IMPROVED COOKSTOVES HALVE AIR POLLUTION PEAKS, BUT AMBIENT EXPOSURE DAMPENS HEALTH BENEFITS

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The adoption of an improved cookstove in Nairobi, Kenya can reduce carbon dioxide (CO_2) emissions by 3.5 tons per year (Berkouwer and Dean 2022). Factoring in the additionality rates, cookstove subsidies (financed, for example, through carbon credits) would reduce emissions at a cost of less than $5 (USD) per total carbon dioxide content (tCO_2)-equivalent, which is much more cost-effective than most available abatement alternatives. In addition, improved stoves can save households up to $120 per year in charcoal expenditures. But what are the effects of the adoption of a modern stove on air pollution and health in the long term?

According to the World Health Organization (WHO), air pollution is "the single biggest environmental threat to human health" (WHO 2017). It is responsible for 7–9 million premature deaths annually, or 10–15% of all deaths. More than 90% of those deaths occur in low- and middle-income countries (LMICs) (*Lancet* 2017).

Air pollution can be broadly categorized into two distinct categories: household-generated air pollution (HAP) and ambient air pollution (AAP). HAP is generated by household activities such as cooking—according to the World Bank (2020b), "four billion people are without access to modern energy cooking services," AAP is generated by other people or businesses, for example through transportation, energy generation, industrial activity, waste disposal, or other economic activity.

The two billion people who live in cities in LMICs are uniquely exposed to both high average AAP as well as even higher transient peaks in HAP. For them, adopting cleaner cooking technologies may reduce their HAP, but because of their continued exposure to high levels of AAP generated by other sources of air pollution this may or may not improve their health. In this type of context, how much do clean cooking technologies improve health?

This question is difficult to answer, and answering it well requires several key ingredients:

1. It is not sufficient to look at correlations between pollution and health. Since higher-income families tend to live in urban neighborhoods with cleaner air, correlations between pollution and health could be driven by lower-income families' lack of access to nutrition or health care. However, a recent review in the *Lancet Global Health* found that only six of 437 papers studying pollution and health were randomized trials (Lee et al. 2020).
2. Health benefits may compound over years, but following up with households several years after cookstove adoption can be difficult logistically. Urban households frequently move around, and households may also change cooking technologies between the initial adoption and the long-term follow-up survey.
3. Air pollution can vary minute-to-minute depending on what activity someone is engaged in (say, cooking, sleeping, working, or commuting) and whether they are indoors or outdoors. Measuring an individual's true air pollution exposure accurately thus requires using personal monitors that are co-located with the individual, and which take high-frequency pollution recordings.

Our recent working paper, "Private Actions in the Presence of Externalities: The Health Impacts of Reducing Air Pollution Peaks But Not Ambient Exposure," tackles this question (Berkouwer and Dean 2023). In a previous study, we provided 1,000 households in Nairobi, Kenya with the opportunity to

FIGURE 1: THE KENYAN CERAMIC JIKO AND THE IMPROVED JIKOKOA

Two-thirds of Kenyan households still use a traditional stove as their primary cooking technology. Displayed here is the '*Kenyan Ceramic Jiko*' (KCJ), a mid-tier charcoal cookstove (left). The Jikokoa (right) is a modern charcoal cookstove sold in East Africa produced by Burn Manufacturing.

Source: Burn Manufacturing (2021)

adopt an improved charcoal cookstove. We found that improved stoves could reduce charcoal usage by 39% (saving households more than $100 per year in charcoal expenditures, with an investment return of 300% on the $40 cost of the stove) and that access to credit was a key driver of adoption (Berkouwer and Dean 2022). The current study followed up with these households three years later to measure the long-term impacts of improved stove adoption on pollution exposure and health.

IMPROVED COOKSTOVE ADOPTION AMONG THE URBAN POOR

Three billion people are expected to live in slums in Africa and Asia by 2050 (UN 2022). Across many cities in Sub-Saharan Africa, more than 80% of residents use biomass as their primary cooking energy (FAO 2017). Charcoal usage is expected to continue growing in coming decades due to rising incomes and rapid urbanization, as households that currently gather firewood for cooking adopt charcoal cooking technologies (Hanna and Oliva 2015).

However, most of the existing literature studying the health impacts of improved cookstove adoption focuses on rural populations. This includes, for example, the RESPIRE trial in rural Guatemala (McCracken et al. 2007; Smith et al. 2011; Smith-Sivertsen et al. 2009) and the more recent HAPIN trial in Guatemala, India, Peru, and Rwanda (Clasen et al. 2022). One notable exception is Alexander et al. (2018), which studies the impact of ethanol cookstove adoption by pregnant women on birthweight and other pregnancy outcomes in Ibadan, Nigeria.

To answer our research question, our study enrolled 1,000 households residing in informal settlement areas around Nairobi. Within each household, we surveyed the primary cookstove user—95% of whom were women—and also asked questions about the health of any children under five years old who spent significant amounts of time in the home. At baseline, all households were using a *Kenyan Ceramic Jiko* (KCJ), shown on the left in Figure 1. In Kenya, more than two-thirds of households still use a KCJ or other traditional wood and charcoal stoves as their primary cooking technology (Kenya 2019 Census).

THE IMPROVED JIKOKOA COOKSTOVE

We studied the Jikokoa, an improved charcoal cookstove produced by *Burn Manufacturing*, available for around $30 in stores and supermarkets across Africa (shown on the right in Figure 1). The cooking experience of using the Jikokoa is very similar to the KCJ; respondents report no change in the taste or smell of food, they can continue buying the same charcoal from their preferred vendor, and effectively no learning is required to switch from the KCJ to the Jikokoa. In 2019, different study participants received different subsidies for the Jikokoa, causing some study participants to adopt the stove and others to continue using the KCJ (Berkouwer and Dean 2022). By comparing improved stove users and KCJ users, this allowed us to study the long-term impacts of improved stove ownership.

A key concern when conducting a long-term follow-up survey is whether study participants still own the cookstoves they originally adopted. Reassuringly, this was the case. Three years after the initial surveys, 83% of respondents who purchased a Jikokoa still owned one, and 90% of respondents who did not purchase a Jikokoa still did not own one. Reflecting widespread adoption of liquid petroleum gas (LPG) cookstoves globally, around 50% of respondents owned an LPG stove (and this is balanced across those who adopted the Jikokoa and those who didn't), up from around 20% in 2019, possibly due to ongoing government LPG subsidies. Fuel stacking is thus common: respondents who own both a charcoal stove and an LPG stove often report using their LPG stove when wanting to cook a quick, small meal or a hot drink and using their charcoal cookstove for larger daily meals such as maize or beans.

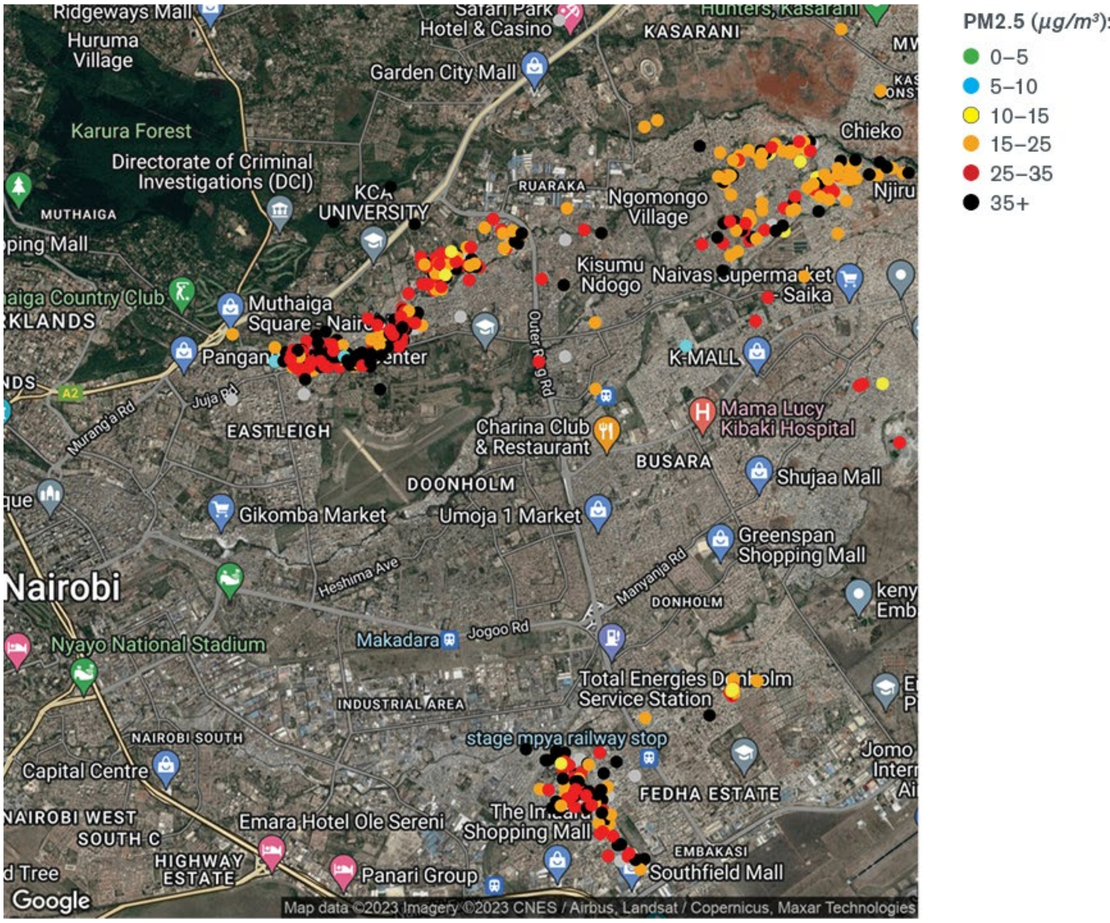
To measure air pollution as directly experienced by cookstove users, study participants received personally wearable monitors that record high-frequency air pollution measurements. The implementation of this deployment benefited from a close collaboration with the Berkeley Air Monitoring Group, who have extensive experience conducting similar research (see, for example, Chillrud et al. 2021; Gould et al. 2022; Johnson 2021; Burrowes et al. 2020).

Each respondent was asked (and compensated) to wear a backpack containing two air pollution monitoring devices and a battery pack. The Purple Air device recorded particulate matter below 1.0 or 2.5µm in diameter (PM1.0 and PM2.5, respectively, measured in *ug/m^3*) once every two minutes. The LASCAR device recorded parts-per-million of carbon monoxide (CO, measured in *ppm*) once every minute. Respondents kept the backpacks for 48 hours, during which the devices were continuously measuring air pollution. The purple air device, the LASCAR device, and the backpack containing both devices (together with a battery pack) are shown in Figure [2]. We recorded data between October and April, and we saw no seasonal differences over this period.

FIGURE 2: PERSONALLY WEARABLE DEVICES USED TO MONITOR CONTINUOUS POLLUTION EXPOSURE

The Purple Air device (used to measure PM2.5), the LASCAR device (used to measure CO), and the backpack containing both devices (and a battery pack) given to each respondent for 48 hours. Each respondent received a clean backpack and was allowed to keep the backpack after the 48 hours.

FIGURE 3: STUDY PARTICIPANTS' RESIDENTIAL LOCATIONS AND AVERAGE PM2.5 EXPOSURE



Participating households reside in informal settlement areas across Nairobi, Kenya. Around 50 respondents had moved and were now located in rural areas; they are not shown on this map.

To determine which health outcomes to focus on, and to develop rigorous survey procedures to measure these in the field, we spoke with numerous public health researchers and consulted the existing public health literature related to cookstoves. To get a comprehensive picture of respondent health, we conducted a wide range of quantitative and self-reported measures of health. Quantitatively, enumerators measure respondents' blood oxygen levels and blood pressure, following the standard methodology prescribed by Centers for Disease Control and Prevention National Health and Nutrition Examination Survey (CDC NHANES 2019).

Enumerators also collected child development outcomes such as height, weight, and arm circumference. They also asked about 13 different self-reported health diagnoses by a health professional (such as pneumonia, asthma, and cardiovascular disease) as well as 26 self-reported health symptoms that include respiratory symptoms (such as a runny nose, persistent cough, sore throat, breathlessness, or wheezing) as well as non-respiratory symptoms (such as skin rash, weight loss, or chronic tiredness).

To measure cognitive well-being, enumerators conducted the Reverse Corsi Block task to measure working memory (Brunetti et al. 2014), the Hearts and Flowers task to measure response inhibition (Davidson et al. 2006), and the d2 task to measure sustained attention (Bates and Lemay Jr. 2004; Brickenkamp and Zillmer 1998). Finally, we asked about health behaviors such as doctor visits and health expenditures.

THE CHARCOAL AND POLLUTION IMPACT OF IMPROVED COOKSTOVES

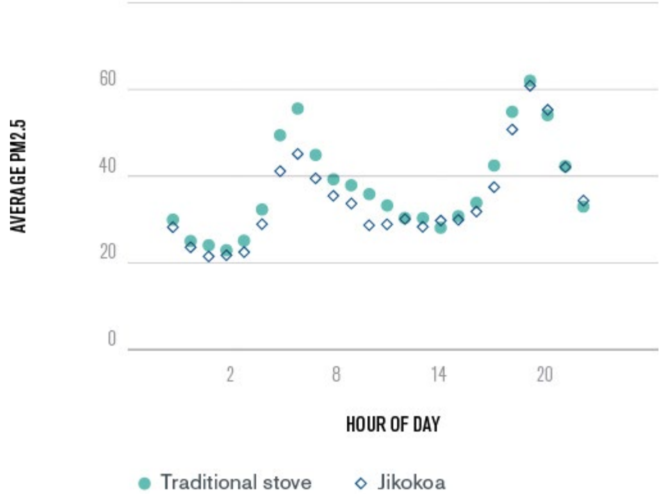
Our first finding is that the financial savings identified in Berkouwer and Dean (2022), conducted among a sample of households residing in Nairobi, largely persist: even three years after adoption, stove ownership causes charcoal expenditures to decrease by 39%. Ninety-two percent of respondents continue to live in Nairobi, where households often spend up to 10–20% of income on energy expenditures. For these households, the financial savings from reduced charcoal expenditures add up to around $1.65 per week (those who continue to use a traditional stove as their primary cookstove spend around $3.80 per week).

Turning to the PM2.5 air pollution data, we find that most respondents experience air pollution levels well in excess of the WHO's recommended standard of 5 ug/m³ on a daily basis. Figure 3 shows the residential locations of study participants across Nairobi, as well as their average pollution exposure (in PM2.5) over the approximately 48 hours during which they were wearing the pollution monitors.

The data indicate that the impact of improved cookstove adoption on air pollution exposure is complex. We use the self-reported time use data to determine during which of the 48 hours each respondent is cooking. To begin, the average level of median non-cooking pollution is 25 ug/m³. For many respondents the worst 15 minutes of air pollution experienced each day occurs during cooking. For participants cooking with their old charcoal cookstove, the worst 15 minutes of air pollution experienced during cooking is, on average, 150 ug/m³—a 125 ug/m³ increase.

However, adoption of the improved Jikokoa stove decreases this by 52 ug/m³, or around 42%. This number coincides exactly with the reduction in charcoal expenditures caused by improved cookstove adoption and is therefore likely a direct result of needing less charcoal to cook the same meals. Figure 4 shows the hourly differences graphically: average hourly pollution is similar for users of the improved stove and the traditional stove during most hours of the day but is lower for improved stove users during key cooking hours.

FIGURE 4: AVERAGE HOURLY PM2.5 BY PRIMARY COOKSTOVE TYPE



PM2.5 is similar for Jikokoa users and Kenyan Ceramic Jiko (KCJ) users during most hours of the day, but is slightly lower for Jikokoa users during key cooking hours.

Adoption of the improved stove also causes a modest reduction in time spent cooking each day, likely because the stove lights and heats up more quickly than their old charcoal stoves. As a result, average pollution during the most polluted cooking hour is 67 ug/m³ higher than ambient levels, but adoption of the improved Jikokoa stove reduces this increase by 31 ug/m³, or around 46%.

While the reduction in air pollution during cooking is very large, households only cook for two hours per day on average. Adoption of the improved stove does not cause any changes in ambient pollution—generated, for example, by traffic, nearby factories, or industrial machinery—during the remaining 22 hours of the day. Given the high levels of pollution during these other hours, the effect of improved stove adoption on average daily PM2.5 exposure is very small and not statistically different from zero.

We find no impacts on carbon monoxide. This is in line with recent laboratory tests performed by the Centre for Research in Energy and Energy Conservation (CREEC) at Makerere University in Uganda. CREEC scored the Jikokoa G3.5 as Tier 3 for PM2.5 but Tier 1 for CO (a more recent version of the Jikokoa achieves Tier 2 for CO), resulting from a desire to increase the durability and efficiency of the stove by limiting peak cooking temperatures to 700˚C. While this improves durability and efficiency of the stove, it limits oxygenation and increases the production of CO instead of CO_2 while cooking.

THE HEALTH BENEFITS OF REDUCED POLLUTION SPIKES

The improved stove reduced pollution spiked during hours when study participants were cooking but did not meaningfully reduce average aggregate daily PM2.5 exposure. How does this combination affect cookstove users' health?

Our first key result is that the improvement in pollution during cooking spikes causes a 28% reduction in the number of respiratory health symptoms that respondents report (0.24 standard deviations). This is driven by reductions in the fraction of people who self-report having had a sore throat, headache, persistent cough, or tiredness in the past month.

Short spikes in pollution may therefore be responsible for these types of health symptoms. This is confirmed when we investigate the relationship between pollution exposure and health symptoms in a separate regression: the maximum of hourly average pollution is correlated with self-reported health symptoms, whereas average pollution and the duration of high pollution exposure are not.

However, despite these improvements in self-reported health, we find no meaningful improvements in blood pressure, blood oxygen, self-reported non-respiratory symptoms, or self-reported diagnoses as made by health professionals. It may be that these health symptoms only improve with prolonged reductions in average levels of pollution exposure beyond the three years that we observe.

One concern with relying on the self-reported health symptoms is that they may be inaccurate, for example because respondents who received a sizable subsidy to adopt an improved stove may feel some pressure to self-report health improvements to the surveying team. However, additional data tests suggest that the effects above are likely strongly driven by real health outcomes. First, conditional on adopting the improved stove, we do not see that respondents who received larger subsidies report fewer symptoms than respondents who received only a small subsidy. Second, even controlling for subsidy size, we see a strong correlation between pollution and self-reported health symptoms.

POLICY IMPLICATIONS OF IMPROVED COOKSTOVES

These findings have important policy implications. On the one hand, households can meaningfully reduce short-term health symptoms themselves, by adopting improved cooking technologies that reduce air pollution peaks during cooking.

On the other hand, households who live in urban areas with high ambient pollution concentrations may see little change in average pollution exposure from adopting an improved cookstove. Significant improvements to chronic underlying health conditions—such as blood pressure, blood oxygen, and pneumonia—may only be achieved by reducing average levels of pollution, which urban households themselves have little control over. These types of longer-term benefits will require government intervention regulating the negative externalities generated by transportation and industrial activity.

This study has human subjects research approval in Kenya (KEMRI/RES/7/3/1 and AMREF ESRC P1195/2022) and the United States (University of Chicago IRB22-0943 and Penn IRB# 849048). This academic research was conducted independently and Burn Manufacturing has provided no funding for this research. Read the disclosure statement.

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