DISSERTATION

CHARACTERIZING ASSOCIATIONS BETWEEN HOUSEHOLD ENERGY-RELATED EXPOSURES TO AIR POLLUTION AND BIOLOGICAL INDICATORS OF RESPIRATORY HEALTH

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ABSTRACT

CHARACTERIZING ASSOCIATIONS BETWEEN HOUSEHOLD ENERGY-RELATED EXPOSURES TO AIR POLLUTION AND BIOLOGICAL INDICATORS OF RESPIRATORY HEALTH

In 2022, household air pollution (HAP) from solid fuel combustion contributed to an estimated 3.8 million premature deaths globally, with approximately 2.3 million associated with cardiopulmonary conditions (1). These burdens fell disproportionately on low- and middle-income countries (LMICs), where biomass fuels remained predominant sources of cooking, heating, and lighting (2). Despite progress toward cleaner energy transitions, many households remained reliant on biomass due to limited access to affordable and sustainable alternatives. Consequently, exposures to fine particulate matter ($PM_{2.5}$) and black carbon (BC)—primary components of HAP—continued to pose significant public health threats.

Cleaner-burning cookstove interventions have offered promising solutions to reduce exposures and promote health equity. Although the biological mechanisms linking HAP to respiratory outcomes are relatively well-established—particularly for chronic obstructive pulmonary disease and asthma (3,4)—important gaps remain. Evidence demonstrating consistent respiratory health benefits following cleaner stove interventions has remained limited and variable, especially in chronically exposed LMIC populations (5–8). Few studies have incorporated sensitive biomarkers of airway inflammation or examined lung function across diverse field settings(9,10).

This dissertation addressed these gaps by evaluating the association between HAP exposure and biomarkers of respiratory health using data from two field studies: a randomized improved cookstove intervention in rural Honduras and a cross-sectional baseline assessment from a clean household energy trial in Rwanda. Fractional exhaled nitric oxide (FeNO), a non-invasive biomarker of airway inflammation, and spirometry-based lung function metrics—including forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), mid-expiratory flow rate (FEF_{25}–75), and FEV_1/FVC ratio—were assessed to characterize respiratory impacts across these settings. Study details and dissertation aims were as follows:

Honduras (FeNO and Intervention Study)

The Honduras intervention trial evaluated the impact of a cleaner-burning biomass stove intervention (Justa stove) on airway inflammation, as measured by FeNO, among women in rural Honduras. The project was built on existing partnerships between Colorado State University (CSU) and Trees, Water & People (TWP) in Fort Collins, Colorado, USA, and the Honduran Association for Development (Asociación Hondureña para el Desarrollo, AHDESA, Tegucigalpa, Honduras). The study area included 10 rural communities near the town of La Esperanza in the Department of Intibucá, Honduras. Traditional stoves typically burned wood and had griddles and homemade chimneys, but did not have an engineered combustion chamber.

In Aim 1, for the intent-to-treat (ITT) analysis, we assessed the association between assigned stove type and FeNO using linear mixed models. We evaluated the impact of the *Justa* stove intervention on FeNO among a subset of 90 women selected from 230 participants, nested within the larger randomized intervention trial. Inclusion criteria for enrollment included the following characteristics: female, 24-59 years of age, primary cook of the household, and used a wood-burning traditional stove (i.e., no evidence of an engineered combustion chamber).

Exclusion criteria included self-reported pregnancy at the time of recruitment, currently smoking, or regular exposure to secondhand smoke. The study employed a stepped-wedge design between 2015 and 2018, including 6 visits to each household, with households randomized to receive the improved wood-burning Justa stove, equipped with a chimney and engineered combustion chamber, either after Visit 2 or Visit 4. This subset provided 455 observations collected over a three-year study period. FeNO was measured repeatedly using the NIOX Vero device. In addition to this ITT analysis, actual stove use was evaluated via “per protocol” analyses utilizing self-reporting, where participants indicated whether they used only the Justa stove, combined the Justa with another improved stove, stacked the Justa with a traditional stove, or used only a traditional stove.

In Aim 2, we utilized the same subset of 90 rural Honduras women to characterize the exposure-response relationship between FeNO and exposure to HAP measured repeatedly using the UPAS (Ultrasonic Personal Air Sampler) monitors and assessed as 24-hour gravimetric $PM_{2.5}$ and BC as well as predicted long-term personal and kitchen exposures to $PM_{2.5}$ and BC.

For both Aims 1 and 2, we utilized linear mixed models to answer our research questions. The primary ITT included a spline for time and random effect for participant ID. Secondary ITT further adjusted for age, height, and socioeconomic status – potential confounders (i.e., to help overcome uneven distribution across arms in this subset of participants following randomization) and variables that might impact model precision. Exposure response models adjusted for age, height, socioeconomic status, kerosene use, and included a random effect for participant ID. For the per-protocol analysis, linear mixed models included a random effect for participant ID, self-reported primary stove use (categorized into three groups: Justa plus other improved stove, Justa plus traditional stove, traditional stove only) as the exposure variable of interest, and adjusted for age, kerosene use, height, socioeconomic status, and a spline for time.

In the primary ITT analysis, the effect of the assigned Justa stove versus traditional stove on FeNO was negligible: percent change = 0.01% (95% CI: –2.4%, 4.3%). The secondary ITT model adjusted showed a percent change of -0.6(95% CI: –3.6%, 2.6%).

Consistent inverse associations were observed in exposure-response models using 24-hour and predicted long-term exposures (all results are presented for a 25% increase in the exposure of interest). For personal $PM_{2.5}$, a 25% increase in the 24-hour exposure was associated with a –0.95% change in FeNO (95% CI: –2.1%, 0.2%), and a 25% increase in predicted long-term exposure was associated with a –3.6% change in FeNO (95% CI: –6.3%, –0.8%). Kitchen $PM_{2.5}$ showed similar inverse associations: –1.6% (95% CI: –2.5%, –0.8%) for 24-hour and –1.9% (95% CI: –3.4%, –0.4%) for long-term exposure. Personal BC exposure showed a –0.9% change in FeNO for 24-hour (95% CI: –1.5%, –0.3%) and –1.8% for long-term exposure (95% CI: –3.1%, –0.5%). Kitchen BC was similarly negatively associated: –1.0% (95% CI: –1.6%, –0.5%) for 24-hour and –1.4% (95% CI: –2.3%, –0.4%) for long-term exposure. Results were consistent to the exposure-response results, in per-protocol models. Compared to traditional stove users (reference, N = 236 observations), participants using both Justa and traditional stoves (N = 138 observations) showed a 3.5% increase in FeNO (95% CI: 1.3%, 5.8%), while Justa plus improved stove users (N = 81 observations) had a 2.3% increase (95% CI: –0.4%, 5.0%).

These increases in FeNO, associated with reductions in HAP exposure observed over the course of the trial, were contrary to the initial hypothesis. Similar to findings in the smoking cessation literature, where quitting smoking leads to increased FeNO, these results may suggest that reducing chronic HAP exposure might similarly elevate FeNO, potentially reflecting complex feedback mechanisms involving nitric oxide synthase pathways.

SHEAR: Lung Function and Cross-Sectional Exposure

The Sustainable Household Energy Adoption in Rwanda (SHEAR) study is a randomized controlled trial conducted in rural Rwanda through in-country partnerships with Colorado State University, the University of Rwanda, and MeshPower Inc. The ongoing study substituted traditional household energy sources with solar power and liquefied petroleum gas (LPG) stoves to reduce household air pollution. Eligible households were recruited from the eastern lowlands of Rwanda, at least one adult and adolescent-aged child per household. Participants were followed for three years with repeated measurements of household air pollution exposure, energy use, and health outcomes.

In Aim 3, we utilized baseline SHEAR data to conduct a baseline cross-sectional analysis to determine associations between HAP and lung function among adults and children (N = 1,460 individuals: 342 men, 542 women, and 579 children, from 650 households). Participants wore UPAS personal monitors to measure 48-hour $PM_{2.5}$ and BC exposures. Spirometry was assessed using EasyOne software, validated by an independent reviewer, and metrics were standardized using race-neutral Global Lung Function Initiative (GLI) z-scores. Multivariable analyses included selected exposures of interest along with a weighted asset index in linear regression models. The lung function z-scores, which incorporated age and height based on the race-neutral American Thoracic Society/European Respiratory Society (ATS/ERS) reference equations, were used as the dependent outcomes in all models. The asset index was included as a covariate in all models, and biological sex was included in models for children to account for any potential confounding arising from sex-related differences in lung function development.

Among adult men, higher $PM_{2.5}$ was suggestively associated with modest increases in FEV_1 (0.152; 95% CI: –0.031, 0.335), FVC (0.065; 95% CI: –0.136, 0.266), $FEF_{25–75}$ (0.171; 95% CI: –0.022, 0.365), and FEV_1/FVC (0.155; 95% CI: –0.029, 0.339) z-scores. Higher BC exposure was associated with decreases in FEV_1 (–0.080; 95% CI: –0.242, 0.083) and FVC (–0.223; 95% CI: –0.400, –0.047), and suggestive increases in $FEF_{25–75}$ (0.122; 95% CI: –0.055, 0.300) and FEV_1/FVC (0.171; 95% CI: 0.002, 0.339) z-scores. Among adult women, associations between $PM_{2.5}$ and BC exposures and lung function were modest and inconsistent. For $PM_{2.5}$, effect estimates were close to null for FEV_1 (–0.029; 95% CI: –0.184, 0.127), FVC (–0.059; 95% CI: –0.217, 0.099) and FEV_1/FVC (0.038; 95% CI: –0.106, 0.182, with a small positive trend for $FEF_{25–75}$ (0.108; 95% CI: –0.076, 0.291). For BC, negative trends were observed across outcomes, though confidence intervals included the null.

Among children, $PM_{2.5}$ exposure was associated with small negative trends in FEV_1 (–0.061; 95% CI: –0.221, 0.098), $FEF_{25–75}$ (–0.092; 95% CI: –0.261, 0.078), and FEV_1/FVC (–0.091; 95% CI: –0.224, 0.042), with minimal change in FVC (0.005; 95% CI: –0.157, 0.166). BC exposure showed similarly small negative associations. Effect modification plots revealed that among boys aged 10 and 13, associations between $PM_{2.5}$ exposure and lung function (FEV_1 and FVC) were relatively flat or slightly positive (i.e., consistent with the null association), indicating minimal impact, whereas among 16-year-old boys, there were pronounced inverse associations with both FEV_1 and FVC z-scores, potentially suggesting a period of heightened susceptibility during adolescent lung development. In contrast, girls showed flatter associations across all age groups with no strong trends on lung function by exposure level. Interaction models further supported these findings, revealing significant age-by-sex modification for boys with $PM_{2.5}$ exposure and both FEV_1 (p-interaction = 0.0452) and FVC (p-interaction = 0.0051) z-scores. No significant effect modification was observed for BC exposures (p-interaction = 0.4632 for FEV_1 and 0.8881 for FVC).

Overall, the results revealed heterogeneity in associations between exposure to $PM_{2.5}$ and BC and lung function across all age and sex groups, with varying degrees of effect. Among men, exposure to BC was associated with reductions in several spirometric measures, including FEV_1 and FVC, and slight increases in the FEV_1/FVC ratio. These results, by which both FEV1 and FVC are decreasing with exposure and the FEV1/FVC ratio is increasing with exposure means that FVC is decreasing more than FEV1, which could suggest a restrictive process. While the observed associations in women and children were more variable and generally weaker, there were still suggestive trends of adverse effects on lung function, particularly in male children exposed to $PM_{2.5}$.

Conclusion

This dissertation contributed novel evidence on the respiratory health effects of household air pollution in LMICs. In Honduras, while the Justa stove significantly reduced $PM_{2.5}$ exposures, it did not improve airway inflammation as measured by FeNO. However, exposure-response analyses identified consistent inverse associations between $PM_{2.5}$ and BC with FeNO, suggesting complex or possibly blunted inflammatory feedback responses. In Rwanda, while most results suggested no associations between HAP exposure and lung function in cross-sectional analyses, the associations observed with BC in men and with $PM_{2.5}$ in the effect modification results among the children emphasize the need to consider age and sex in HAP-related exposure-response relationships. Our study is unique in that it evaluates the impact of household air pollution exposure on lung function across both adult men and adolescents, providing critical insights into demographic groups that have been historically understudied in this context. These findings underscore the importance of multifaceted approaches to evaluating health impacts of clean cooking interventions—including biomarker diversity, attention to vulnerable subgroups, and longitudinal follow-up—to inform policy and programming in LMICs.

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Chapter 1: Introduction

An area of research of great significance in global health is household air pollution (HAP) resulting from the combustion of solid fuels in cookstoves, which are used for cooking and heating purposes. HAP is widely recognized as a prominent contributor to premature mortality and morbidity on a global scale (1,2,11). According to estimates made in 2022, HAP was responsible for almost 3.8 million premature deaths, exceeding the cumulative effects of contaminated drinking water, insufficient sanitation, and other environmental exposures (1,2,12). Of the 3.8 million deaths attributable to HAP in 2022, over 2.3 million were believed to be associated with cardiopulmonary disease (1,13).

Globally, the transition to cleaner cooking technologies remains an urgent health equity and environmental justice issue. Traditional biomass stoves contribute substantially to household air pollution, a leading environmental risk factor for premature death and disease, particularly in low- and middle-income countries. However, decades of improved cookstove design and dissemination have not consistently translated into widespread or sustained use. One key reason is that stove programs often prioritize technical specifications such as fuel efficiency or emissions over usability, cultural acceptability, and the complex realities of everyday cooking practices (8,12,14,15). Without addressing user-centered design and implementation, even the most technically advanced stoves may fail to replace traditional stoves fully—undermining their potential to reduce indoor air pollution exposure and improve health outcomes.

Achieving sustainable and equitable improvements in household energy use requires a broader, more inclusive approach that centers local needs and fosters long-term behavioral change. Efforts must move beyond assumptions about cooking habits and instead incorporate diverse stakeholder perspectives, including youth, who are often excluded from program planning but represent both current and future users (15,16). Monitoring adoption, stacking behaviors, and sustained use—now possible through sensor-based technologies—allows implementers to better understand how stoves integrate into the household and adapt programs accordingly (17). As climate change, energy access, and public health become increasingly interconnected, clean cooking initiatives must evolve into holistic, community-driven strategies that prioritize health equity and the lived experience of all users.

At its core, the push for cleaner cooking technologies is a matter of health equity. The burden of household air pollution falls disproportionately on women, children, and low-income communities—groups that often have limited decision-making power or access to health-promoting infrastructure. These populations are more likely to suffer from respiratory infections, cardiovascular disease, adverse pregnancy outcomes, and other pollution-related illnesses, not because of individual choices, but because of systemic inequities in access to clean energy(16,17)Addressing these disparities requires more than just distributing improved stoves—it demands sustained investment in community engagement, education, and culturally responsive technologies that empower households to make lasting changes. Clean cooking is not only an environmental or technical issue; it is a human rights issue that intersects with gender, poverty, and global public health. Ensuring equitable access to clean household energy must be a priority for the global health and sustainable development agendas alike. Despite decades of investment in cleaner cooking technologies, substantial gaps remain in ensuring these solutions are effective, accessible, and equitably adopted. Bridging these gaps is critical not only to improve health and environmental outcomes but also to advance the broader goals of energy justice and sustainable development. Many cookstove interventions have fallen short because they fail to integrate social, cultural, and behavioral dimensions into design and implementation. As a result, even well-engineered stoves may go unused, disadopted, or supplemented with polluting alternatives. Addressing these gaps requires a multidisciplinary approach that unites engineering, public health, anthropology, and community-based development to create solutions that are technically sound *and* socially embedded. By identifying and correcting these disconnects, the cleaner cooking sector can move beyond incremental improvements and toward transformative change that prioritizes long-term usability, equitable access, and meaningful health benefits for those most impacted. To help address these persistent gaps and contribute to more effective, equitable cookstove interventions, this dissertation aims to investigate engineered cook stove and LPG energy transitions with a focus on aligning technical performance with real-world usability and community context.

Access to modern energy, such as electricity and solar energy, as a fundamental human right is juxtaposed with the reality that around 3 billion individuals continue to depend on conventional energy sources, such as wood, charcoal, and kerosene, to fulfill essential household requirements like cooking, heating, and lighting. Access to cleaner, lower-emission energy poses a significant barrier in rural regions of low- and middle-income countries (LMICs) (18). The assessment and comparison of various levels of household cooking and energy implementations can be contextualized using the National Institute for Occupational Safety and Health (NIOSH) Hierarchy of Controls. In the hierarchy, elimination of a hazard or a pollution source is preferred to less effective controls such as substitution, engineering controls, personal behavior or administrative changes, and the use of personal protective equipment to reduce exposure (19). Of the levels of the hierarchy, this dissertation examines the efficacy of engineering controls, such as modified cookstoves in Honduras, and a combination of elimination and substitution controls as seen in interventions involving the exclusive use of liquefied petroleum gas (LPG) and solar energy for lighting within households, such as in the Sustainable Household Energy Adoption in Rwanda (SHEAR) study.

The evaluation of these levels of intervention can be conducted using multiple approaches. This dissertation aims to assess the effectiveness and impact of household energy interventions at different levels of the household energy ladder, from the lowest rung (modified biomass stoves) to the highest rung (solar and LPG implementation) by utilizing longitudinal data from the Honduras stepped-wedge randomized control trial and baseline data from the SHEAR study (17,18). The assessment utilizes air pollution measurements of biomass exposure and biological indicators of respiratory health, including fractional exhaled nitric oxide (FeNO) and spirometry-based lung function metrics such as forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), and forced expiratory flow between 25% and 75% of vital capacity (FEF_{25}–$_{75}$). Biomarkers and other health outcomes are difficult to measure in remote field locations, and as a result, relatively little has been characterized about the specific mechanisms of disease resulting from exposure to HAP (20,21). Further research is required to comprehensively understand the extent of health-relevant emissions stemming from different cookstove designs and the health consequences associated with exposure to air pollution generated by cookstoves. Such research is necessary to adequately determine whether implementing cleaner cooking technologies and other household energy interventions will lead to reduced health impacts. To address these critical knowledge gaps, this dissertation sets out to evaluate the relationship between HAP exposure and respiratory health outcomes, with a particular focus on FeNO and spirometry across multiple intervention levels.

Aim 1: Evaluate the impact of the improved Justa stove intervention on FeNO in a subset of Honduran women participating in a randomized stepped-wedge trial. A total of 230 women residing in rural Honduran households, the primary users and operators of traditional biomass stoves, were selected for enrollment in the study. Women were randomly and independently assigned to one of two study groups. The study intervention, the Justa stove, is a locally sourced wood-burning device with a designed combustion chamber and chimney. A total of six visits were made between 2015 and 2018 to evaluate the impact of the intervention. The intervention was administered to 50% of the households following Visit 2, whereas the remaining 50% received it after Visit 4. Ninety women were then selected for the FeNO sub-study to determine the impact of HAP on respiratory inflammation. In this aim, an intent-to-treat analysis using linear mixed models was conducted to assess the impact of the engineered Justa stove compared to the local traditional stove on FeNO throughout the three-year study period, including a spline to adjust for time. Two sensitivity analyses were also conducted, testing the effectiveness of the intervention among those who did not report using anti-inflammatory medication prior to FeNO testing and among those who reported mucus symptoms.

Aim 2: Characterize the exposure-response association between 24-hour personal and kitchen black carbon (BC) and $PM_{2.5}$*, as well as the predictive long-term average BC and* $PM_{2.5}$ *values, on FeNO values over time in Honduran women participating in the Justa intervention study.* During each of the six visits conducted over three years, 24-hour gravimetric personal and kitchen $PM_{2.5}$ concentrations were collected. Using two exposure metrics—the predicted long-term average and the 24-hour exposures—linear mixed models with log-transformed personal and kitchen BC and $PM_{2.5}$ values were separately evaluated as independent variables, adjusted for confounders, to determine the exposure-response association.

Aim 3: Characterize the cross-sectional associations between exposure to HAP and lung function parameters (FEV_1*, FVC,* FEF_{25-75}*, and* FEV_1/FVC*) separately among Rwandan women, men, and children from 650 households*. To achieve this goal, HAP exposure measurements and lung function (spirometry) were compared at baseline within the SHEAR study, a whole-household energy randomized controlled trial. Six hundred fifty households were enrolled in the eastern province of Rwanda, with at least one adult and one child per household. Participants underwent a series of baseline assessments, including 48-hour personal air sampling for exposures of interest ($PM_{2.5}$ and BC) and spirometry prior to randomization to liquefied petroleum gas (LPG) and solar energy interventions. Linear regression models were used to assess the association between baseline lung function parameters and HAP exposure, adjusting for confounders.

Summary: This dissertation assessed exposure to HAP and respiratory health indicators. Exposure to air pollution from traditional and modified cookstoves and household cooking and energy interventions was characterized by measuring pollutants such as $PM_{2.5}$ and BC. The randomized study design in Honduras presented in this work helps to determine the efficacy of different levels of interventions evaluate outcomes relative to the NIOSH Hierarchy of Controls, while our baseline cross-sectional analysis in Rwanda contributes important data toward characterizing lung function in an historically understudied rural population, establishing critical pre-intervention measures before randomization in the SHEAR trial. These analysis contribute to the growing body of knowledge regarding HAP's impacts on respiratory health. Furthermore, this work quantifies exposure-response associations due to exposures from various cookstoves, providing critical insights that may help inform ideal pollution reduction targets. This body of work provides valuable information for determining the appropriate level of intervention to improve the health consequences of HAP globally.

Chapter 2: Literature Review

Introduction to Household Air Pollution

Approximately 50% of the global population resides in rural regions, where biomass fuels remain the predominant energy source. The combustion of biomass fuels has been widely recognized as a leading cause of household air pollution (HAP), resulting in a substantial increase in household exposure to particulate matter ($PM_{2.5}$) and a host of harmful chemicals, including carcinogens (1,2). Exposure to HAP disproportionately affects populations in low- and middle-income countries (LMICs), where traditional biomass fuels remain common due to limited access to affordable and sustainable alternatives (8,11,18). HAP contributes significantly to global disease burden, with an estimated 3.8 million premature deaths each year, including from chronic respiratory diseases, ischemic heart disease, and stroke (3,9,22,23). Women of reproductive age and young children under five are thought to be particularly susceptible due to their greater time spent in the domestic environment, and thus have served as the primary participants in most studies evaluating HAP (17,18,24–26)

Exposure to Household Air Pollution

Fuel use patterns in LMICs reflect gradual but uneven energy transitions. Globally, the use of gaseous fuels for cooking increased from 31% in 1990 to 49% in 2020, while electricity use rose modestly from 4% to 8% over the same period—primarily in urban areas with better infrastructure (12,27). These figures suggest global progress, but stark disparities persist; in rural sub-Saharan Africa, for example, over 60% of households still rely on polluting fuels (12,28). Such dependence reflects not only access limitations but also the adaptive strategies of households navigating affordability, availability, and cultural preferences.

Figure 1 demonstrates how the energy ladder model has evolved into the stacked energy model to better reflect real-world behaviors. Households often use multiple fuels simultaneously—a practice known as fuel stacking—due to financial, cultural, and logistical constraints (16–18,23). The complexity of household energy decisions—shaped by income, fuel availability, gender dynamics, and cooking preferences—can limit the efficacy of interventions based on single-fuel transitions and highlights the need for nuanced implementation strategies that address socioeconomic and gendered dimensions of household energy use (17,18,23).

Cookstove Interventions and Impacts on Exposure

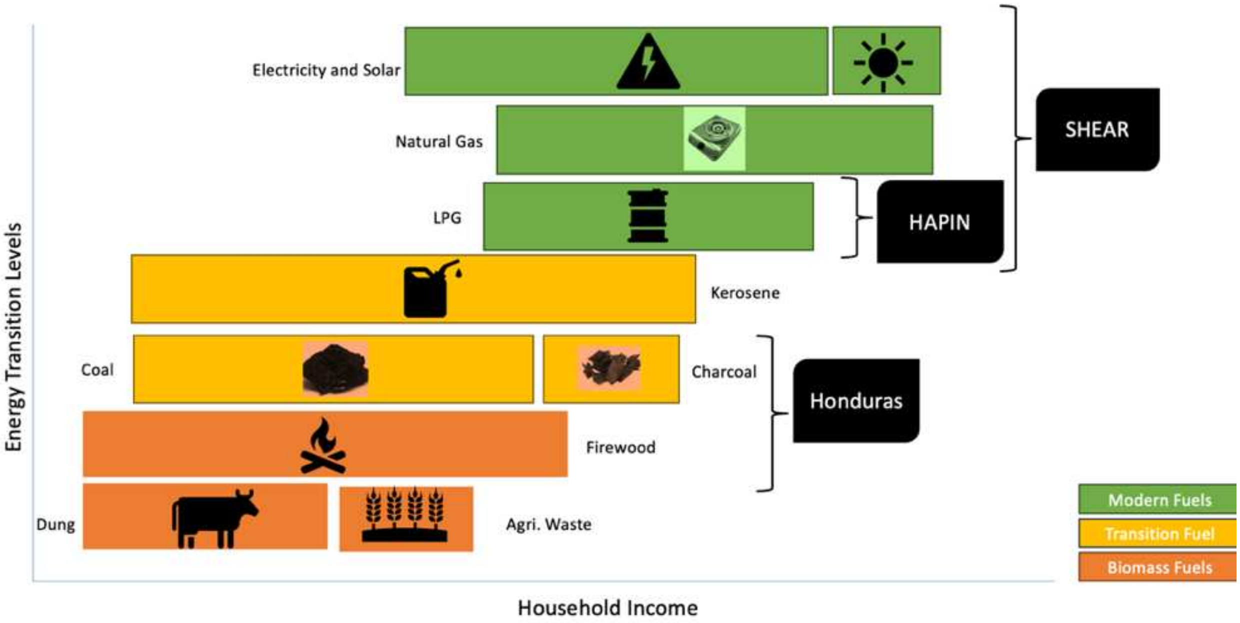

Figure 1:Stacked Energy Ladder, modified stacked energy use model adapted from Waleed and Mirza 2023 with Honduras, the Sustainable Energy Adoption in Rwanda (SHEAR) study, and the (Household Air Pollution Intervention Network (HAPIN) Study

Cleaner-burning cookstoves, including improved biomass stoves like the Justa and those powered by liquefied petroleum gas or electricity, offer promising strategies to reduce household air pollution exposure in low- and middle-income countries. These technologies have been shown to reduce concentrations of fine particulate matter ($PM_{2.5}$) and black carbon (BC) by more than 50% compared to traditional open-fire or rudimentary stoves (14,29,30). However, uptake and sustained use of these cleaner alternatives remain inconsistent due to cultural preferences, fuel access, affordability, and maintenance challenges. Large-scale trials such as the Household Air Pollution Intervention Network (HAPIN) study highlight both the feasibility and the limitations of these interventions in real-world settings. While these types of studies have previously documented meaningful reductions in personal pollutant exposure and some improvements in health outcomes—such as birth weight and blood pressure—their effects on respiratory-specific biomarkers remain inconclusive (3,20,23,31). This inconsistency underscores an ongoing gap in understanding the specific biological mechanisms by which reduced HAP exposure translates into respiratory health benefits. In particular, further investigation is needed into how chronic and acute exposure to combustion-related pollutants drives inflammation, immune modulation, and long-term lung function decline.

Household Air Pollution and Health Outcomes

Long-term exposure to HAP has been linked to an array of adverse health outcomes, including chronic obstructive pulmonary disease (COPD), asthma, lower respiratory infections, and cardiovascular diseases (3,20,32). Vulnerability varies across age, sex, location, and socioeconomic status. Prenatal and early life exposure can impair lung development and increase lifetime susceptibility to respiratory diseases (33–37), while adult men with comorbidities may also suffer disproportionately due to cumulative occupational and household exposures (38) However, men are not well studied in household air pollution research, leaving a gap in understanding how gendered patterns of exposure affect respiratory health.

Despite considerable epidemiological evidence, limitations in characterizing biological pathways associated with exposure to HAP remain. The use of biomarkers is increasingly recognized as critical to bridging the gap between exposure and clinical outcomes, offering more granular insights into the physiological processes underlying pollution-related disease(20,39–41). In HAP studies, two respiratory biomarkers have gained increasing traction—fractional exhaled nitric oxide (FeNO) and spirometry—due to their ability to non-invasively assess airway inflammation and lung function, respectively. These measures are particularly valuable when evaluating the effectiveness of cookstove interventions, as they help detect subclinical responses that may precede overt respiratory disease.

FeNO and Spirometry as Indicators of Respiratory Effects

Fractional Exhaled Nitric Oxide (FeNO)

Fractional exhaled nitric oxide is a non-invasive biomarker that reflects eosinophilic inflammation in the airways and is commonly used in clinical and research settings to assess asthma and other allergic airway conditions. FeNO levels represent the concentration of nitric oxide (NO) produced by epithelial and inflammatory cells in the respiratory tract, which can rise in response to environmental exposures such as fine particulate matter ($PM_{2.5}$) and other inhaled irritants. The NIOX Vero, a portable and user-friendly device, enables accurate and reproducible FeNO measurement in field-based settings. Its rapid assessment capability, minimal training requirements, and ease of transport make it especially well-suited for environmental health studies in low- and middle-income country (LMIC) contexts.

FeNO levels rise in the presence of Type 2 inflammation, involving cytokines like IL-13 and immune cells such as eosinophils (39,42,43). Although primarily studied in ambient air pollution contexts, emerging evidence suggests that FeNO also responds to biomass smoke exposure, though the magnitude and consistency of this response remain variable. Several cross-sectional studies have examined FeNO in relation to environmental and occupational exposures. For example, Werthmann et al. (2023) examined FeNO levels among 419 women and children in Costa Rica, finding that 20% of women and 13% of children had elevated levels, with associations between rhinitis, wheeze, and agricultural exposures (44). Nigatu et al. (2022)

conducted a cross-sectional study of 248 female flower farm workers in Ethiopia and found that, despite higher endotoxin exposures among greenhouse workers compared to outdoor workers, FeNO concentrations did not differ significantly between high- and low-exposure groups (45). Similarly, Ndlovu et al. (2014) in South Africa reported elevated FeNO among 211 women exposed to pesticides and indoor pollutants (46). Pollard et al. (in Puno, Peru) assessed the association between biomass smoke exposure and FeNO levels among rural and urban households, finding that rural households with open-fire stove use exhibited higher levels of biomarkers related to biomass smoke exposure (47). They reported that among rural participants, median FeNO increased by 2 parts per billion (ppb) (p=0.006) and blood oxygen saturation (SpO_2) decreased by 1% (p=0.02) following cooking, although the magnitudes of these changes were small and the study may have been limited by confounding associated with other urban and rural differences. These findings collectively underscore FeNO's potential as a sensitive, non-invasive biomarker of airway inflammation influenced by environmental and occupational exposures, while also highlighting variability due to study populations, exposures, and protocols.

These studies demonstrate FeNO’s promise as a field-ready biomarker in HAP studies. However, interpretation must account for measurement error in instrumentation in respiratory conditions, medication use, and device calibration, as well as the temporal relationship between exposure and biomarker measurement. More standardized, longitudinal studies are needed to examine FeNO’s responsiveness to cleaner energy interventions over time and to better understand the long-term biological impacts of reduced household air pollution exposure.

Spirometry

Spirometry is the gold standard for assessing pulmonary function and is essential in both clinical and research settings. It provides objective measures of lung mechanics, including forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), the FEV_1/FVC ratio, and forced expiratory flow between 25% and 75% of exhalation (FEF_{25}–$_{75}$).

FEV_1 reflects the degree of airway obstruction, helping to identify obstructive conditions such as asthma and chronic obstructive pulmonary disease (COPD). FVC measures the total volume of air a person can exhale and is used to assess restrictive diseases that reduce lung capacity, often linked to long-term pollutant exposure. The FEV_1/FVC ratio helps distinguish between obstructive and restrictive patterns by indicating whether airway narrowing or loss of lung volume predominates. FEF_{25}–$_{75}$ provides insight into small airway function, detecting early signs of small airway obstruction that may be especially sensitive to fine particulate matter exposure and other pollutants.(48)

Together, these spirometry parameters offer a comprehensive understanding of how environmental exposures affect different regions and mechanisms of the respiratory system, allowing for early detection and monitoring of lung disease progression in exposed populations (47,48). Pollutants like $PM_{2.5}$ and BC can impair lung function through pathways involving inflammation, oxidative stress, and structural remodeling of the airway(49–51). Chronic exposure has been shown to cause narrowing of the bronchioles, alveolar damage, and impaired gas exchange (3,21,22,52). Epidemiological studies have linked higher levels of $PM_{2.5}$ and BC with reductions in FEV_1 and FVC, particularly among vulnerable populations. In Malawi, the Cooking and Pneumonia Study (CAPS**)** trial evaluated the impact of cleaner-burning biomass cookstoves on respiratory health across different age groups (9,10,53). conducted a cross-sectional analysis among over 1,400 adults and found a high prevalence of chronic respiratory symptoms and spirometric abnormalities, particularly restriction, but no consistent associations between measured $PM_{2.5}$ exposures and lung function outcomes. Separately, Rylance et al. conducted a longitudinal analysis of adults and children enrolled in CAPS and reported that although access to cleaner cookstoves were used in the population they did not reduced $PM_{2.5}$ exposures, and there was no significant impact on the rate of lung function decline over three years (10). They concluded that lung function deficits observed in adulthood likely originated from impaired early-life lung growth rather than from accelerated decline later in life. Together, these findings underscore the challenges of reversing respiratory damage with adult interventions alone and highlight the critical importance of addressing early-life exposures in biomass-reliant settings. (6,53). Similarly, Oluwole et al. (2013) conducted a cross-sectional study in Nigeria examining pulmonary function among women and children aged 7 to 17 years exposed to biomass smoke (49,54). This study evaluated 59 mother–child pairs from households exclusively using firewood and found that both groups—the mothers and their children—had significantly reduced lung function compared to predicted normal values across multiple spirometric parameters, including FVC, FEV_1, FEV_1/FVC, $FEF_{25–75}$, and peak expiratory flow rate (PEFR). The reductions were not limited to the FEV_1/FVC ratio but extended to both volume (FVC) and flow (FEV_1, $FEF_{25–75}$, PEFR) parameters, underscoring widespread pulmonary impairment. Although this was not an intervention study and no comparison arm was included, the overall reduced lung function compared to predicted norms suggests that chronic, long-term exposures to elevated household $PM_{2.5}$ levels—substantially exceeding World Health Organization (WHO) guidelines—may result in persistent lung function deficits that are unlikely to be quickly reversible. These findings highlight the respiratory risks linked to sustained exposure to household air pollution from biomass fuels.

Despite its diagnostic utility, spirometry is often underused in LMIC settings due to logistical barriers and limited clinical capacity (20,55). Standardized protocols and quality assurance measures, including repeated acceptable maneuvers and z-score interpretation, are essential to ensure valid and comparable results across settings (56).

Together, FeNO and spirometry represent a powerful toolkit for understanding the multi-dimensional health effects of household air pollution. FeNO captures dynamic, short-term inflammatory responses, while spirometry provides evidence of longer-term structural and functional impacts. When applied in household air pollution studies, particularly those evaluating cookstove interventions, these biomarkers can help clarify physiological mechanisms and quantify the effectiveness of exposure mitigation strategies.

Conclusion

This dissertation aimed to contribute to the growing body of literature on household air pollution by using respiratory biomarkers to better understand the health implications of biomass fuel use and the potential benefits of energy transitions. Through the application of FeNO and spirometry, we assessed subclinical and clinical respiratory outcomes in populations chronically exposed to $PM_{2.5}$ and BC. By leveraging longitudinal and cross-sectional study designs, our work addressed important gaps related to exposure measurement, sex- and age-specific susceptibility, and the physiological response to cleaner cookstove technologies. In doing so, this research enhanced the scientific understanding of how household energy transitions impacted respiratory health and informed future interventions and policy efforts aimed at reducing the global burden of disease linked to household air pollution.

Chapter 3:

Impact of the wood-burning *Justa* stove on Fractional Exhaled Nitric Oxide: A stepped-wedge randomized trial in Honduras

Chapter Summary

This chapter evaluated the impact of a cleaner-burning biomass stove intervention (Justa stove) on airway inflammation, as measured by fractional exhaled nitric oxide (FeNO), among women in rural Honduras. The analysis was nested within a larger randomized stepped-wedge cookstove trial and included repeated FeNO and household air pollution measurements from 90 participants over 6 visits. The intent-to-treat analysis comparing Justa stove assignment to traditional stove use showed no significant effect on FeNO levels. Specifically, the estimated percent change in FeNO was 0.01% (95% CI: -2.4%, 4.3%) in the primary model, and -0.6% (95% CI: -3.6%, 2.6%) after adjustment for age, socioeconomic status, and height. However, our exposure-response analysis revealed consistent inverse associations between both 24-hour gravimetric and predicted long-term exposures to fine particulate matter ($PM_{2.5}$) and black carbon (BC) with FeNO. A 25% increase in 24-hour personal $PM_{2.5}$ exposure was associated with a -0.95% change in FeNO (95% CI: -2.1%, 0.2%), and a 25% increase in predicted long-term $PM_{2.5}$ exposure was associated with a -3.6% change in FeNO (95% CI: -6.3%, -0.8%). Similarly, 24-hour personal BC exposure was associated with a -0.9% change in FeNO (95% CI: -1.5%, -0.3%), and predicted long-term BC exposure was associated with a -1.8% change (95% CI: -3.1%, -0.5%). These consistent findings suggest that participants with lower exposure, a result observed over the course of the trial, demonstrated higher FeNO levels. Overall, this chapter highlights the complexity of biological responses to real-world stove interventions. While direct intervention effects were minimal, the observed exposure-response relationships with pollutant exposures emphasize the importance of using longitudinal exposure measures to assess the respiratory impacts of household air pollution, over time. Interestingly, the inverse association between pollutant exposures and FeNO may reflect a blunted or suppressed inflammatory feedback response due to chronic exposure—a pattern that has also been observed in smoking cessation studies, where FeNO levels tend to rise after individuals quit smoking. This suggests that reduced exposure to combustion-related pollutants, whether from tobacco or biomass, may allow recovery of nitric oxide signaling pathways in the airway. These findings underscore the potential of FeNO as a sensitive, non-invasive biomarker for evaluating respiratory effects in environmental health interventions.

Introduction

Household air pollution (HAP) remains one of the most significant environmental risks to human health, ranking second only to ambient air pollution in terms of premature mortality worldwide (57–60). In low- and middle-income countries (LMICs), the primary sources of HAP stem from the use of solid fuels—such as biomass, animal dung, crop residues, and charcoal—as well as kerosene for cooking, heating, and lighting (59–61). In 2019 alone, exposure to HAP from solid fuel combustion was responsible for an estimated 2.5 million deaths and 77.2 million disability-adjusted life years (DALYs) globally (1,2). The incomplete combustion of these fuels emits high levels of fine particulate matter ($PM_{2.5}$), black carbon (BC), and other hazardous pollutants (59,61,62). contributing to a wide range of chronic diseases including chronic obstructive pulmonary disease (COPD), lung cancer, asthma, and respiratory infections (3,63,64). The WHO estimates that 23% of adult COPD deaths are attributable to HAP, and PM—one of the main constituents of HAP—has been classified as a Group 1 carcinogen by the International Agency for Research on Cancer (1,2,65,66).

While the global transition to affordable, renewable clean energy remains the long-term goal, interim solutions such as improved biomass cookstoves offer promising near-term benefits. The Justa stove, which features an engineered combustion chamber and chimney, has shown significant reductions in personal $PM_{2.5}$ exposures without the provision of fuel (67,68). In our stepped-wedge trial in rural Honduras, post-intervention exposures among women using the Justa stove were notably lower than those recorded in earlier chimney stove studies across Latin America (47,68,69), and approached levels typically observed in households using gas as their primary fuel (63,70). However, results from cookstove interventions remain mixed. Challenges like stove stacking, inconsistent adoption, maintenance issues, and lack of access to sustainable financing all contribute to variable outcomes (17,29,58,70). These implementation barriers illustrate the complexities of clean energy transitions and underscore the need for realistic, community-centered strategies to reduce HAP in the short and medium term.

Fractional exhaled nitric oxide (FeNO) is a well-characterized, non-invasive biomarker of eosinophilic airway inflammation, primarily regulated by Th2 cytokines such as IL-4 and IL-13 (43,71,72). In clinical settings, FeNO is routinely used to assess asthma control and allergic inflammation. Recent studies have also linked FeNO to ambient air pollution exposures (39,73). However, despite its established role in clinical respiratory medicine, FeNO remains underutilized in household air pollution research, especially in rural LMIC settings where pollution sources and exposures differ substantially from urban environments. To date, no studies have employed FeNO longitudinally to evaluate airway inflammation in the context of household energy interventions. Our study addressed this gap by tracking FeNO over three years in a stepped-wedge trial of an improved biomass stove in rural Honduras, offering novel insights into the relationship between reduced household air pollution and inflammatory responses over time.

In a cross-sectional analysis of women in rural Honduras, Benka-Coker et al. (2018) found exposure-response results assessing the association between exposure to HAP and FeNO that were generally consistent with the null hypothesis, contributing to the growing body of inconsistent evidence on household air pollution (HAP) and airway inflammation(64). Other studies have also reported mixed findings. In Costa Rica, Werthmann et al. (2023) observed elevated FeNO levels among women and children exposed to indoor biomass smoke, particularly in households with poor ventilation or longer cooking durations. Their findings suggest that chronic exposure to wood smoke may induce eosinophilic airway inflammation, potentially mediated by particulate matter and volatile organic compounds that trigger immune responses involving Th2 cytokines (44). Similarly, Nigatu et al. (2022) conducted a cross-sectional study of 248 female flower farm workers in Ethiopia and found that, despite higher endotoxin exposures among greenhouse workers, FeNO concentrations did not differ significantly between high- and low-exposure groups(45). This suggests that FeNO may not respond sensitively to biologically active dust exposures within the timeframe measured, highlighting the complexity of using FeNO as a biomarker of airway inflammation in agricultural settings, where chronic exposure to diverse allergens and irritants may confound its interpretation. In contrast, Pollard et al. (2014) conducted a cross-sectional study in Puno, Peru, where rural women had significantly higher exposures to particulate matter ($PM_{2.5}$) and carbon monoxide (CO) than their urban counterparts; however, FeNO levels did not significantly differ between the two groups (47). This lack of association may reflect variability in exposure intensity, stove use behaviors, or host factors such as baseline atopy or respiratory infections, further underscoring the inconsistency in the literature.

Our study builds upon this limited and inconsistent evidence base by employing a longitudinal, stepped-wedge randomized design in rural Honduras. We tracked changes in FeNO over a three-year period as women transitioned from traditional stoves to the Justa cookstove. Additionally, we incorporated personal and kitchen-based $PM_{2.5}$ and BC measurements to assess exposure-response relationships with airway inflammation. This study aims to clarify whether reductions in household air pollution through improved stove technology are associated with measurable changes in FeNO, providing insight into one possible biological pathway linking cleaner cooking practices to better respiratory health.

Methods and Materials

Study Population

The study took place in nine rural communities near La Esperanza, Intibucá, Honduras, situated at elevations between 1700 and 2200 meters. Intibucá is a mountainous region with an economy centered on agriculture, where residents primarily cultivate potatoes, beans, coffee, and other fruits and vegetables. This research is part of ongoing collaborations between Colorado State University (CSU) and Trees, Water & People (TWP) in Fort Collins, Colorado, and the Honduran Association for Development (AHDESA) in Tegucigalpa, Honduras, as outlined in our protocol paper (74). The study communities were selected in partnership with local leaders and advisory boards, reflecting these long-established relationships.

At the baseline, most households in these communities used self-built wood-burning cookstoves, which often had poorly functioning chimneys or combustion chambers. The improved Justa stove, which was introduced as part of the intervention, features an engineered combustion chamber, chimney, and griddle surface designed to enhance combustion efficiency and reduce emissions.(74)

Intervention and Participant Recruitment

Eligible participants were women aged 24–59 who were the primary cooks in their households, non-smokers, not pregnant, and exclusive users of traditional biomass cookstoves at baseline. A total of 337 women were screened for eligibility, and 230 met the inclusion criteria and were enrolled in the study.

Trial Design and Study Visits

This intervention study utilized an individual-level, stepped-wedge design, a type of a randomized controlled trial. Participants were randomly assigned to study arm 1 (n=115) or arm 2 (n=115) by blindly drawing a number from a bag at a community meeting. 90 participants (39%) were randomly assigned to the FeNO sub study from the primary study, arm 1 (n=48) or arm 2 (n=42). Table 3.1 outlines our study design, showing stove types and timing of the intervention for both study arms. Data were collected at 6 repeated visits from August 2015 through May 2018, with approximately 6 months between each visit. All participants cooked on traditional stoves for the first 2 visits, and then those in study arm 1 received the *Justa* cookstove intervention after visit 2, and those in study arm 2 received the intervention after visit 4 (Table 3.1). This study design offered a sequential roll-out of the intervention in a stepped timeline to allow each study arm its own pre- and post-intervention observations at different time points (75). Blinding of participants and researchers was not possible because the intervention was a new cookstove.

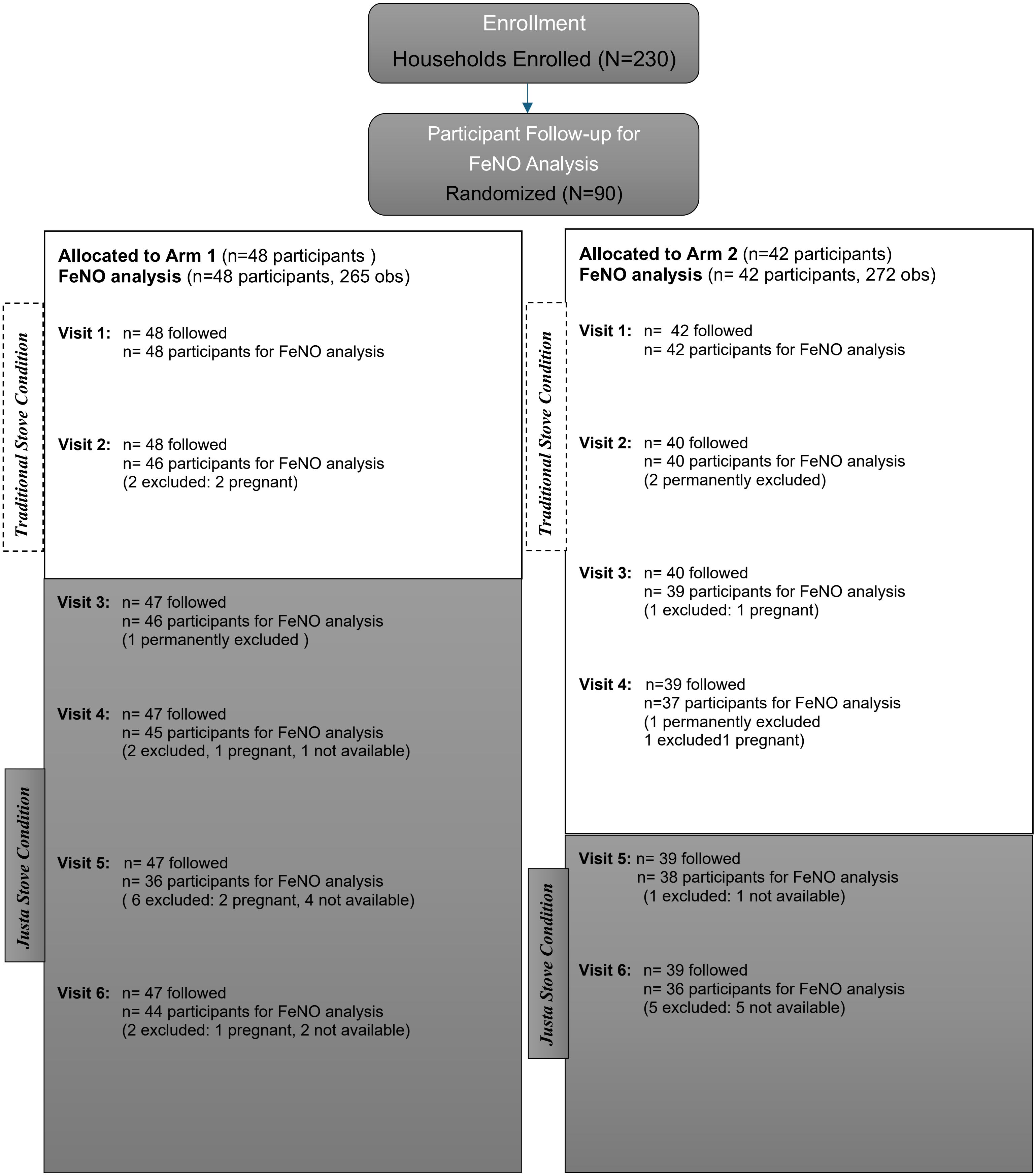

Figure 3.1. Flow diagram for participant follow-up and total FeNO results for analysis.

Figure 3.1. illustrates participant retention and availability of fractional exhaled nitric oxide (FeNO) measurements across six visits in the randomized cohort. Of the 230 participants assessed for eligibility, 90 participants were randomized into Arm 1 (traditional stove condition) and Arm 2 (Justa stove condition). FeNO data were available for 47 participants in Arm 1 and 39 participants in Arm 2 at baseline. Attrition over time was primarily due to pregnancy, permanent withdrawal, or unavailable FeNO measurements at specific visits. By Visit 6, FeNO data were retained for 44 participants in Arm 1 and 36 participants in Arm 2. This figure highlights the strong follow-up rates throughout the study despite minor losses to follow-up.

Table 3.2 Study design for the stepped-wedge randomized cookstove intervention, Honduras, 2015-2018.

Study visit number:	**1**	**2**	**3**	**4**	**5**	**6**
Timing of data collection:	Aug – Dec 2015	Jan – May 2016	Sep – Dec 2016	Feb – May 2017	Sep – Dec 2017	Feb – May 2018
Condition: Arm 1 (n=48 participants) Assigned stove type	Traditional	Traditional	*Justa*	*Justa*	*Justa*	*Justa*
Condition: Arm 2 (n=42 participants) Assigned stove type	Traditional	Traditional	Traditional	Traditional	*Justa*	*Justa*

Assigned stove conditions and exposure assessment

Participants were randomly assigned to one of two study arms, which determined the timing of their stove intervention (traditional stove vs. Justa cookstove). This assignment defined the primary condition of interest—referred to as the assigned stove type. The primary exposures assessed were 24-hour gravimetric personal and kitchen $PM_{2.5}$ and black carbon (BC) concentrations. Additionally, stove use was evaluated via “per protocol” self-reporting, where participants indicated whether they used only the Justa stove, combined the Justa with another improved stove, stacked the Justa with a traditional stove, or used only a traditional stove.

For personal exposure, monitors were placed in a small bag or attached to a cloth necklace, positioning the air inlet close to the participant's breathing zone. Participants were instructed to wear the monitors continuously for 24 hours, only removing them to bathe, and to keep them nearby while sleeping. Kitchen monitors were installed 76–127 cm above the primary stove's front edge, also near the breathing zone, while avoiding direct smoke plumes and nearby windows or doors. $PM_{2.5}$ samples were collected over 24 hours using 37 mm filters (Fiberfilm, Pall Corporation, NY, USA, and Teflo, VWR, Radnor, PA, USA) for both personal and kitchen locations. Sampling was done with a Triplex cyclone inlet (BGI, Inc., NJ, USA) attached to an Airchek pump (XR5000, SKC Inc., PA, USA) set to 1.5 L/min and calibrated with a DryCal Lite (Mesa Labs, NJ, USA) before each use. At visit 5, we transitioned to using the Ultrasonic Personal Aerosol Sampler (UPAS, Access Sensor Technologies, Fort Collins, CO, USA) for personal exposure. Due to product availability, we switched from Pallflex fiberfilm filters to Teflo filters prior to exposure monitoring for the fifth study visit. The UPAS operated at 1.0 L/min with a custom cyclone and enclosed filter and offered a more compact, lightweight, and quieter alternative, which reduced participant burden (76). Field blanks were collected once per week.

To ensure consistency between filter types (Fiberfilm vs. Teflo) and monitoring setups (Triplex cyclone/Airchek vs. UPAS), field comparisons were conducted. These yielded high Spearman correlations: 0.96 for paired filters (n=11) ((55) and 0.91 for personal monitoring devices (n=43) (77). All filters were stored at -20°C at the Honduras field house, then transported to CSU and kept at -80°C prior to analysis. Briefly, the PM2.5 limit of detection (LOD) for each phase was estimated by adding the mean mass of the field blanks to 3 times the standard deviation of the field blank masses. Samples that were below the LOD were were substituted with LOD/sqrt(2).Samples were blank-corrected by subtracting the mean blank mass for the phase. Final 24-h PM2.5 concentrations were estimated by dividing the blank-corrected filter mass by the volume of the air sampled through the pump over the measurement period. Further details on field blanks, equilibration, filter weighing, and $PM_{2.5}$ detection limits are available in previous publications (68,78).

Methods for BC measurement and calculation are described elsewhere. (citation) Briefly, BC mass concentrations for personal and kitchen settings were determined using the Sootscan Transmissometer (OT21, Magee Scientific), based on changes in 880 nm light transmission through filters pre- and post-sampling. The calculations incorporated effective filter areas—0.00071 m^2 for Teflo and 0.00078 m^2 for Fiberfilm—the total air volume sampled over 24 hours (at 1.0 or 1.5 L/min), and a mass attenuation cross-section of 12.5 m^2/g (74).

FeNO/ health endpoints

Fractional exhaled nitric oxide (FeNO) was measured to estimate airway inflammation with the NIOX Vero device (Circassia Pharmaceuticals Inc., Morrisville, NC, USA). Due to the high costs of the FeNO tests, a subset of 90 women (39%) was randomly selected at the first study visit to conduct the test, and then asked to repeat the test at each subsequent visit (74). .Participants stood upright, emptied their lungs, inhaled steadily through the NIOX VERO, and then exhaled at a slow and steady rate for 10s. Participants exhaled at 50 mL/s after a full inspiration, and FeNO was recorded in ppb. If the first two measurements differed by >10%, a third was taken. Final values were averaged for analysis.

In-person questionnaires conducted by our study team provided comprehensive self-reported information on health and socio-demographic factors that were relevant for the FeNO models. These factors were selected based on a literature review identifying potential confounders and variables that could improve the precision of the models. Anthropometric data, including weight (measured using an electronic scale in kilograms), height (measured with a tape and level against a wall in meters), and body mass index (BMI in kg/m^2), were collected at each visit. Women reported any recent illnesses and provided information on their dietary diversity, which was assessed through a 24-hour dietary recall of commonly consumed Honduran foods. The foods were categorized into 11 groups: cereals (corn, grains, rice, chips), pulses (beans, nuts), potatoes, vegetables, fruits, sweets (desserts, cakes, cookies, candy, sweet breads), eggs, dairy (milk, cheese, butter, cream), meat, fat (oils, lard), and sweetened drinks (coffee, soda, juice). Each food category was recorded as a yes/no based on the recall, and the total dietary diversity score ranged from 1 to 11, collected at every visit.

Medication use was documented based on participants' recall of current medications, herbal remedies, or vitamins, with verification by sight. This included medications such as ibuprofen (Advil, Motrin), acetaminophen (Tylenol), prenatal vitamins, antibiotics, antihypertensives, asthma medications, pain relievers, aspirin, nonsteroidal anti-inflammatory drugs, and birth control. Mucous symptoms were also assessed based on participant recall, specifically noting whether they experienced mucous at the time of the test or when participant was actively cooking.

Physical activity levels were estimated each visit using metabolic equivalent of tasks (MET), based on 10 common activities in this population, adapted from the 2011 Compendium of Physical Activity scores: cutting wood (MET=5.5), grinding corn (MET=3.3), washing clothes (MET=4), milking a cow (MET=3.5), working in the field (MET=4.8), moderate walking (MET=3.5), cooking (MET=3.3), cleaning (MET=3.3), sitting (MET=1.3), and sleeping (MET=0.95). Each participant’s MET score was calculated by multiplying the self-reported hours of each activity per week by the corresponding MET value, then summing the results.

Household material wealth was estimated at baseline using a weighted index based on the presence of 9 culturally relevant household items: bicycle, car, motorbike, television, radio, refrigerator, cell phone, computer, and sewing machine. Rare items (e.g., car, computer) were given greater weight than more common ones (e.g., radio). At the time of testing, participants were also asked whether they used kerosene as a lighting source in the home.

Cooking behaviors, such as the use of secondary stoves (i.e., "stove stacking"), were self-reported during each visit. Stove stacking referred to using another improved stove, such as the Envirofit or Project Mirador stove, which featured rocket-elbow combustion chambers, metal griddles, chimneys, and wood fuel. Stove stacking could also include temporary or permanent use of traditional stoves, often in outdoor locations. Field research staff conducted in-person stove assessments at each study visit to observe the condition and maintenance of the Justa stove, which were recorded during the visits.

Statistical Analysis

Handling of Missing Data and Descriptive Analysis

Observations that were missing FeNO values or covariates included in the final models were excluded from the analysis. Similarly, observations missing exposure data were dropped from the exposure-response models. Descriptive analyses were conducted on exposures (medians, 25th, and 75th percentiles), FeNO, and other health and household characteristics. Data were summarized using means, standard deviations, ranges, and frequencies, depending on the data type. The success of randomization was assessed by comparing baseline characteristics such as age, household wealth, and health measures across study arms. Randomization was generally successful in the full study population, with covariates and potential confounders distributed relatively evenly between assigned stove arms. However, within the FeNO sub-study population, imbalances were observed for two key variables: dichotomized age and socioeconomic status. The dichotomized age variable (used later in the effect modification analysis) and the weighted household asset index (included as a covariate in the secondary ITT and exposure-response models) were not equally distributed between arms. These differences could reflect chance variation, especially given the relatively small sample size. To account for potential confounding, these variables were included as covariates in the relevant models. Pearson correlation coefficients were calculated for the correlations between household air pollution (HAP) measures, $PM_{2.5}$ and black carbon (BC), across all participants at all time points.

Intent-to-Treat Analysis

For the intent-to-treat (ITT) analysis, we assessed the association between assigned stove type and FeNO using linear mixed models. These models included a fixed effect for assigned stove condition (Justa vs. traditional), a random effect for participant ID to account for repeated measures, and a natural cubic spline for calendar date with 6 degrees of freedom to adjust for potential temporal confounding due to the stepped-wedge design (75). Secondary ITT models additionally adjusted for three covariates: age (continuous), kerosene use (dichotomous yes/no), and the weighted household asset index (continuous).

Exposure-Response Models

For the exposure-response analyses, linear mixed models with a random effect for participant ID were used. Each model evaluated either 24-hour or long-term average exposures to personal or kitchen $PM_{2.5}$ and BC separately. Exposures were log-transformed to better meet linear model assumptions. Covariates included in all exposure-response models were: age (continuous), height (continuous), and the weighted household asset index (continuous). Time was not included as a covariate in the exposure-response models to avoid overadjustment, given that stove assignment explained most temporal variation in exposure.

Long-Term Average Exposure

For additional exposure-response analyses, given our interest in characterizing the long-term impacts of exposure on health outcomes, we assessed predicted long-term averages of PM2.5 and BC as alternative exposures (79)The long-term averages were estimated from a mixed model that included assigned stove status, a natural cubic spline function for time with 6 degrees of freedom, and a random effect for participant. This method ensures that the long-term averages are influenced by both the concentration averages for each household and the between-household averages for each assigned stove status. See Keller & Clark (2022) for further details (79).

Per-Protocol Analysis

For the primary per-protocol analysis, Linear mixed models included a random effect for participant ID self-reported primary stove use (categorized into three groups: Justa plus improved stove, Justa plus traditional stove, traditional stove only) was the exposure variable with a spline for time. Our secondary ITT additionally adjusted for age, kerosene use, and household asset index.

Effect Modification and Sensitivity Analysis

Effect modification was evaluated by adding interaction terms between assigned stove condition or exposure variables and the following pre-specified modifiers: age group (<40 vs. ≥40 years), BMI category (normal <25 vs. overweight/obese ≥25), diet diversity score (<6 vs. ≥6), and physical activity level (<300 METS vs. ≥300 METS). Interaction models adjusted for the same covariates as the corresponding primary model (age, kerosene use, household asset index for ITT; age, height, household asset index for exposure-response).

Two sensitivity analyses were conducted. First, observations where participants reported anti-inflammatory medication use were excluded, given that such medications can suppress airway inflammation and lower FeNO levels independent of environmental exposures (61,80). Second, observations where participants reported mucus symptoms were further excluded. Mucus production could act as a confounder if it is independently associated with both unmeasured factors related to exposure to household air pollution and FeNO levels. Alternatively, mucus could function as a mediator if exposure to household air pollution increases mucus production, which then affects FeNO, or as a collider if it is influenced by both exposure and FeNO. Given these complex potential pathways, we conducted the sensitivity analysis to provide results for both scenarios, accounting for mucus and not accounting for mucus (81–83). Sensitivity models included the same covariates as their corresponding primary models.

All data management and statistical analyses were performed in R Statistical Software and RStudio (version 4.4.1, The R Foundation for Statistical Computing Platform).

Results

Table 3.2: Comparison of Population Characteristics Between the Main Trial and FeNO sub study Among Nonsmoking Primary Female Cooks in Rural Honduras (N=90)

Characteristic	All Participants (N=230) (SD) or N (%)	Arm 1 (N=48) (SD) or N (%)	Arm 2 (N=42) (SD) or N (%)
Age, years	38.2 (8.6)	38.3 (8.4)	38.3 (10.2)
Age Category			
Less than 40	137 (60%)	28 (58%)	16 (38%)
40 or more	93 (40%)	20 (42%)	26 (62%)
Body Mass Index (BMI, kg/m²)	26.1 (4.2)	26.0 (4.1)	26.1 (4.0)
Body Mass Index (BMI, kg/m²)			
≥25 (Overweight/Obese)	146 (64%)	27 (56%)	22 (52%)
<25 (Normal/Underweight)	84 (36%)	21 (44%)	20 (48%)
Height (cm)	157.3 (2.2)	157.1 (2.1)	157.6 (2.3)
Dietary Diversity Score	6.4 (1.8)	5.9 (1.7)	6.2 (1.8)
Dietary Diversity Score[1]			
DDS < 6	76 (33%)	21 (44%)	15 (36%)
DDS ≥ 6	154 (67%)	26 (54%)	27 (64%)
Physical Activity (METs)[2]			
≥300 METs	188 (81%)	21 (44%)	23 (55%)
<300 METs	42 (19%)	27 (56%)	19 (45%)
Kerosene Use[3]			
Yes	49 (21%)	10 (21%)	11 (26%)
No	181 (79%)	38 (79%)	31 (74%)
Household Assets Index (range 0–45)[4]	6.6 (7.2)	4.8 (5.5)	8.0 (9.3)
Current Use of Medication[5]	64 (28%)	17 (35%)	14 (33%)
Yes	162 (72%)	31 (65%)	28 (67%)
No			
Mucous Symptoms (Now)[6]		13 (27%)	13 (31%)
Yes	71 (31%)	35 (73%)	29 (69%)
No	159(69%)		
FeNO (log ppb)		2.9 (0.6)	2.8 (0.7)

Dietary Diversity Score: Sum of food groups consumed in the past 24 hours across 11 categories — cereals (grains, corn, rice, chips), pulses (beans, nuts), potatoes, vegetables, fruit, sweets (desserts, cake, cookies, candy, sweet breads), eggs, dairy (milk, cream, cheese, butter), meat, fats/oils, and sweetened beverages (coffee, soda, juice).Physical Activity: Based on metabolic equivalent tasks (METs) from 10 common lifestyle activities, calculated as MET-hours per week; activities included cutting wood, grinding corn, washing clothes, milking cows, working in fields, walking, cooking, cleaning, sitting relaxed, and sleeping. Kerosene Use: Current use of kerosene for any household activity (e.g., cooking or lighting).Household Assets Index: Weighted index based on ownership of nine assets — radio, mobile phone, bicycle, television, sewing machine, refrigerator, car, motorbike, and computer. Current Use of Medication: Self-reported regular use of any listed medications, including analgesics, antibiotics, respiratory medications, blood pressure medications, and others. Mucous Symptoms: Self-reported mucous symptoms at the time of the study visit (yes/no).

Table 3.3: 24-h average kitchen and personal fine particulate matter and black carbon concentrations with predicted long term averages (LTA), traditional and Justa stove users, rural Honduras. PM2.5: fine particulate matter. (N=90 participants, total observations are included in the table for each pollutant)

Variable	N	Study Arm	Min	Q1	Median	Mean	Q3	Max µg/m³	SD
Personal PM µg/m³	445	Arm 1	5.47	30.65	51.19	98.97	97.20	1560.55	172.56
		Arm 2	5.47	37.86	65.91	120.69	118.37	2165.15	120.69
Personal BC µg/m³	436	Arm 1	0.09	2.21	8.03	34.74	22.30	2364.44	163.72
		Arm 2	0.09	2.82	6.62	23.96	17.33	665.35	66.96
Area PM µg/m³	445	Arm 1	4.31	35.64	74.15	231.43	161.01	4174.72.	500.75
		Arm 2	5.01	41.61	91.60	254.47	248.66	5426.20	524.20
Area BC µg/m³	436	Arm 1	0.08	3.11	12.56	91.73	83.79	1377.24	205.17
		Arm 2	0.09	6.38	20.01	77.65	58.63	1418.34	167.68
LTA Personal PM µg/m³	455	Arm 1	22.2	39.25	59.74	57.97	87.36	198.34	1.62
		Arm 2	22.20	50.91	67.36	68.03	97.51	190.57	2.94
LTA Personal BC µg/m³	453	Arm 1	1.05	2.80	6.75	6.89	13.60	217.02	2.20
		Arm 2	1.06	3.94	6.82	6.89	12.06	26.84	2.23
LTA Kitchen PM µg/m³	455	Arm 1	3.25	23.10	89.12	92.76	159.17	871.31	2.23
		Arm 2	1.79	14.01	113.30	112.17	194.42	742.48	3.97
LTA Kitchen BC Log-µg/m³	453	Arm 1	1.38	5.21	15.03	16.28	40.04	685.40	3.00
		Arm 2	2.08	9.78	23.10	20.49	51.42	129.02	3.00

Descriptive statistics

Table 3.2 shows that at baseline, the 90 participants in Arms 1 and 2 had comparable characteristics across study arms. The average FeNO level was 2.9 log ppb (SD 0.6) in Arm 1 and 2.8 log ppb (SD 0.7) in Arm 2. Participants in both arms were similar in age, with a mean of 38.3 years (SD 8.4) in Arm 1 and 38.3 years (SD 10.2) in Arm 2. However, categorically in Arm 1, 58% (n=28) were under age 40 compared to 38% (n=16) in Arm 2. The average BMI was 26.0 kg/m² (SD 4.1) in Arm 1 and 26.1 kg/m² (SD 4.0) in Arm 2, with over half of participants in both arms classified as overweight or obese (56% in Arm 1, 52% in Arm 2). Dietary diversity scores averaged 5.9 (SD 1.7) in Arm 1 and 6.2 (SD 1.8) in Arm 2, with a majority scoring 6 or higher in both arms. Physical activity levels were similar in both groups, with 56% of Arm 1 and 55% of Arm 2 reporting more than 300 METs. Self-reported kerosene use was low overall, with 21% (n=10) in Arm 1 and 26% (n=11) in Arm 2 reporting use. Mean household asset scores were higher in Arm 2 (8.0, SD 9.3) than Arm 1 (4.8, SD 5.5). Current medication use was reported by 35% (n=17) in Arm 1 and 33% (n=14) in Arm 2. Mucous symptoms at baseline were reported by 27% (n=13) in Arm 1 and 31% (n=13) in Arm 2, further highlighting the overall comparability of groups prior to intervention.

Table 3.1 presents descriptive statistics for personal and kitchen exposures to $PM_{2.5}$ and BC, based on 24-hour samples and predicted long-term averages (LTA), stratified by study arm. Median personal $PM_{2.5}$ exposures were 51.2 µg/m³ in Arm 1 and 65.9 µg/m³ in Arm 2, while median personal BC exposures were 8.0 µg/m³ and 6.6 µg/m³, respectively. Area $PM_{2.5}$ exposures were higher overall, with medians of 74.2 µg/m³ in Arm 1 and 91.6 µg/m³ in Arm 2. Median area BC exposures were 12.6 µg/m³ for Arm 1 and 20.0 µg/m³ for Arm 2.

For long-term average exposures, median $PM_{2.5}$ levels were 59.74 µg/m³ in Arm 1 and 67.36 µg/m³ in Arm 2, while personal BC medians were 6.75 µg/m³ and 6.82 µg/m³ , respectively. Kitchen long-term average $PM_{2.5}$ medians were 89.12 µg/m³ for Arm 1 and 113.30 µg/m³ for Arm 2, and kitchen BC long-term medians were 15.03 µg/m³ and 23.10 µg/m³ , respectively.

Intent-to-Treat (Assigned Stove Type)

The primary analysis of the intent-to-treat (ITT) (N=455 observations) effects of the assigned Justa stove compared to the traditional stove (reference) demonstrated a minimal difference in percent change. The Justa stove, with 217 observations, showed a percent change of 0.01%, with a 95% confidence interval (CI) ranging from -2.4% to 4.3%, indicating no significant impact on the outcome when compared to the traditional stove. The primary ITT model included stove assignment (Justa vs. traditional) as the exposure variable and a natural cubic spline with 6 degrees of freedom to adjust for time, along with a random intercept for participant ID. Figure 3.1 shows FeNO by study arm across the course of the study.

The secondary ITT analysis, which additionally adjusted for key precision variables, included stove assignment, age (continuous), socioeconomic status (SES; continuous weighted household asset index; also included since we observed differences across the arms), and height (continuous) as fixed effects, with a random intercept for participant ID. The secondary analysis estimated a percent change of -0.6%, with a CI of -3.6% to 2.6%, again showing no significant difference.

Exposure-Response with 24-hour $PM_{2.5}$ and Predicted Long-Term Average (Natural Log-transformed)

Exposure-response models were conducted separately for each exposure metric (24-hour and predicted long-term average personal and kitchen $PM_{2.5}$) and included the log-transformed exposure variable, age (continuous), height (continuous), and SES (continuous weighted household asset index) as covariates, with a random intercept for participant ID; estimates are presented for each 25% increase in the exposure of interest and are presented in Table 3.4. The exposure-response analysis for personal 24-hour $PM_{2.5}$ exposure revealed a slight negative association with FeNO, with a percent change of -0.95% per 25% increase in $PM_{2.5}$, and a 95% CI of -2.1% to 0.2%.

When examining the long-term average predicted $PM_{2.5}$ exposure, the percent change in FeNO was more substantial at -3.6% (CI: -6.3% to -0.8%), suggesting a stronger inverse relationship with the outcome. A similar inverse association was observed for kitchen $PM_{2.5}$ exposure, with a percent change of -1.6% (CI: -2.5% to -0.8%), and for long-term average kitchen $PM_{2.5}$ exposure with a percent change of -1.9% (CI: -3.4% to -0.4%).

Exposure-Response with 24-hour Black Carbon and Predicted Long-Term Average (Natural Log-transformed)

The analysis of personal black carbon (BC) exposure indicated a modest negative association, with a percent change of -0.9% per 25% increase in pollutant and a CI ranging from -1.5% to -0.3%. Models for BC exposure were similarly adjusted for age, height, and SES, with a random intercept for participant ID. For the predicted long-term average BC exposure, the percent change was -1.8% (CI: -3.1% to -0.5%). Kitchen BC exposure showed a percent change of -1.0% (CI: -1.6% to -0.5%), and long-term average kitchen BC exposure showed a percent change of -1.4% (CI: -2.3% to -0.4%).

Per Protocol Analysis

The per protocol analysis results (Table 3.4) further supported the findings of the exposure-response analysis. Those using a traditional stove (N=236 observations) were considered the reference. For individuals using both the Justa and traditional stoves (N=138 observations), the percent change was 3.5% (CI: 1.3% to 5.8%). Those using only the Justa stove or another improved stove (N=81 observations) demonstrated a smaller percent change of 2.3% (CI: -0.4% to 5.0%). The per protocol models included stove use category as the exposure variable and adjusted for age, kerosene use, and SES, with a random intercept for participant ID.

Adjustment for Potential Confounders

The secondary ITT analyses were adjusted for stove assignment, age, SES, and height with a spline for time and a random intercept for participant ID. The exposure-response analyses adjusted for log-transformed pollutant exposure, age, height, and SES. The per protocol analyses adjusted for stove use category, age, kerosene use, and SES. These adjustments addressed variations in key demographic and exposure-related variables across study participants and ensured the robustness of the associations observed between stove use, pollutant exposure, and respiratory health outcomes.

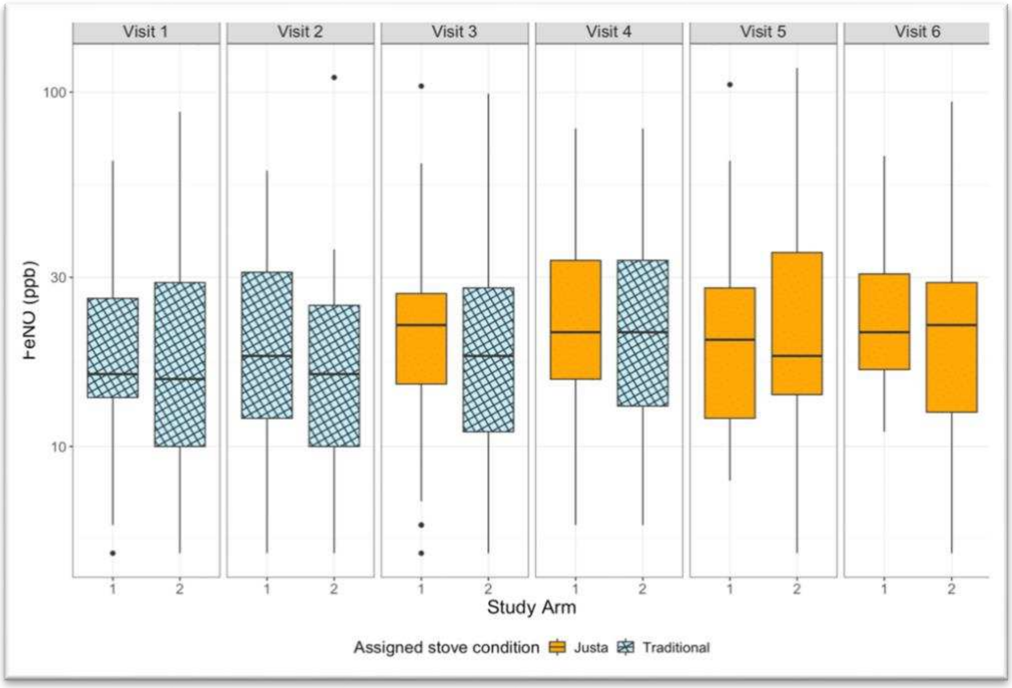

Figure 3.2: Distribution of FeNO levels by assigned stove condition and study visit in the Honduras Justa Cookstove Trial. This figure presents boxplots of fractional exhaled nitric oxide (FeNO) concentrations (ppb, log y-axis scale) measured across six study visits for participants assigned to either the Justa stove intervention or traditional stove condition.

Table 3.4 Primary results. Adjusted mixed-effects regression models for intent-to-treat, personal and kitchen $PM_{2.5}$ and BC exposure-response, and self-reported cookstove use models for effects on FeNO values. Participant ID is a random effect in all models. (N=455 observations)

Main Exposure	Percent Change (%)	95% CI (Low)	95% CI (High)
Intent-to-Treat (Assigned Stove Type)			

Justa stove (N = 217) - Primary Traditional stove (reference) (N = 238)	0.01 Reference	-2.4 Reference	4.3 Reference
Justa stove (N=217) - Secondary Traditional stove (reference)(N=238)	0.6 Reference	-2.3 Reference	3.5 Reference
Exposure-Response with 24-hour PM2.5 and predicted long term average (μg/m³, natural log-transformed)	**Per 25% Increase in Pollutant (%)**	**95% CI (Low)**	**95% CI (High)**
Personal (N = 445)	-0.95	-2.1	0.2
Personal predicted long-term average (N = 455)	-3.6	-6.3	-0.8
Kitchen (N = 445)	-1.6	-2.5	-0.8
Kitchen predicted long-term average (N = 455)	-1.9	-3.4	-0.4
Exposure-Response with 24-hour Black Carbon and predicted long term average(μg/m³, natural log-transformed)			
Personal BC2 (N = 436)	-0.9	-1.5	-0.3
Personal predicted long-term average BC2,3 (N = 453)	-1.8	-3.1	-0.5
Kitchen BC2 (N = 436)	-1.0	-1.6	-0.5
Kitchen predicted long-term average BC2,3 (N = 453)	-1.4	-2.3	-0.4
Per Protocol Analysis based on self-reported stove use	**Percent Change (%)**	**95% CI (Low)**	**95% CI (High)**
Traditional stove (N = 236) Justa and traditional stove (N = 138) Justa + improved stove (N = 81)	Reference 3.5 2.3	Reference 1.3 -0.4	Reference 5.8 5.0

BC = black carbon, CI = confidence interval, N = number of observations, $PM_{2.5}$ = fine particulate matter ≤2.5 microns in diameter.[1a] Fixed effect term for "time" is a natural cubic spline function with 6 degrees of freedom.[1b]Fixed effect term for "time" is a natural cubic spline function with 6 degrees of freedom with additional covariates age, household weighted assets, and height.[2] Additional covariates in model: Age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), kerosene use (none/any).[3] Predicted long-term average exposure, estimated from intercept and random effect for household. Two exposures per household, one for each stove type, combining stove group mean and the household random effect[4] Stove use for primary stove and fuel stacking estimated from intercept and random effect for household. Additional covariates in model: Age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), kerosene use (none/any

Table 3.5 Sensitivity results. Adjusted mixed-effects regression models for intent-to-treat, personal and kitchen $PM_{2.5}$ and BC exposure-response, and self-reported cookstove use models for effects on FeNO values, those who reported medication use were removed (N=31). Participant ID is a random effect in all models. (N=414 observations)

Main Exposure	Percent Change (%)	95% CI Low	95% CI High
Intent-to-Treat (Assigned Stove Type)			

Justa stove[1a] (N = 200) Traditional stove (reference) (N = 214)	3.0 Reference	-12 Reference	21 Reference
Justa stove[1b] (N = 200) Traditional stove (reference) (N = 214)	-0.6 Reference	-3.6 Reference	2.6 Reference
Exposure-Response with 24-hour PM2.5 and predicted long term average (µg/m³, natural log-transformed)	**Per 25% Increase in Pollutant (%)**	**95% CI (Low)**	**95% CI (High)**
Personal $PM_{2.5}$[2] (N = 404)	-0.9	-1.9	0.2
Personal predicted long-term average $PM_{2.5}$[2,3] (N = 414)	-3.5	-6.3	-0.7
Kitchen $PM_{2.5}$[2] (N = 404)	-1.3	-2.2	-0.4
Kitchen predicted long-term average $PM_{2.5}$[2,3] (N = 414)	-1.9	-3.5	-0.4
Exposure-Response with 24-hour Black Carbon and predicted long term average(µg/m³, natural log-transformed			
Personal BC[2] (N = 395)	-0.7	-1.3	-0.2
Personal predicted long-term average BC[2,3] (N = 412)	-1.5	-3.1	-0.2
Kitchen BC[2] (N = 395)	-0.9	-1.3	-0.2
Kitchen predicted long-term average BC[2,3] (N = 412)	-1.3	-2.2	-0.2
Per Protocol ITT	**Percent Change (%)**	**95% CI (Low)**	**95% CI (High)**
Traditional stove (N = 211) Justa and traditional stove (N = 125) Justa only (N = 78)	Reference 3.0 1.9	Reference 0.6 -0.8	Reference 5.2 4.7

BC = black carbon, CI = confidence interval, N = number of observations, $PM_{2.5}$ = fine particulate matter ≤2.5 microns in diameter.[1a] Fixed effect term for “time” is a natural cubic spline function with 6 degrees of freedom. [b]Fixed effect term for “time” is a natural cubic spline function with 6 degrees of freedom with additional covariates age, household weighted assets, and height.[2] Additional covariates in model: Age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), kerosene use (none/any).[3] Predicted long-term average exposure, estimated from intercept and random effect for household. Two exposures per household, one for each stove type, combining stove group mean and the household random effect[4] Stove use for primary stove and fuel stacking estimated from intercept and random effect for household. Additional covariates in model: Age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), kerosene use (none/yes)

Table 3.6. Percent Change in FeNO by Subgroup and Exposure Type

Percent change in FeNO associated with assigned stove type, personal $PM_{2.5}$, personal black carbon, area $PM_{2.5}$, and area black carbon exposures, stratified by age, BMI, physical activity level, and diet diversity score (DDS). Models used linear mixed effects regression with a random intercept for participant. Interaction p-values assess effect modification by subgroup.

Exposure Type	Subgroup	N	Estimate (%)	CI Low	CI High	p-value (interaction)

Assigned Stove (Justa vs Traditional)	Age < 40 years	263	0.0	-15.6	18.5	0.44
	Age ≥ 40 years	192	-6.3	-22.0	12.7	
	BMI < 25 (normal)	184	-8.6	-24.4	9.4	0.20
	BMI ≥ 25 (overweight/obese)	271	1.0	-14.8	19.7	
	Physical Activity < 300	288	0.2	-15.6	18.5	0.40
	Physical Activity ≥ 300	166	-8.6	-23.7	11.6	
	DDS < 6	130	18.5	-3.9	46.2	0.20
	DDS ≥ 6	324	-0.1	-14.8	18.5	
Personal $PM_{2.5}$	Age < 40 years	257	-4.9	-11.3	1.5	0.40
	Age ≥ 40 years	188	0.7	-8.6	7.3	
	BMI < 25 (normal)	185	-8.6	-15.6	-0.2	0.10
	BMI ≥ 25 (overweight/obese)	263	1.0	-6.8	6.2	
	Physical Activity < 300	280	-1.0	-6.8	5.1	0.01
	Physical Activity ≥ 300	164	-12.2	-18.9	5.1	
	DDS < 6	127	-19.7	-27.4	-10.4	0.0001
	DDS ≥ 6	317	1.9	-7.7	4.1	
Personal Black Carbon	Age < 40 years	235	0.0	-5.8	6.2	0.50
	Age ≥ 40 years	160	-3.0	-6.8	2.0	
	BMI < 25 (normal)	166	-8.6	-15.6	-0.2	0.06
	BMI ≥ 25 (overweight/obese)	229	0.5	-6.8	6.2	
	Physical Activity < 300	273	-3.0	-5.8	2.0	0.16
	Physical Activity ≥ 300	162	-5.8	-10.4	2.0	
	DDS < 6	129	-6.8	-11.3	-1.0	0.34
	DDS ≥ 6	306	4.1	-6.8	0.6	
Area $PM_{2.5}$	Age < 40 years	260	-7.7	-12.2	2.0	0.87
	Age ≥ 40 years	185	7.3	-12.2	1.0	
	BMI < 25 (normal)	180	-9.5	-14.8	-4.9	0.16
	BMI ≥ 25 (overweight/obese)	265	5.1	-9.5	0.5	
	Physical Activity < 263	282	-4.9	-9.5	-0.1	0.10
	Physical Activity ≥ 263	262	-10.4	-15.6	5.1	
	DDS < 6	129	-14.8	-19.7	-8.6	0.004
	DDS ≥ 6	315	4.1	-8.6	0.3	
Area Black Carbon	Age < 40 years	252	-4.9	-7.7	-2.0	0.83

	Age ≥ 40 years	184	4.1	-7.7	7.3	
	BMI < 25 (normal)	181	-5.8	-9.5	-3.0	0.23
	BMI ≥ 25 (overweight/obese)	255	3.0	0.1	7.3	
	Physical Activity < 300	275	-3.9	-6.8	1.0	0.18
	Physical Activity ≥ 300	160	-6.8	-10.4	3.0	
	DDS < 6	128	-7.7	-11.3	-30.2	0.09
	DDS ≥ 6	307	5.1	-6.8	0.8	

All models include a product (interaction) term between the exposure of interest (e.g., stove assignment, personal or area $PM_{2.5}$, or black carbon) and each effect modifier (age, BMI, physical activity, or dietary diversity score). Each model also adjusts for potential confounders: age, height, household asset-weighted index, and kerosene use. A random intercept for participant ID was included to account for repeated measures.

Results from Sensitivity Analyses and Effect Modification

Sensitivity Analysis 1: Exclusion of Anti-inflammatory Medication Users

We conducted a sensitivity analysis excluding individuals using anti-inflammatory medications to evaluate whether these medications might temporarily or artificially negate the impact of exposure on FeNO. Table 3.5 shows that after removing participants who were on anti-inflammatory medications, we found that the effect of the Justa stove on FeNO remained relatively unchanged. In the intent-to-treat analysis, Justa stove users showed a 3.0% increase in FeNO compared to traditional stove users (95% CI: -12% to 21%). This suggests that the stove intervention effect on FeNO is robust, even after excluding individuals on medications that might affect inflammation.

The exposure-response analysis showed similar trends. Personal PM2.5 exposure was associated with a slight negative trend in FeNO, with a 0.9% decrease (95% CI: -1.9% to 0.2%), and personal black carbon (BC) exposure showed a 0.7% decrease in FeNO (95% CI: -1.3% to -0.2%). These results further suggest that excluding those on anti-inflammatory medications does not substantially alter the relationship between air pollution exposure and FeNO levels, confirming the robustness of the findings.

Sensitivity Analysis 2: Exclusion of Individuals with Mucous Symptoms

We also conducted a sensitivity analysis excluding individuals who reported mucus symptoms (e.g., mucus production) at the time of the FeNO test. Mucus symptoms could be considered confounders, colliders, or mediators on the causal path between household air pollution (HAP) exposure and FeNO. After excluding these individuals, the results for the Justa stove intervention were similar and suggested no effect of the intervention on FeNO. Table A.1 shows the intent-to-treat analysis, Justa stove users showed a small 0.5% decrease in FeNO compared to traditional stove users (95% CI: -4.1% to 3.2%). The primary ITT model included assigned stove type (Justa vs. traditional), a natural cubic spline for calendar date (6 degrees of freedom), and a random intercept for participant ID. The secondary ITT models adjusted for stove type, calendar date, age (continuous), socioeconomic status (SES; continuous weighted household asset index), and height (continuous).

Table A.1 shows the exposure-response analyses, removing individuals with mucus symptoms did not change the interpretation of the negative associations between FeNO and air pollution exposure. Personal $PM_{2.5}$ exposure showed a -0.9% change in FeNO (95% CI: -2.1% to 0.3%), and personal black carbon (BC) exposure showed a -0.6% change (95% CI: -1.2% to 0.0%). Additionally, the predicted long-term average $PM_{2.5}$ exposure led to a -3.4% change in FeNO (95% CI: -6.2% to -0.5%), and long-term BC exposure showed a -1.6% change (95% CI: -3.0% to -0.2%). The exposure-response models included log-transformed exposure ($PM_{2.5}$ or BC), age, height, and SES, with a random intercept for participant ID. These findings suggest that excluding individuals with mucus symptoms did not significantly change the interpretation of the results, and the association between air pollution exposure and FeNO remained consistent.

Effect Modification

To evaluate whether the association between the cookstove intervention or air pollution exposure and FeNO differed across participant characteristics, we conducted stratified analyses and tested for effect modification by age, body mass index (BMI), physical activity, and dietary diversity score (DDS). The effect modification models shown in Table 3.6 included the main exposure variable (stove assignment or log-transformed exposure), the effect modifier (e.g., age group, BMI category, DDS, or physical activity level), and an interaction term between exposure and the modifier, along with covariates: age (continuous), height (continuous), SES, a spline for time, and random intercept for participant ID.

Subgroup-specific estimates were generally in the same direction as the main effects, with some variability in magnitude. While most interaction terms were not statistically significant, we observed suggestive trends indicating potential effect modification by DDS and physical activity.

Among participants with lower dietary diversity (DDS <6), personal $PM_{2.5}$ exposure was associated with a −19.7% change in FeNO (95% CI: −27.4, −10.4), while among those with higher DDS (≥6), the association was attenuated (1.9%, 95% CI: -7.7, 4.1), with a p-value for interaction of 0.0001. A similar trend was observed for area $PM_{2.5}$ and black carbon exposures, with stronger negative associations among those with lower DDS (p-values for interaction = 0.004 and 0.09, respectively), suggesting that diet quality may influence susceptibility to air pollution-related airway inflammation.

Physical activity also appeared to modify the relationship between pollution and FeNO. Among participants with physical activity above the median (>300 MET-minutes/day), personal $PM_{2.5}$ exposure was associated with a −12.2% change in FeNO (95% CI: −18.9, 5.1), compared to −1.0% (95% CI: −6.8, 5.1) among those below the median, with a p-value for interaction of 0.01. For area $PM_{2.5}$, the corresponding effect estimates were −10.4% (high physical activity) vs. −4.9% (low physical activity), with a p-value of 0.1. These results suggest that individuals with higher physical activity levels may experience lower airway inflammation in response to pollution exposures, possibly due to increased inhaled dose during exertion.

In contrast, effect modification by age and BMI was less consistent. Interaction p-values for age were 0.40 (personal $PM_{2.5}$), 0.50 (personal black carbon), 0.87 (area $PM_{2.5}$), and 0.83 (area BC). For BMI, interaction p-values were 0.1 (personal $PM_{2.5}$), 0.06 (personal black carbon), 0.16 (area $PM_{2.5}$), and 0.23 (area BC). These suggest limited evidence that age or BMI significantly modified the exposure-response relationship.

Discussion

Household Air Pollution and Lung Inflammation (Fractional Exhaled Nitric Oxide)

Household air pollution, particularly from using biomass fuels such as wood, charcoal, and crop residues in traditional cookstoves, is a major global health concern. Chronic exposure to household air pollution has been linked to respiratory and cardiovascular diseases, especially in low- and middle-income countries where clean cooking technologies are not widely available. We employed the use of Fractional Exhaled Nitric Oxide, a biomarker commonly used in clinical settings to assess airway inflammation in rural Honduras. This biomarker is important because elevated levels typically reflect inflammation, as seen in conditions like asthma, while lower levels may indicate a lack of inflammation or adaptation to chronic exposures. Notably, Fractional Exhaled Nitric Oxide testing is not effort-dependent, meaning it does not require the same level of cooperation or performance as other lung function tests like spirometry. This makes it particularly useful for populations in resource-limited settings or in cases where other types of testing are not feasible (71).

FeNO and Household Air Pollution: Interpretation in Context

The primary finding of our study is the absence of significant changes in FeNO levels following the introduction of the Justa stove, despite notable reductions in personal and kitchen $PM_{2.5}$ and BC exposures. However, our exposure-response analyses revealed consistent inverse associations between exposure levels and FeNO, indicating that individuals with higher exposures had lower FeNO concentrations. This pattern, also reflected in our per-protocol analysis, suggests that exposure reductions may initiate biological recovery pathways similar to those observed in smoking cessation literature, where FeNO levels increase following removal of combustion-related exposures. Although we achieved substantial exposure reductions, these were not accompanied by meaningful short-term increases in FeNO, suggesting that biological recovery of airway inflammation may require sustained reductions or may be limited by chronic exposure effects. Additionally, our effect modification analysis highlighted that dietary diversity and physical activity played a stronger role in modifying the association between HAP exposure and FeNO compared to age or BMI.

Across our intent-to-treat, exposure-response, and per-protocol analyses, the consistency of findings supports the presence of non-differential misclassification of exposure, which likely biased results toward the null. Specifically, short-term personal exposure measurements, while rigorous, may not fully capture habitual or long-term exposure patterns that drive airway inflammation. Furthermore, variability in individual behavior, time-activity patterns, and household stove stacking practices may have introduced random measurement error that is unrelated to FeNO values, leading to attenuation of the true exposure-response relationship. Because this misclassification is likely non-differential—affecting participants across both intervention and control groups equally—it would be expected to dilute observed associations rather than generate spurious effects. Taken together, these findings emphasize the complexity of airway inflammatory recovery following exposure interventions and highlight the need for longer-term follow-up and more integrated exposure assessment to capture delayed or cumulative biological responses.

Mechanisms: Nitric Oxide Synthase Cycle and Smoking Cessation Literature

Our findings demonstrated that decreased HAP exposure over the trial was associated with modest FeNO increases, a pattern that echoes recovery of airway NO production seen after smoking cessation. Nitric oxide is generated throughout the respiratory tract by constitutive and inducible NOS enzymes and serves as both a signaling molecule and modulator of airway inflammation (39,43,43,84–86). Chronic inhalation of combustion byproducts—whether from biomass stoves or tobacco—downregulates NOS activity via oxidative stress and disruption of essential cofactors, such as tetrahydrobiopterin (BH4) and NADPH(39,42,43). This biochemical interference results in lower NO output despite the presence of inflammatory signals. Inflammatory cytokines such as IL-4 and IL-13, which drive iNOS expression in eosinophilic airway inflammation, may not adequately stimulate NO production in the context of pollutant-related enzymatic suppression. When pollutant exposures decline, partial recovery of NOS activity and NO production can occur, but the speed and completeness of this rebound likely depend on the duration, intensity, and chronicity of past exposures(39,42,43).

This mechanistic framework is well supported by smoking cessation studies, where former smokers exhibit rising FeNO over time, though normalization may take months or years (84,86,87). In our study population, chronic exposure to biomass smoke may have led to sustained suppression of NOS activity, such that even substantial short-term exposure reductions were insufficient to fully restore NO synthesis. These dynamics may help explain why observed changes in FeNO were modest, despite meaningful reductions in particulate exposure. Compounding this, FeNO is highly sensitive to multiple biological and environmental factors—including undiagnosed asthma, atopy, dietary nitrates, circadian variation, physical activity, and secondhand smoke exposure—all of which introduce variability and complicate interpretation. Tobacco exposure alone has been shown to reduce FeNO by 25–40% in both healthy and asthmatic adults across different time and health condition (80,87). Notably, while FeNO is widely used in research and clinical settings as a biomarker of airway inflammation, its application has been concentrated almost exclusively in asthma-related contexts. As a result, our understanding of FeNO behavior in populations with high environmental exposures but no formal asthma diagnosis remains limited. Taken together, these biological complexities and contextual limitations underscore the need for longer follow-up periods, integrated exposure assessment, and improved phenotyping of airway inflammation to fully understand FeNO's responsiveness in household air pollution interventions.

Implications for Fractional Exhaled Nitric Oxide as a Biomarker in Household Air Pollution Research

These findings have important implications for the use of Fractional Exhaled Nitric Oxide as a biomarker of airway inflammation in research on household air pollution. While this biomarker is a valuable tool for assessing airway inflammation, its responsiveness to short-term interventions may be limited in populations with chronic exposure. As we observed in this study, the biomarker did not show significant changes following the intervention (i.e., in ITT analyses), but was responsive to reductions in exposure to particulate matter and black carbon. This highlights the possibility that more chronic exposure reductions are needed to observe meaningful changes in airway inflammation, which may require a longer period of follow-up.

Given that fractional exhaled nitric oxide testing is not effort-dependent, it is particularly useful in populations that may not be able to perform more demanding tests, such as spirometry, or where such tests are logistically challenging and expensive to implement. However, our results suggest that, in populations with long-term exposure to household air pollution, it may take several months or even years for reductions in pollutant exposure to produce measurable improvements in airway inflammation as reflected by Fractional Exhaled Nitric Oxide. Further studies with longer follow-up periods may help elucidate whether this biomarker can be used effectively to assess the longer-term benefits of stove interventions.

Strengths of the Study

This study benefits from several strengths that contribute to its overall rigor. First, the stepped-wedge design of the intervention addressed ethical considerations by ensuring that all participants received the biomass stove intervention at some point during the study. This design allowed for natural comparisons between stove users and non-users, enhancing the reliability of estimates regarding the intervention's impact on airway inflammation (64,75). Second, the Justa stove used in this study was locally manufactured and designed explicitly for this study population. This local production ensured cultural and practical relevance, addressing specific cooking needs and environmental conditions of the community. Furthermore, the longitudinal analysis spanning a three-year period, the longest follow-up for a HAP-related trial to our knowledge, provided robust insights into the temporal dynamics of airway inflammation in response to potential for sustained changes in household air pollution. Collectively, these methodological strengths underscore the study's ability to generate comprehensive and contextually relevant findings regarding the long-term health impacts of improved stove technologies in resource-constrained settings.

Lastly, our exposure-response models used long-term average exposures for particulate matter and black carbon, which is a key strength of this study. Long-term exposures provide a more reliable estimate of cumulative pollutant exposure, as they are less influenced by day-to-day variability. This approach is increasingly recognized as important for understanding the long-term health effects of air pollution (79).

Limitations

While the study has several strengths, it also has limitations that should be acknowledged. One key limitation is the breaking of randomization. The stepped-wedge design was intended to randomize households to the intervention at different time points, but deviations from this design could introduce bias into the analysis. For example, excluding participants who used medications or had mucus symptoms, which was done to reduce potential bias, also represents a breaking of randomization, as this could lead to imbalances between groups that would otherwise not exist. Another limitation is the potential for selection bias in our sensitivity analysis, particularly with the exclusion of participants with mucous symptoms. We conducted the sensitivity analysis because mucus production could act as a confounder if it is independently associated with both unmeasured factors related to exposure to household air pollution and FeNO levels. While mucous production is associated with acute and chronic respiratory conditions, its exclusion from the analysis could have introduced bias. For example, mucus could function as a mediator if exposure to household air pollution increases mucus production, which then affects FeNO, or as a collider if it is influenced by both exposure and FeNO.

Additionally, our analysis remains at risk of residual confounding or the potential to have not identified important effect modifiers — such as genetic factors, other environmental exposures, or underlying health conditions — which could have influenced our results. The relatively small sample size and sub-study distribution of covariates may also have reduced the study's statistical power, making it more difficult to detect small but meaningful effects of the stove intervention.

Conclusion

In conclusion, while the Justa stove intervention did not significantly improve Fractional Exhaled Nitric Oxide, reductions in long-term exposure to particulate matter and black carbon was associated with higher levels of this biomarker, particularly in participants with lower body mass index and dietary diversity. These findings underscore the importance of sustained exposure reductions and suggest that more time may be needed to observe improvements in airway inflammation. The study also highlights the utility of Fractional Exhaled Nitric Oxide as a non-invasive biomarker of subclinical respiratory inflammation, particularly in populations exposed to household air pollution. However, future studies with larger sample sizes, longer follow-up periods, and more robust designs are needed to understand better how household air pollution affects airway inflammation and determine the long-term effectiveness of stove interventions.

This study contributes to the growing body of research on the effects of household air pollution and highlights the need for more comprehensive studies that explore the long-term impacts of exposure reduction on lung health.

Chapter 4

Associations between fine particulate matter and lung function during late childhood and adolescence: Baseline evaluation of the Sustainable Household Energy Adoption in Rwanda (SHEAR) Study

Summary

This study evaluated baseline associations between personal exposure to household air pollution—measured as 48-hour average concentrations of fine particulate matter (PM2.5) and black carbon (BC)—and lung function in men, women, and children participating in the SHEAR study, an ongoing trial to characterize transitions from traditional to more modern cooking and lighting fuels. Lung function outcomes, including FEV1, FVC, FEF25–75, and FEV1/FVC, were standardized to z-scores using Global Lung Initiative Race: Other reference equations. Linear regression models were stratified by demographic group among adults, and effect modification by age and sex was explored among children.

Among adult men, higher PM$_{2.5}$ was suggestively associated with modest increases in FEV$_1$ (0.152; 95% CI: –0.031, 0.335), FVC (0.065; 95% CI: –0.136, 0.266), FEF$_{25–75}$ (0.171; 95% CI: –0.022, 0.365), and FEV$_1$/FVC (0.155; 95% CI: –0.029, 0.339) z-scores. Higher BC exposure was associated with decreases in FEV$_1$ (–0.080; 95% CI: –0.242, 0.083) and FVC (–0.223; 95% CI: –0.400, –0.047), and suggestive increases in FEF$_{25–75}$ (0.122; 95% CI: –0.055, 0.300) and FEV$_1$/FVC (0.171; 95% CI: 0.002, 0.339) z-scores. Among adult women, associations between PM$_{2.5}$ and BC exposures and lung function were modest and inconsistent. For PM$_{2.5}$, effect estimates were close to null for FEV$_1$ (–0.029; 95% CI: –0.184, 0.127), FVC (–0.059; 95% CI: –0.217, 0.099) and FEV$_1$/FVC (0.038; 95% CI: –0.106, 0.182, with a small positive trend for FEF$_{25–75}$ (0.108; 95% CI: –0.076, 0.291)). For BC, negative trends were observed across outcomes, though confidence intervals included the null.

Among children, $PM_{2.5}$ exposure was associated with small negative trends in FEV_1 (–0.061; 95% CI: –0.221, 0.098), FEF_{25}–$_{75}$ (–0.092; 95% CI: –0.261, 0.078), and FEV_1/FVC (–0.091; 95% CI: –0.224, 0.042), with minimal change in FVC (0.005; 95% CI: –0.157, 0.166). BC exposure showed similarly small negative associations. Effect modification plots revealed that among boys aged 10 and 13, associations between $PM_{2.5}$ exposure and lung function (FEV_1 and FVC) were relatively flat or slightly positive (i.e., consistent with the null association), indicating minimal impact, whereas among 16-year-old boys, there were pronounced inverse associations with both FEV_1 and FVC z-scores, potentially suggesting a period of heightened susceptibility during adolescent lung development. In contrast, girls showed flatter associations across all age groups with no strong trends on lung function by exposure level. Interaction models further supported these findings, revealing significant age-by-sex modification for boys with $PM_{2.5}$ exposure and both FEV_1 (p-interaction = 0.0452) and FVC (p-interaction = 0.0051) z-scores. No significant effect modification was observed for BC exposures (p-interaction = 0.4632 for FEV_1 and 0.8881 for FVC). These findings suggest that HAP-related biological mechanisms or exposure patterns may contribute to early lung function impairment among men, particularly in relation to black carbon exposure, whereas women appeared less impacted, with more modest and inconsistent associations across lung function outcomes. For children, these results suggest that HAP-related biological mechanisms or specific exposure pathways may uniquely affect lung development among older boys, whereas girls appeared less impacted, indicating potential differences in biological response or exposure patterns by sex.

Introduction

Household air pollution (HAP) remains a critical environmental health issue in rural settings, where reliance on traditional biomass fuels—such as wood and charcoal—for cooking and heating is widespread (2,23,59–61). In many low- and middle-income countries (LMICs), including Rwanda, this practice leads to elevated exposure to fine particulate matter (PM2.5) and black carbon (BC), both of which are associated with adverse health outcomes, including respiratory illness, cardiovascular disease, and poor pregnancy outcomes (60,88,89). Women and children typically experience higher exposures due to household roles that keep them near indoor cooking environments. However, the burden of HAP-related disease is not exclusive to these groups; global burden of disease (GBD) estimates suggest men may experience elevated risk due to higher baseline rates of comorbidities and cumulative exposure across different contexts (16,17,59). This complexity highlights the importance of studying all household members when assessing the health impacts of air pollution.

Global energy transition initiatives that promote cleaner alternatives—such as liquefied petroleum gas (LPG) and solar, wind, and hydro powered electricity—have the potential to reduce HAP exposure and its associated health risks (62,90,91). While such interventions aim to lower disease burden and improve well-being, their long-term effects on respiratory health remain understudied, particularly in rural African communities where exposure sources, fuel use behaviors, and household structures vary widely (91). Evidence is especially limited on how cleaner energy adoption impacts measurable respiratory outcomes over time. Understanding the relationship between HAP and pulmonary function in these diverse contexts is essential to inform policy and implementation strategies that effectively mitigate harm (41,61,92).

The current analysis of the SHEAR study addresses these knowledge gaps by characterizing baseline lung function in a population of adults and children aged 8 to 17 years in rural Rwanda prior to a cleaner energy intervention. Spirometric measurements—including forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), forced expiratory flow between 25% and 75% of the pulmonary volume (FEF_{25}–$_{75}$), and the FEV_1/FVC ratio—are well-established indicators of respiratory health (1,3,5,38). These metrics are critical for identifying impaired lung function and evaluating potential risk for chronic respiratory disease (9,10,93). Assessing these parameters at baseline offers an opportunity to evaluate the health impacts of traditional biomass use and provides a foundation for evaluating future changes associated with the adoption of cleaner energy technologies.

Lung function trajectories are established early in life, with childhood deficits often persisting into adulthood and predisposing individuals to respiratory diseases such as chronic obstructive pulmonary disease (COPD) and asthma (17,66,94). The developmental period between ages 8 and 17 is important for pulmonary health, as lung growth and alveolar development continue (68). Impairments due to household air pollution exposure during these critical years may have long-lasting consequences, reinforcing the importance of early intervention and exposure mitigation strategies (94).

Biologically, exposure to pollutants such as $PM_{2.5}$ and black carbon (BC) can trigger oxidative stress, airway inflammation, and epithelial remodeling. These responses can lead to structural damage in both large and small airways, reduced lung elasticity, and impaired alveolar development, ultimately contributing to measurable changes in lung function (33,94,95). Changes in lung function parameters, like reductions in FEV_1 reflect compromised airflow, often due to airway obstruction or reduced lung volume. FVC, the total amount of air forcibly exhaled after a full inhalation, can be reduced in both restrictive and obstructive patterns, but when considered alongside FEV_1, helps differentiate between the two. A lower FEV_1/FVC ratio is a key indicator of airflow obstruction and is commonly used in the diagnosis of obstructive airway diseases. Forced expiratory flow between 25% and 75% of exhaled volume ($FEF_{25–75}$) captures the flow rate in the mid-portion of exhalation and is particularly sensitive to small airway narrowing, making it an important early marker of subclinical disease (48,96).

Given the high concentrations of $PM_{2.5}$ and BC in biomass-burning households, it is critical to assess how these exposures affect distinct aspects of pulmonary physiology. Doing so can improve our understanding of how early-life and chronic exposures contribute to patterns of spirometric impairment across the life course in children and adults (70,97).

Despite growing awareness of the health effects of HAP, there remains a significant gap in research evaluating lung function at baseline before energy transition interventions in sub-Saharan Africa (58,90). The SHEAR study is among the first to systematically examine lung function parameters in a Rwandan population, providing a unique opportunity to compare pulmonary health outcomes across different demographic groups before cleaner energy solutions are introduced. The findings from this study will inform future interventions aimed at reducing exposure and improving respiratory health, while also contributing to broader global discussions on energy transition and environmental health equity.

In summary, the SHEAR study will provide valuable insights into the pulmonary health impacts of HAP exposure in a rural Rwandan population. By focusing on adults and children aged 8 to 17, assessing key spirometric parameters at baseline, and contextualizing findings within the broader framework of environmental health and energy transition, this research will contribute to the growing body of evidence supporting cleaner energy interventions as a critical strategy for reducing respiratory health burdens in vulnerable communities (98,99). As global efforts to phase out biomass fuel reliance continue, studies like SHEAR will be instrumental in guiding policy decisions, improving health outcomes, and advancing sustainable energy solutions for at-risk populations.

Methods

Study Design and Population

The SHEAR study is a randomized controlled trial conducted in rural Rwanda, aimed at transitioning households from traditional biomass-based cooking and kerosene lighting to cleaner energy sources, including liquefied petroleum gas (LPG) stoves and solar power. The study involves a collaboration between Colorado State University (CSU), the University of Rwanda (UR), and MeshPower, a local solar microgrid provider. A total of 650 eligible households currently using traditional energy sources were recruited from the eastern lowlands of Rwanda. Each participating household contributed at least one adult (and could contribute one adult male and one adult female) and one child aged 8-17 years. Baseline assessments were conducted prior to randomization into one of two clean energy arms (i.e., a subset of 250 households received full subsidies for LPG and solar power and 150 households received discounted subsidies for LPG and solar power) and one control arm. Over a three-year period, repeated measurements of HAP exposure, energy consumption, and health outcomes were collected. For the present analysis, baseline lung function, air pollution exposure, and covariate data prior to intervention implementation were utilized.

Exposure Assessment

Personal exposure to household air pollution was assessed using the UPAS V2 Plus (Ultrasonic Personal Aerosol Sampler; Access Sensor Technologies, Fort Collins, CO), a wearable air quality monitor designed to measure 48-hour average concentrations of fine particulate matter ($PM_{2.5}$) and black carbon (BC) in the breathing zone. The UPAS employs a silent piezoelectric pump to draw air at a flow rate of 1 $L \cdot min^{-1}$ through a 2.5 μm size-selective cyclone inlet and onto a 37 mm PTFE filter (PT37, MTL LLC, Minneapolis, MN). In parallel, it estimates real-time $PM_{2.5}$ concentrations at 30-second intervals using a light-scattering sensor (SPS30, Sensirion AG, Stäfa, Switzerland), while simultaneously logging GPS, air temperature, relative humidity, atmospheric pressure, and three-axis accelerometry.

Participants were instructed to wear the UPAS on their chest via a custom-made harness during waking hours and to place the device near the breathing zone—on a bedside table or wall hook—while sleeping or bathing. To support uninterrupted 48-hour sampling, a portable charging cradle was provided, and participants were trained to charge the device overnight. The sensor pouch was consistently positioned at chest height to approximate personal exposure within the breathing zone during daily routines.

After sample collection, filters were stored in a freezer at –20 °C in Rwanda until bi-monthly air freight shipments to Colorado State University (CSU). At CSU, filters were stored at –80 °C before analysis. Gravimetric analysis was performed in triplicate using a microbalance (XS3DU, Mettler-Toledo, Columbus, OH, USA) inside a climate-controlled weighing chamber. Filters were equilibrated for at least 24 hours under controlled temperature and humidity conditions before both pre- and post-weighing. Field blanks collected at the beginning of each sampling day were used to adjust for potential contamination and handling artifacts. Final 48-hour $PM_{2.5}$ concentrations were calculated by subtracting the average blank mass from the difference between the pre- and post-sampling filter mass and then dividing the mass by the volume of air sampled.

For the exposure assessment, three metrics were used to determine whether a participant's personal exposure sample was valid for analysis. First, real-time PM2.5 data must exceed 36 hours to be considered representative. This threshold was established by analyzing the correlations between 48-hour mean PM2.5 concentrations and their respective concentrations with varying lag times (48-n hours), among samples that had the full 48-hour coverage. The analysis showed that samples with at least 36 hours of logged data were 92% representative of their full 48-hour average PM2.5 concentrations. As a result, 139 personal exposure samples were excluded from the analysis for having less than 36 hours of data.

We also evaluated compliance with wear-time protocols using UPAS-recorded accelerometry. For each compliant sample, we grouped 30-second x-axis acceleration data into 15-minute windows and calculated the standard deviation (SD) of movement. Among waking-hour periods (6:00–21:00) when the UPAS was not connected to the charging cradle, an SD ≥ 6 mG in a 15-minute window was used as a threshold to indicate the device was worn. If >75% of waking-hour time chunks met this movement threshold, the sample was considered compliant. Accelerometry data were successfully recorded for 80% of all samples.

To estimate black carbon concentrations, we measured net optical attenuation on the collected filters using a standard transmissometer. BC concentrations were calculated using the formula:

$$BC\ (\mu g/m^3) = (\text{net attenuation} \times \text{filter area} / \text{sample volume}) \times (1 / MAC)$$

A mass absorption cross-section (MAC) value of 9 m^2/g was used, consistent with prior studies in biomass-burning environments. This approach enabled standardized, field-ready BC estimates across participants.

Spirometry

Spirometry was conducted by trained SHEAR technicians following American Thoracic Society/European Respiratory Society (ATS/ERS) guidelines using an EasyOne-PC spirometer (ndd Medical Technologies, Zurich, Switzerland). Calibration was performed the day before each field visit per the manufacturer's instructions, and ambient barometric pressure saturated was recorded within the EasyOne software prior to each testing session. Participant demographic information—including age, height, and weight—was recorded at the time of testing.

Participants performed spirometry either standing or seated, in accordance with American Thoracic Society/European Respiratory Society (ATS/ERS) recommendations, and were instructed to use a nose clip during each maneuver (48,96). Field teams provided standardized verbal coaching and encouragement to ensure maximal effort and reproducibility. Each participant was allowed up to 16 spirometry attempts—exceeding the standard 8-attempt limit outlined in ATS/ERS guidelines—to accommodate limited familiarity with the maneuver in this population (48,96). Key spirometry outcomes included forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), and the FEV_1/FVC ratio.

The EasyOne software (ndd Medical Technologies, Zurich, Switzerland) automatically assigned spirometry quality grades (A–F) based on ATS/ERS criteria for both acceptability and reproducibility (48,96). Acceptability refers to technical performance, including a rapid start of exhalation, absence of coughing in the first second, and a smooth, continuous exhalation of at least six seconds or until a plateau is reached. Reproducibility is determined by whether the two highest FVC and FEV_1 values are within 150 mL of each other. A Grade A indicates at least three acceptable maneuvers with high reproducibility; Grade B requires at least two acceptable maneuvers within 150 mL reproducibility; and Grade C allows slightly greater variability (150–200 mL). Grades D through F reflect insufficient quality—either due to a lack of acceptable efforts or excessive variability—and were excluded from analysis. Only tests with an overall grade of A, B, or C were retained for analysis

Final values for FVC and FEV_1 were selected as the best efforts from all acceptable maneuvers, regardless of whether they occurred during the same attempt. This approach reflects standard clinical and epidemiologic practice and accommodates individual variability across blows. All spirometry traces and assigned grades were reviewed by an independent expert (LZ) to ensure consistency with ATS/ERS standards.

Questionnaires and Potential Confounders and Precision Variables

Participants self-reported demographic information using structured questionnaires,with anthrpometry measures that included age, height, and weight. Socioeconomic status was assessed through a weighted household asset index, derived from self-reported ownership of 36 household material goods. Study staff visually verified the presence of these items during household visits, which included appliances and furnishings such as frying pans, cell phones, televisions, and refrigerators. The weighted asset index assigned higher weights to less common items and lower weights to more common ones, creating a dimensionless measure of relative wealth (see below).

Age and height were also used to calculate lung function z-scores based on the race-neutral American Thoracic Society/European Respiratory Society (ATS/ERS) spirometry reference equations.

Statistical Analysis

All variables included in the analysis were selected a priori based on a literature review identifying key determinants of lung function parameters. Descriptive statistics were used to summarize outcome and exposure variables, including frequency distributions, means, quantiles, and measures of variability. Given the known correlation among lung function parameters, FEV_1, FVC, $FEF_{25}–_{75}$, and FEV_1/FVC were analyzed separately. Untransformed lung function parameters were first examined descriptively, and z-score transformations were applied to account for age and height within population subgroups (adult men, adult women, girls, and boys). The z-score transformations allow standardized comparisons by expressing deviations from predicted values in standard deviation units according to the Global Lung Initiative (GLI). Z-scores were calculated directly by the EasyOne spirometry software as the difference between measured and predicted values divided by the residual standard deviation (56), and these values were included in the spirometry dataset.

For univariable analyses, separate linear regression models were fitted for each exposure of interest and lung function parameter. Residual diagnostics were conducted to evaluate assumptions of linearity and approximate normality, with transformations applied as necessary. Associations between independent variables (including potential confounders and covariates) and lung function parameters were reported as regression coefficients with 95% confidence intervals.

To adjust for wealth distribution in the study population and to minimize oversaturation with multiple indicator variables, a weighted asset index was created as a proxy for household socioeconomic status. The index was constructed based on the prevalence of household assets, assigning lower scores to commonly owned items (e.g., phones, beds, radios) and higher scores to less common items (e.g., televisions, computers, vehicles). Asset rankings were informed by ownership frequencies within the study population (~650 households). This method provides a more reliable assessment of household wealth compared to self-reported income, thus reducing measurement error in estimating socioeconomic status (100).

Age and height were also used to create lung function z-scores based on the race-neutral American Thoracic Society/European Respiratory Society (ATS/ERS) spirometry reference equations. Biological sex was included as an adjustment variable in models for children to account for any potential confounding arising from sex-related differences in lung function development.

Multivariable analyses included selected exposures of interest along with the asset index in linear regression models. The lung function z-scores, which incorporated age and height based on the race-neutral American Thoracic Society/European Respiratory Society (ATS/ERS) reference equations, were used as the dependent outcomes in all models. The asset index was included as a covariate in all models, and biological sex was included in models for children to account for any potential confounding arising from sex-related differences in lung function development. Separate models were constructed for each exposure measure and lung function outcome across the specified demographic subgroups, resulting in a total of 24 adjusted models

Effect Modification Analysis in Children

To further explore potential differences in susceptibility among children, we evaluated effect modification by age and biological sex. We constructed interaction terms between age group (age was kept as a continuous variable and we plotted estimates at ages 10, 13, and 16 years for visualization), biological sex, and either $PM_{2.5}$ or black carbon exposure. Analyses were performed separately for FEV_1 and FVC outcomes only. These outcomes were selected because they represent core spirometry measures of lung function: FEV_1 reflects airway obstruction, and FVC measures lung capacity. Both parameters are widely validated and have clear clinical interpretation in children. In contrast, $FEF_{25}–_{75}$ is a more variable marker of small airway function with less standardized use in pediatric populations, and FEV_1/FVC ratios can be influenced by growth-related changes in lung volumes, making them less stable for cross-sectional evaluations of developmental stages. Therefore, we prioritized FEV_1 and FVC to maximize biological relevance, clinical interpretability, and comparability across age groups.

All data management and statistical analyses were performed using R v4.4.1, and RMarkdown was employed to ensure reproducible documentation of data processing and analytical procedures.

Results

Table 4.1. Descriptive statistics of predictors, lung function parameters, and exposure for Men (N=342).

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
Age (years)	342	49.47	11.34	24	41	47	57	85
Height (cm)	341	166.39	6.24	144.8	162	166.1	170.1	186.5
Weight (kg)	341	59.63	9.00	37.6	54.25	58.5	64.3	115.6
BMI **(kg/m²)**	341	21.50	2.77	15.53	19.82	21.17	22.66	38.85
FEV1 (L)	324	3.0	1.04	1.47	2.59	3.0	3.4	4.99
FVC (L)	324	3.8	14.9	3.13	3.50	3.79	4.09	4.99
FEV1/FVC	321	0.78	0.07	0.47	0.74	0.79	0.83	1.00
FEF25–75 (L/s)	319	2.84	1.1	0.37	2.03	2.75	3.54	6.34
PM2.5 (µg/m³)	280	139.81	122.23	0.04	58.65	96.73	173.29	739.1
Black Carbon (µg/m³)	206	8.48	7.03	0.07	3.91	6.46	11.23	34.63

Table 4.2. Descriptive statistics of predictors, lung function parameters, and exposure for Women (N=542).

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
Age (years)	542	46.21	10.28	21	39	44	53	77
Height (cm)	542	156.63	5.57	141.55	152.62	156.5	160	181.05
Weight (kg)	542	57.28	10.97	36	49.6	55	62.9	102.2
BMI **kg/m²**	542	23.31	4.04	14.91	20.41	22.35	25.49	37.09
FEV1 (L)	500	2.3	1.07	0.93	2.01	2.30	2.60	3.60
FVC (L)	501	2.89	1.36	2.33	2.64	2.88	3.10	3.67
FEV1/FVC	494	0.80	0.07	0.40	0.76	0.80	0.84	0.98
FEF25–75 (L/s)	487	2.42	0.93	0.43	1.77	2.35	3.06	5.47
PM2.5 (µg/m³)	469	276.97	720.14	13.45	103.09	178.71	298.94	14722.62
Black Carbon (µg/m³)	307	12.23	7.36	0.46	7.40	10.92	15.84	52.66

Table 4.3. Descriptive statistics of predictors, lung function parameters, and exposure for Children (N=579).

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
Age (years)	579	13.51	2.17	9	12	13	15	18
Height (cm)	579	141.03	11.89	111.45	131.68	140.5	150.62	173
Weight (kg)	579	34.68	9.22	18.9	27.75	32.3	41.15	70.6
BMI **kg/m²**	579	17.11	2.08	12.6	15.66	16.74	18.21	24.9
FEV1 (L)	570	1.94	1.11	-0.86	1.56	1.87	2.25	4.10
FVC (L)	570	2.23	1.28	-1.56	-1.86	2.15	1.50	4.10
FEV1/FVC	565	0.87	0.05	0.55	0.84	0.87	0.9	1.0
FEF25–75 (L/s)	520	2.41	0.76	0.48	1.90	2.30	2.88	5.08
PM2.5 (µg/m³)	514	253.87	210.81	3.71	117.26	190.57	328.11	1986.75
Black Carbon (µg/m³)	351	12.09	7.78	0.62	7.03	11.00	14.86	58.74

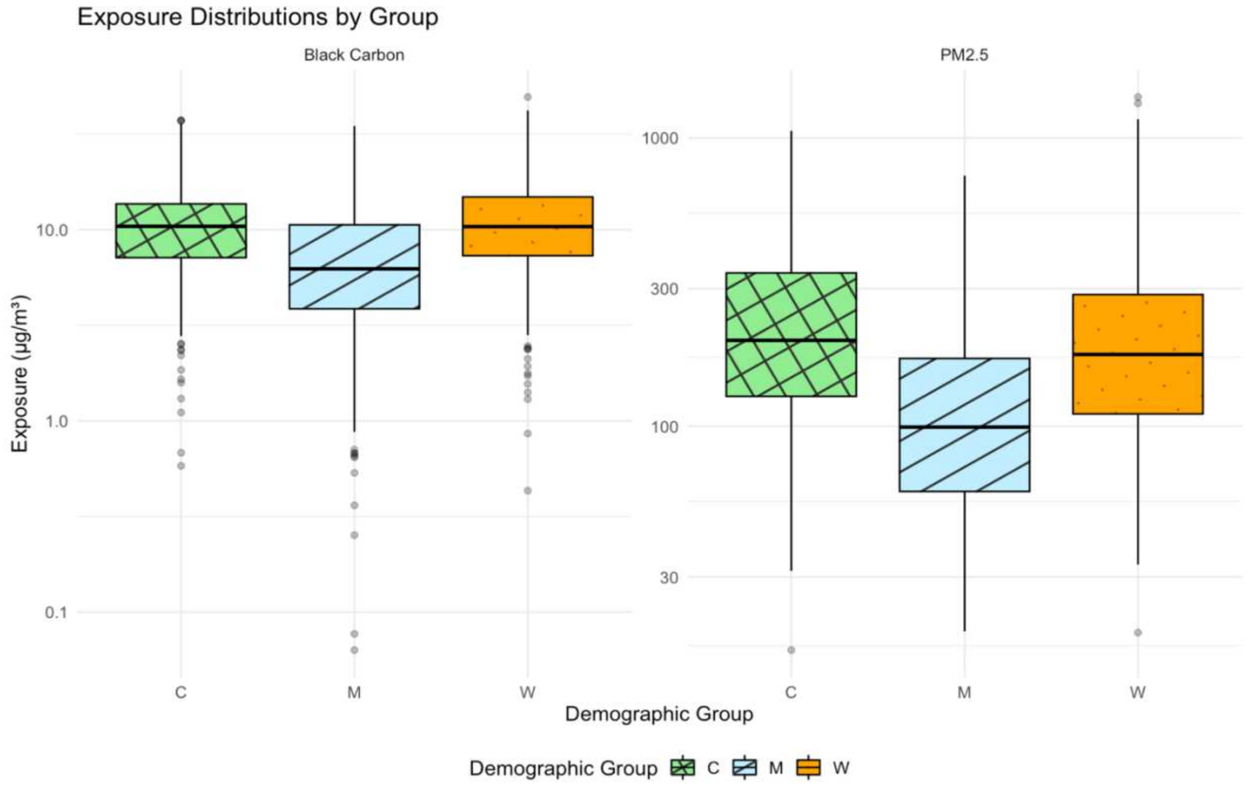

Figure 4.2. *Distributions of Black Carbon and $PM_{2.5}$ Exposure by Demographic Group.* Boxplots depict distributions of 24-hour personal exposures to Black Carbon (left panel) and $PM_{2.5}$ (right panel) among children (C, green with cross-hatch), men (M, blue with horizontal stripes), and women (W, orange with dots). Median values, interquartile ranges, and outliers are shown. Exposure levels were consistently higher among women compared to men and children, with wider variability observed for $PM_{2.5}$ compared to Black Carbon across all groups.

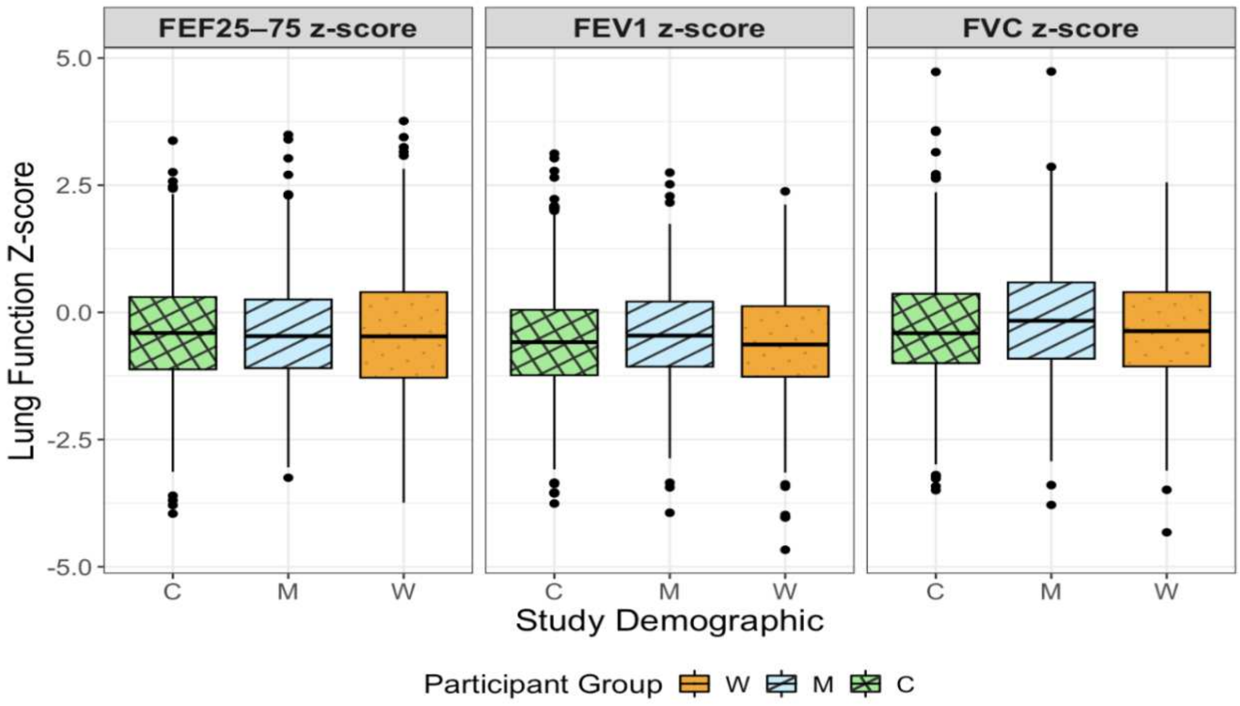

Figure 4.3. *Distribution of Lung Function Z-scores by Demographic Group.*

Boxplots show the distributions of standardized lung function measurements (z-scores) for $FEF_{25}–_{75}$ (left panel), FEV_1 (middle panel), and FVC (right panel) among children (C, green with cross-hatch), men (M, blue with horizontal stripes), and women (W, orange with dots). Medians, interquartile ranges, and outliers are displayed.

Participant Characteristics

This study included spirometry and exposure data for 1,463 participants, comprising men (N=342), women (N=542), and children (N=579).

Among men, the median age was 47 years (Q1, Q3: 41, 57), with a median height of 166.1 cm (Q1, Q3: 162, 170.1) and median weight of 58.5 kg (Q1, Q3: 54.3, 64.3). Median BMI was 21.17 kg/m² (Q1, Q3: 19.82, 22.66). Lung function measurements indicated a median FEV_1 of 3.0 L, a median FVC of 3.79 L, and a median FEV_1/FVC ratio of 0.79. The median FEF_{25-75} was 2.75 L/s. Personal exposure levels for men showed a median $PM_{2.5}$ concentration of 96.7 µg/m³ and a median black carbon concentration of 6.5 µg/m³.

Among women, the median age was 44 years (Q1, Q3: 39, 53), height was 156.5 cm (Q1, Q3: 152.6, 160), and weight was 55 kg (Q1, Q3: 49.6, 62.9). Their median BMI was 22.35 kg/m² (Q1, Q3: 20.41, 25.49). Median FEV_1 was 2.30 L, median FVC was 2.88 L, and median FEV_1/FVC ratio was 0.80. Median FEF_{25-75} was 2.35 L/s. Women had higher exposure levels, with a median $PM_{2.5}$ concentration of 178.7 µg/m³ and a median black carbon concentration of 10.9 µg/m³.

Among children, the median age was 13 years (Q1, Q3: 12, 15), median height was 140.5 cm (Q1, Q3: 131.7, 150.6), and median weight was 32.3 kg (Q1, Q3: 27.8, 41.2). Median BMI was 16.74 kg/m² (Q1, Q3: 15.66, 18.21). Lung function showed a median FEV_1 of 1.87 L, a median FVC of 2.15 L, and a median FEV_1/FVC ratio of 0.87. Median FEF_{25-75} was 2.30 L/s. Children also experienced high exposures, with a median $PM_{2.5}$ concentration of 190.6 µg/m³ and a median black carbon concentration of 11.0 µg/m³.

Data Quality

In the SHEAR study, spirometry data quality (Figure 4.1) was high across all demographic groups. Among children (C), 97% of FEV_1 and 96% of FVC tests were graded as valid. For men (M), 96% of both FEV_1 and FVC tests met validity criteria. Among women (W), 92% of FEV_1 and 91% of FVC tests were considered valid. Rates of invalid tests were low overall, with slightly higher proportions among women for FVC compared to other groups. These findings highlight strong field performance of spirometry protocols, supported by standardized training, centralized review, and the use of race-neutral z-scores for interpretation. Consistently high validity across groups strengthens the reliability of lung function measures for cross-sectional and longitudinal analyses.

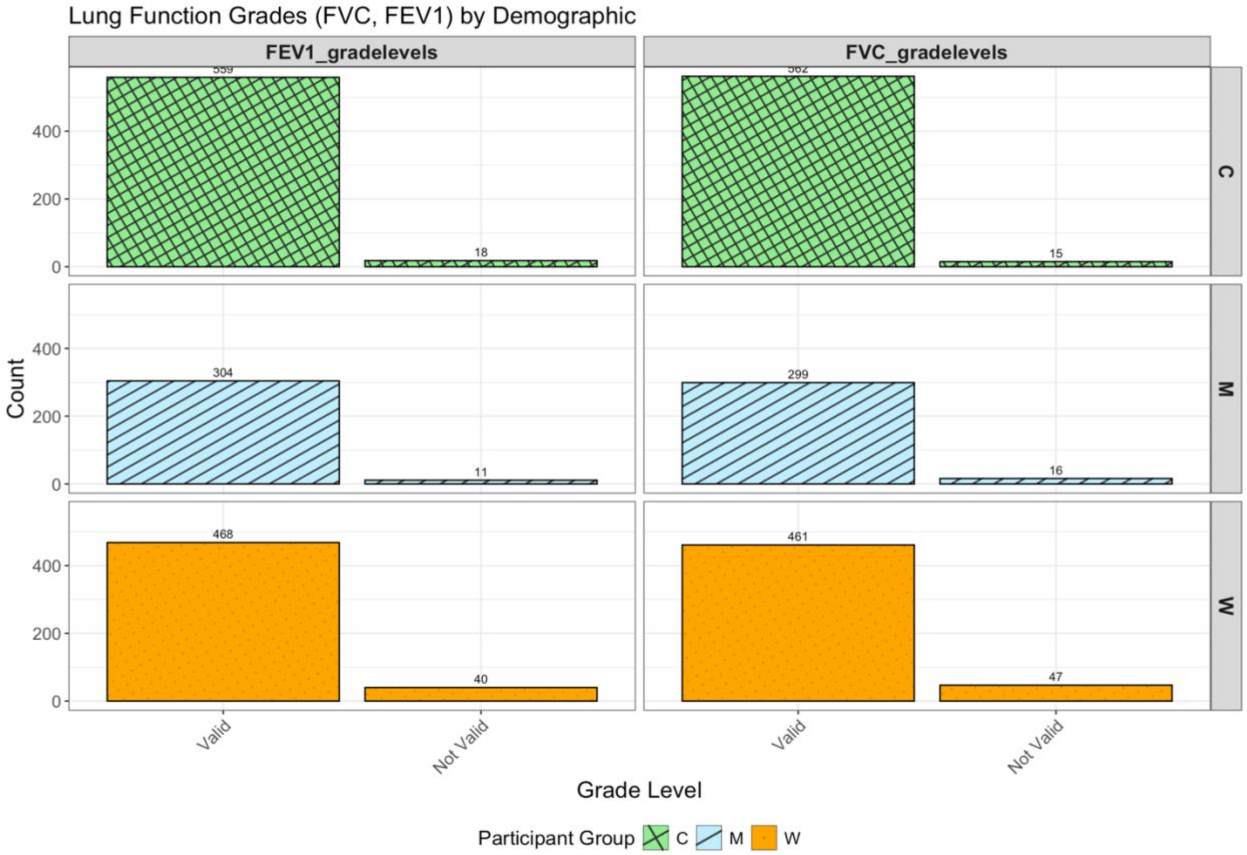

Figure 4.1. Barplot displaying the number of valid and non-valid spirometry tests for FEV_1 and FVC outcomes across demographic groups (Children, Men, Women) in the SHEAR study. Validation was determined according to ATS/ERS standards. Across all groups, the majority of spirometry efforts were valid, with the highest validation rates observed in children (96% for FEV_1 and 95% for FVC). Men and women showed slightly lower validity rates, particularly for FVC. Colors and patterns distinguish demographic groups: green crosshatch for children, blue diagonal lines for men, and orange dots for women.

Table 4.4. Primary results. Linear regression models characterizing the associations between baseline personal $PM_{2.5}$ and BC exposure and lung function parameters among men women and children.

Group	Outcome	Pollutant (µg/m³)	Estimate (Z-score)	CI Lower	CI Upper	Sample Size (N)
Men	FEV1 (z-score)	PM2.5	0.152	-0.0307	0.335	263
Men	FVC (z-score)	PM2.5	0.0651	-0.136	0.266	263
Men	FEF25-75 (z-score)	PM2.5	0.171	-0.0221	0.365	263
Men	FEV1/FVC (z-score)	PM2.5	0.155	-0.0294	0.339	263
Men	FEV1 (z-score)	BC	-0.0796	-0.242	0.0825	222
Men	FVC (z-score)	BC	-0.223	-0.4	-0.0473	222
Men	FEF25-75 (z-score)	BC	0.122	-0.0551	0.3	222
Men	FEV1/FVC (z-score)	BC	0.171	0.00226	0.339	222
Women	FEV1 (z-score)	PM2.5	-0.0286	-0.184	0.127	424
Women	FVC (z-score)	PM2.5	-0.0592	-0.217	0.0985	424
Women	FEF25-75 (z-score)	PM2.5	0.108	-0.0756	0.291	424
Women	FEV1/FVC (z-score)	PM2.5	0.0384	-0.106	0.182	424
Women	FEV1 (z-score)	BC	-0.0946	-0.27	0.0811	351
Women	FVC (z-score)	BC	-0.0568	-0.239	0.125	351
Women	FEF25-75 (z-score)	BC	-0.0255	-0.239	0.188	351
Women	FEV1/FVC (z-score)	BC	-0.0895	-0.261	0.0819	351
Children	FEV1 (z-score)	PM2.5	-0.0614	-0.221	0.098	448
Children	FVC (z-score)	PM2.5	0.00459	-0.157	0.166	448
Children	FEF25-75 (z-score)	PM2.5	-0.0916	-0.261	0.0777	448
Children	FEV1/FVC (z-score)	PM2.5	-0.0908	-0.224	0.0424	448
Children	FEV1 (z-score)	BC	-0.0633	-0.263	0.136	366
Children	FVC (z-score)	BC	0.0167	-0.179	0.213	366
Children	FEF25-75 (z-score)	BC	-0.0389	-0.262	0.184	366
Children	FEV1/FVC (z-score)	BC	-0.11	-0.287	0.0671	366

Z scores are age and height adjusted. Additional covariates in model for men: weighted index for household material assets at baseline (continuous), exposure. For women: weighted index for household material assets at baseline (continuous), exposure, and bmi. For children: weighted index for household material assets at baseline (continuous), exposure, and biologic sex. CI = confidence interval, N = number of observations, $PM_{2.5}$ = fine particulate matter ≤2.5 microns in diameter.

Note: We defined the relative wealth of participating households using a dimensionless scalar term. At baseline, participants self-reported 36 household-owned material goods, which our team visually verified. These items included various appliances and furnishings such as a frying pan, cell phone, TV, and refrigerator. We created a weighted asset index to measure household wealth, assigning higher scores to less common items and lower scores to more common ones.

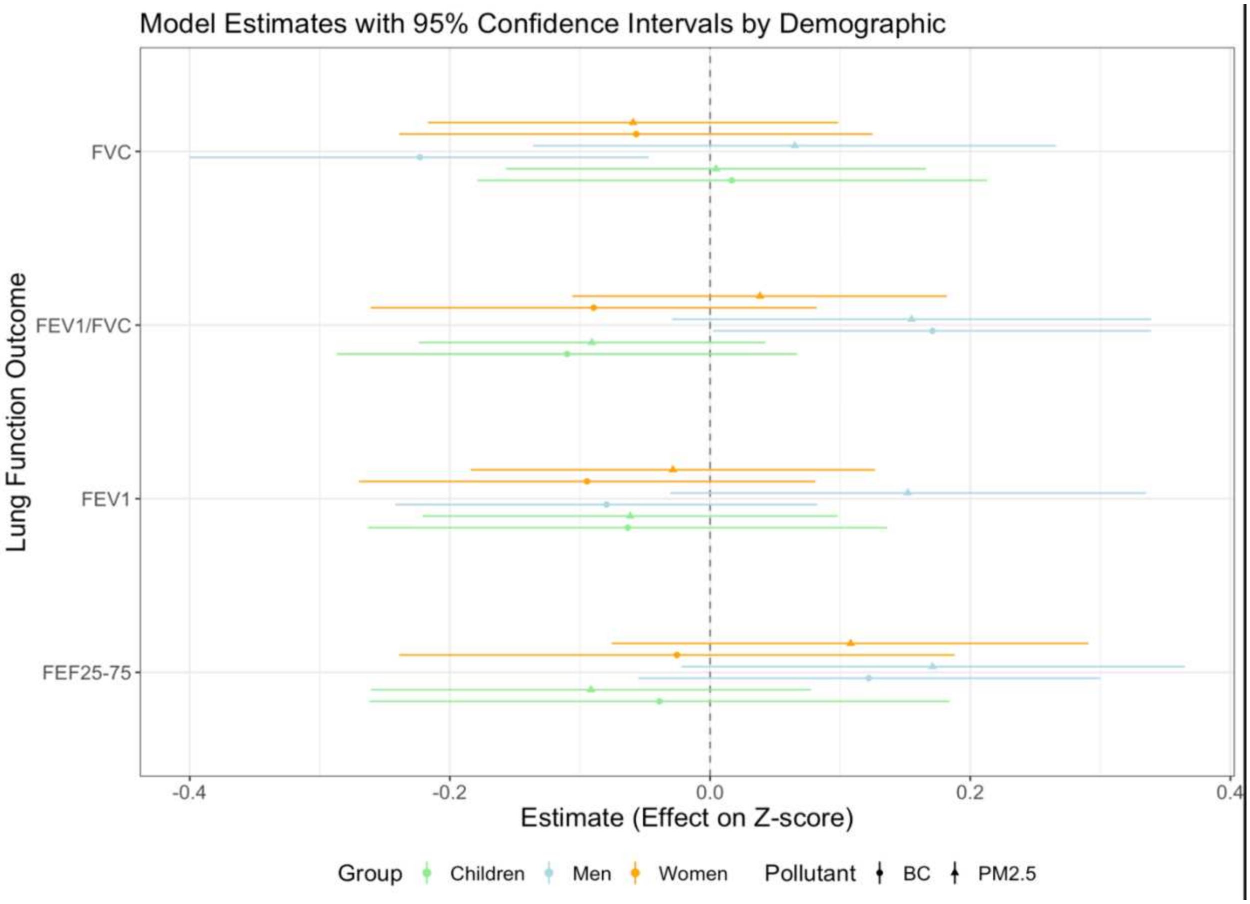

Figure 4.5. *Effect Estimates and 95% Confidence Intervals for Associations Between Air Pollution Exposure and Lung Function Z-scores, by Demographic Group.*

Forest plot displaying model estimates and 95% confidence intervals for the association between exposure to black carbon (BC) and fine particulate matter (PM$_{2.5}$) and spirometric outcomes (FEF$_{25}$–$_{75}$, FEV$_1$, FEV$_1$/FVC, and FVC) among children (green), men (blue), and women (orange). Each point represents the estimated effect on the z-score per unit increase in exposure, with triangles indicating PM$_{2.5}$ effects and circles indicating BC effects.

Our study examined baseline associations between household air pollution (HAP), measured as 48-hour average concentrations of fine particulate matter ($PM_{2.5}$) and black carbon (BC), and lung function parameters—FEV_1, FVC, $FEF_{25–75}$, and the FEV_1/FVC ratio—in Rwandan men, women, and children participating in the SHEAR study. Full results are presented in Table 4.4 and in Figure 4.1.

Among men, $PM_{2.5}$ exposure showed suggestive positive associations across lung function parameters with most confidence intervals including the null value. For FEV_1, the estimated change per 1 log unit change in $PM_{2.5}$ was 0.152 (95% CI: –0.0307, 0.335; N = 263), and for FVC, the estimate was 0.0651 (95% CI: –0.136, 0.266; N = 263). A similar suggestive association was observed for $FEF_{25–75}$ (estimate: 0.171; 95% CI: –0.0221, 0.365; N = 263) and for FEV_1/FVC (estimate: 0.155; 95% CI: –0.0294, 0.339; N = 263).For black carbon (BC), the association with FVC was inverse (estimate: –0.223; 95% CI: –0.400, –0.0473; N = 222), indicating that every 1 log-unit increase in BC was associated with a .22 SD decrease in FVC. There was a positive association between exposure to BC and FEV_1/FVC (0.171; 95% CI: 0.00226, 0.339; N = 222). Associations for FEV_1 (–0.0796; 95% CI: –0.242, 0.0825; N = 222), and $FEF_{25–75}$ (0.122; 95% CI: –0.0551, 0.300; N = 222) were weak or null.

Among women, associations with $PM_{2.5}$ were mostly null. For FEV_1, the estimate was –0.0286 (95% CI: –0.184, 0.127; N = 424), for FVC it was –0.0592 (95% CI: –0.217, 0.0985; N = 424), and for FEV_1/FVC it was 0.0384 (95% CI: –0.106, 0.182; N = 424). A slight suggestive positive association was noted for $FEF_{25–75}$ (estimate: 0.108; 95% CI: –0.0756, 0.291; N = 424).For BC, results remained null. The estimates were: FEV_1 (–0.0946; 95% CI: –0.270, 0.0811; N = 351), FVC (–0.0568; 95% CI: –0.239, 0.125; N = 351), $FEF_{25–75}$ (–0.0255; 95% CI: –0.239, 0.188; N = 351), and FEV_1/FVC (–0.0895; 95% CI: –0.261, 0.0819; N = 351).

Among children, $PM_{2.5}$ exposure showed mixed but weak and null associations. For FEV_1, a slight negative association was observed (estimate: –0.0614; 95% CI: –0.221, 0.098; N = 448), and for $FEF_{25–75}$ (estimate: –0.0916; 95% CI: –0.261, 0.0777; N = 448). Associations for FVC (estimate: 0.00459; 95% CI: –0.157, 0.166; N = 448) and FEV_1/FVC (estimate: –0.0908; 95% CI: –0.224, 0.0424; N = 448) were essentially null. For BC exposure, associations remained null across all outcomes: FEV_1 (estimate: –0.0633; 95% CI: –0.263, 0.136; N = 366), FVC (estimate: 0.0167; 95% CI: –0.179, 0.213; N = 366), $FEF_{25–75}$ (estimate: –0.0389; 95% CI: –0.262, 0.184; N = 366), and FEV_1/FVC (estimate: –0.110; 95% CI: –0.287, 0.0671; N = 366).

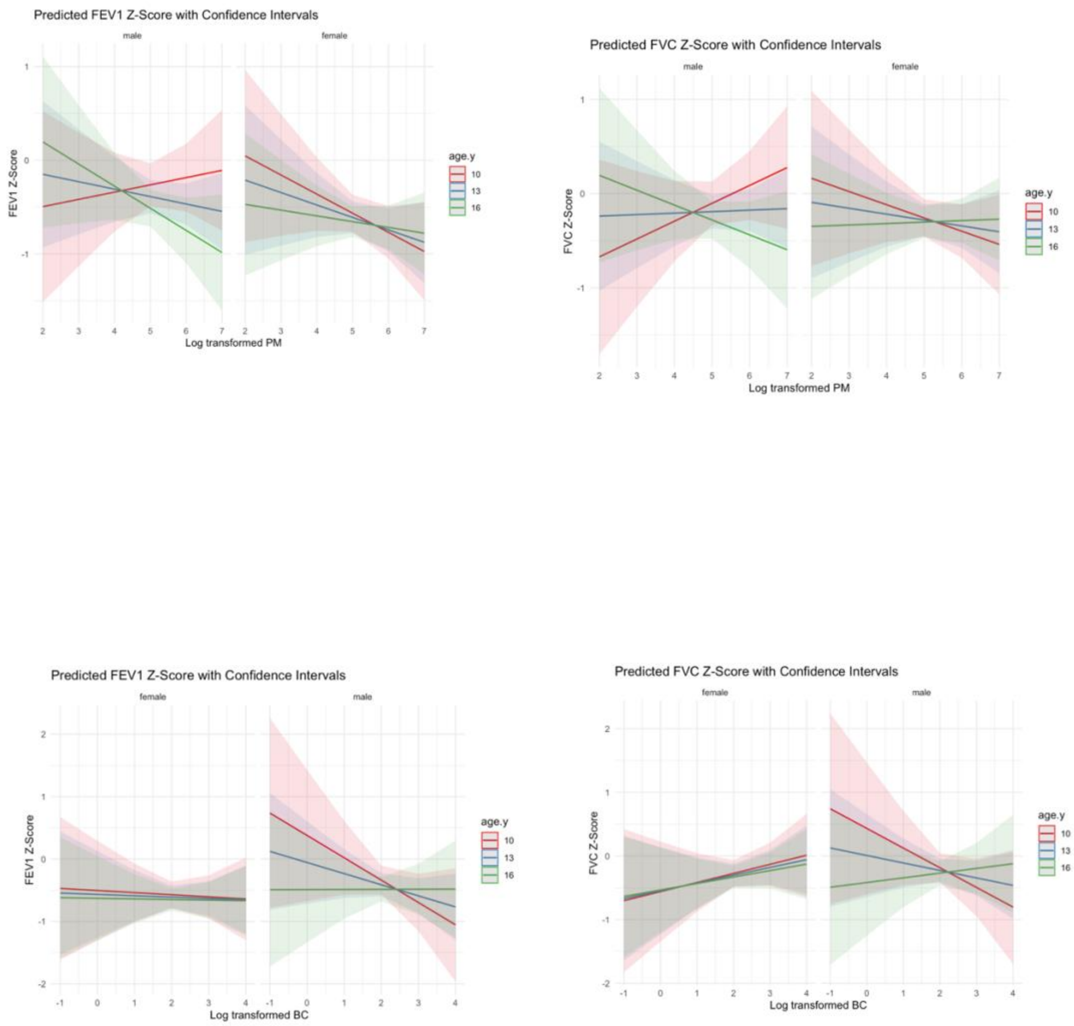

Figure 4.5. *Effect Modification Models Evaluating Interactions Between Age, Biological Sex, and Air Pollution Exposure Among Children for FEV_1 and FVC Z-scores.*
Four plots displaying predicted FEV_1 and FVC z-scores by log-transformed $PM_{2.5}$ and black carbon (BC) exposures, stratified by biological sex (male, female) and displaying by representative ages (10, 13, and 16 years).For $PM_{2.5}$ and FEV_1, the p-value for interaction was 0.045. For $PM_{2.5}$ and FVC, the p-value for interaction was 0.005 For BC and FEV_1, the p-value for interaction was 0.5.For BC and FVC, the p-value for interaction was 0.8881.
Significant interactions ($p < 0.05$) were observed between $PM_{2.5}$ exposure, age, and sex for both FEV_1 and FVC outcomes, suggesting age- and sex-specific susceptibility to particulate exposure among children.

We evaluated effect modification by age (choosing 10, 13, and 16 years to display the results) and biological sex in children for the associations between household air pollution exposure and lung function z-scores (FEV_1 and FVC). We observed significant effect modification for $PM_{2.5}$ exposure but not for black carbon.

For FEV_1, the interaction between $PM_{2.5}$, age, and sex was statistically significant ($p = 0.0452$), and for FVC, the interaction was also statistically significant ($p = 0.0051$). In contrast, for black carbon exposure, no significant effect modification by age and sex was observed for either FEV_1 ($p = 0.4632$) or FVC ($p = 0.8881$).

When evaluating by age and sex, the associations between $PM_{2.5}$ and lung function varied notably. Among boys, the slope of the exposure-response relationship became increasingly negative with age. Boys aged 16 exhibited the steepest decline in both FEV_1 and FVC z-scores with increasing $PM_{2.5}$ exposure, suggesting that older boys may be more susceptible to the adverse respiratory effects of air pollution. In contrast, boys aged 10 and 13 showed flatter slopes, with minimal or even slightly positive associations between $PM_{2.5}$ and lung function.

Among girls, associations between $PM_{2.5}$ exposure and lung function were generally flatter across all age groups. For FVC, there was some indication of a slight negative trend with increasing $PM_{2.5}$ at age 10, but the magnitude of decline was smaller compared to that observed among boys. Girls at other ages (13 and 16) demonstrated relatively stable lung function across the exposure range, with little evidence of strong positive or negative associations.

Discussion

This baseline, cross-sectional analysis provides valuable insights into the differential effects of household air pollution (HAP) on lung function across demographic groups in rural Rwanda. In our primary exposure-response analysis, we observed largely null or suggestive associations between exposures to particulate matter ($PM_{2.5}$) and black carbon (BC) and spirometric outcomes across men, women, and children. Among men, there were associations between BC exposure and lung function, particularly affecting FVC and FEV_1/FVC. Among women, associations were weaker and generally null across spirometric outcomes for both $PM_{2.5}$ and BC exposures. In children, there were suggestive inverse associations between $PM_{2.5}$ and measures of lung function, with some evidence of greater vulnerability in older boys identified in our effect modification analysis, which evaluated interactions between age, biological sex, and pollutant exposures specifically for FEV_1 and FVC outcomes. These patterns indicate demographic-specific variability in susceptibility to HAP and provide new insights beyond previous studies, which have not consistently identified or presented such differences by sex or age.

Vulnerability of Men to HAP Exposure

The findings suggest that men in this rural context may face under-recognized risks from HAP. While traditionally assumed to have lower household exposure, men may be exposed to high pollutant levels through indoor work, maintenance of cooking stoves, and ambient biomass smoke from neighboring households. Additionally, men may have cumulative occupational exposures, contributing to steeper age-related declines in small airway function(101–104). In this study, the pattern of both FEV_1 and FVC decreasing with exposure, alongside a positive association with the FEV_1/FVC ratio, suggests that FVC is decreasing more than FEV_1, a finding consistent with a restrictive physiological process. Moreover, the concurrent declines observed in mid-expiratory flow rates (FEF_{25-75}) strengthen the evidence for early airway dysfunction, as FEF_{25-75} is sensitive to changes in small airways that may not manifest as impacts on FVC alone. Of note is that FEF_{25-75} cannot be calculated or predicted without full completion of the FVC maneuver. Together, reductions in both FVC and FEF_{25-75} may reflect a combined process of early small airway involvement and reduced lung volume, highlighting the complex impacts of biomass smoke exposure on lung health.

Lung Function Patterns in Women and Children

Among women and children, associations between exposure and lung function were more variable. In children, the lungs are undergoing rapid development, particularly between the ages of 8 and 17. During this critical window, exposure to fine particulate matter ($PM_{2.5}$) may disrupt alveolar growth, impair airway caliber, and promote inflammation and oxidative stress—mechanisms implicated in long-term lung function deficits (34,54,96). A systematic review found that HAP was associated with reduced growth rates in FVC, FEV_1, and FEF_{25}–75, but not the FEV_1/FVC ratio, suggesting parallel declines in both forced volume and capacity (105).

Comparison with Previous Studies

Our findings align with and build upon previous field studies in similar settings. The CAPS study, as reported by Nightingale et al. (2019), highlighted a high prevalence of spirometric restriction among adults exposed to biomass smoke in rural Malawi, though no consistent associations were found between $PM_{2.5}$ exposure and spirometry outcomes. Similarly, Rylance et al. (2020) observed that while cleaner cookstove access modestly reduced $PM_{2.5}$ exposures, no significant improvements in lung function trajectories were detected. However, it is important to note that neither the Nightingale et al. nor the Rylance et al. studies specifically examined differential vulnerability by sex. Their analyses combined men and women, with sex included as a covariate rather than being modeled separately. Thus, while adults were studied broadly, male-specific susceptibility was not evaluated.

Our study newly highlights a potential under-recognized risk among men in rural biomass-reliant settings. The observation that men may experience early small airway dysfunction via FVC and and $FEF_{25–75}$ adds to the growing evidence of the diverse and demographic-specific impacts of

HAP. In contrast, Oluwole et al. (2013) focused exclusively on women and children in Nigeria and documented significant pulmonary dysfunction associated with elevated indoor $PM_{2.5}$ levels. They further linked oxidative stress biomarkers such as C- reactive protein (CRP) and Superoxide dismutase (SOD) to impaired lung function, providing biological plausibility that chronic biomass exposure disrupts antioxidant defenses and drives inflammation. Our findings, particularly regarding small airway impairment in men and suggestive reductions in children's lung function, reinforce these mechanisms and highlight the importance of disaggregated analysis by demographic subgroups.

Biological Mechanisms

The respiratory effects of household air pollution (HAP) on spirometry outcomes are primarily mediated by oxidative stress, airway inflammation, and immune dysregulation. Inhalation of $PM_{2.5}$ and black carbon (BC) leads to the generation of reactive oxygen species, which damage epithelial cells, impair mucociliary clearance, and stimulate proinflammatory cytokines (106). Over time, these pathways contribute to airway remodeling, goblet cell hyperplasia, and subepithelial fibrosis, resulting in measurable declines in spirometric parameters such as FEV_1, FVC, and $FEF_{25}–_{75}$. Chronic exposure during critical periods of lung development can lead to reduced alveolarization, fixed airway narrowing, and long-term reductions in lung function, manifesting as both obstructive and restrictive patterns detectable via spirometry.

Policy and Practice Implications

Our findings highlight the urgent need for household energy interventions in biomass-dependent settings. Policies promoting cleaner-burning technologies, access to liquefied petroleum gas (LPG), and reduction of community-level biomass smoke could mitigate lung function impairment across vulnerable populations. Public health programs should also integrate respiratory surveillance and spirometry screening, particularly targeting men and older children in rural areas.

Study Strengths

Strengths of this study include its large, representative sample spanning children, women, and men in rural Rwanda; rigorous spirometry standardized with independent review; and the use of both gravimetric and real-time monitoring for exposure assessment. This dual-method approach is relatively rare in field studies and enhances exposure validity. Additionally, results from the SHEAR longitudinal analysis will contribute critical information on adoption rates, infrastructure requirements, behavioral factors influencing intervention uptake, and provide deeper insights into biological mechanisms underlying exposure-response relationships.

Study Limitations

Despite the study's strengths, several limitations must be acknowledged. First, potential dust interference in BC estimation could have resulted in exposure misclassification. Second, reliance on a single 48-hour monitoring period to characterize personal air pollution exposures may not capture habitual or cumulative exposures over time. Third, the cross-sectional design inherently limits causal inference, making it difficult to disentangle temporality between exposure and spirometric outcomes, as this is only the baseline assessment characterizing lung function. Additionally, variability in spirometry effort, particularly among younger participants and adult women, may have introduced measurement noise, although the centralized independent review process helped to ensure quality control. Finally, although we adjusted for key confounders and considered modes for measurement error, unmeasured variables, such as environmental dust or seasonal effects, could still influence the observed associations. These limitations highlight the need for complementary longitudinal studies, such as the ongoing SHEAR project, to better capture long-term exposure patterns, respiratory trajectories, and intervention impacts.

Conclusion

Our findings highlight the potential for demographic-specific impacts of household air pollution (HAP) on lung function across a range of spirometric parameters. Among men, there was suggestive evidence of associations linked to increasing exposure to air pollution with reductions observed in FVC and increases observed in FEV_1/FVC. In women, associations between pollutant exposures and lung function outcomes were generally weaker and more variable across FEV_1, FVC, FEV_1/FVC, and FEF_{25-75}, potentially reflecting heterogeneity in exposure patterns or underlying resilience factors. In children, we did not observe main effect associations. However, the effect modification results demonstrated heterogeneity of effect by age and sex, primarily driven by differences in the boys, indicating that older boys may be particularly vulnerable. These findings reinforce the importance of considering both demographic characteristics and the full suite of spirometric indicators when evaluating the respiratory effects of HAP exposure.

Comparison with CAPS and Oluwole et al’s Nigeria study reinforces both biological plausibility and regional relevance (9,53,55). This evidence base supports urgent implementation of clean energy interventions and respiratory surveillance in biomass-dependent settings.

CHAPTER 5: CONCLUSIONS

This dissertation investigated the respiratory health impacts of household air pollution (HAP) arising from biomass cookstove use, employing two complementary study designs: a stepped-wedge randomized controlled trial (RCT) in rural Honduras and a baseline cross-sectional analysis within a household energy intervention trial in Rwanda. Collectively, these studies evaluated associations between HAP and two critical respiratory outcomes: airway inflammation, measured through fractional exhaled nitric oxide (FeNO), and lung function, measured via spirometry. These findings contribute novel insights into the biological impacts of HAP exposure and the potential health benefits associated with improved cookstove technologies.

Aims 1 and 2 of this dissertation assessed the effect of introducing Justa biomass stoves on airway inflammation among women in rural Honduras, using fractional exhaled nitric oxide (FeNO) as a biomarker. Despite significant reductions in personal and kitchen particulate matter ($PM_{2.5}$) and black carbon (BC) exposures, we did not observe meaningful changes in FeNO levels in the intent-to-treat (ITT) analysis. This lack of substantial impact aligns with previous studies reporting modest and inconsistent associations between exposure to biomass smoke and FeNO changes) (44–47,64). However, our exposure-response models are supported by the results of the per-protocol analysis, which reinforce the observed trends. Specifically, increasing levels of personal and kitchen $PM_{2.5}$ and black carbon exposures—whether based on 24-hour measurements or predicted long-term averages—were associated with modest reductions in FeNO, suggesting a exposure-response relationship. These directional trends were mirrored in the per-protocol analysis, where individuals using cleaner stoves (Justa with traditional stoves or with additional improved stoves) showed small but consistent increase in FeNO relative to traditional stove users. Similar to patterns observed in the smoking cessation literature, our findings suggest that reductions in household air pollution exposure may lead to recovery of airway nitric oxide production, as indicated by higher FeNO levels among participants with lower exposures.

Effect modification analyses further highlighted that individual factors such as age, body mass index (BMI), physical activity, and dietary diversity may influence inflammatory responses to biomass smoke exposure, adding complexity to the interpretation of FeNO as a biomarker. This complexity is similar to what is observed in smoking cessation, where individual characteristics can affect recovery from tobacco-related inflammation (84,103). Taken together, our findings underscore the importance of integrating continuous exposure metrics and behavioral adherence when evaluating the effects of household energy interventions. Future research should aim for longer-term follow-ups, broader exposure contrasts, and additional inflammatory biomarkers to further explore the cumulative biological impact of reducing household air pollution.

Lung Function and Household Air Pollution Exposure in Rwanda

Aim 3 of this dissertation utilized baseline data from the SHEAR study to examine the association between personal HAP exposure and spirometric lung function among adults and children. The results revealed heterogeneity in associations between exposure to $PM_{2.5}$ and BC and lung function across all age and sex groups, with varying degrees of effect. Among men, exposure to BC was associated with reductions in several spirometric measures, including FEV_1 and FVC, and slight increases in the FEV_1/FVC ratio. These results, by which both FEV1 and FVC are decreasing with exposure and the FEV1/FVC ratio is increasing with exposure means that FVC is decreasing more than FEV1, which could suggest a restrictive process. While the observed associations in women and children were more variable and generally weaker, there were some suggestive trends of adverse effects on lung function, particularly in male children exposed to $PM_{2.5}$.

These findings align with the broader literature on the detrimental impacts of chronic exposure to air pollution on lung function (89,94). Mechanistically, exposure to $PM_{2.5}$ and BC can lead to airway inflammation, oxidative stress, and disruption of normal lung development, potentially contributing to long-term respiratory impairments(94,105). Notably, our study benefited from a combination of real-time optical sensor data and gravimetric filter-based measurements, providing a robust exposure assessment framework despite potential measurement errors or contamination issues. Furthermore, spirometry allowed for the detection of subtle but clinically relevant changes in lung function, including early signs of small airway dysfunction, which could predict later respiratory diseases (51,96,107).

While the overall results suggest that household air pollution exposure may contribute to subtle but important reductions in lung function, the lack of consistent, statistically significant associations in some groups highlights the complexity of assessing the health impacts of household air pollution. These findings suggest that individual factors such as age, sex, and baseline health conditions may play a significant role in modulating the effects of HAP exposure on lung health. The implications of these results support the importance of continued interventions aimed at reducing household air pollution, particularly through cleaner cooking technologies, and further research is needed to explore the long-term impacts and potential for recovery in exposed populations.

Overall Conclusions and Implications for Energy Transition

Collectively, these findings emphasize the complexities associated with evaluating respiratory health impacts of biomass cookstoves and the importance of addressing methodological and measurement challenges. Biomass stoves like the Justa represent meaningful transitional technologies in broader energy transitions, capable of rapidly reducing pollutant exposure and maintaining compatibility with local cooking practices (23,47,64). However, our results also highlight that moderate reductions in pollutant exposure may yield limited respiratory health benefits, emphasizing the necessity of more comprehensive energy interventions involving cleaner fuels, such as liquefied petroleum gas (LPG) or solar-powered electricity.

As global energy transitions evolve, understanding the respiratory health implications of household energy choices is critical. Future longitudinal assessments within the SHEAR cohort will provide valuable insights into long-term health outcomes associated with clean energy adoption, informing policies and interventions aimed at reducing respiratory health burdens in low- and middle-income settings (61). Recognizing the variability in individual responses and demographic vulnerabilities, our findings underscore the need for targeted, culturally appropriate interventions supported by robust infrastructure and sustained policy initiatives.

Ultimately, this dissertation advances the understanding of lung function and inflammation responses in the context of energy transitions. It highlights the critical role of improved household energy solutions in protecting respiratory health and reinforces the necessity of ongoing research and policy efforts to ensure the broad adoption of effective, sustainable, and culturally acceptable clean cooking technologies.

References

1. Billions of people still breathe unhealthy air: new WHO data [Internet]. [cited 2025 Apr 26]. Available from: https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data

2. World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide [Internet]. World Health Organization; 2021 [cited 2021 Sep 22]. xxi, 267 p. Available from: https://apps.who.int/iris/handle/10665/345329

3. Gordon SB, Bruce NG, Grigg J, Hibberd PL, Kurmi OP, Lam KB, et al. Respiratory risks from household air pollution in low and middle income countries. Lancet Respir Med. 2014 Oct;2(10):823–60.

4. Kurmi OP, Sadhra CS, Ayres JG, Sadhra SS. Tuberculosis risk from exposure to solid fuel smoke: a systematic review and meta-analysis. 2014 Jul 31;

5. Clark SN, Schmidt AM, Carter EM, Schauer JJ, Yang X, Ezzati M, et al. Longitudinal evaluation of a household energy package on blood pressure, central hemodynamics, and arterial stiffness in China. Environ Res. 2019 Oct 1;177:108592.

6. Checkley W. Household Air Pollution and Health: A Multi-Country LPG Intervention Trial. 2016 Oct 19.

7. Anenberg SC, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, et al. Cleaner cooking solutions to achieve health, climate, and economic cobenefits. Env Sci Technol. 2013 May 7;47(9):3944–52.

8. Cundale K, Thomas R, Malava JK, Havens D, Mortimer K, Conteh L. A health intervention or a kitchen appliance? Household costs and benefits of a cleaner burning biomass-fuelled cookstove in Malawi. Soc Sci Med. 2017 Jun;183:1–10.

9. Nightingale R, Lesosky M, Flitz G, Rylance SJ, Meghji J, Burney P, et al. Noncommunicable Respiratory Disease and Air Pollution Exposure in Malawi (CAPS). A Cross-Sectional Study. Am J Respir Crit Care Med. 2019 Mar 1;199(5):613–21.

10. Rylance S, Nightingale R, Naunje A, Mbalume F, Jewell C, Balmes JR, et al. Lung health and exposure to air pollution in Malawian children (CAPS): a cross-sectional study. Thorax. 2019 Nov;74(11):1070–7.

11. Bonjour S, Adair-Rohani H, Wolf J, Bruce NG, Mehta S, Pruss-Ustun A, et al. Solid fuel use for household cooking: country and regional estimates for 1980-2010. Env Health Perspect. 2013 Jul;121(7):784–90.

12. IEA [Internet]. 2022 [cited 2025 Apr 26]. World Energy Outlook 2022 – Analysis. Available from: https://www.iea.org/reports/world-energy-outlook-2022

13. Brook RD, Newby DE, Rajagopalan S. Air Pollution and Cardiometabolic Disease: An Update and Call for Clinical Trials. Am J Hypertens. 2017 Dec 8;31(1):1–10.

14. Bruce N, de Cuevas RA, Cooper J, Enonchong B, Ronzi S, Puzzolo E, et al. The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation. Energy Sustain Dev. 2018 Jul 9;46:103–10.

15. Moses ND, Pakravan MH, MacCarty NA. Development of a practical evaluation for cookstove usability. Energy Sustain Dev. 2019 Feb 1;48:154–63.

16. Lindgren SA. Clean cooking for all? A critical review of behavior, stakeholder engagement, and adoption for the global diffusion of improved cookstoves. Energy Res Soc Sci. 2020 Oct;68:101539.

17. Ruiz-Mercado I, Masera O. Patterns of Stove Use in the Context of Fuel-Device Stacking: Rationale and Implications. Ecohealth. 2015 Feb 28;12(1):42–56.

18. Waleed K, Mirza FM. Examining fuel choice patterns through household energy transition index: an alternative to traditional energy ladder and stacking models. Environ Dev Sustain. 2023 Jul 1;25(7):6449–501.

19. Hierarchy of Controls | NIOSH | CDC [Internet]. 2023 [cited 2024 Jan 3]. Available from: https://www.cdc.gov/niosh/topics/hierarchy/default.html

20. Rylance J, Gordon SB, Naeher LP, Patel A, Balmes JR, Adetona O, et al. Household air pollution: a call for studies into biomarkers of exposure and predictors of respiratory disease. Am J Physiol Lung Cell Mol Physiol. 2013 May 1;304(9):L571-8.

21. Misra A, Longnecker MP, Dionisio KL, Bornman RMS, Travlos GS, Brar S, et al. Household fuel use and biomarkers of inflammation and respiratory illness among rural South African Women. Env Res. 2018 Jun 6;166:112–6.

22. Barnes BR. Behavioural change, indoor air pollution and child respiratory health in developing countries: a review. Int J Env Res Public Health. 2014 May;11(5):4607–18.

23. Shen GF. Changes from traditional solid fuels to clean household energies - Opportunities in emission reduction of primary PM2.5 from residential cookstoves in China. Biomass Bioenergy. 2016 Mar;86:28–35.

24. Bensch et al. Efficient biomass cooking in Africa for climate change mitigation and development. One Earth. 2021 Jun 18;4(6):879–90.

25. Ahmed S, Ibrahimou B, Kader SB, Chowdhury MAH, Ahsan H, Yunus M. Household biomass fuel use is associated with chronic childhood malnutrition: Result from a nationwide cross-sectional survey in Bangladesh. Indoor Air. 2021;31(6):2167–75.

26. Adaji EE, Ekezie W, Clifford M, Phalkey R. Understanding the effect of indoor air pollution on pneumonia in children under 5 in low- and middle-income countries: a systematic review of evidence. Env Sci Pollut Res Int. 2019 Feb;26(4):3208–25.

27. International Energy Agency (IEA). World Energy Outlook 2020. 2020. SDG7: Data and Projections: Access to affordable, reliable, sustainable and modern energy. Available from: https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking

28. Quinn AK, Bruce N, Puzzolo E, Dickinson K, Sturke R, Jack DW, et al. An analysis of efforts to scale up clean household energy for cooking around the world. Energy Sustain Dev. 2018 Jul 4;46:1–10.

29. Grieshop AP, Marshall JD, Kandlikar M. Health and climate benefits of cookstove replacement options. Energy Policy. 2011;39:7530–42.

30. Grieshop AP, North Carolina State University at Raleigh Department of Civil C and EERNCU, Jain G, Resource Optimization Initiative Bangalore India, Sethuraman K, Resource Optimization Initiative Bangalore India, et al. Emission factors of health- and climate-relevant pollutants measured in home during a carbon-finance-approved cookstove intervention in rural India. GeoHealth. 2017;1(5):222–36.

31. Checkley W, Williams KN, Kephart JL, Fandiño-Del-Rio M, Steenland NK, Gonzales GF, et al. Effects of a Household Air Pollution Intervention with Liquefied Petroleum Gas on Cardiopulmonary Outcomes in Peru. A Randomized Controlled Trial. Am J Respir Crit Care Med. 2021 Jun;203(11):1386–97.

32. Bisgaard H, Jensen SM, Bønnelykke K. Interaction between Asthma and Lung Function Growth in Early Life. Am J Respir Crit Care Med. 2012 Jun 1;185(11):1183–9.

33. Agustí A, Noell G, Brugada J, Faner R. Lung function in early adulthood and health in later life: a transgenerational cohort analysis. Lancet Respir Med. 2017 Dec;5(12):935–45.

34. Alderman H, Behrman JR, Glewwe P, Fernald L, Walker S. Evidence of Impact of Interventions on Growth and Development during Early and Middle Childhood. In: Bundy DAP, Silva N de, Horton S, Jamison DT, Patton GC, editors. Child and Adolescent Health and Development [Internet]. 3rd ed. Washington (DC): The International Bank for Reconstruction and Development / The World Bank; 2017 [cited 2023 Feb 17]. Available from: http://www.ncbi.nlm.nih.gov/books/NBK525234/

35. Caravedo MA, Herrera PM, Mongilardi N, Ferrari A de, Davila-Roman VG, Gilman RH, et al. Chronic exposure to biomass fuel smoke and markers of endothelial inflammation. Indoor Air. 2016;26(5):768–75.

36. Boamah-Kaali E, Jack DW, Ae-Ngibise KA, Quinn A, Kaali S, Dubowski K, et al. Prenatal and Postnatal Household Air Pollution Exposure and Infant Growth Trajectories: Evidence from a Rural Ghanaian Pregnancy Cohort. Environ Health Perspect. 2021 Nov;129(11):117009.

37. Burke H, Leonardi-Bee J, Hashim A, Pine-Abata H, Chen Y, Cook DG, et al. Prenatal and Passive Smoke Exposure and Incidence of Asthma and Wheeze: Systematic Review and Meta-analysis. Pediatrics. 2012 Apr 1;129(4):735–44.

38. Kurmi OP, Semple S, Simkhada P, Smith WCS, Ayres JG. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. Thorax. 2010 Mar;65(3):221–8.

39. Anand A, Castiglia E, Zamora ML. The Association Between Personal Air Pollution Exposures and Fractional Exhaled Nitric Oxide (FeNO): A Systematic Review. Curr Environ Health Rep. 2024 Jun 1;11(2):210–24.

40. Barr Dana B., Wang Richard Y., Needham Larry L. Biologic Monitoring of Exposure to Environmental Chemicals throughout the Life Stages: Requirements and Issues for Consideration for the National Children's Study. Environ Health Perspect. 2005 Aug 1;113(8):1083–91.

41. Dutta A, Ray MR. Hypertension and respiratory health in biomass smoke-exposed premenopausal Indian women. Air Qual Atmosphere Health. 2014 Jun 1;7(2):229–38.

42. Munakata M. Exhaled Nitric Oxide (FeNO) as a Non-Invasive Marker of Airway Inflammation. Allergol Int. 2012 Jan 1;61(3):365–72.

43. Nagase H, Toda T, Kamiyama A, Nakase Y, Sugimoto N, Yoshihara H, et al. Usefulness of Measuring Fractional Exhaled Nitric Oxide (FeNO) In Various Respiratory Diseases. J Allergy Clin Immunol. 2011 Feb 1;127(2):AB7.

44. Werthmann D, Van Wendel De Joode B, Cuffney MT, Reich BJ, Soto-Martinez ME, Corrales-Vargas A, et al. A cross-sectional analysis of medical conditions and environmental factors associated with fractional exhaled nitric oxide (FeNO) in women and children from the ISA birth cohort, Costa Rica. Environ Res. 2023 Sep;233:116449.

45. Nigatu AW, Bråtveit M, Deressa W, Moen BE. Respiratory symptoms, fractional exhaled nitric oxide & endotoxin exposure among female flower farm workers in Ethiopia. J Occup Med Toxicol. 2015 Feb 26;10(1):8.

46. Ndlovu V, Dalvie MA, Jeebhay MF. Asthma associated with pesticide exposure among women in rural Western Cape of South Africa. Am J Ind Med. 2014;57(12):1331–43.

47. Pollard SL, Williams KN, O'Brien CJ, Winiker A, Puzzolo E, Kephart JL, et al. An evaluation of the Fondo de Inclusión Social Energético program to promote access to liquefied petroleum gas in Peru. Energy Sustain Dev. 2018 Oct 1;46:82–93.

48. Graham BL, Steenbruggen I, Miller MR, Barjaktarevic IZ, Cooper BG, Hall GL, et al. Standardization of Spirometry 2019 Update. An Official American Thoracic Society and European Respiratory Society Technical Statement. Am J Respir Crit Care Med. 2019 Oct 15;200(8):e70–88.

49. Oluwole O, Arinola GO, Ana GR, Wiskel T, Huo D, Olopade OI, et al. Relationship between Household Air Pollution from Biomass Smoke Exposure, and Pulmonary Dysfunction, Oxidant-Antioxidant Imbalance and Systemic Inflammation in Rural Women and Children in Nigeria. Glob J Health Sci. 2013 Mar 18;5(4):p28.

50. Arora S, Rasania SK, Bachani D, Gandhi A, Chhabra SK. Air pollution and environmental risk factors for altered lung function among adult women of an urban slum area of Delhi: A prevalence study. Lung India. 2018 Jun;35(3):193.

51. Brakema EA, Vermond D, Pinnock H, Lionis C, Kirenga B, An PL, et al. Implementing lung health interventions in low- and middle-income countries: a FRESH AIR systematic review and meta-synthesis. Eur Respir J. 2020 Jul 23;56(1):2000127.

52. Berry CE, Billheimer D, Jenkins IC, Lu ZJ, Stern DA, Gerald LB, et al. A Distinct Low Lung Function Trajectory from Childhood to the Fourth Decade of Life. Am J Respir Crit Care Med. 2016 Sep 1;194(5):607–12.

53. Rylance S, Nightingale R, Naunje A, Mbalume F, Jewell C, Balmes JR, et al. Lung health and exposure to air pollution in Malawian children (CAPS): a cross-sectional study. Thorax. 2019 Nov;74(11):1070–7.

54. Oluwole O, Arinola GO, Huo D, Olopade CO. Household biomass fuel use, asthma symptoms severity, and asthma underdiagnosis in rural schoolchildren in Nigeria: a cross-sectional observational study. BMC Pulm Med. 2017 Jan 5;17(1):3.

55. Oluwole O, Arinola GO, Ana GR, Wiskel T, Huo D, Olopade OI, et al. Relationship between household air pollution from biomass smoke exposure, and pulmonary dysfunction, oxidant-antioxidant imbalance and systemic inflammation in rural women and children in Nigeria. Glob J Health Sci. 2013 Mar 18;5(4):28–38.

56. Ben Salah N, Bejar D, Snène H, Ouahchi Y, Mehiri N, Louzir B. The Z-score: A new tool in the interpretation of spirometric data. Tunis Med. 2017;95(8–9):767–71.

57. Health Effects Institute (HEI), Institute for Health Metrics and Evaluation (IHME). State of Global Air: Household Air Pollution Exposure [Internet]. 2022 [cited 2022 Sep 19]. Available from: https://www.stateofglobalair.org/air/hap

58. Murray CJL, Aravkin AY, Zheng P, Abbafati C, Abbas KM, Abbasi-Kangevari M, et al. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. The Lancet. 2020 Oct 17;396(10258):1223–49.

59. Smith KR. Changing Paradigms in Clean Cooking. Ecohealth. 2015 Apr 17;12(1):196–9.

60. Balmes JR. Household air pollution from domestic combustion of solid fuels and health. J Allergy Clin Immunol. 2019;143(6):1979–87.

61. Apte K, Salvi S. Household air pollution and its effects on health. F1000Research [Internet]. 2016 Oct 28 [cited 2020 Jul 21];5. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089137/

62. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, et al. Woodsmoke Health Effects: A Review. Inhal Toxicol. 2007 Jan;19(1):67–106.

63. Pope D, Bruce N, Dherani M, Jagoe K, Rehfuess E. Real-life effectiveness of “improved” stoves and clean fuels in reducing PM2.5 and CO: Systematic review and meta-analysis. Environ Int. 2017 Apr;101:7–18.

64. Benka-Coker ML, Clark ML, Rajkumar S, Young BN, Bachand AM, Balmes JR, et al. Exposure to Household Air Pollution from Biomass Cookstoves and Levels of Fractional Exhaled Nitric Oxide (FeNO) among Honduran Women. Int J Env Res Public Health. 2018 Nov 13;15(11).

65. Farmer PB, Singh R, Kaur B, Sram RJ, Binkova B, Kalina I, et al. Molecular epidemiology studies of carcinogenic environmental pollutants. Mutat Res Mutat Res. 2003 Nov;544(2–3):397–402.

66. Loomis D, Grosse Y, Lauby-Secretan B, Ghissassi FE, Bouvard V, Benbrahim-Tallaa L, et al. The carcinogenicity of outdoor air pollution. Lancet Oncol. 2013 Dec 1;14(13):1262–3.

67. Young BN, Clark ML, Rajkumar S, Benka-Coker ML, Bachand A, Brook RD, et al. EXPOSURE TO HOUSEHOLD AIR POLLUTION FROM BIOMASS COOKSTOVES AND BLOOD PRESSURE AMONG WOMEN IN RURAL HONDURAS: A CROSS-SECTIONAL STUDY. Indoor Air. 2019 Jan;29(1):130–42.

68. Benka-Coker ML, Young BN, Keller JP, Walker ES, Rajkumar S, Volckens J, et al. Impact of the wood-burning Justa cookstove on fine particulate matter exposure: A stepped-wedge randomized trial in rural Honduras. Sci Total Environ. 2021 May 1;767:144369.

69. Boy E, Bruce N, Delgado H. Birth Weight and Exposure to Kitchen Wood Smoke during Pregnancy in Rural Guatemala. Environ Health Perspect. 2002;110(1):109–14.

70. Quansah R, Semple S, Ochieng CA, Juvekar S, Armah FA, Luginaah I, et al. Effectiveness of interventions to reduce household air pollution and/or improve health in homes using solid fuel in low-and-middle income countries: A systematic review and meta-analysis. Environ Int. 2017 Mar 22;103:73–90.

71. Dweik RA, Boggs PB, Erzurum SC, Irvin CG, Leigh MW, Lundberg JO, et al. An Official ATS Clinical Practice Guideline: Interpretation of Exhaled Nitric Oxide Levels (FeNO) for Clinical Applications. 2011;184:14.

72. Kang SY, Lee SM, Lee SP. Measurement of Fractional Exhaled Nitric Oxide in Adults: Comparison of Two Different Analyzers (NIOX VERO and NObreath). Tuberc Respir Dis. 2021 Jul;84(3):182–7.

73. Berhane K, Zhang Y, Linn WS, Rappaport EB, Bastain TM, Salam MT, et al. The effect of ambient air pollution on exhaled nitric oxide in the children’s health study. Eur Respir J. 2011;37(5):1029–36.

74. Young BN, Peel JL, Benka-Coker ML, Rajkumar S, Walker ES, Brook RD, et al. Study protocol for a stepped-wedge randomized cookstove intervention in rural Honduras: household air pollution and cardiometabolic health. BMC Public Health. 2019 Jul 8;19(1):903.

75. Hemming K, Haines TP, Chilton PJ, Girling AJ, Lilford RJ. The stepped wedge cluster randomised trial: rationale, design, analysis, and reporting. BMJ. 2015 Feb 6;350:h391.

76. Volckens J, Quinn C, Leith D, Mehaffy J, Henry CS, Miller-Lionberg D. Development and evaluation of an ultrasonic personal aerosol sampler. Indoor Air. 2017 Mar;27(2):409–16.

77. Pillarisetti A, Carter E, Rajkumar S, Young BN, Benka-Coker ML, Peel JL, et al. Measuring personal exposure to fine particulate matter (PM2.5) among rural Honduran women: A field evaluation of the Ultrasonic Personal Aerosol Sampler (UPAS). Environ Int. 2019 Feb 1;123:50–3.

78. Young BN, Good N, Peel JL, Benka-Coker ML, Keller JP, Rajkumar S, et al. Reduced Black Carbon Concentrations following a Three-Year Stepped-Wedge Randomized Trial of the Wood-Burning Justa Cookstove in Rural Honduras. Environ Sci Technol Lett. 2022 Jun 14;9(6):538–42.

79. Keller JP, Clark ML. Estimating long-term average household air pollution concentrations from repeated short-term measurements in the presence of seasonal trends and crossover. Environ Epidemiol. 2021 Dec 20;6(1):e188.

80. Rouhos A, Ekroos H, Karjalainen J, Sarna S, Haahtela T, Sovijärvi ARA. Smoking attenuates increase in exhaled nitric oxide in atopic but not in nonatopic young adults with asthma. Int Arch Allergy Immunol. 2010;152(3):226–32.

81. Zhu Z, Xie Y, Guan W, Gao Y, Xia S, Zhong N, et al. FeNO for detecting lower airway involvement in patients with allergic rhinitis. Exp Ther Med. 2016 Oct;12(4):2336–40.

82. Gao J, Wu F. Association between fractional exhaled nitric oxide, sputum induction and peripheral blood eosinophil in uncontrolled asthma. Allergy Asthma Clin Immunol Off J Can Soc Allergy Clin Immunol. 2018;14:21.

83. Castro M, Papi A, Porsbjerg C, Lugogo NL, Brightling CE, González-Barcala FJ, et al. Effect of dupilumab on exhaled nitric oxide, mucus plugs, and functional respiratory imaging in patients with type 2 asthma (VESTIGE): a randomised, double-blind, placebo-controlled, phase 4 trial. Lancet Respir Med. 2025 Mar 1;13(3):208–20.

84. Westergaard CG, Porsbjerg C, Backer V. The effect of smoking cessation on airway inflammation in young asthma patients. Clin Exp Allergy. 2014;44(3):353–61.

85. Dogan EB, Rossignol PA. An Olfactometer for Discriminating Between Attraction, Inhibition, and Repellency in Mosquitoes (Diptera: Culicidae). J Med Entomol. 1999;36(6):788–93.

86. Ahovuo-Saloranta A, Csonka P, Lehtimäki L. Basic characteristics and clinical value of FeNO in smoking asthmatics-a systematic review. J Breath Res. 2019 May 3;13(3):034003.

87. Xu X, Hu H, Kearney GD, Kan H, Carrillo G, Chen X. A population-based study of smoking, serum cotinine and exhaled nitric oxide among asthmatics and a healthy population in the USA. Inhal Toxicol. 2016 Dec 5;28(14):724–30.

88. Choumert J, Combes P, Le Roux L. Stacking up the ladder: A panel data analysis of Tanzanian household energy choices. World Dev. 2018 Jan 8;115:222–35.

89. Lee KK, Bing R, Kiang J, Bashir S, Spath N, Stelzle D, et al. Adverse health effects associated with household air pollution: a systematic review, meta-analysis, and burden estimation study. Lancet Glob Health. 2020 Nov;8(11):e1427–34.

90. Rosa G, Majorin F, Boisson S, Barstow C, Johnson M, Kirby M, et al. Assessing the impact of water filters and improved cook stoves on drinking water quality and household air pollution: a randomised controlled trial in Rwanda. PLoS One. 2014;9(3):e91011.

91. Bradbrook AJ, Gardam JG. Placing Access to Energy Services within a Human Rights Framework. Hum Rights Q. 2006;28(2):389–415.

92. Barnes BR. Behavioural change, indoor air pollution and child respiratory health in developing countries: a review. Int J Env Res Public Health. 2014 May;11(5):4607–18.

93. Bruce N, Dherani M, Liu R, Hosgood HD, Sapkota A, Smith KR, et al. Does household use of biomass fuel cause lung cancer? A systematic review and evaluation of the evidence for the GBD 2010 study. Thorax. 2015 Mar 10;70(5):433–41.

94. Garcia E, Rice MB, Gold DR. Air pollution and lung function in children. J Allergy Clin Immunol. 2021 Jul 1;148(1):1–14.

95. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3–95-yr age range: the global lung function 2012 equations. Eur Respir J. 2012 Dec 1;40(6):1324–43.

96. Bao et al. Small-Airway Function Variables in Spirometry, Fractional Exhaled Nitric Oxide, and Circulating Eosinophils Predicted Airway Hyperresponsiveness in Patients with Mild Asthma [Internet]. [cited 2024 Mar 21]. Available from: https://www.tandfonline.com/doi/epdf/10.2147/JAA.S295345?needAccess=true

97. Burke PJ, Dundas G. Female Labor Force Participation and Household Dependence on Biomass Energy: Evidence from National Longitudinal Data. World Dev. 2015 Mar 1;67:424–37.

98. Rinne ST, Rodas EJ, Bender BS, Rinne ML, Simpson JM, Galer-Unti R, et al. Relationship of pulmonary function among women and children to indoor air pollution from biomass use in rural Ecuador. Respir Med. 2006 Jul;100(7):1208–15.

99. Chakaya JM, Carter EJ, Hopewell PC. Pulmonary Specialty Training to Improve Respiratory Health in Low- and Middle-Income Countries. Needs and Challenges. Ann Am Thorac Soc. 2015 Apr;12(4):486–90.

100. Howe LD, Hargreaves JR, Huttly SR. Issues in the construction of wealth indices for the measurement of socio-economic position in low-income countries. Emerg Themes Epidemiol. 2008 Jan 30;5(1):3.

101. Bates JHT, Peters U, Daphtary N, MacLean ES, Hodgdon K, Kaminsky DA, et al. Altered airway mechanics in the context of obesity and asthma. J Appl Physiol. 2021 Jan;130(1):36–47.

102. Gerlich J, Ohlander J, Kromhout H, Vermeulen R, Söhler S, Radon K, et al. Cumulative occupational exposure to gases and fumes is associated with impairment in lung function and disease-related quality of life in a German COPD patient cohort. Occup Environ Med. 2023 Dec 30;81(1):26–33.

103. Chuang KJ, Yan YH, Chiu SY, Cheng TJ. Long-term air pollution exposure and risk factors for cardiovascular diseases among the elderly in Taiwan. Occup Environ Med. 2011 Jan 1;68(1):64–8.

104. Marchetti N, Garshick E, Kinney GL, McKenzie A, Stinson D, Lutz SM, et al. Association between Occupational Exposure and Lung Function, Respiratory Symptoms, and High-

Resolution Computed Tomography Imaging in COPDGene. Am J Respir Crit Care Med. 2014 Oct 1;190(7):756–62.

105. Aithal SS, Gill S, Satia I, Tyagi SK, Bolton CE, Kurmi OP. The Effects of Household Air Pollution (HAP) on Lung Function in Children: A Systematic Review. Int J Environ Res Public Health. 2021 Nov 15;18(22):11973.

106. Aghasafari P, George U, Pidaparti R. A review of inflammatory mechanism in airway diseases. Inflamm Res. 2019 Jan 1;68(1):59–74.

107. Kwon DS, Choi YJ, Kim TH, Byun MK, Cho JH, Kim HJ, et al. FEF25-75% Values in Patients with Normal Lung Function Can Predict the Development of Chronic Obstructive Pulmonary Disease. Int J Chron Obstruct Pulmon Dis. 2020 Nov 12;15:2913–21.

Table A.1Sensitivity Analysis Results. Adjusted mixed-effects regression models for intent-to-treat, personal $PM_{2.5}$ and BC exposure-response for effects on FeNO values. Participant ID is a random effect in all models.

Exposure	**N obs used**	**Estimate (percent change)**	**95% CI**
Intent-to-treat (assigned stove type)			
Intent-to-treat[1] Removed those with mucous symptoms AND anti-inflammatory medications *Justa* stove Traditional stove (reference)	388	-0.5 Ref	-4.1,3.2 Ref
Personal exposure-response with 24-hour $PM_{2.5}$ and black carbon (μg/m^3, natural log transformed) and Long-term average		**Estimate (25 percent change)**	
Personal $PM_{2.5}$[2] Removed those with mucous symptoms	379	-0.9	-2.1, 0.3
Personal BC Removed those with mucous symptoms	370	-0.6	-1.2, 0.0
Personal predicted long-term average PM Removed those with mucous symptoms	388	-3.4	-6.2, -0.5
Personal predicted long-term average BC Removed those with mucous symptoms	387	-1.6	3.0, -0.2

BC = black carbon, CI = confidence interval, N = number of observations, $PM_{2.5}$ = fine particulate matter ≤2.5 microns in diameter.[1] Fixed effect term for "time" is a spline function with 6 degrees of freedom.

[2] Additional covariates in model: Age at baseline (continuous), BMI (continuous), waist-to-hip ratio (continuous), physical activity as METs (continuous), dietary diversity score (continuous), weighted index for household material assets at baseline (continuous).[3] Predicted long-term average exposure, estimated from intercept, stove type, spline for time (6 df), and random effect for household. Two exposures per household, one for each stove type, combining stove group mean and the household random effect.

Table A.2. Crude associations (univariable linear regression models) between log transformed FeNo and SES, demographic, and health characteristics at baseline (Phase 1). Variables in with *p*-values in red font are further explored in multivariate models

Baseline crude associations with log transformed FeNo	**N obs used**	**Estimate(in percent change)**	**95% CI**		***p*-value**
Age at baseline (years) (age_baseline)	90	0.00	-2.96	0.20	0.09
Height (in) (height)	90	0.00	-6.76	5.13	0.74
BMI (kg/m^2) (bmi)	90	0.01	-2.96	3.05	0.99
Waist-to-hip ratio (whr)	90	-4.88	-89.97	802.50	0.97
Physical activity (METs, continuous) (phys_act)	90	0.10	-0.10	0.20	0.62
Dietary diversity score, 1-11 continuous (dds_total)	89	-1.00	-8.61	7.25	0.82
Household assets (SES weighted sum, continuous), range 0-45 (ses_weighted_sum)	90	0.00	-2.96	0.20	0.08
Number of people living in the house (no_people)	90	0.00	-4.88	6.18	0.76
Years of school (school_bi)	90	0.20	-22.89	29.69	0.99
<6 (n=)					
6+ (n=) (ref)		Ref	Ref		Ref
Working electricity in home	90	25.86	-5.82	68.20	0.12

0 No (n=)					
1 Yes (n=) (reference)		Ref	Ref		
(electricity)					
Any medication use of anti-inflammatory meds (allergy, ibuprofen, misc pain meds)					
0 None (n=)					
1 One or more (n=) (Reference)	90	39.10	-12.19	118.15	0.16
(med_combined_antiinfl_2)		Ref	Ref		Explore in sens analys
Any medication use (includes allergy, ibuprofen, misc pain, vitamins, blood pressure, diabetes, birth control, antibiotic, acetaminophen, lipids)					
0 None (n=)					
1 One or more (n=) (Reference)					
(med_combined_2)	90	32.31	-2.96	75.07	0.07
		Ref	Ref		
Other sources of HAP: use of kerosene, gas lamps, ocote as light					
0 No (n=)					0.62
1 Yes (n=) (Reference)					
(haplight)					
Other sources of HAP: use of kerosene					
0 No (n=)					0.08
1 Yes (n=) Reference)					

(hapkerosene)					
Other sources of HAP: burning trash					
0 No (n=)					0.34
1 Yes (n=) (Reference)					
(haptrash)					
Self-reported mucous/phlegm symptoms at visit (mucous_now)					
0 No		-11.31	-37.50	24.61	0.48
1 Yes (reference)		Ref	Ref		
Self-reported cough (cough_now)					
Self-reported difficulty breathing (breathing_now)					
0 No					
1 Yes (reference)					
					0.53
Secondhand tobacco smoke exposure (ets)					
0 No (90, 100%)		n/a	n/a		n/a
1 Yes (0)					

Baseline crude associations were assessed between participant characteristics and log-transformed FeNO. Continuous variables were modeled per unit increase. Categorical variables were modeled with the first listed category coded as 0 and the second category as the reference group unless otherwise specified:

[1] Dietary diversity score calculated as the sum of distinct food groups consumed in the prior 24 hours (range 1–11: cereals, pulses, potatoes, vegetables, fruits, sweets, dairy, meat, fats/oils, sweetened beverages, eggs).

[2] Physical activity estimated as total metabolic equivalent hours per week based on reported lifestyle activities, using the 2011 Compendium of Physical Activities.

[3] Kerosene use defined as household use of kerosene for lighting or cooking.

[4] Household assets score calculated as a weighted sum of nine items: radio, mobile phone, bicycle, television, sewing machine, refrigerator, car, motorcycle, computer.

[5] Medication use includes allergy medications, pain relievers (ibuprofen, acetaminophen), blood pressure medications, diabetes medications, birth control, antibiotics, and lipid-lowering drugs.

[6] Mucous symptoms defined as self-reported presence of mucous or phlegm at the time of the study visit.

[7] Schooling categorized as <6 years versus ≥6 years (reference group).

[8] Working electricity defined as 0 = no working electricity; 1 = working electricity (reference group).

[9] Use of anti-inflammatory medications defined as 0 = no use; 1 = use of one or more anti-inflammatory medications (reference group).

[10] Any medication use defined as 0 = no use; 1 = use of one or more medications (reference group).

[11] Additional household air pollution sources (use of kerosene lamps, gas lamps, or ocote wood for lighting) defined as 0 = no use; 1 = reported use (reference group).

[12] Burning trash for waste disposal defined as 0 = no burning; 1 = burning trash reported (reference group).

[13] Self-reported cough defined as 0 = no cough; 1 = cough present (reference group).

[14] Self-reported difficulty breathing defined as 0 = no difficulty breathing; 1 = difficulty breathing present (reference group).

ETS exposure (secondhand tobacco smoke) was not observed among participants (0% prevalence).

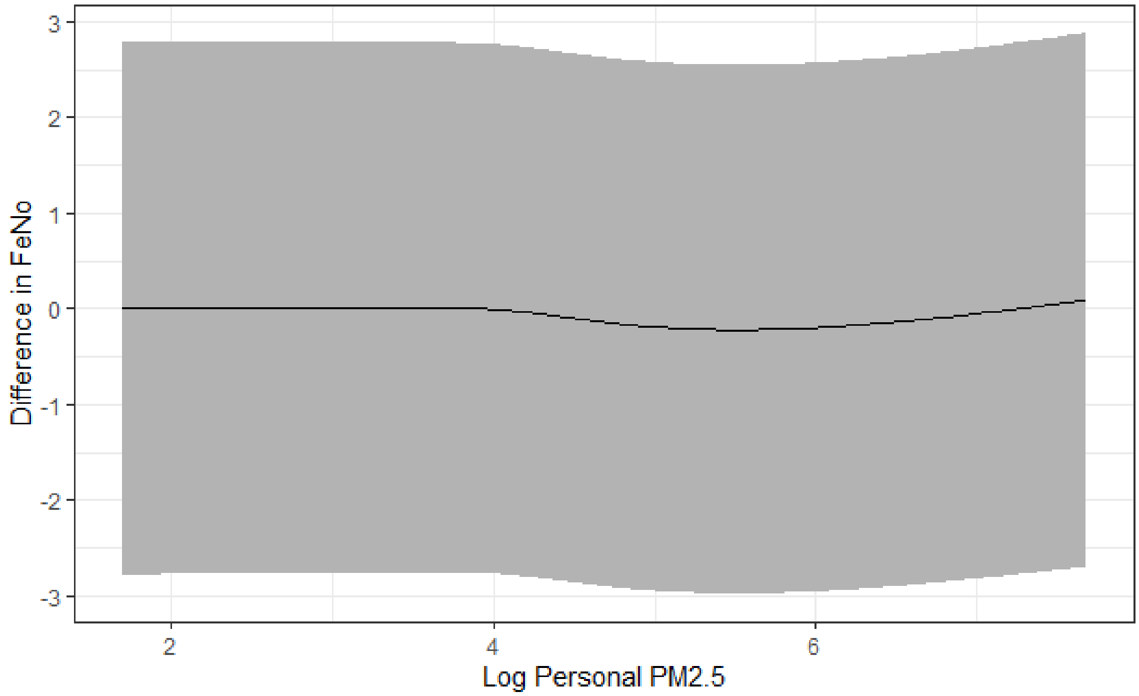

Figure. A.3a: Add uncertainty. Plot of personal $PM_{2.5}$ spline with 4 df[1]. Subset of n=400 without 90th percentile of log_pm_twa, plot of personal $PM_{2.5}$ spline with 6 df[1]. [1] Model included dependent variable of log_feno, natural cubic spline function for log_p_twa (df=4), and adjusted for age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), self-reported symptom of mucous/phlegm (yes/no), combined medication use (none/any).

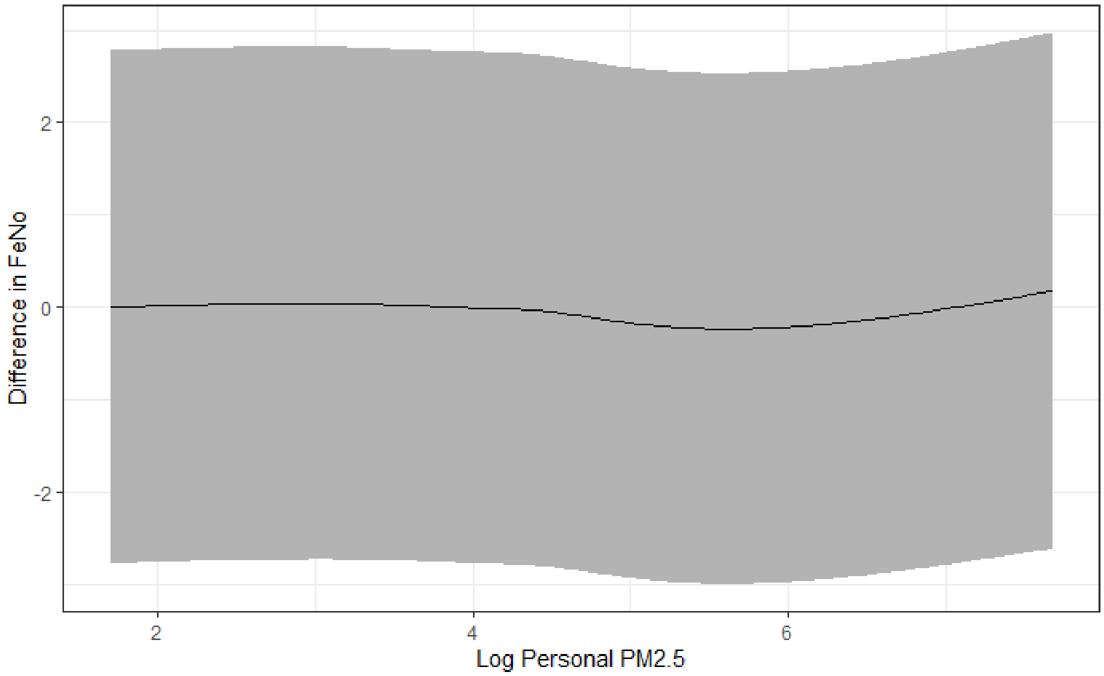

Figure A.3b: Add uncertainty. Plot of personal $PM_{2.5}$ spline with 6 df[1]. Subset of n=400 without 90th percentile of log_pm_twa, plot of personal $PM_{2.5}$ spline with 6 df[1]. [1] Model included dependent variable of log_feno, natural cubic spline function for log_p_twa (df=4), and adjusted for age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), self-reported symptom of mucous/phlegm (yes/no), combined medication use (none/any).

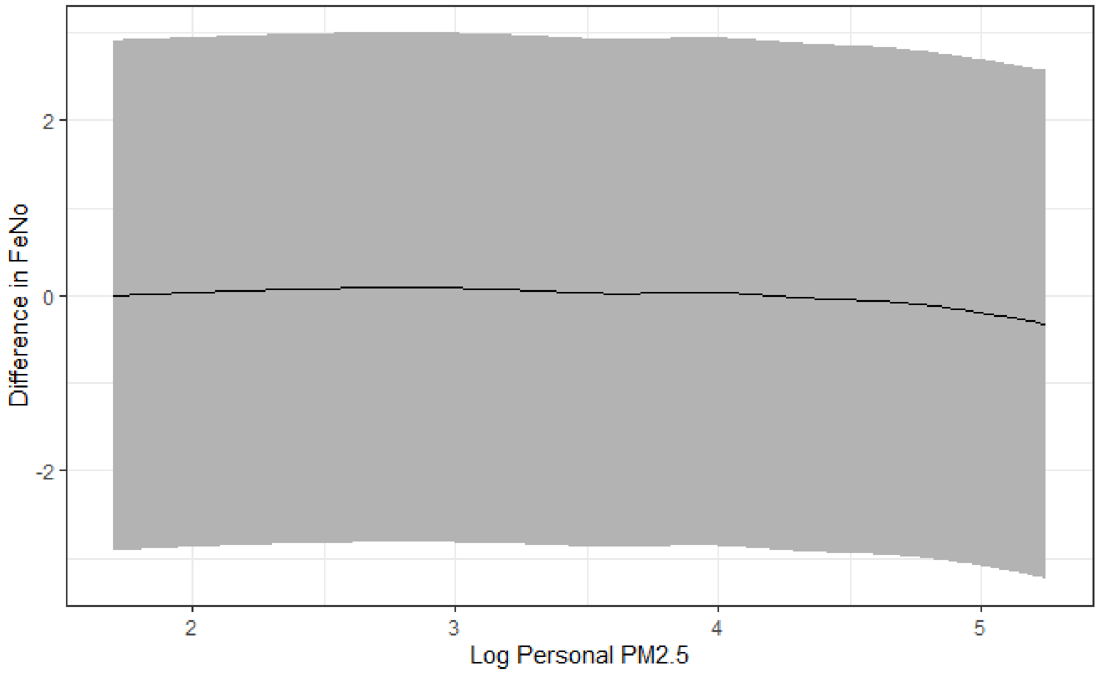

Figure A.3c Subset of n=400 without 90th percentile of log_pm_twa, plot of personal $PM_{2.5}$ spline with 6 df[1]. [1] Model included dependent variable of log_feno, natural cubic spline function for log_p_twa (df=4), and adjusted for age at baseline (continuous), height (continuous), weighted index for household material assets at baseline (continuous), self-reported symptom of mucous/phlegm (yes/no), combined medication use (none/any).

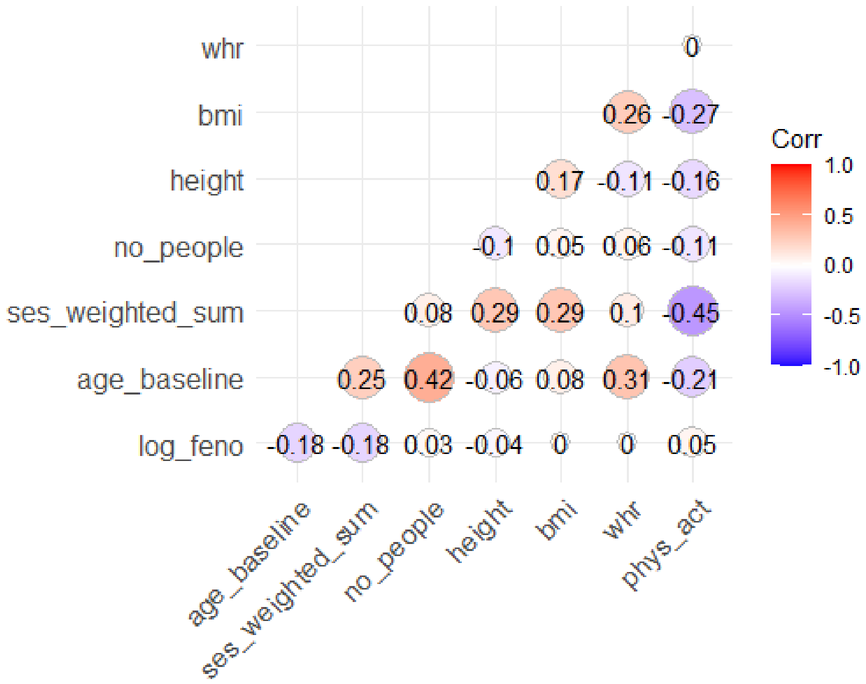

Figure A.4. Correlation matrix of baseline participant characteristics and log-transformed fractional exhaled nitric oxide (FeNO).
Pearson correlation coefficients are displayed for age at baseline, household asset score (SES weighted sum), number of people in the household, height, body mass index (BMI), waist-to-hip ratio (WHR), and physical activity (measured in METs), along with log-transformed FeNO levels. Positive correlations are shown in red, negative correlations in blue, with the color intensity indicating the strength of the association.

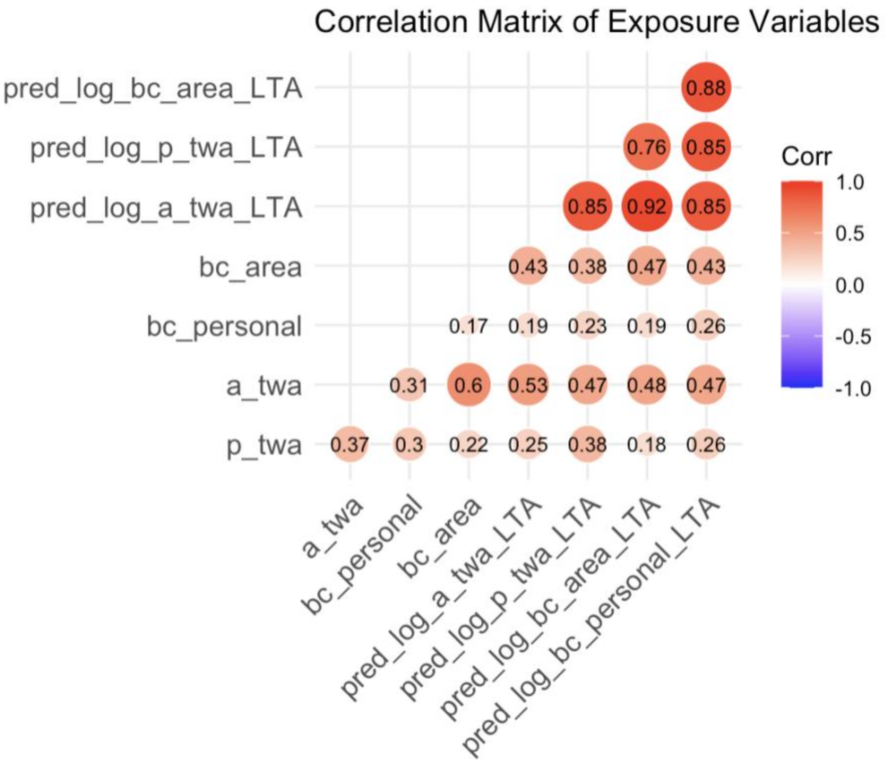

Figure A.5. Correlation matrix of exposure variables related to household air pollution. Pearson correlation coefficients are displayed for personal and kitchen (area) measurements of particulate matter (p_twa, a_twa) and black carbon (bc_personal, bc_area), as well as for predicted long-term average exposures (pred_log_p_twa_LTA, pred_log_a_twa_LTA, pred_log_bc_personal_LTA, pred_log_bc_area_LTA).