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Assessing the Effects of Stove Use Patterns and Kitchen Chimneys on Indoor Air Quality during a Multiyear Cookstove Randomized Control Trial in Rural India

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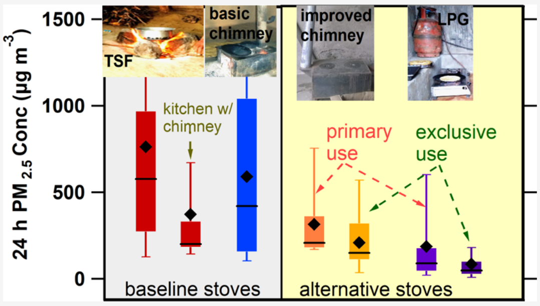
ABSTRACT: We conducted indoor air quality (IAQ) measurements during a multiyear cookstove randomized control trial in two rural areas in northern and southern India. A total of 1205 days of kitchen PM$_{2.5}$ were measured in control and intervention households during six ∼3 month long measurement periods across two study locations. Stoves used included traditional solid fuel (TSF), improved biomass, and liquefied petroleum gas (LPG) models. Intent-to-treat analysis indicates that the intervention reduced average 24 h PM$_{2.5}$ and black carbon in only one of the two follow-up measurement periods in both areas, suggesting mixed effectiveness. Average PM$_{2.5}$ levels were ∼50% lower in households with LPG (for exclusive LPG use: >75% lower) than in those without LPG. PM$_{2.5}$ was 66% lower in households making exclusive use of an improved chimney stove versus a traditional chimney stove and TSF-exclusive kitchens with a built-in chimney had ∼60% lower PM$_{2.5}$ than those without a chimney, indicating that kitchen ventilation can be as important as the stove technology in improving IAQ. Diurnal trends in real-time PM$_{2.5}$ indicate that kitchen chimneys were especially effective at reducing peak concentrations, which leads to decreases in daily PM$_{2.5}$ in these households. Our data demonstrate a clear hierarchy of IAQ improvement in real world, "stove-stacking" households, driven by different stove technologies and kitchen characteristics.



KEYWORDS: *chimney, indoor air quality, intervention effectiveness, LPG, stove use*

1.0. INTRODUCTION

Globally around 3 billion people used solid fuel stoves in 2018 as their household energy source for cooking and/or heating.[1] Emissions from these stoves cause ambient air pollution[2−4] and household air pollution (HAP).[5−7] Exposure to HAP is linked with adverse health impacts. For example, exposure to indoor PM$_{2.5}$ is associated with increased risks of pneumonia in children and pulmonary diseases in adults.[8−14] Globally 2.31 million premature deaths and 91.5 million lost disability-adjusted life years were associated with HAP in 2019.[15] Black carbon (BC), a component of PM$_{2.5}$, is also emitted during incomplete combustion and is associated with adverse health[16] and climate impacts.[17,18]

In India, around 846 million people (60% of the population) used solid fuels for cooking and were exposed to HAP in 2017, contributing to 482,000 annual deaths.[19] In part to reduce the harmful HAP impacts of traditional solid fuel (TSF) stoves, India has previously initiated cookstove intervention programs (e.g., National Program on Improved Chulha and National Biomass Cookstove Initiative) and currently subsidizes and helps distribute liquefied petroleum gas (LPG) as a cooking fuel via the Pradhan Mantri Ujjwala Yojana (PMUY) program.[20] In India and elsewhere, past intervention programs introducing improved biomass and modern fuel stoves have shown mixed effectiveness in reducing HAP, fuel use, and cooking time. For example, a forced draft model was found to reduce PM$_{2.5}$ and CO concentrations by 20−80% and 19−93%, respectively, in north Indian kitchens.[21] Some studies[22,23] observed substantial reductions in biomass fuel use and cooking time associated with clean stoves (e.g., biogas, LPG, and electric). However, a study of carbon-financed-supported intervention in southern India[24] found minor impacts on indoor particulate matter (PM) and fuel use in intervention households with rocket stoves, possibly due to limited uptake/adoption of the stoves and their poor emission performance.[25]

Availability of clean cooking technologies and fuels does not guarantee their continued adoption as sole sources of household energy and often leads to stove stacking, the combined use of multiple stoves/fuels.[26−29] Therefore,

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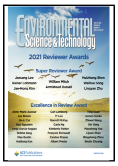

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assessing the effectiveness of interventions in increasing stove adoption and reducing stove emissions, HAP and fuel use over longer time periods is important. In addition, evaluation of regional differences in intervention effectiveness is needed since stove adoption and HAP levels may vary geographically due to environmental (e.g., fuel type, climate, and housing) and cultural factors (e.g., beliefs, cooking practices, and cuisine).[30,31] Our randomized control trial (RCT) explores the effectiveness, on socio-economic (stove adoption, fuel choice, and use) and technical [emissions and indoor air quality (IAQ)] bases, of a multiyear stove intervention in two rural areas, one each in North and South India. Thus far, analysis from this project has characterized stove emissions[32] and identified factors affecting stove adoption,[33] the diffusion of information through intervention communities,[34] LPG use,[20] and biomass consumption.[35] In this paper, we focus on the effectiveness of this RCT, and various associated stove use and ventilation characteristics, in improving IAQ. Our field measurements, by including a range of alternative stoves and household types studied longitudinally, provide real-world evidence of what "cleaner stacking"[29] can look like. We analyze a total of 1205 days' kitchen $PM_{2.5}$ concentration measurements in ~480 households over six measurement periods to accomplish four objectives: (a) present data on air quality in home kitchens in rural North and South India, (b) assess the effectiveness of the RCT in improving IAQ, (c) compare the air quality benefits achieved by different stove configurations, and (d) explore the differences in intervention effectiveness between the study locations and measurement periods.

2.0. METHODOLOGY

2.1. Site Description and Study Design. We conducted a multiyear cookstove intervention study in collaboration with two local non-governmental organizations with active stove programs in two distinct rural areas in India: Kullu district in Himachal Pradesh in northern India and Koppal district in Karnataka in southern India (site details are given in Section S1 and location in Figure S1). Four communities from each district were included in the study, nominally including 50 intervention and 10 control households (83 and 17%, respectively) selected randomly from each community (480 households in total). We denote communities from Himachal Pradesh and Karnataka states as "Himachal Pradesh" and "Karnataka," respectively, throughout the manuscript. At baseline, rural households in Karnataka primarily used traditional "chulhas," commonly known as TSF stoves, for cooking. Himachal Pradesh households had a higher prevalence (56%) of LPG at baseline[33] and, due to winter heating demand, used a combined cooking and heating chimney stove called a tandoor in winter months (Table S1). Around 58% of Karnataka kitchens had a built-in chimney over the hearth, primarily used with TSF stoves (Figure S2b). Note that in Karnataka households, a chimney was a part of the house, whereas in Himachal Pradesh, a chimney was a part of the stove: a metal stovepipe attached to tandoor stoves [e.g., traditional tandoor (TT) and himanshu tandoor (HT)]. Both household and stove chimneys may provide direct, though incomplete, exhaust of emissions and serve as an important source of natural ventilation. After baseline measurements, a selection of stoves ranging from alternative biomass stoves (e.g., rocket, gasifiers, and improved tandoor) to modern fuel stoves (LPG and electric induction) were offered to intervention households (Table S1). We varied stove pricing (free vs subsidized) among the four communities in each location. Additionally, stove exchange options varied (fixed throughout the study vs switch-out to another stove ~9−12 months later); details on study design and stove dissemination are given elsewhere.[33] IAQ measurements were conducted before (baseline) and after the stove selections (follow-up-1 and follow-up-2). Therefore, we conducted six measurement campaigns in total (three in each location) between March 2015 and November 2017 (see Table S2 for details).

2.2. Indoor $PM_{2.5}$ Concentration Measurements. Indoor $PM_{2.5}$ concentrations were measured using the RTI MicroPEM, a lightweight monitor for personal and indoor PM[36,37] (sensor details including limit of detection are given in Section S2). We initially aimed to use MicroPEM to measure personal $PM_{2.5}$ exposure. However, analysis of its accelerometer readings after the baseline measurement period in Himachal Pradesh indicated poor wearing compliance. Therefore, for the next five measurement periods, we measured kitchen $PM_{2.5}$ concentration by placing the MicroPEMS an average (± standard deviation) 1.2 m (±0.2 m) above and 1.0 m (±0.2 m) away from the stove. In total, we conducted 468 and 1205 days of personal and kitchen $PM_{2.5}$ concentration measurements, respectively. However, we exclude personal exposure measurements from this analysis due to the low compliance rate, retaining five measurement periods of kitchen $PM_{2.5}$ data. Outdoor $PM_{2.5}$ was not measured, though analysis of real-time data can yield some insights into background concentrations (Section 3.5).

We identified "stove-influenced" (SI) periods in real-time kitchen $PM_{2.5}$ data in each measurement day, following a previously established method[38] (details and caveats are given in Section S4). In this paper, SI time and PM refer to total stove influenced (cooking) period and average $PM_{2.5}$ concentration during these identified periods in a day, respectively. A SootScan transmissometer (model OT21, Magee Scientific, Berkeley, CA) determined equivalent BC concentration (eBC) from microPEM filter samples (details are given in Section S3); we use eBC here to distinguish our SootScan measurements from those collected via other methods.

2.3. Household Survey. In addition to a seasonal household survey described elsewhere,[33] we conducted exposure-assessment-oriented surveys at the end of each MicroPEM measurement session in a household. These surveys collected information about household's primary and secondary stove use, number of meals and types of foods cooked, number of people for whom foods were cooked, and use of other emission sources (e.g., incense and kerosene lamps) throughout the measurement period. We also measured cooking room dimensions and horizontal and vertical distances from MicroPEM to stove-tops and noted kitchen ventilation characteristics such as the number of opened and closed doors and windows and the presence of light vents. Note that the analysis in this paper focuses on the influence of stove use and direct ventilation of stove emissions (via household chimneys or chimney stoves) on kitchen $PM_{2.5}$ and eBC; a subsequent paper will explore the influence of these other household characteristics.

2.4. Analysis Matrix. We initially assessed the effectiveness of the intervention in improving IAQ via an intent-to-treat (ITT) analysis, which solely compares households based on whether they were in the control or intervention groups. ITT analysis compares kitchen $PM_{2.5}$ in control and intervention

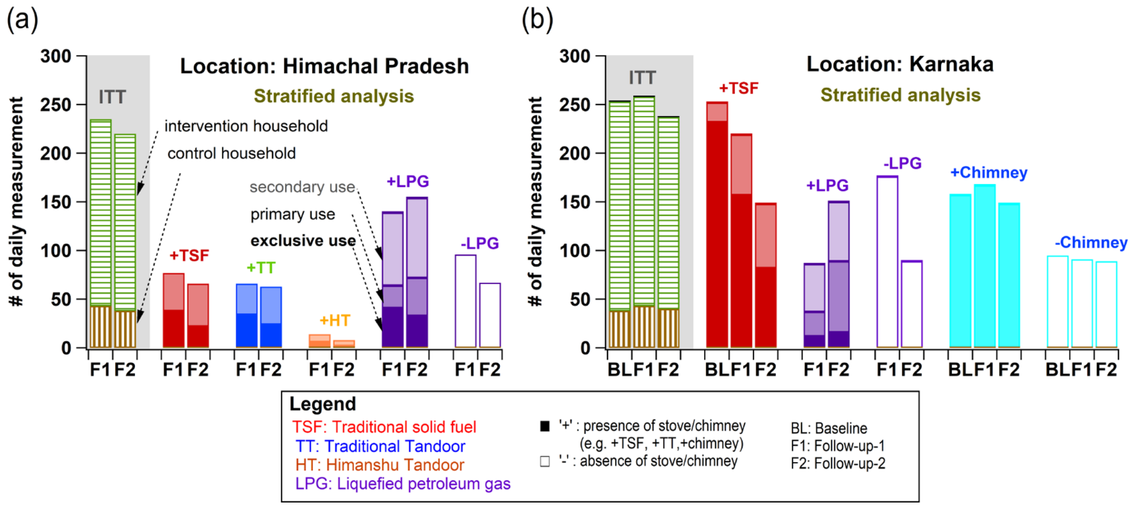

Figure 1. Categorization of study data in Himachal Pradesh (panel a) and Karnataka (panel b) based on treatments (ITT analysis of control vs intervention) and stratified by stove types, stove use types (exclusive, primary, secondary), and presence of built-in chimneys. Colors and acronyms used in this figure to represent different stove types have been used consistently throughout the manuscript. For example, red, blue, orange, and purple colors are used for TSF, TT, HT, and LPG stoves, respectively, throughout the manuscript. Stove use is represented by the same color as the stove type but with varying transparency: darker to lighter for exclusive to primary to secondary use. Secondary stove use is only shown for LPG as we used this classification for LPG only. "+chimney" and "−chimney" notation represent kitchens with and without a built-in chimney, respectively. Similarly, "+LPG" and "−LPG" indicate kitchen with and without LPG, respectively. BL, F1, and F2 on category axes represent measurements during baseline, follow-up-1, and follow-up-2 periods, respectively.

Table 1. Baseline Household Characteristics in Two Study Locations

	Karnataka				Himachal Pradesh			
characteristics	control	intervention	*p*-value[a]	total	control	intervention	*p*-value[a]	total
own land	95%	91%	0.32	92%	100%	99%	0.08	99%
grid access	100.0%	100.0%	NA	100.0%	92.9%	98.0%	0.22	97.1%
main fuel at baseline								
dung cakes	0.0%	0.0%	0.44	0.0%	0.0%	1.0%	0.46	0.8%
wood	100%	99%		99%	95%	90%		91%
kerosene	0.0%	0.5%		0.4%	0.0%	0.0%		0.0%
LPG	0.0%	1.0%		0.8%	4.8%	9.4%		8.6%
had LPG at baseline	0.0%	1.0%	0.25	0.8%	66.7%	57.1%		58.8%
caste								
SC and ST	50%	45%	0.65	46%	41%	39%	0.88	39%
OBC	50%	55%		54%	2%	3%		3%
other_caste	0%	1%		0%	57%	58%		58%
household size	6.2	5.9	0.47	6	4.9	5.1	0.49	5
land ownership (ha)	1.8	1.7	0.76	1.8	0.4	0.4	0.97	0.4
asset index	0.2	−0.04	0.21	0	−0.05	0.01	0.7	0

[a] Scalar variables use a *t*-test assuming unequal variances, whereas nominal variables use a Wilcoxon rank sum test.

households, regardless of the stoves present/used on a particular day. Interpreting ITT results was complicated because intervention households in Karnataka and Himachal Pradesh often retained pre-existing traditional stoves, and there was a high baseline prevalence of LPG stoves (56%) in Himachal Pradesh households.[33] In addition, a portion (~45%) of control households in Karnataka received LPG stoves from a government-led program (PMUY) that started during our study. Measurement period survey responses indicate nearly universal mixed stove use/stove stacking.[29] Therefore, in this paper we mainly assessed intervention effectiveness based on reported stove use by households, regardless of intervention status. Although chimney installation in the kitchen was not a part of our intervention, we explored the effect on IAQ of the built-in chimneys present in some Karnataka kitchens. Thus, our overall analysis assessing intervention effectiveness was classified into two broad categories: (a) "as a whole" (ITT) analysis and (b) stratified analysis (based on alternative stove use and presence of chimney). For ITT analysis, we divided the $PM_{2.5}$ concentration measurements into control and intervention groups, whereas for stratified analyses, grouping was based on stove use and presence of chimney, as shown in Figure 1. ITT analysis comprises groupwise and household-level paired (difference-in-difference) comparison in $PM_{2.5}$ concentrations. For paired analysis, we evaluated intervention effectiveness by calculating the difference in $PM_{2.5}$ concentrations ($\Delta PM_{2.5}$) between each follow-up and baseline in each household. In most cases, group mean $PM_{2.5}$ and eBC concentrations were higher than corresponding medians, indicating non-normal distributions of $PM_{2.5}$ and eBC. Hence, we apply the non-parametric Wilcoxon rank sum test to assess the statistical significance (*p*

< 0.05) in differences between groups. To explore the differences between stove/ventilation/usage groups in stratified analysis, and to control for the influence of village on observed differences, we constructed linear mixed-effect models employing natural log-transformed $PM_{2.5}$ as the dependent variable (more details are given in Supporting Information, Section S5). Finally, note that our analysis is based on household-reported (1 day recall) stove use information, which has proved useful in measuring technology adoption,[39] but future studies can be further enhanced using sensors as objective measures.

3.0. RESULTS AND DISCUSSION

3.1. Household Characteristics and Randomization of Treatments. Table 1 describes baseline household characteristics of control and intervention groups in the two study locations using parameters describing land ownership, electricity access, fuel types used for cooking, family size, and household assets. In general, no significant differences were observed in household characteristics between the control and intervention groups at the study locations, suggesting that the randomization of treatments was successful. In Karnataka, 99% of households used wood as their primary fuel at baseline; the rest (1%) used kerosene or LPG. Likewise, most households (91%) in Himachal Pradesh used wood as their primary fuel. However, the fraction of households using LPG as their primary fuel was higher in Himachal Pradesh (8.6%) than in Karnataka (0.8%). Furthermore, Himachal Pradesh had much higher LPG stove ownership (~60% of households) at baseline than in Karnataka (0.8%). Household size was similar for both locations. Percent of households owning land was slightly higher in Himachal Pradesh (99%) relative to Karnataka (92%), and vice versa for grid/electricity access. Finally, the average asset index, a proxy indicator of household economic status,[40] differed slightly between treatment and control households in each location, but the differences were not significant.

3.2. Kitchen Air Quality in Study Areas. Figure S4a shows distributions of kitchen $PM_{2.5}$ concentration in each measurement period in all control and intervention households in Himachal Pradesh and Karnataka. Kitchen $PM_{2.5}$ concentrations varied widely in both control and intervention households in all measurement periods. Average daily indoor $PM_{2.5}$ levels (in different measurement periods) were from 8.5 to 12 times higher than the World Health Organization (WHO) annual interim target-1 (IT-1) for indoor $PM_{2.5}$ of 35 $\mu g\ m^{-3}$.[41] Even 25th percentile values surpassed the WHO target, indicating the severity of indoor air pollution levels in study households. Kitchen $PM_{2.5}$ concentration distributions in control groups differed between the study locations. In general, $PM_{2.5}$ was higher in Karnataka versus Himachal Pradesh control households, except during follow-up-2. For example, mean 24 h $PM_{2.5}$ concentration in control households in Karnataka (over baseline and follow-up-1) was 520 $\mu g\ m^{-3}$, 37% higher than the average in Himachal Pradesh control households. However, mean $PM_{2.5}$ during follow-up-2 for the Karnataka control group was lower than that for control groups in other measurement periods in Karnataka and Himachal Pradesh, an observation discussed further in Section 3.3.

3.3. Intervention Effectiveness: Intent-to-Treat Analysis. Our first ITT analysis (in Karnataka only, due to the lack of baseline data in Himachal Pradesh) was a household-level paired (difference-in-difference) analysis to control for inter-household variability. Figure S4b shows the distributions of $\Delta PM_{2.5}$ in Karnataka control and intervention households. The decrease in kitchen $PM_{2.5}$ concentrations was significantly greater (42% difference in mean $\Delta PM_{2.5}$) in intervention households than in control households in follow-up-1 only, not in follow-up-2, indicating inconsistent effectiveness of the intervention. Interestingly, $\Delta PM_{2.5}$ distributions in intervention households in follow-up-1 and follow-up-2 were similar, but $\Delta PM_{2.5}$ distribution in control households was significantly lower (192% in mean) in follow-up-2 than in follow-up-1 (Figure S4b). This is likely because ~45% of Karnataka control households had received LPG stoves via the PMUY program before follow-up-2 (vs 0% at baseline). We observed a 38% lower average $PM_{2.5}$ concentration ($p = 0.08$) in the "control + LPG" group than the "control-noLPG" group (Figure S5a). This suggests that LPG use in control households was likely a factor driving the similarity in the $PM_{2.5}$ concentration between control and intervention households during follow-up-2. However, a household-level paired comparison to test this hypothesis for a subset of control households was inconclusive (Figure S5b).

The next ITT analysis for Karnataka compares group (control and intervention) $PM_{2.5}$ concentrations, as shown in Figure S4a. In follow-up-1, average 24 h kitchen $PM_{2.5}$ concentration in intervention households was 45% lower than that in control households ($p < 0.05$). However, we did not observe a significant difference in follow-up-2 (Figure S4a), consistent with paired analysis (Figure S4b). Likewise, mean eBC concentrations for intervention households were 33% lower ($p < 0.05$) than that in the control group in follow-up-1 but not in follow-up-2 (Figure S6a). We did not see a significant difference in eBC/$PM_{2.5}$ distributions between control and intervention groups in any follow-ups (Figure S6b), indicating no trend in the relative abundance of eBC among the groups.

In Himachal Pradesh, the absence of baseline kitchen $PM_{2.5}$ data prevents a household-level paired analysis, but we performed groupwise comparisons during follow-ups (Figure S4a). Mean $PM_{2.5}$ was 18% lower ($p < 0.05$) in intervention versus control households in follow-up-2 but not significantly different in follow-up-1 (Figure S4a). Thus, we observed inconsistent intervention effectiveness in Himachal Pradesh, as in Karnataka. However, differences arise if we disaggregate households by TSF stove use during the measurement period. Note that we explore the effect of disaggregating groups by stove use further below (Section 3.4), and here, we briefly discuss it in the context of the ITT results. During follow-up-1, 13% of intervention households used the TSF stove exclusively. The mean SI PM and time in those households were 118 and 56% higher than exclusive TSF households in the control group, respectively (Figure S7). The intervention households' use of TSF rather than alternative stoves clearly affects the overall group distribution. In follow-up-2, only 7% of intervention households used TSF exclusively. Although we observed longer SI time ($p = 0.09$) in exclusive TSF users in the intervention versus control group households, SI PM distributions were not significantly different (Figure S7). Hence, unlike in follow-up-1, use of TSF stoves in intervention households did not seem to drive the overall group PM distribution in follow-up-2. Note that the difference in baseline prevalence of LPG (as the main fuel) between control and intervention groups in Himachal Pradesh may affect the ITT result. However, due to the lack of baseline measurements, we

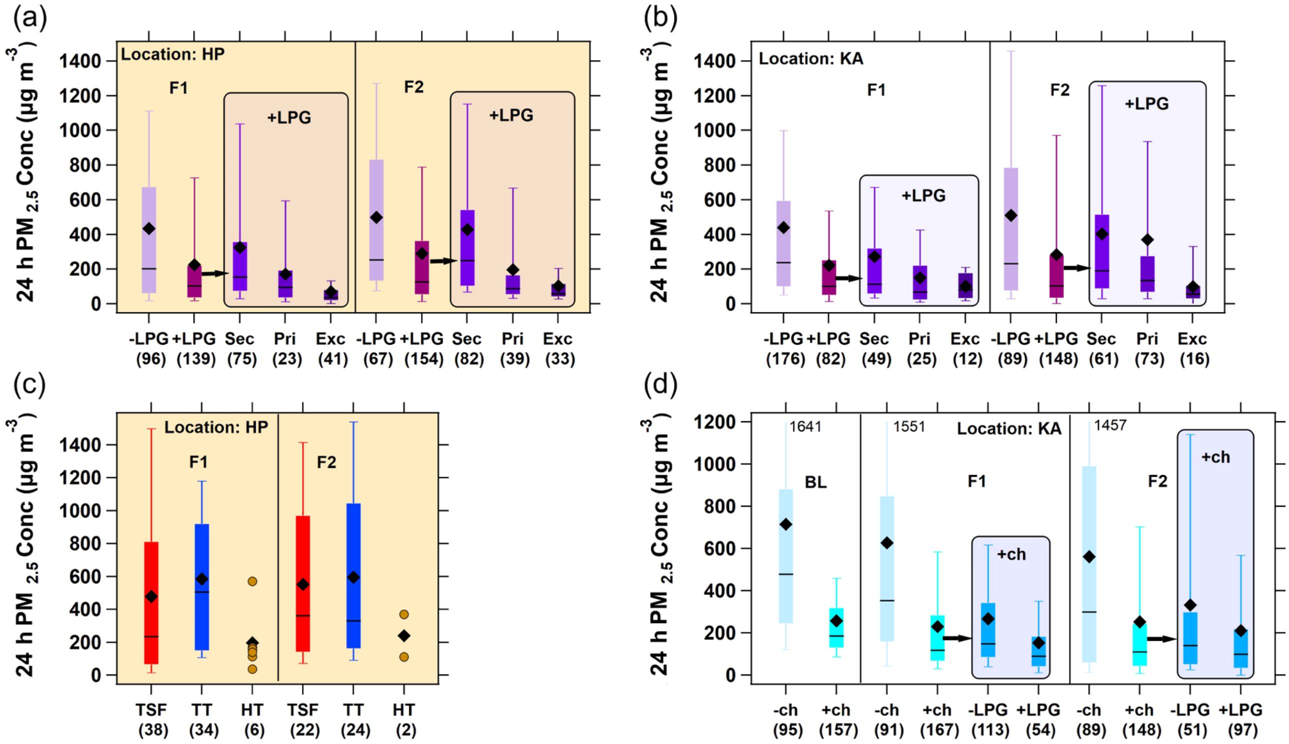

Figure 2. Box and whisker plots of 24 h kitchen $PM_{2.5}$ concentrations (a) stratified by households with and without a LPG stove ("+LPG" and "−LPG," respectively, on the *x*-axis) in Himachal Pradesh (HP); "+LPG" households are further classified into "Sec," "Pri," and "Exc" (secondary, primary, and exclusive use of LPG, respectively) based on household-reported use information; (b) as in (a) but for Karnataka (KA); (c) stratified by exclusive TSF, TT, and HT use in Himachal Pradesh; (d) stratified by the presence of the built-in chimney in Karnataka kitchens. "+ch" and "−ch" represent households with and without chimneys, respectively. The "+ch" group is further categorized into "+LPG" and "−LPG" for chimney households with and without LPG, respectively. Note that "+LPG" here (panel d) indicates LPG ownership, not LPG use. The beige-shaded portion in each panel indicates measurements in Himachal Pradesh throughout the paper. BL, F1, and F2 represent measurements during baseline, follow-up-1, and follow-up-2 period, respectively, and the number in the category axis shows the number of measurement days for each category. The boxes in this paper represent the interquartile range; horizontal line and diamond inside the box indicate median and mean, respectively. The top and bottom whiskers are 90th and 10th percentile, respectively. The upper whiskers for some categories are out of scale on the *y*-axis and, hence, are shown with numbers. We show points (circles) instead of box and whiskers for any groups with less than 10 tests. Red, blue, orange, and purple colors are used for TSF, TT, HT, and LPG stoves, respectively, as in other figures of the manuscript. Stove use is represented by the same color as the stove type but with varying transparency: darker to lighter for exclusive to primary to secondary use.

were not able to directly explore this effect in the ITT framework.

Like $PM_{2.5}$, eBC in Himachal Pradesh intervention households was significantly lower than that in control households in follow-up-2 but not in follow-up-1 (Figure S6a). For example, intervention group mean eBC concentration was 17% lower ($p < 0.05$) than that for the control group in follow-up-2. Mean eBC/$PM_{2.5}$ were also significantly lower (22%) in intervention households than that in control households in follow-up-2 in Himachal Pradesh, unlike Karnataka where eBC fractions showed no trend across control and intervention groups during any measurement period (Figure S6b).

3.4. Intervention Effectiveness: Stratified Analysis. We also assessed the effectiveness for PM reductions of individual elements of the intervention based on their use during the intervention trial; first, we discuss the influence of LPG stoves. Figure 2a,b shows the impact of LPG stoves on kitchen $PM_{2.5}$ in Himachal Pradesh and Karnataka households. Mean 24 h $PM_{2.5}$ was 40−50% lower in households with LPG relative to those without. When we further subdivide households with LPG into exclusive, primary, and secondary LPG users based on survey responses about their cooking activity on the day of measurement, we observe that average $PM_{2.5}$ decreases with the increased intensity of LPG use (Figure 2a,b). In Himachal Pradesh during follow-up-1, $PM_{2.5}$ in exclusive, primary, and secondary LPG users was 84, 78, and 59% lower than that in households without LPG, respectively (Figure 2a). The trend is similar for follow-up-2 in Himachal Pradesh and both follow-ups in Karnataka (Figure 2a,b). In general, secondary LPG users did not show a significant reduction in indoor $PM_{2.5}$ compared to non-LPG users in Himachal Pradesh and Karnataka (except follow-up-1 in Karnataka). A household-level paired (difference-in-difference) analysis—performed by calculating the difference in $PM_{2.5}$ concentrations ($\Delta PM_{2.5}$) between each follow-up and baseline in LPG-owning households in Karnataka—also indicates smaller IAQ benefit associated with secondary relative to exclusive LPG use (Figure S8). Overall, our results confirm that having but not routinely using LPG provides minimal IAQ benefit.

Consistent with $PM_{2.5}$ observations, we also observed reductions in eBC in LPG households (Figure S9a,c). For example, mean eBC for households with LPG in Himachal Pradesh and Karnataka were 28−48% lower than those for households without. Exclusive LPG users also showed a significant reduction in eBC relative to primary and secondary use groups in all follow-ups except for follow-up-1 in Karnataka. Mean eBC concentrations for exclusive LPG users

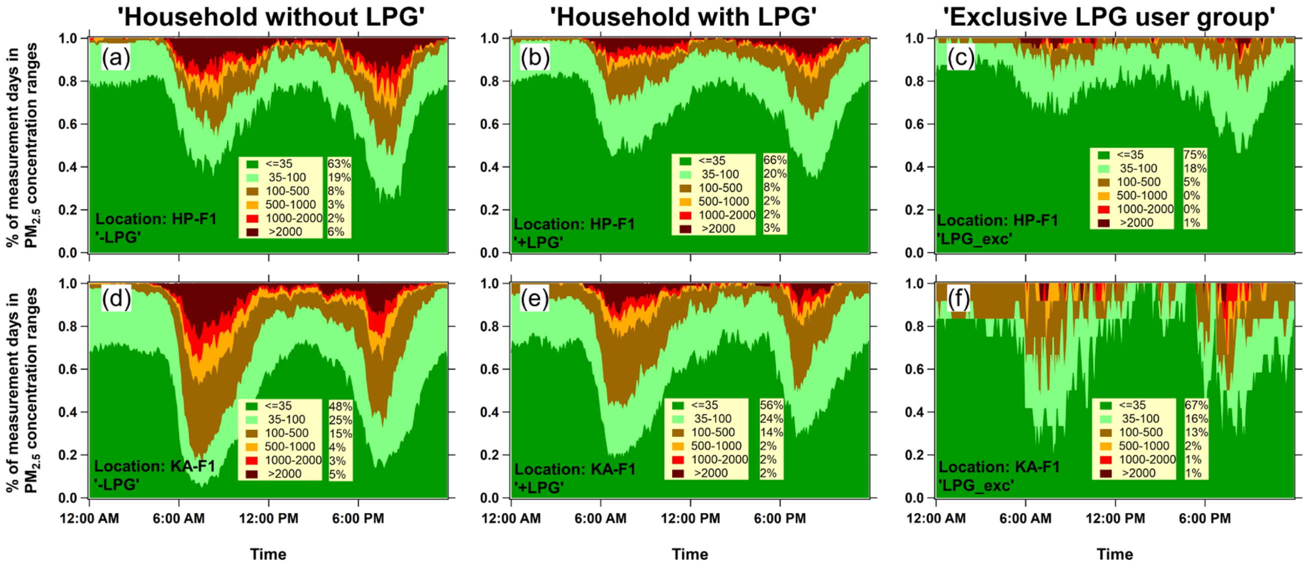

Figure 3. Diurnal histograms of indoor $PM_{2.5}$ concentrations (5 min resolution) in study household kitchens during follow-up-1 (F1), categorized by reported use of LPG stoves. Subplots (a−c) are shown for households without LPG (−LPG), households with LPG (+LPG), and exclusive LPG users (LPG_exc) in Himachal Pradesh (HP), respectively; subplots (d−f) are shown for "−LPG," "+LPG," and "LPG_exc" groups in Karnataka (KA), respectively. The different colors indicate $PM_{2.5}$ concentration ranges, and percentages to the right of color legend indicate the fraction of total days within each $PM_{2.5}$ ranges.

were 5.1 and 4.5 μg m^{-3} in follow-up-1 and follow-up-2 in Himachal Pradesh, respectively, 45 and 38% lower than the corresponding measurements for primary LPG users. In general, distributions of eBC/$PM_{2.5}$ for households with and without LPG showed substantial overlap (Figure S9b,d). However, exclusive LPG users showed a significant reduction in eBC/$PM_{2.5}$ relative to secondary and primary LPG users in some measurement periods. For example, mean eBC/$PM_{2.5}$ for exclusive LPG users was significantly lower than those for primary LPG users in follow-up-1 in Himachal Pradesh and follow-up-2 in Karnataka (45 and 32%, respectively).

Figure 2c shows the effect of the improved chimney stove (HT) and pre-existing traditional chimney stove (TT) on IAQ in Himachal Pradesh households. In follow-up-1, mean $PM_{2.5}$ was 66% lower ($p < 0.05$) in exclusive HT users versus exclusive TT users (Figure 2c). In follow-up-2, there were insufficient exclusive HT users ($N = 2$) to make any conclusion. Like $PM_{2.5}$, mean eBC for exclusive HT users was significantly lower (60%) than that for exclusive TT users in follow-up-1 (Figure S10a). eBC/$PM_{2.5}$ showed a substantial overlap between these two stove use groups (Figure S10b). Although kitchen $PM_{2.5}$ and eBC concentrations associated with the use of these two stove types were different, interestingly, $PM_{2.5}$ and BC emission factors (g kg fuel^{-1}) measured separately from these two stove types were not significantly different,[32] suggesting that stove emission performance was not the main factor influencing IAQ. The newly installed and higher-quality chimney pipes of the HT stoves possibly played an important role in the greater reduction in indoor PM than that for TTs, whose chimneys were often in poor condition, thus leading to higher fugitive emissions. Chimney condition was also found to be an important moderator of IAQ in Honduran communities where households with low-quality chimneys had ~6 times higher mean indoor 8 h average $PM_{2.5}$ concentration than those with high-quality chimneys.[42]

Figure 2c also compares kitchen $PM_{2.5}$ in households with chimney stoves (TT, HT) and non-chimney (TSF) stoves. Exclusive HT users in follow-up-1 had 59% lower mean 24 h $PM_{2.5}$ concentration than exclusive TSF user households. This is in contrast to comparisons between exclusive TT and exclusive TSF users. For example, in follow-up-1, mean $PM_{2.5}$ and eBC were 18 and 34% higher ($p < 0.05$) in exclusive TT compared to exclusive TSF user households (Figures 2c and S10a). Mean eBC/$PM_{2.5}$ for exclusive TT users was also 32% higher ($p < 0.05$) than that for exclusive TSF users in follow-up-1 (Figure S10b). In follow-up-2, mean $PM_{2.5}$, eBC, and eBC/$PM_{2.5}$ of exclusive TT users were also higher (8, 30, and 37%, respectively) than TSF users, although only distributions of eBC/$PM_{2.5}$ showed significant difference. Higher $PM_{2.5}$ and eBC concentrations in TT households is surprising since chimney stoves are believed to improve IAQ by ventilating emissions. Note that Himachal Pradesh households used chimney stoves not only for cooking but also for heating purposes in winter, and the mean SI time (see Section S4) for households with chimney stoves was 20−45% higher than for those with TSF (Figure S11). This longer stove use time is likely an important factor, driving higher $PM_{2.5}$ concentrations in exclusive TT households. In contrast, despite additional stove use time, HT use is associated with substantial improvements relative to TSF. This suggests that the poor condition and thus higher fugitive emissions from TT stoves may offset much of the potential benefit from the presence of the chimney, emphasizing the importance of stove condition and not only configuration.

Although chimney installation was not a part of the intervention in Karnataka, the effect of a chimney over the hearth in improving IAQ was evident in Karnataka households. Figures 2d and S12 show kitchen $PM_{2.5}$ and eBC concentration distributions in Karnataka households with and without a built-in chimney. Mean $PM_{2.5}$ concentration of households with a chimney was significantly lower than those without (Figure 2d). For example, mean $PM_{2.5}$ levels for households with

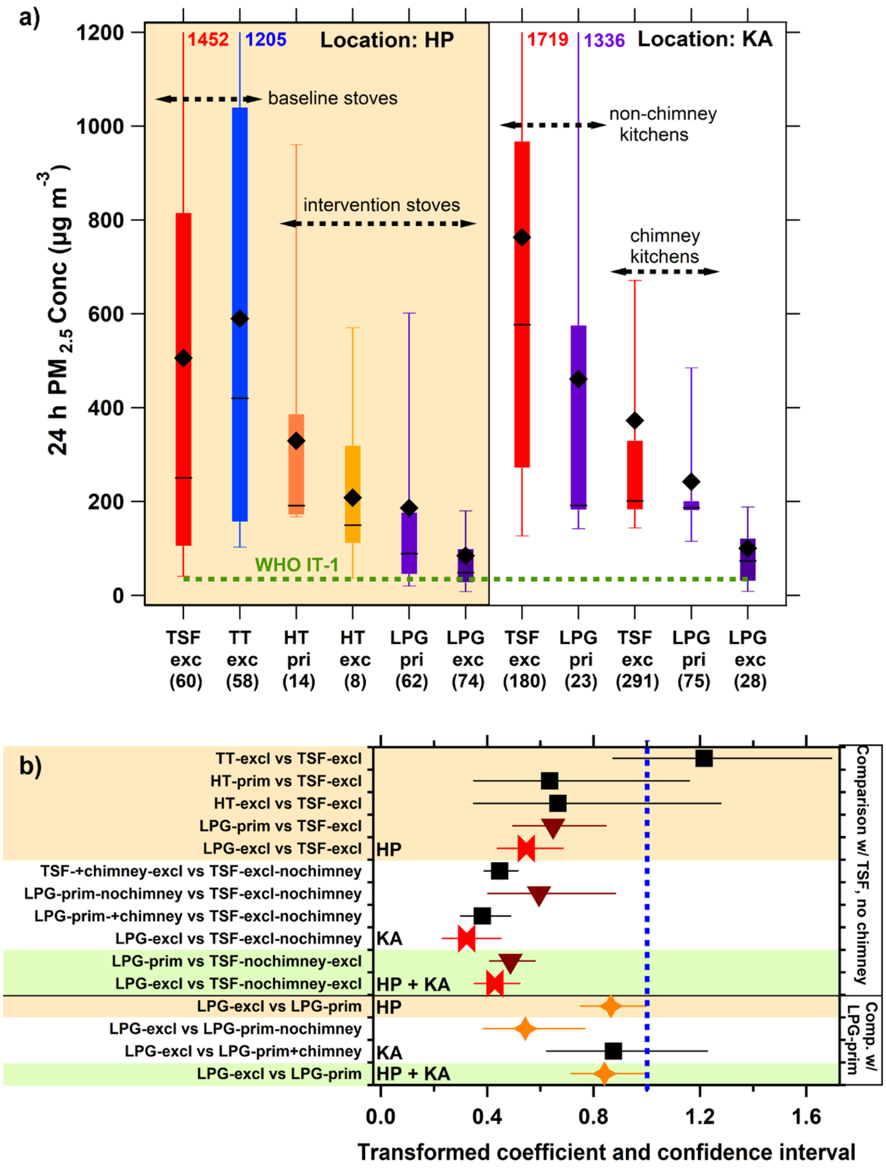

Figure 4. Plots exploring the influence of different cooking and ventilation combinations in Himachal Pradesh (HP) and Karnataka (KA), illustrating their relative effectiveness in improving IAQ. (a) Box and whisker plots of 24 h kitchen $PM_{2.5}$ concentrations. The number in the category axis indicates the total number (not stratified by measurement periods) of measurement days for each category in each location. "TSF exc," "TT exc," "HT exc," and "LPG exc" represent exclusive users of TSF, TT, HT, and LPG stoves, respectively, whereas "HT pri" and "LPG pri" indicate primary users of HT and LPG stoves, respectively. The boxes represent the interquartile range; horizontal line and diamond inside the box indicate median and mean, respectively. The top and bottom whiskers are 90th and 10th percentile, respectively. The upper whiskers for some categories are out of scale on the *y*-axis and, hence, are shown with numbers. Red, blue, orange, and purple colors are used to represent TSF, TT, HT, and LPG stoves, respectively, as shown in other figures of the manuscript. (b) Dot and whisker plots showing effect size from mixed modeling of selected pairs from panel (a), showing the exponent of the model coefficient and CI associated with a comparison between the indicated pair. Shading and labels indicate the location from which the sample is drawn (HP; KA; HP + KA). All models included a random effect to control for village within locations. Comparisons in the "KA + HP" segment are based on pooled samples of categories (TSF exc, LPG pri, and LPG exc) that are found in both locations; these models control for both location and village. Common symbols (other than the square) indicate common categories that are combined in the "HP + KA" models. The lowest four points show comparisons between exclusive and primary LPG usage, whereas the upper points are all comparisons with non-chimney TSF data.

chimney were 64, 63, and 55% lower than for those without chimneys in measurements during baseline, follow-up-1, and follow-up-2, respectively. Mean eBC levels for households with chimneys were also significantly lower (63, 49, and 43%, respectively, in baseline, follow-up-1, and follow-up-2) (Figure S12a). Figure 2d also shows further classification of households with chimneys into those with and without LPG. Chimney households with LPG had a greater reduction in indoor $PM_{2.5}$ relative to those without LPG (Figure 2d), demonstrating the increased benefit of having a built-in chimney and a LPG stove simultaneously. For example, mean $PM_{2.5}$ levels for chimney households with LPG were 42 and 37% lower than for those without LPG in follow-up-1 and follow-up-2, respectively. Note that "with LPG" here only indicates the presence of LPG in household, it does not necessarily indicate its use during testing. Also note that Karnataka households' built-in chimneys typically contained TSF stoves, rather than another stove type. Thus, results from chimney households with LPG do not represent the benefit of having a built-in chimney over the LPG stove in a kitchen.

3.5. Diurnal Kitchen PM Levels. We also explored the effect of intervention in changing diurnal trends in kitchen air quality. Here, we stratified real-time $PM_{2.5}$ concentrations into six concentration ranges: <35, 35−100, 100−500, 500−1000, 1000−2000, and >2000 $\mu g\ m^{-3}$.[5,43] We discuss these trends across households grouped by LPG use and presence of a chimney.

Figure 3a−c shows the fraction of measurement days during 5 min time windows within set ranges of $PM_{2.5}$ for households without LPG, households with LPG, and exclusive LPG households during follow-up-1 in Himachal Pradesh. Figure S13a−c displays the same but during follow-up-2. As expected, indoor $PM_{2.5}$ concentrations were highest during the morning (5:00 AM−11:00 AM) and evening (5:00 AM−10:00 AM) cooking events in a day. We saw traces of high $PM_{2.5}$ concentrations (>500 $\mu g\ m^{-3}$) between the cooking events for a small fraction of households, suggesting some intermediate cooking or other PM-emitting activities. Levels of indoor $PM_{2.5}$ during cooking events were higher for households without LPG than for those with LPG. Exclusive use of LPG was associated with the lowest indoor $PM_{2.5}$ during cooking periods. For example, households without LPG had $PM_{2.5}$ concentration >2000 $\mu g\ m^{-3}$ for 6% of the day (in follow-up-1 and follow-up-2 in Himachal Pradesh), two and six times higher than households with LPG and exclusive LPG households, respectively (Figures 3a−c and S13a−c). We also observed substantial differences in daily fraction with $PM_{2.5}$ > 100 $\mu g\ m^{-3}$ between households without LPG and with exclusive LPG use; however, households with and without LPG did not show a marked difference. For example, households without LPG, with LPG, and with exclusive LPG use had $PM_{2.5}$ > 100 $\mu g\ m^{-3}$ for 19, 15, and 6% of the day, respectively, in follow-up-1 (Figure 3a−c). This finding indicates that the difference in daily $PM_{2.5}$ concentrations (Figure 2a) between households with and without LPG was dominated by their diurnal differences in peak concentrations ($PM_{2.5}$ > 2000 $\mu g\ m^{-3}$), while exclusive LPG use helped reduce occurrence of all higher $PM_{2.5}$ ranges. Exclusive LPG use also influenced households' time with indoor $PM_{2.5}$ below 35 $\mu g\ m^{-3}$, the WHO IT-1. During follow-up-1, households with and without LPG remained below 35 $\mu g\ m^{-3}$ for a similar percent of time in a day. In contrast, exclusive LPG use households remained below the WHO threshold for 15−19% more time, emphasizing the importance of exclusive LPG use in achieving air quality targets. In follow-up-2 (Figure S13a−c), both households with LPG and with exclusive LPG use had higher percent of time with $PM_{2.5}$ < 35 $\mu g\ m^{-3}$ than those without LPG, with the fraction higher for exclusive LPG households.

Figures 3d−f and S13d−f show that Karnataka households also had a strong decreasing trend in the daily fraction with $PM_{2.5}$ > 2000 $\mu g\ m^{-3}$ from households without to those with LPG to those making exclusive use of it (5, 2, and 1%, respectively, in follow-up-1). Like in Himachal Pradesh, the difference in time with $PM_{2.5}$ > 100 $\mu g\ m^{-3}$ was prominent between households without LPG and those exclusively using LPG. However, the difference between them was less pronounced in follow-up-1 (27% vs 17%) than that in follow-up-2 (25% vs 8%), suggesting less beneficial effect of exclusive LPG use in reducing these high $PM_{2.5}$ concentrations in follow-up-1 relative to follow-up-2. Interestingly, in Karnataka, households without LPG had substantially less time with $PM_{2.5}$ < 35 $\mu g\ m^{-3}$ than those in Himachal Pradesh, suggesting higher "baseline" $PM_{2.5}$ levels in Karnataka households relative to Himachal Pradesh, which could be attributed to many factors including, but not limited to, higher community-scale emissions, transport of more air pollutants to the villages from nearby sources, and lower air exchange rates in Karnataka households. However, the fraction of time with $PM_{2.5}$ < 35 $\mu g\ m^{-3}$ was similar for households with LPG and with exclusive LPG use between Himachal Pradesh and Karnataka. This suggests that LPG use was associated with a larger incremental reduction in higher $PM_{2.5}$ concentration ranges in Karnataka than that in Himachal Pradesh households.

Figure 2d indicates that household chimneys in Karnataka had substantial impacts on measured daily $PM_{2.5}$. Figure S14 explores this effect using diurnal $PM_{2.5}$ profiles, showing that chimneys were especially effective at reducing peak concentrations. For example, the percent of the day with $PM_{2.5}$ > 2000 $\mu g\ m^{-3}$ was ∼3 times higher for households without versus with chimneys, suggesting that the reduction in peak $PM_{2.5}$ concentration (>2000 $\mu g\ m^{-3}$) dominates the decrease in daily average $PM_{2.5}$ concentration in chimney households (Figure 2d). We also observed somewhat lower presence of high $PM_{2.5}$ concentration levels (>500 $\mu g\ m^{-3}$) between cooking events—possibly associated with intermediate cooking or other PM-emitting activities—in households with chimneys versus those without chimneys (Figure S14), indicating the importance of chimneys in ventilating emissions from indoor PM sources throughout the day. Diurnal profiles of $PM_{2.5}$ in Karnataka (Figures 3d−f, S13d−f, and S14) also show that households with chimneys had a similar percent of the time with $PM_{2.5}$ > 2000 $\mu g\ m^{-3}$ to those having LPG. However, households with LPG were within the WHO's interim threshold for more time than those with chimneys. In both cases, households making exclusive use of LPG had the best IAQ.

3.6. Hierarchy of Effectiveness. The diurnal $PM_{2.5}$ plots show that levels of reduction, and thus relative effectiveness, of kitchen chimney and LPG use varied across different $PM_{2.5}$ ranges. Here, we assess relative daily kitchen $PM_{2.5}$ reductions from different options in Himachal Pradesh and Karnataka households. Figure 4a shows that households in our study fall into a clear hierarchy in terms of IAQ, depending on technology availability and use. We summarize the resulting (decreasing) hierarchy of daily kitchen $PM_{2.5}$ in Himachal Pradesh as follows: exclusive use of baseline cooking options (TSF, TT); primary use of an improved chimney stove (HT); exclusive use of the improved chimney stove; primary use of LPG; and exclusive use of LPG, as illustrated in Figure 4a (left side). We observe a similar hierarchy in Karnataka households (Figure 4a—right side), although the presence of built-in chimneys in some kitchens adds complexity. There, we observe improving air quality moving from exclusive use of baseline cooking options with no chimney; primary use of LPG and secondary use of TSF with no chimney; exclusive use of TSF with a chimney; primary use of LPG and secondary use of TSF with a chimney; and exclusive use of LPG. That average kitchen $PM_{2.5}$ for primary LPG with TSF households is lower in those with versus those without chimneys further demonstrates the impact of chimneys, even in households using LPG as a primary stove. Exclusive LPG use households without chimneys had the lowest average $PM_{2.5}$ (Figure 4a), emphasizing the significance of exclusive LPG use on IAQ.

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A more effective way to explore effect sizes is via mixed models that account for non-normality of data and for other potential confounding factors. Figure 4b displays effect sizes (and associated 95% confidence intervals, CIs) from mixed models constructed based on natural-log-transformed $PM_{2.5}$ to compare different groups while controlling for the village in which the measurement was conducted (see Supporting Information Section S5 for model descriptions). The "village" random effect was not significant for any of the models, indicating that the "pooled" effect sizes displayed in Figure 4a are appropriate. The resulting effect sizes are generally consistent with ranking discussed above, though provide more reasonable estimates of the expected impact (vs comparison of means, which are biased by extreme values). For example, in HP, primary or exclusive HT use and primary LPG use are both associated with ∼35% lower $PM_{2.5}$ relative to exclusive TSF use (one minus effect size), though the CIs for the HT models indicate that these effects are not significant, and there is no significant difference between exclusive and other usage of the HT in our data set, in contrast to direct comparison of group means. This and the extreme right skewness of the HT distributions (Figure 4a) suggest that though these stoves have the potential to reduce $PM_{2.5}$, their actual field performance was inconsistent. Exclusive LPG users in HP had the largest reduction relative to TSF users (45%; CI: 31−56%) and had a significant ($p < 0.05$) reduction relative to "primary" LPG users (15%; CI: 0−25%).

Model results for KA and HP are relatively consistent, though the presence of a household chimney is an important modifier for HP. For example, in exclusive TSF households, a chimney was associated with 55% (CI: 48−61%) lower $PM_{2.5}$, whereas primary use of LPG in a chimney household is associated with 62% (CI: 51−70%) lower $PM_{2.5}$ than a non-chimney TSF user. As expected, the largest difference (68%; CI: 55−77%) is from exclusive TSF in non-chimney households to exclusive LPG use. The move from primary to exclusive LPG was also associated with substantial reductions, though larger in KA than in HP. The mixed model construct also enables comparisons including both locations for overlapping categories (TSF and LPG stoves, comparing only non-chimney households in KA). The green-shaded sections of Figure 4b displays these comparisons and show that, relative to exclusive TSF users, primary and exclusive LPG use were associated with 51% (CI: 42−59%) and 57% (CI: 47−65%) lower $PM_{2.5}$, and a shift from primary to exclusive LPG use was associated with a 16% reduction (CI: 1−29%). These results reaffirm the importance of ventilation and exclusive LPG use.

3.7. Comparison with Other Field Measurements. The kitchen $PM_{2.5}$ concentrations and observed reductions due to intervention in this study were generally consistent with previous observations. For example, the exclusive LPG use households showed a more than 75% reduction in mean kitchen $PM_{2.5}$ relative to those without LPG in Himachal Pradesh and Karnataka, consistent with a reported 74−86% reduction in exclusive-LPG-use households relative to households with traditional stoves in Punjab and Telangana states.[44,45] Measurement period average daily $PM_{2.5}$ in exclusive LPG use households in Himachal Pradesh and Karnataka ranged from 70 to 103 $\mu g\ m^{-3}$, also in line with averages in Punjab (80 $\mu g\ m^{-3}$)[45] but higher than that in Telangana (30 $\mu g\ m^{-3}$).[44] Furthermore, the observed reduction in $PM_{2.5}$ (∼60%) for exclusive HT households relative to exclusive TSF use households was similar to other studies[46−48] where 44−71% reduction in $PM_{2.5}$ concentration was achieved in rural households in Honduras, China, and Peru via improved chimney stoves. Additionally, the improvement in IAQ associated with a built-in chimney in our Karnataka households (55−64% reduction in $PM_{2.5}$) was consistent with another study conducted in the Karnataka state (58% reduction).[24] Diurnal kitchen $PM_{2.5}$ profiles from TSF use from the same study[43] were also similar to that in our Karnataka location (Figure S14a,c,e) with extremely high $PM_{2.5}$ concentrations (>1000 $\mu g\ m^{-3}$) persisting (7−13%) during cooking events. Note that ambient $PM_{2.5}$ levels were not monitored in our study; however, we expect that the ambient pollution scenario was similar to that measured in the previous study[24] conducted in a nearby village in Karnataka, in which residential biomass burning was found to dominate village-scale PM concentrations. This is also likely true in Himachal Pradesh, although the use of stoves for heating and more complex topography will both have large impacts on the influence of nearby stove use on ambient concentrations.

4.0. IMPLICATIONS

For decades, cookstove intervention programs have promoted more efficient solid fuel stoves to households using traditional stoves. More recently, cleaner fuels like LPG, biogas, and natural gas have gained favor[49,50] because many alternate biomass stoves have not delivered sufficient reductions in emissions and subsequent adverse health and climate impacts.[24,51,52] A modeling study[53] showed that WHO IT-1 of $PM_{2.5}$ (35 $\mu g\ m^{-3}$) can only be achieved by near-total displacement (∼95%) of TSF stoves by IWA tier-4 stoves.[54] However, multiple lines of evidence from the field[20,29,55−57] suggest that access to clean cooking options does not guarantee consistent and exclusive use of those options, and a full transition away from pre-existing cooking approaches is elusive, leading to stove "stacking." Our multiyear multilocation RCT study also observed stove stacking.[33] Recognizing the prevalence of stove stacking, those implementing interventions are now striving for "cleaner stacking" options.[29]

Our field measurements, by including a range of alternative stoves and household types, reveal a hierarchy of effectiveness of efforts deployed or observed in this study (Figure 4) and present a real-world picture of "cleaner stacking." This data set provides evidence of successive improvements in IAQ, leading toward WHO IT-1, from different stove technologies, extents of use (e.g., exclusive, primary, and secondary), and emission venting approaches. Baseline cooking technologies (TSF and TT) were associated with the worst kitchen air quality, which improved with the use of alternative biomass and LPG stoves. The scenario with the least indoor PM pollution was the exclusive use of LPG stoves; 34% of samples of this group had daily $PM_{2.5}$ below 35 $\mu g\ m^{-3}$ (WHO IT-1). The substantially higher IAQ benefit of alternative cookstoves' exclusive use relative to mixed stove use demonstrates the importance of ensuring complete adoption of alternative cooking technologies rather than just disseminating them. In all scenarios, the presence of kitchen chimneys showed a high reduction (∼40−60%) potential for indoor $PM_{2.5}$, highlighting that kitchen ventilation characteristics are an important driver, along with cleaner cooking technologies, of IAQ. Our results provide real-world demonstration that household ventilation and the introduction of household chimneys deserve more attention, especially as the evidence is clear that even the availability of modern fuels does not guarantee the disadoption of traditional cooking methods.[58,59] They also show that use of an older/degraded chimney stove may provide limited or no benefit over an open fire, so that both presence and quality/condition of stove chimneys are critical and that household chimneys (as in Karnataka) may provide more robust benefits. Subsequent publications exploring our extensive data set will discuss the seasonal, diurnal, and inter-location variability in IAQ, identify determinants of this variability, and use it to evaluate the performance of an existing WHO IAQ modeling framework and explore factors influencing the model performance.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c07571.

> Information on study sites, indoor $PM_{2.5}$ concentration measurement using MicroPEM, eBC concentration measurement, SI analysis, mixed effect modeling comparing groups, ITT analysis, eBC data, microPEMS quality assurance, SI time/concentration, and diurnal distribution plots of PM concentration for additional groups (PDF)

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Notes

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