.09)	-0.09 (0.09)	-0.06 (0.09)	-0.04 (0.09)	0.03 (0.17)
24-h mean KC (log)					0.07* (0.04)					0.08** (0.03)
Endline	-0.16** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13* (0.08)	-0.05 (0.12)	-0.16** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13* (0.08)	-0.07 (0.12)
Primary cook		0.48*** (0.07)	0.49*** (0.07)	0.52*** (0.08)	0.50*** (0.10)		0.48*** (0.06)	0.49*** (0.07)	0.52*** (0.08)	0.49*** (0.10)
Secondary cook		0.08 (0.09)	0.07 (0.09)	0.10 (0.09)	0.09 (0.15)		0.10 (0.08)	0.08 (0.09)	0.11 (0.09)	0.08 (0.15)
Main cooks (#)		-0.01 (0.04)	-0.03 (0.04)	-0.04 (0.04)	0.00 (0.07)		-0.01 (0.04)	-0.03 (0.04)	-0.05 (0.04)	0.01 (0.07)
PE daytime wearing compliance (#)		0.49*** (0.14)	0.53*** (0.16)	0.48*** (0.16)	0.57*** (0.26)		0.46*** (0.14)	0.50*** (0.15)	0.44*** (0.16)	0.57** (0.26)
Participant's age			-0.01** (0.00)	-0.00* (0.00)	-0.01 (0.00)			-0.00** (0.00)	-0.00* (0.00)	-0.01 (0.00)
Participant is homemaker			-0.02 (0.06)	-0.04 (0.06)	-0.08 (0.10)			-0.03 (0.06)	-0.05 (0.06)	-0.10 (0.10)
Participant is literate			0.06 (0.08)	0.06 (0.08)	-0.04 (0.11)			0.07 (0.08)	0.07 (0.08)	-0.04 (0.11)
HH is primarily Wolof (d)			-0.08 (0.07)	-0.06 (0.08)	0.10 (0.09)			-0.07 (0.07)	-0.05 (0.08)	0.10 (0.09)
HH size (#)			0.01* (0.00)	0.00 (0.01)	0.00 (0.01)			0.01 (0.00)	0.00 (0.01)	0.00 (0.01)
HH has a private tap (d)			-0.05 (0.07)	-0.03 (0.07)	-0.16 (0.10)			-0.06 (0.07)	-0.04 (0.07)	-0.18 (0.11)
HH has modern electricity (d)			0.14 (0.10)	0.10 (0.10)	0.08 (0.16)			0.14 (0.10)	0.10 (0.10)	0.10 (0.17)
HH's normalized wealth index			-0.01 (0.04)	0.00 (0.04)	-0.06 (0.06)			-0.00 (0.04)	0.01 (0.04)	-0.06 (0.06)
Traditional wood stove + other fuel(s)				0.05 (0.08)	0.13 (0.13)				0.04 (0.08)	0.12 (0.12)
Basic metal stove				0.03 (0.14)	0.16 (0.20)				0.04 (0.14)	0.17 (0.20)
Improved woodfuel stove				-0.04 (0.15)	-0.08 (0.19)				-0.05 (0.15)	-0.08 (0.19)
LPG stove				-0.16 (0.16)	0.20 (0.20)				-0.16 (0.17)	0.17 (0.20)
Share of cooking on OFS				0.09 (0.11)	0.13 (0.13)				0.09 (0.11)	0.12 (0.13)
Total cooking duration				0.00 (0.00)	-0.00 (0.00)				0.00 (0.00)	-0.00 (0.00)
Simple treatment stove				-0.08 (0.11)	-0.25 (0.19)				-0.07 (0.11)	-0.23 (0.19)
Advanced treatment stove				0.01 (0.10)	-0.09 (0.18)				0.01 (0.10)	-0.08 (0.18)
Person-caterings per day				0.00 (0.00)	0.00 (0.00)				0.00 (0.00)	0.00 (0.00)
Burn agricultural waste at home (d)				0.03 (0.06)	0.13 (0.08)				0.03 (0.06)	0.14 (0.09)
Participant avoids kitchen smoke				0.02 (0.07)	-0.02 (0.10)				0.01 (0.07)	-0.02 (0.10)
Smell neighbours' smoke weekly (d)				0.06 (0.06)	0.14 (0.09)				0.06 (0.06)	0.15 (0.09)
Constant	4.75*** (0.19)	4.01*** (0.20)	3.97*** (0.25)	3.88*** (0.30)	3.55*** (0.41)	4.84*** (0.16)	4.20*** (0.18)	4.17*** (0.22)	4.05*** (0.28)	3.63*** (0.40)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	417	417	411	410	200	418	418	412	411	200
Mean(Y) reference cat.	101.6	101.6	101.6	101.6	93.7	137.7	137.7	138.7	138.7	138.6
R-squared	0.11	0.23	0.25	0.27	0.40	0.10	0.21	0.24	0.26	0.39
delta									1.5	
	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)

PANEL D: composite ventilation indicators

(continued on next page)

Table E.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Aggregated ventilation	-0.15 (0.11)	-0.12 (0.11)	-0.10 (0.11)	-0.13 (0.11)	-0.05 (0.19)					
Aggregated ventilation: poor						0.04 (0.09)	0.06 (0.09)	0.05 (0.08)	0.02 (0.08)	-0.08 (0.13)
Aggregated ventilation: substantial						-0.12 (0.08)	-0.12* (0.07)	-0.13* (0.07)	-0.15** (0.08)	-0.09 (0.11)
Aggregated ventilation: full						-0.05 (0.09)	-0.03 (0.08)	-0.02 (0.09)	-0.05 (0.09)	-0.06 (0.15)
24-h mean KC (log)					0.07** (0.04)					0.07** (0.04)
Endline	-0.16** (0.06)	-0.22*** (0.06)	-0.21*** (0.06)	-0.13* (0.08)	-0.06 (0.12)	-0.16** (0.06)	-0.22*** (0.06)	-0.22*** (0.06)	-0.13* (0.08)	-0.05 (0.12)
Primary cook		0.47*** (0.07)	0.49*** (0.07)	0.52*** (0.08)	0.49*** (0.10)		0.48*** (0.07)	0.50*** (0.07)	0.52*** (0.08)	0.48*** (0.10)
Secondary cook		0.10 (0.08)	0.08 (0.09)	0.11 (0.09)	0.08 (0.15)		0.11 (0.08)	0.10 (0.09)	0.13 (0.09)	0.08 (0.15)
Main cooks (#)		-0.01 (0.04)	-0.03 (0.04)	-0.05 (0.04)	0.01 (0.07)		-0.01 (0.03)	-0.03 (0.04)	-0.04 (0.04)	0.00 (0.07)
PE daytime wearing compliance (#)		0.48*** (0.14)	0.51*** (0.15)	0.44*** (0.16)	0.58** (0.26)		0.50*** (0.14)	0.53*** (0.15)	0.47*** (0.16)	0.58** (0.25)
Participant's age			-0.01** (0.00)	-0.00* (0.00)	-0.01 (0.00)			-0.00* (0.00)	-0.00 (0.00)	-0.01 (0.00)
Participant is homemaker			-0.03 (0.06)	-0.05 (0.06)	-0.10 (0.10)			-0.04 (0.06)	-0.06 (0.06)	-0.10 (0.10)
Participant is literate			0.07 (0.08)	0.07 (0.08)	-0.04 (0.11)			0.07 (0.08)	0.07 (0.08)	-0.05 (0.11)
HH is primarily Wolof (d)			-0.07 (0.07)	-0.05 (0.08)	0.10 (0.09)			-0.08 (0.07)	-0.06 (0.08)	0.09 (0.10)
HH size (#)			0.01* (0.00)	0.00 (0.01)	0.00 (0.01)			0.01* (0.00)	0.00 (0.01)	0.00 (0.01)
HH has a private tap (d)			-0.06 (0.07)	-0.04 (0.07)	-0.18 (0.11)			-0.08 (0.07)	-0.06 (0.07)	-0.18* (0.11)
HH has modern electricity (d)			0.14 (0.10)	0.10 (0.10)	0.10 (0.17)			0.15 (0.10)	0.11 (0.10)	0.09 (0.16)
HH's normalized wealth index			-0.01 (0.04)	0.00 (0.04)	-0.06 (0.06)			-0.01 (0.04)	-0.00 (0.04)	-0.06 (0.06)
Traditional wood stove + other fuel(s)				0.04 (0.08)	0.12 (0.12)				0.03 (0.07)	0.11 (0.12)
Basic metal stove				0.05 (0.14)	0.18 (0.20)				0.00 (0.14)	0.17 (0.20)
Improved woodfuel stove				-0.05 (0.15)	-0.08 (0.19)				-0.07 (0.15)	-0.07 (0.19)
LPG stove				-0.16 (0.17)	0.16 (0.20)				-0.21 (0.17)	0.13 (0.20)
Share of cooking on OFS				0.11 (0.11)	0.12 (0.13)				0.09 (0.11)	0.13 (0.13)
Total cooking duration				0.00 (0.00)	-0.00 (0.00)				0.00 (0.00)	-0.00 (0.00)
Simple treatment stove				-0.07 (0.11)	-0.23 (0.19)				-0.06 (0.11)	-0.22 (0.19)
Advanced treatment stove				0.01 (0.10)	-0.09 (0.18)				0.01 (0.10)	-0.09 (0.17)
Person-caterings per day				0.00 (0.00)	0.00 (0.00)				0.00 (0.00)	0.00 (0.00)
Burn agricultural waste at home (d)				0.03 (0.06)	0.13 (0.08)				0.03 (0.06)	0.14 (0.08)
Participant avoids kitchen smoke				0.01 (0.07)	-0.03 (0.10)				0.02 (0.07)	-0.04 (0.10)
Smell neighbours' smoke weekly (d)				0.07 (0.06)	0.15* (0.09)				0.07 (0.06)	0.16* (0.09)
Constant	4.89*** (0.18)	4.24*** (0.19)	4.21*** (0.23)	4.12*** (0.28)	3.69*** (0.43)	4.86*** (0.18)	4.18*** (0.18)	4.15*** (0.24)	4.08*** (0.28)	3.74*** (0.44)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	.	.	.	.	98.0	144.9	144.9	145.4	145.4	149.9
R-squared	0.10	0.22	0.24	0.26	0.39	0.11	0.22	0.25	0.27	0.39
delta					-4158.0					

PANEL E: composite ventilation indicators

(continued on next page)

Table E.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PCA ventilation	-0.22*	-0.16	-0.15	-0.17	-0.03					
Quartile PCA ventilation: poor						0.03	0.02	-0.01	-0.02	0.05
Quartile PCA ventilation: substantial						(0.08)	(0.08)	(0.07)	(0.08)	(0.14)
Quartile PCA ventilation: full						-0.02	-0.01	-0.07	-0.08	0.06
						(0.08)	(0.08)	(0.08)	(0.08)	(0.13)
24-h mean KC (log)					0.08**					0.09**
					(0.04)					(0.03)
Endline	-0.16**	-0.22***	-0.21***	-0.13*	-0.07	-0.16**	-0.22***	-0.21***	-0.13*	-0.08
	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)
Primary cook		0.47***	0.49***	0.51***	0.49***		0.47***	0.49***	0.51***	0.50***
		(0.07)	(0.07)	(0.07)	(0.10)		(0.07)	(0.07)	(0.07)	(0.10)
Secondary cook		0.10	0.08	0.11	0.08		0.09	0.07	0.10	0.07
		(0.08)	(0.09)	(0.09)	(0.15)		(0.09)	(0.09)	(0.09)	(0.16)
Main cooks (#)		-0.01	-0.03	-0.04	0.01		-0.01	-0.03	-0.05	0.01
		(0.04)	(0.04)	(0.04)	(0.07)		(0.04)	(0.04)	(0.04)	(0.07)
PE daytime wearing compliance (#)		0.48***	0.51***	0.44***	0.57**		0.48***	0.51***	0.45***	0.57**
		(0.14)	(0.15)	(0.16)	(0.26)		(0.14)	(0.15)	(0.16)	(0.26)
Participant's age			-0.00*	-0.00*	-0.01			-0.01**	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.05	-0.10			-0.03	-0.05	-0.10
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.07	0.07	-0.04			0.08	0.08	-0.04
			(0.08)	(0.08)	(0.11)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.07	-0.05	0.10			-0.08	-0.06	0.10
			(0.07)	(0.08)	(0.10)			(0.07)	(0.08)	(0.09)
HH size (#)			0.01*	0.00	0.00			0.01*	0.00	0.00
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.06	-0.04	-0.18			-0.06	-0.04	-0.17
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.11)
HH has modern electricity (d)			0.14	0.09	0.10			0.14	0.10	0.10
			(0.10)	(0.10)	(0.17)			(0.10)	(0.10)	(0.18)
HH's normalized wealth index			-0.01	0.00	-0.06			-0.00	0.01	-0.06
			(0.04)	(0.04)	(0.06)			(0.04)	(0.04)	(0.06)
Traditional wood stove + other fuel(s)				0.04	0.12				0.03	0.12
				(0.07)	(0.12)				(0.08)	(0.13)
Basic metal stove				0.05	0.18				0.03	0.18
				(0.14)	(0.20)				(0.14)	(0.20)
Improved woodfuel stove				-0.05	-0.08				-0.05	-0.07
				(0.15)	(0.19)				(0.15)	(0.20)
LPG stove				-0.16	0.16				-0.18	0.19
				(0.17)	(0.20)				(0.17)	(0.20)
Share of cooking on OFS				0.11	0.12				0.10	0.11
				(0.11)	(0.13)				(0.11)	(0.13)
Total cooking duration				0.00	-0.00				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.07	-0.22				-0.06	-0.22
				(0.11)	(0.19)				(0.11)	(0.19)
Advanced treatment stove				0.02	-0.08				0.01	-0.08
				(0.10)	(0.18)				(0.10)	(0.17)
Person-caterings per day				0.00	0.00				0.00	0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.03	0.13				0.04	0.13
				(0.06)	(0.08)				(0.06)	(0.09)
Participant avoids kitchen smoke				0.01	-0.02				0.01	-0.03
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.06	0.15*				0.06	0.14
				(0.06)	(0.09)				(0.06)	(0.09)
Constant	4.93***	4.26***	4.24***	4.14***	3.67***	4.83***	4.19***	4.17***	4.07***	3.57***
	(0.18)	(0.19)	(0.23)	(0.28)	(0.43)	(0.18)	(0.18)	(0.23)	(0.28)	(0.41)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	.	.	.	.	.	138.1	138.1	139.4	139.4	130.7
R-squared	0.10	0.22	0.24	0.26	0.39	0.10	0.21	0.24	0.26	0.39
delta					34.9					

PANEL F: composite ventilation indicators

(continued on next page)

Table E.1 (continued)

	coeff (se)	coeff (se)	coeff (se)	coeff (se)	coeff (se)
	(1)	(2)	(3)	(4)	(5)
CHAID ventilation: poor	0.03 (0.16)	0.09 (0.16)	0.05 (0.17)	0.09 (0.19)	0.07 (0.19)
CHAID ventilation: substantial	-0.04 (0.15)	0.07 (0.14)	0.01 (0.14)	0.01 (0.15)	0.03 (0.15)
CHAID ventilation: full	-0.07 (0.15)	0.02 (0.14)	-0.04 (0.14)	-0.04 (0.16)	0.01 (0.16)
24-h mean KC (log)					0.07** (0.03)
Endline	-0.24** (0.10)	-0.33*** (0.09)	-0.32*** (0.10)	-0.04 (0.12)	-0.06 (0.12)
Primary cook		0.49*** (0.09)	0.50*** (0.09)	0.53*** (0.09)	0.49*** (0.10)
Secondary cook		-0.03 (0.13)	0.00 (0.14)	0.09 (0.15)	0.08 (0.15)
Main cooks (#)		0.03 (0.06)	0.03 (0.06)	-0.02 (0.07)	0.00 (0.07)
PE daytime wearing compliance (#)		0.56** (0.26)	0.65** (0.25)	0.64** (0.25)	0.59** (0.26)
Participant's age			-0.01 (0.00)	-0.01 (0.00)	-0.01 (0.00)
Participant is homemaker			-0.03 (0.10)	-0.08 (0.10)	-0.10 (0.10)
Participant is literate			-0.00 (0.11)	0.01 (0.10)	-0.04 (0.11)
HH is primarily Wolof (d)			0.08 (0.09)	0.12 (0.10)	0.11 (0.10)
HH size (#)			0.01 (0.01)	0.00 (0.01)	0.00 (0.01)
HH has a private tap (d)			-0.21* (0.11)	-0.17 (0.11)	-0.18 (0.11)
HH has modern electricity (d)			0.19 (0.17)	0.09 (0.18)	0.10 (0.17)
HH's normalized wealth index			-0.04 (0.06)	-0.05 (0.06)	-0.06 (0.06)
Basic metal stove				0.16 (0.13)	0.13 (0.12)
Improved woodfuel stove				0.27 (0.21)	0.19 (0.21)
LPG stove				-0.05 (0.19)	-0.08 (0.19)
Share of cooking on OFS				0.12 (0.23)	0.17 (0.20)
Total cooking duration				0.17 (0.13)	0.12 (0.13)
Simple treatment stove				-0.00 (0.00)	-0.00 (0.00)
Advanced treatment stove				-0.20 (0.20)	-0.22 (0.20)
Person-caterings per day				-0.11 (0.18)	-0.09 (0.18)
Burn agricultural waste at home (d)				0.00 (0.00)	0.00 (0.00)
Participant avoids kitchen smoke				0.13 (0.09)	0.14 (0.09)
Smell neighbours' smoke weekly (d)				-0.02 (0.10)	-0.03 (0.10)
Constant	4.98*** (0.25)	4.09*** (0.33)	4.11*** (0.37)	3.91*** (0.40)	3.65*** (0.39)
Community	Yes	Yes	Yes	Yes	Yes
Observations	201	201	201	200	200
Mean(Y) reference cat.	146.1	146.1	146.1	146.1	146.1
R-squared	0.15	0.28	0.31	0.38	0.39

Notes: The dependent variable is log of 24-h average personal exposure to PM_{2.5}. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. ***p < 0.01, **p < 0.05, *p < 0.1.

Table E.2
Correlates of behavioural smoke avoidance

	avoids smoke									
	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL A										
Walls: poor	-0.26 (0.32)									
Walls: substantial	0.01 (0.42)									
Walls: full	-0.36 (0.47)									
Roof: poor		-0.10 (0.42)								
Roof: substantial		-0.29 (0.41)								
Roof: full		-0.35 (0.40)								
Openings: poor			0.35 (0.49)							
Openings: substantial			-0.56 (0.40)							
Openings: full			-0.32 (0.37)							
Volume: medium				0.68** (0.34)						
Volume: large				-0.57* (0.33)						
Volume: open				-0.45 (0.49)						
Open air					-0.41 (0.42)					
Aggregated ventilation						-0.82 (0.54)				
Aggregated ventilation: poor							-0.29 (0.43)			
Aggregated ventilation: substantial							-0.12 (0.38)			
Aggregated ventilation: full							-0.70* (0.42)			
PCA ventilation								-0.97* (0.56)		
Quartile PCA ventilation: poor									0.07 (0.35)	
Quartile PCA ventilation: substantial									-0.45 (0.35)	
Quartile PCA ventilation: full									-0.31 (0.36)	
CHAID ventilation: poor										0.11 (1.29)
CHAID ventilation: substantial										-2.35** (0.98)
CHAID ventilation: full										-2.51*** (0.95)
Constant	1.17 (1.17)	1.32 (1.17)	1.22 (1.16)	1.36 (1.16)	1.19 (1.16)	1.53 (1.15)	1.58 (1.18)	1.61 (1.16)	1.17 (1.17)	3.28 (2.62)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Further cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	393	393	393	393	393	393	393	393	393	182
Pseudo R-squared	0.10	0.10	0.10	0.13	0.10	0.10	0.10	0.10	0.10	0.23
share of cooking time spent off the stove										
	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PANEL B										
Walls: poor	-0.05* (0.03)									
Walls: substantial	-0.03 (0.03)									
Walls: full	-0.06 (0.04)									
Roof: poor		-0.03 (0.03)								

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Table E.2 (continued)

	share of cooking time spent off the stove									
	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Roof: substantial		-0.05 (0.04)								
Roof: full		0.00 (0.04)								
Openings: poor			0.04 (0.04)							
Openings: substantial			-0.03 (0.03)							
Openings: full			-0.00 (0.03)							
Volume: medium				0.04 (0.03)						
Volume: large				0.06** (0.03)						
Volume: open				-0.00 (0.04)						
Open air					-0.03 (0.03)					
Aggregated ventilation						-0.02 (0.04)				
Aggregated ventilation: poor							0.00 (0.03)			
Aggregated ventilation: substantial							-0.02 (0.03)			
Aggregated ventilation: full							-0.01 (0.03)			
PCA ventilation								0.00 (0.05)		
Quartile PCA ventilation: poor									0.08** (0.03)	
Quartile PCA ventilation: substantial									0.03 (0.03)	
Quartile PCA ventilation: full									0.02 (0.03)	
CHAID ventilation: poor										-0.06 (0.08)
CHAID ventilation: substantial										-0.14** (0.07)
CHAID ventilation: full										-0.08 (0.06)
Constant	0.32*** (0.10)	0.31*** (0.10)	0.29*** (0.10)	0.26*** (0.10)	0.29*** (0.09)	0.29*** (0.10)	0.29*** (0.10)	0.28*** (0.10)	0.27*** (0.10)	0.35** (0.15)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Further cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	412	412	412	412	412	412	412	412	412	203
R-squared	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.21	0.28

Table E.3
Ventilation and personal exposure (PM_{2.5}), with health covariates

	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Walls: poor	-0.13* (0.07)								
Walls: substantial	-0.13 (0.08)								
Walls: full	-0.06 (0.10)								
Roof: poor		-0.09 (0.10)							
Roof: substantial		-0.10 (0.09)							
Roof: full		-0.07 (0.09)							
Openings: poor			0.08 (0.10)						

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Table E.3 (continued)

	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>	<i>coeff (se)</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Openings: substantial			0.01 (0.09)						
Openings: full			-0.03 (0.08)						
Volume: medium				0.03 (0.07)					
Volume: large				-0.05 (0.07)					
Volume: open				-0.13 (0.09)					
Separation: attached					0.33** (0.13)				
Separation: separated					0.11 (0.09)				
Separation: open					0.10 (0.13)				
Open air						-0.04 (0.09)			
Aggregated ventilation: poor							0.02 (0.08)		
Aggregated ventilation: substantial							-0.15** (0.08)		
Aggregated ventilation: full							-0.05 (0.09)		
Quartile PCA ventilation: poor								-0.02 (0.08)	
Quartile PCA ventilation: substantial								-0.08 (0.08)	
Quartile PCA ventilation: full								-0.05 (0.07)	
CHAID ventilation: poor									0.09 (0.19)
CHAID ventilation: substantial									0.00 (0.15)
CHAID ventilation: full									-0.03 (0.16)
Participant has normal blood pressure	0.04 (0.06)	0.03 (0.06)	0.03 (0.06)	0.03 (0.06)	0.02 (0.06)	0.03 (0.06)	0.03 (0.06)	0.03 (0.06)	0.09 (0.09)
Participant has red eyes at least sometimes	0.01 (0.07)	-0.01 (0.07)	-0.00 (0.07)	-0.00 (0.07)	-0.02 (0.07)	0.00 (0.07)	0.02 (0.07)	0.00 (0.07)	0.04 (0.11)
Constant	4.11*** (0.29)	4.10*** (0.28)	4.05*** (0.28)	4.07*** (0.29)	3.86*** (0.30)	4.04*** (0.28)	4.06*** (0.29)	4.05*** (0.28)	3.89*** (0.40)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Measurement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	411	411	411	411	410	411	411	411	200
Mean(Y) reference cat.	147.1	130.6	140.8	138.0	101.6	138.9	145.4	139.4	146.1
R-squared	0.27	0.26	0.26	0.26	0.27	0.26	0.27	0.26	0.38

Notes: The dependent variable is log of 24-h average personal exposure to PM_{2.5}. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. ***p < 0.01, **p < 0.05, *p < 0.1.

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