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RESEARCH

Effects of an intervention for a liquefied petroleum gas cook-stove with free fuel on food insecurity and dietary diversity among women and infants: a multi-country randomized controlled trial

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Abstract
Food insecurity and energy insecurity are critical global health issues, with implications for dietary diversity and infant feeding practices. This study evaluated the effects of an intervention for a liquefied petroleum gas (LPG) cook-stove and for free fuel on food security and dietary diversity among women and infants in four diverse settings. The Household Air Pollution Intervention Network (HAPIN) study is a randomized controlled trial that enrolled 800 pregnant women each in Guatemala, Peru, India, and Rwanda. Participants (N=3195) were randomly assigned to intervention or control groups, with intervention households receiving an LPG cook-stove and free fuel for 18 months. We measured household food insecurity using the Food Insecurity Experience Scale and dietary diversity for women and infants using the Minimum Dietary Diversity – Women and WHO infant and young child feeding questionnaires, respectively. We conducted an intention-to-treat analysis to evaluate the effect of the intervention on each outcome. At baseline, 27.4% of households were mildly food insecure, 15.6% were moderately or severely food insecure, and 26.8% of women achieved minimum dietary diversity. At end-line, the intervention significantly reduced moderate or severe food insecurity (RR: 0.75, 95% CI: 0.58–0.97) and improved dietary diversity among our analytic sample of 2868 women (RR: 1.16, 95% CI: 1.01–1.33) and 2836 infants aged 12 months (RR: 1.07, 95% CI: 1.002–1.15). Our findings suggest that interventions that increase energy security can be nutrition-sensitive and contribute to improved food and nutrition security.

Keywords Clean cooking · Energy insecurity · Fuel insecurity · Nutrition-sensitive · Maternal nutrition · Infant nutrition

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1 Introduction

Food security, defined by the United Nations as a condition that exists when "… people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life," remains an grave public health issue globally (Food & Agriculture Organization, 2002). The United Nations Sustainable Development Goal (SDG) 2 is "zero hunger", and one of the indicators to measure progress towards this goal is the "prevalence of moderate or severe food insecurity in the population"(UN General Assembly, 2015). As tracked by the Food and Agriculture Organization (FAO), the global prevalence of moderate or severe food insecurity was approximately 29% in 2023, representing 2.3 billion people (Food & Agriculture Organization, 2023). As a result, the current status of this SDG indicator was categorized as "far from the target" (Food & Agriculture Organization, 2023).

An important determinant of food insecurity is energy poverty, or energy insecurity, defined as "the lack of access to adequate, affordable, reliable, acceptable, and clean sources of energy for a healthy and sustainable livelihood" (Boateng, 2021; Boateng et al., 2020). Specifically, food security has long been recognized to be predicated on energy security for cooking (Bogdanski, 2012; Makungwa et al., 2013). The World Food Programme (WFP) states that "access to energy for cooking plays a critical role in WFP's mandate to achieve zero hunger" (Bisaga et al., 2022). Indeed, SDG 7 is to "ensure access to affordable, reliable and modern energy for all by 2030"(UN General Assembly, 2015). The SDG 7 indicators include a focus on clean fuels, defined by the World Health Organization (WHO) as "those that attain the fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) levels recommended in the WHO global air quality guidelines," such as liquefied petroleum gas (LPG) (UN General Assembly, 2015; World Health Organization, 2022). However, as of 2022, about 2.1 billion people worldwide lacked access to modern energy and still relied on polluting fuels (which, based on WHO categorizations, include wood, charcoal, dung, or agricultural residue) and technologies for cooking (International Energy Agency (IEA) International Renewable Energy Agency (IRENA) United Nations Statistics Division (UNSD) World Bank & World Health Organization (2024)).

Linkages between cooking fuel insecurity and food security can be conceptualized as involving three main pathways, shown in Fig. 1, each of which may have varying relevance and importance across different contexts. The first pathway is through financial resources, in which households spend limited funds on fuel rather than on food (Brouwer et al., 1996; Sola et al., 2016), thereby leading individual household members to reduce the quality (including diversity) and/or quantity of their dietary intake or to choose cheaper options such as street foods or ultra-processed foods (Adekoya et al., 2023). In the second pathway, sourcing fuel requires household members (often women) to spend time that might otherwise be better spent on food purchasing, production, preparation, or processing (Brouwer et al., 1996; Sola et al., 2016). To save time, cooks may choose to cook fewer meals per day, prepare foods that require shorter cooking times, or they may undercook foods; this

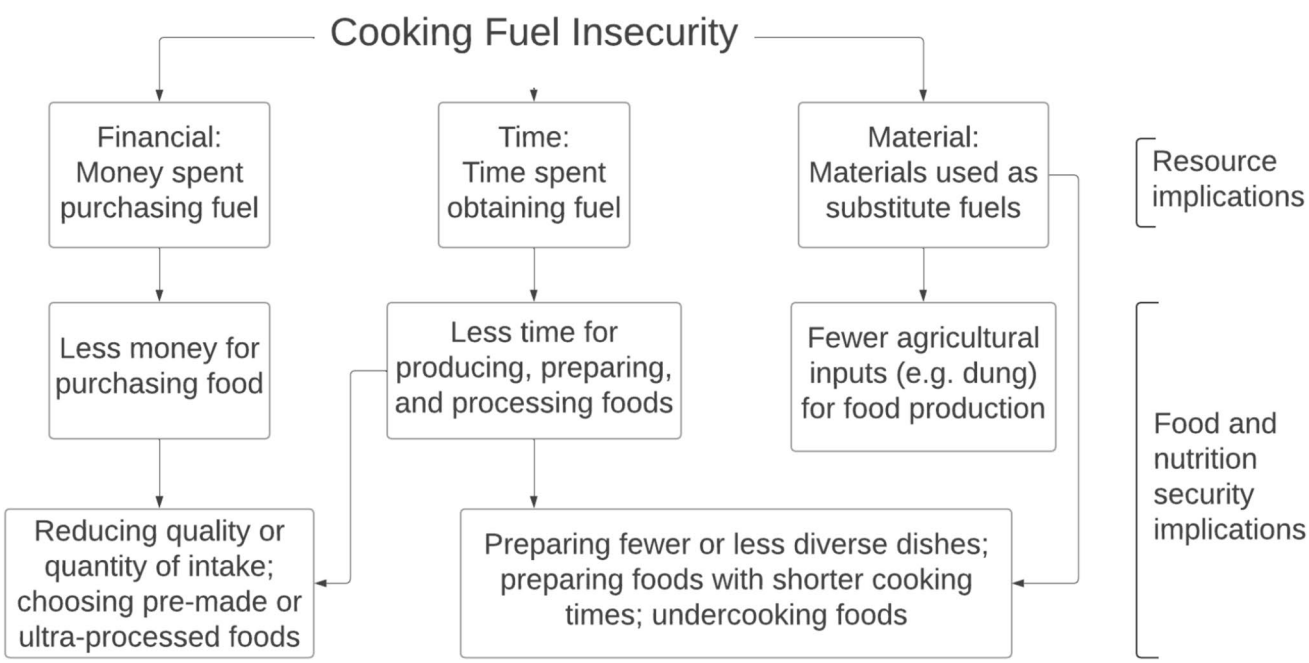

Fig. 1 Conceptual framework of linkages between cooking fuel insecurity and food insecurity

pathway may also lead to the consumption of pre-made or ultra-processed foods, due to their time-saving convenience (Adekoya et al., 2023; Sola et al., 2016; Waswa et al., 2020). In the third pathway, households may use materials such as crop residues or animal dung as fuels. These inferior fuel materials are thus lost to productive purposes (e.g., preparing compost, fertiliser) that could otherwise increase agricultural productivity and sustainability (Sola et al., 2016). This third pathway negatively impacts food security by reducing crop performances. These inferior fuels require higher cooking time and produce less heat than higher-quality fuels, so households may cope by cooking fewer meals, preparing fewer or less diverse dishes, choosing foods with shorter cooking times (e.g. avoiding foods like beans), or undercooking foods (Sola et al., 2016). Such altered practices could impact the quantity, quality, safety, and nutritional value of food consumed. While these pathways have been theorized, they have only rarely been studied empirically, and most studies have been qualitative rather than quantitative (Fadly et al., 2023).

The quantitative research that has focused on cooking fuel, food security, and dietary intake has been primarily cross-sectional. For example, access to clean energy for cooking was observed to be positively associated with food security at the macro (national) level in a study of 36 countries in sub-Saharan Africa (Pondie et al., 2023) and with household food security and household dietary diversity in an analysis of the nationally representative Living Standards Measurement Study data from Nigeria (Adekoya et al., 2023). Similarly, use of wood fuel (compared to other any other cooking fuels) was associated with lower household food security in an analysis of the Ghana Living Standards Survey (Adjei-Mantey et al., 2022) and use of biomass fuels was associated with consuming fewer meals per day across six states of India (Fadly et al., 2023). In another study in Ghana and Nigeria, the broader concept of household energy insecurity (measured through a scale that asked about energy sources for cooking, lighting, and other purposes) was associated with changes in the nature of foods being cooked, potentially resulting in dietary restrictions (Boateng et al., 2020). However, none of these studies included an intervention or a control group, and due to the cross-sectional nature of the data, each study reported only associations rather than causal relationships.

Among quasi-experimental and experimental studies, only two, to our knowledge, have examined relationships between cleaner cooking interventions and food and nutrition outcomes, both focusing on dietary diversity. The first, a matched-control study in Karnataka, India, found that household-level dietary diversity was higher in households that had received a biogas cook-stove in the previous seven years compared to control households (Anderman et al., 2015). In qualitative data from this study, participants reported that since biogas stoves did not require constant tending, cooks were free to add more food items and to cook a greater variety and quantity of dishes in each meal (Anderman et al., 2015). However, the one randomized control trial (RCT) that examined effects of a one-year free stove and LPG fuel intervention on dietary intake among adult women, set in rural Peru, observed no effect on individual dietary intake of food groups or macronutrients as measured through 24-h dietary recalls at either six or 12 months post-randomization (Tarazona-Meza et al., 2023). Therefore, the evidence remains unclear on the effect of cleaner cooking on both food security and dietary diversity.

To address this gap in evidence of the relationship between cleaner cooking, fuel security, and food and nutrition security, we analysed whether a cleaner cook-stove and free fuel intervention, implemented through the Household Air Pollution Intervention Network (HAPIN) trial, could influence food security and dietary diversity among women and infants. Our hypotheses were that the HAPIN intervention would lead to improved food security and dietary diversity among women and infants in an intervention group, compared to a control group.

2 Materials and methods

2.1 Study design and participants

We conducted an RCT of LPG cook-stoves and free fuel distribution compared to traditional biomass burning stoves. We enrolled pregnant women through antenatal clinics in ten geographic strata across four countries: one district in Jalapa, Guatemala; five blocks from two districts in Tamil Nadu, India; six provinces in Puno, Peru; and one district in Eastern Province, Rwanda. All trial settings were rural. The settings were purposively selected to represent diverse geographic regions (i.e., to increase generalizability of results) and based on logistic considerations and the potential to recruit eligible participants (Clasen et al., 2020). For example, based on data from Demographic and Health Surveys in the years immediately preceding the HAPIN trial, antenatal clinic attendance was high across the trial settings: the percentage of pregnant women receiving antenatal care for their last birth from a health professional was 94% in Jalapa, Guatemala; 92% in Tamil Nadu, India; 97% in Puno, Peru; and 99% in Eastern Province, Rwanda (Instituto Nacional de Estadística e Informática - INEI/Perú, 2015; International Institute for Population Sciences = IIPS/India & ICF, 2017; Ministerio de Salud Pública y Asistencia Social - MSPAS/Guatemala et al., 2017; National Institute of Statistics of Rwanda et al., 2016).

The target sample size for the HAPIN trial was 800 participants per country ($N = 3200$ in total), based on power calculations for the primary outcomes of the trial (Clasen et al., 2020). Inclusion criteria were being 18–34 years old and pregnant with a viable singleton foetus of 9 to < 20 weeks gestation confirmed by ultrasound. The focus on pregnant women was due to the strategic importance of pregnancy and infancy for long-term health outcomes. Given that the HAPIN trial aimed to reduce personal exposures to household air pollution, eligible pregnant women were excluded if they reported current tobacco smoking. Other exclusion criteria were living outside of the trial area (or planning to move permanently outside of the trial area within 12 months) or cooking primarily with a clean-fuel stove. Details of the study design and methodology, including participant recruitment, are described elsewhere (Barr et al., 2020; Checkley et al., 2024; Clasen et al., 2020, 2022; Johnson et al., 2020; McCollum et al., 2024).

2.2 Compliance with ethical standards

The study protocol was reviewed and approved by institutional review boards or ethics committees at Emory University (00089799), Johns Hopkins University (00007403), Sri Ramachandra Institute of Higher Education and Research (IEC-N1/16/JUL/54/49), the Indian Council of Medical Research – Health Ministry Screening Committee (5/8/4–30/(Env)/Indo-US/2016-NCD-I), Universidad del Valle de Guatemala (146–08–2016/11–2016), Guatemalan Ministry of Health National Ethics Committee (11–2016), A.B. PRISMA (CE3571·16), the London School of Hygiene and Tropical Medicine (11664), the Rwandan National Ethics Committee (No.357/RNEC/2018), and Washington University in St. Louis (201611159). Participants provided written informed consent. The trial was registered on clinicaltrials.gov (Identifier NCT029446282).

2.3 Randomization and masking

Participants were randomly assigned in a 1:1 ratio stratified by setting (ten geographic strata, as listed above) in permuted blocks of two and four to either receive the intervention or continue their traditional cooking practices with biomass fuels. We sought to randomly assign 1600 participants to the intervention group and 1600 to the control group. Only one pregnant woman per household was allowed to participate. The HAPIN Data Management Core generated randomization lists based on block randomization using randomly selected block sizes, then prepared individual sealed envelopes containing trial group allocation, which were shipped to each study site and selected by participants before opening to conceal allocation. Due to the nature of the intervention, it was not possible to mask participants or data collection teams to the group assignment. However, the study investigators were blinded to the collected data, and primary analyses were conducted on blinded data.

Participants in the control group received compensation, which varied by country, in an attempt to offset the economic benefit of the intervention and encourage their continued enrolment in the study (Quinn et al., 2019). These periodic compensation packages included small items such as baby supplies or cash or a cash-equivalent coupon during the trial (Quinn et al., 2019). At the end of the trial period, participants who remained enrolled in the control group received either an LPG stove and one month of fuel or a household item of equivalent value (Quinn et al., 2019).

2.4 Procedures and outcomes

We enrolled 800 women per country and individually randomized them to intervention or control groups, with intervention households receiving an LPG stove, continuous free fuel delivery on demand, training on stove use, and behavioural reinforcements as needed for 18 months (Williams et al., 2020). We placed temperature sensors near biomass stoves in intervention households to monitor stove use; if the sensors indicated use of biomass stoves, field teams visited households to encourage LPG stove use and answer questions (Williams et al., 2020). Women and their infants were followed through the first year of the infant's life. Primary outcomes of the trial were low birth weight, severe pneumonia, and stunting in infants, along with high blood pressure in non-pregnant adult women residing in the household (Clasen et al., 2020). Food security and dietary diversity at age 12 months are identified in the trial registration as other outcomes.

Data were collected at the household level by trained staff in the local language (Spanish in Guatemala and Peru, Tamil in India, and Kinyarwanda in Rwanda). Data on socio-demographic characteristics, medical history, and behavioural practices including cooking practices and dietary intake were collected from pregnant women at baseline (9–20 weeks' gestation) using structured survey modules that were programmed on tablets equipped with the Research Electronic Data Capture (REDCap) mobile application (Vanderbilt University, Nashville, USA; project-redcap.org) (Harris et al., 2009). Data were collected during household visits at two additional timepoints during pregnancy (24–28 weeks and 34–36 weeks gestation), within 24 h of birth, and when the infant was 3, 6, 9, and 12 months of age. Baseline data collection occurred between 02 May 2018 and 28 February 2020, while endline data collection occurred between 21 September 2019

and 14 September 2021. Details of data collection procedures are described elsewhere (Clasen et al., 2020; Jabbarzadeh et al., 2024). We observed excellent study retention throughout the trial period: of the 3200 women who were enrolled across the four sites, 2949 (92.2%) completed the full 12 months of post-partum follow-up (McCollum et al., 2024).

We measured household food insecurity at baseline and end-line (when the infant was 12 months of age) using the Food Insecurity Experience Scale (FIES), developed and validated by the FAO (Food & Agriculture Organization, 2017). The FIES module includes eight questions, each with yes/no response options, on the household's access to adequate food, and is intended to measure three domains of food insecurity: uncertainty/anxiety, food quantity, and food quality (Food & Agriculture Organization, 2017). Following FAO guidelines, we used a 30-day reference period for the FIES module (Food & Agriculture Organization, 2019).

We measured minimum dietary diversity for women at baseline and end-line using the Minimum Dietary Diversity – Women (MDD-W) questionnaire from the FAO and FHI 360, which allows for either a list-based or open recall format to collect data on foods and beverages consumed by the respondent (Food and Agriculture Organization & FHI 360, 2016). We used the list-based method, adapting the prompts to include lists of locally representative food items for each country. Responses were categorized into ten food groups: starchy staples; pulses (beans, peas and lentils); nuts and seeds; dairy; meat, poultry and fish; eggs; dark green leafy vegetables; other vitamin A-rich fruits and vegetables; other vegetables; and other fruit (Food and Agriculture Organization & FHI 360, 2016). While the MDD-W was designed to be asked for the previous 24 h, we modified the questions to ask how often the respondent consumed each food group during the previous 30 days, to align with the FIES for consistency of reporting. Response options were never, monthly, weekly, or daily.

We measured minimum dietary diversity for children at end-line using the WHO infant and young child feeding questionnaire (World Health Organization, 2010). The questionnaire uses a combination of open and closed recall and asks caregivers to report on foods and beverages consumed by the infant or young child during the previous day and night (24 h). Following updated guidelines from WHO and UNICEF, data were categorized into eight food groups: breast milk; grains, roots, tubers and plantains; pulses, nuts and seeds; dairy; meat, fish, poultry, and organ meats; eggs; vitamin-A rich fruits and vegetables; and other fruits and vegetables (World Health Organization and the United Nations Children's Fund (UNICEF), 2021).

2.5 Statistical analysis

Data were analysed according to a pre-specified plan developed prior to securing data access. Following FAO guidelines, we created an ordinal variable for food insecurity with values of 0, 1, or 2 representing food secure (FIES raw score = 0), mildly food insecure (FIES raw score = 1–3), and moderately or severely food insecure (FIES raw score = 4–8) (Food & Agriculture Organization, 2018). To classify minimum dietary diversity for women, participants who reported consuming a food group "daily" were assigned a value of 1. All others were assigned a value of 0. We first summed values across the ten food groups for a continuous diet diversity score ranging from 0 to 10. We then created a dichotomous variable for minimum dietary diversity using a cut-off of consumption of five or more out of ten food groups (Food and Agriculture Organization & FHI 360, 2016; Martin-Prevel et al., 2017). To classify minimum dietary diversity for infants, we created a dichotomous variable using a cut-off of consumption of five or more out of eight food groups (World Health Organization and the United Nations Children's Fund (UNICEF), 2021). We calculated descriptive statistics by treatment groups at both baseline and end-line.

The three outcome variables (household food insecurity, minimum dietary diversity – women, and minimum dietary diversity – infants) were examined in separate models to assess the intervention effect on each outcome based on the intention-to-treat (ITT) principle (i.e., analysis based on study group assignment regardless of adherence). For the ordinal outcome of food insecurity, we first used an ordered logistic regression model to calculate odds ratios. However, the Brant test of the proportional odds assumption resulted in a statistically significant result ($p < 0.001$), indicating that the assumption was violated (i.e., that the coefficients that describe the relationship between each pair of outcome groups cannot be assumed to be the same). Therefore, we instead implemented a generalized ordered logit model, using the gologit2 command of Stata (Williams, 2016). The generalized ordered logit model estimates the odds of an observation falling into a given category or above, compared to lower categories, and enables the estimation of effects that are asymmetrical and that may differ across categories of the ordinal variable (Williams, 2016). For the binary outcomes of minimum dietary diversity for women and children, given that both outcomes of interest were common in the population studied, we used a modified log-Poisson regression (i.e., a Poisson model with log link and robust standard errors) to derive risk ratios (RRs) (McNutt et al., 2003; Zou, 2004). We controlled for randomization (nested) strata in all models (i.e., trial sites within each

country). In models for food insecurity, we further adjusted for food insecurity at baseline due to imbalance in baseline food security levels between groups.

We performed subgroup analyses by country to assess differential intervention effects. We also conducted two additional post-hoc analyses, which were not included in our pre-specified analysis plan. First, we examined the effect of the intervention on continuous dietary diversity scores using linear regression. Second, to assess whether effects varied over time, we examined the effect of the intervention on the binary outcome of women's minimum dietary diversity at each timepoint when this outcome was measured, using the same methods described above. We controlled for randomization strata in all post-hoc analysis models.

Because our ITT analyses were adjusted for randomization strata, missing data were assumed missing completely at random within study sites, precluding the need for imputation. We estimated RRs and 95% CI to describe the precision of point estimates. A p-value of <0.05 was considered statistically significant and Stata 17.0 IC (Stata Corp LLC, College Station, TX) was used to analyse the data.

3 Results

Between May 7, 2018, and February 29, 2020, we randomly assigned 3200 pregnant women to the intervention or control groups. Five participants were found to be ineligible after randomization, and so were excluded. The remaining 3195 women comprised the HAPIN intervention ($n=1590$) and control ($n=1605$) groups. Baseline data indicated that participant socio-demographic characteristics such as age and highest level of completed schooling were similar in the intervention and control groups (Table 1). Mean dietary diversity score for women at baseline was 3.47 (3.49 intervention, 3.45 control) out of 10 (Table 1).

At baseline, a larger proportion of households in the intervention group (59.4%) reported no food insecurity compared to households in the control group (54.5%), whereas the proportion of women achieving minimum dietary diversity was similar between groups (27.0% intervention vs. 26.6% control) (Table 2).

At the trial end-line, when infants were about 12 months old (mean: 12.1 months), households of the intervention group were more food secure than households of the control group (70.3% households in the intervention group reporting no food insecurity vs. 65.3% in the control group; Table 2). The proportion of women achieving minimum dietary diversity was also higher among the intervention compared to the control group (23.5% intervention vs. 20.2% control), as was the proportion of infants achieving minimum dietary diversity (55.69% intervention vs. 52% control) (Table 2).

Table 1 Baseline socio-demographic characteristics of participants

Variables	Control	Intervention	Total
	$n=1605$ (% by class)	$n=1590$ (% by class)	$n=3195$ (% by class)
Age, number (%)			
<20 y	209 (13.02)	189 (11.89)	398 (12.46)
20-24y	579 (36.07)	616 (38.74)	1195 (37.40)
25-29y	517 (32.21)	500 (31.45)	1017 (31.83)
30-35y	300 (18.69)	285 (17.92)	585 (18.31)
Highest level of completed schooling, *n* (%)			
No formal education or primary school incomplete	558 (34.77)	481 (30.27)	1039 (32.53)
Primary school completed	533 (33.21)	558 (35.12)	1091 (34.16)
Secondary school completed	514 (32.02)	550 (34.61)	1064 (33.31)
Partners/husbands' education, n (%)			
No formal education or primary school incomplete	460 (28.66)	424 (26.70)	884 (27.69)
Primary school completed	514 (32.03)	488 (30.73)	1002 (31.38)
Secondary school completed	570 (35.51)	628 (39.55)	1198 (37.52)
Do not know	61 (3.80)	48 (3.02)	109 (3.41)
Mother lives with husband/partner, *n* (%)			
No	204 (12.71)	226 (14.21)	430 (13.46)
Yes	1401 (87.29)	1364 (85.79)	2765 (86.54)
Maternal main occupation ($n=3193$), *n* (%)			
Agriculture/farming	795 (49.56)	741 (46.63)	1536 (48.11)
Service/Commercial	131 (8.17)	137 (8.62)	268 (8.39)
Household	679 (42.33)	690 (43.42)	1369 (42.88)
Other	76 (4.74)	82 (5.16)	158 (4.95)
Primary type of cooking fuel, *n* (%)			
Cow dung	351 (21.95)	346 (21.77)	697 (21.86)
Wood	1164 (72.80)	1098 (69.10)	2262 (70.95)
Charcoal	72 (4.50)	125 (7.87)	197 (6.18)
Other biomass	12 (0.75)	20 (1.26)	32 (1.00)
Maternal dietary diversity score, mean ± SD	3.45 ± 1.58	3.49 ± 1.61	3.47 ± 1.59

Numbers in parentheses indicate the column-wise percent. Partners/husbands' education was assessed with the question, "What is the highest level of education that the father of the baby has achieved?". Maternal main occupation was assessed with the question, "In the past 6 months, what was your main occupation?" The dietary diversity score is derived from the Minimum Dietary Diversity for Women (MDD-W) questionnaire, which we adapted to cover a 30-day reference period

Table 2 Outcome variables (household food insecurity, women's minimum dietary diversity, and infant minimum dietary diversity*) at trial baseline and end-line

Outcome	*n*	Control *n* (%)	Intervention *n* (%)	Total *n* (%)
Baseline (9–20 weeks gestation)				
Household food insecurity				
Pooled – all country sites	3149			
Mild		448 (28.30)	416 (26.56)	864 (27.44)
Moderate/Severe		272 (17.18)	220 (14.05)	492 (15.62)
Guatemala	790			
Mild		129 (32.58)	126 (31.98)	255 (32.28)
Moderate/Severe		52 (13.13)	43 (10.91)	95 (12.03)
Peru	786			
Mild		146 (36.96)	128 (32.74)	274 (34.86)
Moderate/Severe		47 (11.90)	53 (13.55)	100 (12.72)
India	795			
Mild		60 (15.08)	54 (13.60)	114 (14.34)
Moderate/Severe		17 (4.27)	19 (4.79)	36 (4.53)
Rwanda	778			
Mild		113 (28.68)	108 (28.13)	221 (28.41)
Moderate/Severe		156 (39.59)	105 (27.34)	261 (33.55)
Achieved minimum dietary diversity – women				
Pooled – all country sites	3193	427 (26.62)	429 (27.00)	856 (26.81)
Guatemala	799	54 (13.50)	54 (13.53)	108 (13.52)
Peru	798	282 (70.15)	271 (68.43)	553 (69.30)
India	799	48 (12.03)	39 (9.75)	87 (10.89)
Rwanda	797	43 (10.67)	65 (16.50)	108 (13.55)
End-line (infant age 12 months)				
Household food insecurity				
Pooled – all country sites	2836			
Mild		320 (22.55)	301 (21.24)	621 (21.90)
Moderate/Severe		173 (12.19)	120 (8.47)	293 (10.33)
Guatemala	735			
Mild		46 (12.53)	52 (14.13)	98 (13.33)
Moderate/Severe		22 (5.99)	11 (2.99)	33 (4.49)
Peru	698			
Mild		111 (33.43)	96 (26.23)	207 (29.66)
Moderate/Severe		29 (8.73)	23 (6.28)	52 (7.45)
India	752			
Mild		41 (10.90)	52 (13.83)	93 (12.37)
Moderate/Severe		2 (0.53)	3 (0.80)	5 (0.66)
Rwanda	651			
Mild		122 (35.47)	101 (32.90)	223 (34.25)
Moderate/Severe		120 (34.88)	83 (27.04)	203 (31.18)
Achieved minimum dietary diversity – women				
Pooled – all country sites	2868	290 (20.24)	337 (23.48)	627 (21.86)
Guatemala	736	21 (5.71)	25 (6.79)	46 (6.25)
Peru	708	211 (62.61)	245 (66.04)	456 (64.41)
India	756	0 (0)	0 (0)	0 (0)
Rwanda	668	58 (16.52)	67 (21.14)	125 (18.71)
Achieved minimum dietary diversity – infants				
Pooled – all country sites	2836	745 (51.99)	807 (55.69)	1552 (53.85)
Guatemala	736	194 (53.01)	196 (52.97)	390 (52.99)
Peru	709	291 (86.35)	322 (86.56)	613 (86.46)
India	756	135 (35.81)	129 (34.04)	264 (34.92)
Rwanda	681	125 (35.41)	160 (48.78)	285 (41.85)

* Infant minimum dietary diversity does not exist at baseline, as baseline took place while mothers were pregnant

Household food insecurity is measured by the Food Insecurity Experience Scale (FIES), which was applied with a 30-day reference period. In the FIES, higher scores represent increasing food insecurity (Ballard et al., 2013). The dietary diversity score is derived from the Minimum Dietary Diversity for Women (MDD-W) questionnaire, which we adapted to cover a 30-day reference period. In the MDD-W, minimum dietary diversity is defined as consuming at least 5 of 10 food groups on the previous day (Bennitt et al., 2021)

Results of the adjusted generalized ordered logit model indicated that the HAPIN intervention did not influence mild food insecurity but had a more protective effect against moderate or severe food insecurity (relative risk [RR] of moderate or severe food insecurity: 0.75, 95% CI: 0.58–0.97; $p=0.026$) (Table 3). Furthermore, results of the modified log-Poisson regression models indicated that the HAPIN intervention had a positive effect on dietary diversity for both women and infants. We observed an improvement in women's minimum dietary diversity (RR: 1.16, 95% CI: 1.01–1.33; $p=0.040$). Similarly, infant minimum dietary diversity showed a modest increase (RR: 1.07, 95% CI: 1.002–1.15; $p=0.043$) (Table 3).

We conducted subgroup analyses by country to examine variations in the effect of intervention on the main outcomes of the study (Table 4). With respect to household food insecurity, Peru showed the strongest evidence for a reduction in mild food insecurity (RR: 0.66, 95% CI 0.47–0.92; $p=0.013$) based on ITT analysis, although the result for moderate to severe food insecurity was not statistically significant. Women's dietary diversity improved most notably in Rwanda (RR: 1.28, 95% CI 0.93–1.76; $p=0.128$), while child dietary diversity showed a significant positive effect only in Rwanda (RR: 1.38, 95% CI 1.15–1.65; $p<0.001$). Other countries showed non-significant results across outcomes.

Results of the post-hoc analyses are shown in the Supplemental Materials. As with binary dietary diversity, our analyses indicated that the HAPIN intervention had a positive effect on women's continuous dietary diversity scores. Trial-wide, dietary diversity scores among women in the intervention group were 0.136 food groups (95% CI: 0.025, 0.247; $p=0.016$) higher than in the control group (Table S1). However, in contrast to the results for binary infant dietary diversity, we observed no trial-wide effect of the intervention on infant continuous dietary diversity scores (β: 0.079, 95% CI: −0.033, 0.191; $p=0.165$) (Table S1). Our analysis of the effect of the intervention on women's minimum dietary diversity at each timepoint indicated that the HAPIN intervention had a positive effect on women's dietary diversity at two timepoints (in addition to the trial endpoint). We observed an improvement in women's minimum dietary diversity at the final pregnancy visit (34–36 weeks gestation) (RR: 1.13, 95% CI: 1.01, 1.29; $p=0.040$) and the early postpartum visit (3 months postpartum) (RR: 1.18, 95% CI: 1.02, 1.36; $p=0.030$) (Table S2).

4 Discussion

This very large randomized controlled trial conducted across four country contexts was designed to test the effects of an LPG stove and free fuel intervention on outcomes including food security. We examined food insecurity and dietary diversity among households who were assigned to receive the intervention for about 18 months compared to those who continued using primarily biomass fuel. As hypothesized, we observed that the HAPIN intervention had a protective effect on food insecurity and positive effect on dietary diversity among women and infants in the intervention group, compared to the control group. More specifically, we observed an asymmetrical impact of the intervention on food insecurity, in which the intervention had a stronger protective effect on moderate or severe food insecurity than on mild food insecurity. Women and infants in the intervention group also had a higher likelihood of achieving minimum dietary diversity, compared to controls, but these results were largely driven by the Rwanda sample. To our knowledge, this is the first randomized control trial to provide evidence of the potential for an intervention that reduces fuel insecurity to positively impact food security and dietary diversity.

The effect of the intervention on moderate or severe food insecurity, whereby households of women assigned to the intervention group had significantly lower risk of experiencing moderate or severe food insecurity than households assigned to the control group, could result from several causes. First, it is possible that the intervention freed-up resources such as time and money to be spent in ways

Table 3 Association between the outcome variables and the intervention

Outcome		*n*	*OR/RR (95% CI)	*P*-value
Household food insecurity (end-line)		2797		
	Food secure		Reference	
	Mild food insecurity		OR: 0.85 (0.72, 1.01)	0.063
	Moderate/severe food insecurity		OR: 0.75 (0.58, 0.97)	0.026
Minimum dietary diversity – women (end-line)		2868		
	No		Reference	
	Yes		RR: 1.16 (1.01, 1.33)	0.001
Minimum dietary diversity – infants (end-line)		2882		
	No		Reference	
	Yes		RR: 1.07 (1.002, 1.15)	0.043

*OR: odds ratio; RR: relative risk

All analyses adjusted for the randomization strata (site); the model for food security additionally controlled for food security at baseline

Table 4 Subgroup analyses by country of the outcome variables between the intervention group and control group

Country	*N*	RR (95% CI)	*p*-value
Household food insecurity			
Guatemala (reference: food secure)	726		
Mild food insecurity		0.90 (0.61, 1.32)	0.593
Moderate/severe food insecurity		0.50 (0.24, 1.06)	0.072
India (reference: food secure)	748		
Mild food insecurity		1.36 (0.87, 2.12)	0.183
Moderate/severe food insecurity		1.48 (0.25, 8.86)	0.669
Peru (reference: food secure)	689		
Mild food insecurity		0.66 (0.47, 0.92)	0.013
Moderate or severe food insecurity		0.71 (0.40, 1.26)	0.236
Rwanda (reference: food secure)	634		
Mild food insecurity		0.80 (0.56, 1.13)	0.202
Moderate or severe food insecurity		0.85 (0.60, 1.22)	0.382
Minimum dietary diversity – women			
Guatemala	736	1.19 (0.68, 2.09)	0.543
India*	-	-	-
Peru	708	1.05 (0.94, 1.18)	0.343
Rwanda	668	1.28 (0.93, 1.76)	0.128
Minimum dietary diversity – infants			
Guatemala	736	1.00 (0.87, 1.15)	0.993
India	756	0.95 (0.81, 1.10)	0.473
Peru	709	1.00 (0.95, 1.06)	0.934
Rwanda	681	1.38 (1.15, 1.65)	<0.001

* Not calculated – all women in India had inadequate dietary diversity (less than 5 food groups consumed in the previous 30 days) at end-line; RR: relative risk, adjusted for the randomization strata (the trial sites within each country)

that contributed to improved nutrition. For example, if the intervention led to cost savings (since households did not have to purchase fuel), it is possible that households allocated these financial resources to food purchases. Second, another intervention study has found that participants who received an improved cook-stove reported using the time and energy saved from cooking for economically productive tasks (Jagoe et al., 2020). It is possible that this could have been the case among HAPIN households and that the resulting income could have been allocated for food purchases. It is important to note that moderate/severe food insecurity declined in both intervention and control households trial-wide, which could be related to government food distributions and cash transfers that took place in all four study sites during the COVID lockdown period (Devereux, 2021; Díaz-Bonilla et al., 2021; Sinha, 2021; Vargas, 2021).

While we observed an overall significant positive impact of the intervention on women's self-reported dietary diversity, only 23% of women in the intervention group and 20% of women in the control group achieved minimum dietary diversity at the trial end-line, indicating that women's diets remain poor overall. Of note, Rwanda was also the only country where women's dietary diversity increased over time (from 14% at baseline to 19% at end-line, with increases observed in both study groups). Given that dietary diversity is widely recognized as an important indicator of micronutrient adequacy (Arimond et al., 2010; Verger et al., 2021), a large majority of women in our study were likely at risk of micronutrient malnutrition during the critical periods of pregnancy and lactation. Indeed, in India, all women in the sample had inadequate dietary diversity at end-line. Further, the proportion of women achieving minimum dietary diversity among both groups decreased significantly from baseline (27%) to end-line (22%). This was true despite an increase in self-reported food security. At end-line, 67.8% of respondents (70.3% intervention, 65.3% control) reported being food secure, suggesting that most households had sufficient access to food. However, the diversity of foods available to the household may have been limited, or intra-household allocation of food may have been inequitable; other studies have documented dietary restrictions for women both during pregnancy and in the early postpartum period, so women may be eating less diverse foods than other household members, particularly in India (Craig et al., 2018; Lunkenheimer et al., 2021; Raman et al., 2014; Wang et al., 2022).

In addition, while we observed a significant positive impact of the intervention on infant dietary diversity, this effect was driven entirely by the Rwanda sample; there was no impact on infant dietary diversity in any of the other three countries. Secular trends in Rwanda include a dramatic decrease in moderate stunting among children under five between 2010 and 2020, with a reduction of 14.4% in

Eastern Province (Kalinda et al., 2023); broader efforts to reduce stunting may have created favourable conditions for improved infant diets in our study population. Overall, more than half of infants across both intervention and control groups achieved minimum dietary diversity, based on caregiver report, though this varied by study site. However, as previously reported, infant stunting was not different between intervention and control groups in any of the four countries (Checkley et al., 2024), suggesting that higher dietary diversity did not translate into improved linear growth among infants in the HAPIN trial.

Previous experimental studies of improved cook-stoves have produced mixed results when examining effects on outcomes related to food and nutrition. A study of improved biomass cook-stoves in Odisha, India did not include food security or dietary diversity as outcomes but found that the number of meals cooked per week was higher among intervention households that used and maintained their stoves compared to control households (Hanna et al., 2016). More recently, an RCT of an LPG stove and free fuel intervention in Puno, Peru found no effect on dietary intake, perhaps due to the small study population of 100 women and participants' uniformly low socio-economic status (Tarazona-Meza et al., 2023). Our study expands this existing evidence base by measuring a broader range of outcomes (household food insecurity and both women's and infants' dietary diversity) across a larger and more diverse study population.

4.1 Strengths and limitations

Strengths of this study are the randomized control trial design and inclusion of sites across several global regions, increasing generalizability of results; high study retention and data completeness; and nearly universal fidelity and adherence in the intervention group (Williams et al., 2023). Limitations include that we did not collect data on women's and infants' nutrient intake (e.g., through quantitative 24-h food recalls) or measure biomarkers of micronutrient status, to assess a wider range of nutrition indicators. We modified the recall period of the women's dietary diversity survey module, which could have implications for the accuracy and validity of our estimates of minimum dietary diversity. However, given that our modified questions included a response option for daily consumption of each food group, we expect these implications to be minimal. Finally, we lack data related to some of the potential pathways through which the HAPIN intervention could have impacted food and nutrition outcomes, including whether the provision of an LPG stove and free fuel led people to consume more meals, to cook more diverse foods (including those that require longer cooking times, such as beans), or whether the intervention led to changes in agriculture and food production practices.

4.2 Implications for research and practice

Our results suggest several directions for future research. The HAPIN intervention did not include any components that were explicitly focused on nutrition knowledge or behaviours. Still, by providing material resources in the form of an LPG stove and free fuel, the intervention may have allowed for households to reallocate time and money towards food and nutrition security. Future research should attempt to quantify pathways of impact and should explore whether the importance of each pathway differs by season, as research has observed variability in fuel use (e.g., using more gas in the rainy season) as well as in dietary intake and food availability by season (Gould et al., 2022). Future research on clean cooking and fuel interventions that study health endpoints could also examine the pathways through which improvements in food and nutrition security could contribute to improved health outcomes. Finally, given the decreases in women's dietary diversity from baseline to end-line in our study, future research and programs can explore factors influencing diets among pregnant and lactating women, to further increase the potential positive impacts of clean cooking and fuel interventions on dietary diversity.

Beyond a focus on food and nutrition security, several other research avenues related to clean cooking and fuel interventions merit further exploration. For example, clean cooking interventions may have a range of environmental benefits, including related to climate change. Particularly in South Asia and parts of Sub-Saharan Africa, unsustainable harvesting of wood for cooking fuel and charcoal manufacture may contribute to forest degradation, deforestation, loss of biodiversity, and climate change (Bailis et al., 2015; Wright et al., 2020). Further research is needed to quantify the environmental benefits of clean cooking and fuel interventions. Similarly, studies from Africa have demonstrated large increases in agricultural yields from using organic fertilisers such as compost and manure compared to using no inputs (Romero Antonio et al., 2025). Among households that use dung and agricultural waste as primary cooking fuels, research could explore the agricultural benefits of interventions that jointly promote cleaner cooking fuels and the use of manure as an organic fertiliser.

For practitioners, our results provide support for previous recommendations stating that food security projects and programs should include an explicit focus on access to energy for cooking (Makungwa et al., 2013). Indeed, our results suggest that interventions that promote clean cooking and fuel security could be considered "nutrition-sensitive", broadly defined as interventions that draw on sectors beyond nutrition to address underlying determinants of nutritional status (Ruel & Alderman, 2013). Interventions focused on water, sanitation and hygiene have long been

considered nutrition-sensitive because of their potential to contribute to a healthy household environment and reduced risk of illness (Ruel & Alderman, 2013). Clean cooking programs could similarly be promoted as nutrition-sensitive and could additionally serve as a delivery platform for education and behaviour change communications related to optimal dietary intake. It is widely acknowledged that multi-sectoral interventions are needed to improve nutrition outcomes (Keats et al., 2021; Ruel & Alderman, 2013). While the overall effect sizes observed in our study are small, they could complement other interventions as part of a multi-sectoral effort. Therefore, we argue that practitioners focused on nutrition should consider integrating clean cooking and fuel security in their programs where feasible and contextually appropriate.

5 Conclusions

While we observed a positive impact of the HAPIN intervention on household food insecurity and on women's and infants' dietary diversity, these impacts were not consistent across country sites, with positive results for dietary diversity being driven mostly by the Rwanda sample. Still, our results provide rigorous evidence that improved access to energy for cooking can play a role in improved food security and nutrition outcomes. Future programs and research should continue to explore opportunities to concurrently improve fuel security, food security, and nutrition outcomes for vulnerable populations in low-resource settings globally.

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Data availability Deidentified data associated with these analyses will be available through Emory Dataverse, linked to the DOI (digital object identifier) of this publication.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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