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Fuel savings are in the bag: can heat retention bags reduce charcoal use in the DRC? [1]

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Abstract:

Access to clean cooking remains limited in low-income and fragile settings, where households rely heavily on costly and polluting biomass fuels. We test whether heat-retention bags (HRBs) - low-cost cooking devices that retain heat and allow food to continue cooking without additional fuel - can reduce reliance on these fuels. We distribute HRBs, aluminum pots and hermetic lids to low-income households in the Democratic Republic of Congo. Using a common shock interrupted time series design with household fixed effects, we analyze a panel of 240 household-week observations collected over six survey visits, equally divided before and after the intervention. We measure usage relying on temperature sensors sewn into the HRBs and complement the analysis with focus group discussions. We find that HRB distribution is associated with reductions in charcoal consumption and expenditures of approximately 40%. The intervention is highly cost-effective, with an internal rate of return of 308%. Qualitative evidence suggests that adoption depends on households' ability to plan meals in advance, implying that HRBs may be less suitable for the most vulnerable, food-insecure households.

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[1] We registered a pre-analysis plan of this study on the Open Science Framework registry, see Collart et al (2026). Ethical approval for this study was obtained from the University of Antwerp (SHW_2025_46). We thank Julie Williams from the Virunga Foundation and employees of the Virunga Women's Workshop who contributed to the design and production of the HRB. We are grateful to Rachel Mwengasyali and Christine Cikesa for their help during data collection. We extend our gratitude to Hien Adjemian, Pauline Le Gonidec, Piet Vochten and Suzanne Bickes from the World Food Program team in Goma, who made the first HRB pilots possible. We thank enumerators and the Monitoring & Evaluation team of the Virunga Foundation who participated in the pilot studies, and participants of the IOB Fruit For Thought seminar who provided valuable inputs. Lastly, we thank Sadhbh Moore and Mike Clifford for their valuable insights on HRBs. L. Collart received financial support from FWO (11L9623N & 11L9625N).

I. Introduction

In 2023, 2.1 billion people relied on polluting fuels such as wood, charcoal, agricultural waste, dung or kerosene for cooking (IEA, 2025; WHO, 2025). This reliance disproportionately affects households at the bottom of the wealth distribution (Graham et al, 2018) and imposes substantial economic, social, and environmental costs. Firewood collection is time-intensive and exposes women and girls in particular (Verma & Imelda, 2023) to risks of injury and gender-based violence (WFP, 2012; Gunning, 2014; Vianello, 2016; Barbieri et al, 2017). When fuels must be purchased, they can account for up to a quarter of household expenditures (IEA, 2025), forcing households to skip or undercook meals (Lahn & Grafham, 2015; Njenga et al, 2024). At the same time, unsustainable charcoal and wood production contributes to environmental degradation (Bailis et al, 2015; Luoga et al, 2000) and, in some contexts, fuels conflicts (Patel & Gross, 2019). To date, only a fraction of the clean cooking literature has focused on the most vulnerable populations such as those in fragile or displacement settings (Barbieri et al, 2017).

Heat Retention Bags (HRBs), also known as thermal cookers, offer a promising yet understudied solution. Made of insulating materials,[2] HRBs reduce fuel consumption by allowing food to continue cooking off-heat. The device is particularly well suited to staple foods that constitute the dietary foundation of many low-income households (e.g. beans and rice). Controlled cooking tests suggest fuel savings of 22–48% per meal (Islam, 2014; Hasan & Huque, 2015; Salehin et al, 2016; Zobayer, 2017; Salehin et al, 2021). In addition to fuel savings, HRBs are inexpensive and easy to produce, durable, require no technical maintenance, and are compatible with all fuel and stove types. Their portability also makes them suitable for households facing limited living space or displacement. However, rigorous evidence on real-world adoption and impacts remains scarce. The only existing large-scale study, Roland-Horst et al. (2014), finds substantial reductions in fuel expenditures among self-selected adopters in South Africa using propensity score matching.[3] Yet, it remains unclear whether these findings generalize to poorer households, fragile contexts, or settings where adoption is not driven by self-selection.

We address this gap by evaluating the adoption and impact of HRBs in a low-income conflict-affected setting: eastern Democratic Republic of Congo (DRC). Our intervention consists of the

[2] Polystyrene, foam (as in this study), or any material with isolating properties such as styrofoam, cotton, wool, hay, banana leaves, aluminum or even plastic waste (Matavel et al, 2022; WFP, 2024; WFP Innovation Accelerator, 2025).
[3] Leveraging data from ~4000 South African households, Roland-Horst et al (2014) find reductions in household fuel expenditures of 10-36%, increased food spending of 36-60% and cooking time savings of 8-21% amongst self-selected adopters.

free distribution of locally produced HRBs, along with a set of cooking pots with fitted lids. We collect a rich panel dataset of 240 household-week observations from 40 low-income households over six weekly visits, spanning pre- and post-intervention periods. These data include self-reported HRB usage, fuel expenditures, and charcoal ash weights. In addition, we embed stove unit monitors (SUM) into HRBs to capture high-frequency usage patterns (see Figure 1), and we complement quantitative findings with focus group discussions. We estimate impacts using a household fixed-effects model that exploits within-household variation over time, allowing each household to serve as its own counterfactual while controlling for time-invariant characteristics.

Figure 1: HRB & Stove Use Monitors (SUMs)

Note: Figure 1 displays the heat retention bags (HRBs) used in this study as well as the stove use monitors (SUMs) sewn into HRB to measure temperature and assess usage.

This study was conducted in Goma, the capital of North-Kivu Province, a rapidly growing city of over 1.9 million inhabitants (World Bank, 2020). Most households in Goma (95%) rely on charcoal for cooking (Morisho et al., 2022), which on average accounts for over 20% of monthly household expenditures ($25-$30) (Desbureaux et al, 2026; Brandily et al, 2024). Charcoal production largely takes place illegally in protected areas such as Virunga and Kahuzi-Biega National Parks, often involving armed actors (Morisho et al, 2022), thereby linking household energy demand to environmental degradation and conflict dynamics. The broader context is one of protracted instability: DRC has experienced armed violence for over three decades and remains classified as a conflict-affected setting (World Bank, 2026). The resurgence of the "*Mouvement du 23 Mars*" (M23) militia in 2021 further deteriorated the security situation (IPIS, 2024). Our intervention took

place while Goma was under M23 administration and facing significant humanitarian and economic stress: 62.5% of surveyed households were registered beneficiaries of the World Food Program,[4] underscoring the relevance of our findings for fragile low-income settings.[5]

A large body of literature has examined interventions aimed at reducing reliance on biomass fuels, with a strong focus on improving combustion efficiency through technologies such as improved cookstoves. Evidence on the adoption and sustained use of these stoves, however, remains mixed (Berkouwer & Dean, 2022; Hanna, Duflo and Greenstone, 2016; Agurto Adrianzén, 2013; Bensch & Peters 2012 & 2015, García-Frapolli et al, 2020). While effective in some contexts, many improved cookstoves remain ill-suited to bottom-of-the-pyramid households (Sesan et al, 2012): some are restricted to charcoal use, others are bulky or non-portable, and several require installation or maintenance that is impractical in settings characterized by space constraints or displacement risk (Masera et al, 2007; Diaz et al, 2007, Alem et al, 2015). Alternative solutions such as Liquid Petroleum Gas stoves and electric cooking appliances remain prohibitively expensive and depend on reliable supply chains or electricity access, which are often lacking in low-income or conflict-affected environments (Haselip et al, 2022; Jeuland et al, 2023). Solar cookers and biogas systems face similar limitations related to cost, inflexibility, or maintenance requirements (Vianello, 2016; Hewitt et al, 2022). As a result, many existing solutions fail to meet the needs of vulnerable households due to high upfront costs, infrastructure dependence, or lack of flexibility, whereas HRBs may be better suited to these constraints.

This study contributes to the clean cooking literature in four ways. First, it provides the first empirical evidence on HRB adoption and impacts in a low-income, fragile setting – where improved cooking solutions are greatly needed. Second, it improves on existing evidence by moving beyond self-selected adoption, implementing an intervention with exogenous distribution and exploiting within-household variation over time. Third, we introduce objective, high-frequency measures of HRB usage and fuel consumption, combining stove use monitors with charcoal ash measurements, thereby reducing reliance on self-reported data. Fourth, our HRBs are locally produced at substantially lower cost than existing products ($16 versus $30 as in Roland-Horst et al., 2014), highlighting the potential for cost-effective scaling and local economic

[4] We initially planned a randomized experiment targeting IDPs in informal settlements around Goma, in collaboration with the WFP. However, this was not feasible due to the forced return of IDPs to their areas of origin at the time of the intervention. We therefore implemented the study among impoverished households in the same conflict-affected urban context. WFP beneficiaries are typically selected based on vulnerability and food security criteria.

[5] To the best of our knowledge, HRB were not locally known nor used in our research setting at the time of the study.

spillovers. Together, these contributions provide new insights into the feasibility and effectiveness of low-cost energy-saving technologies among the most vulnerable populations.

The remainder of this paper is organized as follows. Section two introduces the intervention. Section three describes our data and empirical strategy. Main results, supplementary analyses and adoption mechanisms are reported in section four. Finally, we discuss our findings and their policy implications in section five.

II. Study Design

i. Sample

We conducted this study in a low-income peripheral neighborhood of Goma, with no access to the electric grid. Participant selection was facilitated by local community leaders, who helped identify households willing to participate in the clean cooking study.

The research team administered a short recruitment survey with the pre-identified households to determine eligibility. Eligibility criteria included: (1) no access to electricity at the time of the intervention, (2) reliance on wood-based fuels for cooking, and (3) living in the pre-determined neighborhood. The process was repeated until 40 eligible households were enrolled. Within each household, we identified the main adult in charge of cooking, excluding domestic workers, as the primary participant.

The recruitment survey also collected socio-demographic characteristics, reported in Table 1. All primary participants are women, with an average age of 35 years, and a mean education level corresponding to almost eight years of schooling. Households are large (8.53 members on average), and 85% live in low- or very low-quality dwellings, typically constructed from wooden planks or corrugated metal sheets. In pre-intervention surveys, we collected data on average weekly charcoal or firewood expenditures, which amount to $3.77. These indicators point to a particularly low-income sample relative to other urban households in Goma.[6]

Table 1: Baseline respondents characteristics

Variable	Baseline average for full sample (N=40)	SD	Min.	Max.
Age	34.9	11.86	18	66

[6] In two previous samples of electrified households in Goma, only 39.5% (N=1,657) and 38.8% (N=815) lived in low-quality dwellings, compared to 85% in our sample (Desbureaux et al., 2025). Average monthly fuel expenditures are also lower in our sample ($17 vs. $25–30), consistent with fuel rationing among poorer households and suggesting that cooking fuel behaves as a normal good in this context.

Gender (female)	100%	0	0	0
Years of schooling	7.53	4.85	0	15
Household size (number of people)	8.53	2.78	3	16
Low- and very low-quality dwellings (% of respondents)	85%	0.36	0	1
WFP beneficiaries (% of respondents)	62.5%	0.48	0	1
Weekly charcoal/firewood spending ($)	3.77 (N=120)	3.58	0	23.88

Note: This table presents baseline characteristics of participants (N=40). Column 2 reports the sample means, while Columns 3-5 report standard deviations, minimum and maximum values. Shelter quality is classified on a scale from 1 (very poor) to 5 (very high). All variables were collected during the recruitment survey, except for weekly charcoal spending which is calculated as the average spending over the three pre-intervention visits.

ii. Intervention

The bundled intervention entailed the free distribution of a HRB, along with a 10L aluminum cooking pot with a fitted lid. The HRB was produced locally by our partner, the Virunga Foundation, using foam blocks sewn into 'pagne' fabric, at a unit cost of $16. The pot and lid, valued at $8, were provided because HRB use requires a tightly sealed pot.[7]

Locally produced prototypes exhibited heat-retention performance comparable to commercial alternatives, maintaining boiling water above 60°C for up to six hours, while field tests indicated substantial reductions in active cooking time. Controlled cooking tests organized before the intervention confirmed that HRBs are well suited to local dishes requiring prolonged boiling (Appendix A). Further details on HRB design, local production, and heat-retention capacity tests are provided in Appendix A.

All participants (N = 40) received the HRB, pot, and lid bundle during a half-day group demonstration session. During this session, participants received practical guidance on HRB use and were able to taste food prepared using the technology. A follow-up visit was conducted a few days later to answer questions and provide additional support, as HRB use requires adjustments in cooking practices.

[7] Based on recall data collected three months after the study for 32 households, only 16 households (50%) reported owning a lid of similar diameter as their primary pot prior to the intervention.

iii. Data Collection

We rely on four complementary sources of data, combining quantitative and qualitative evidence.

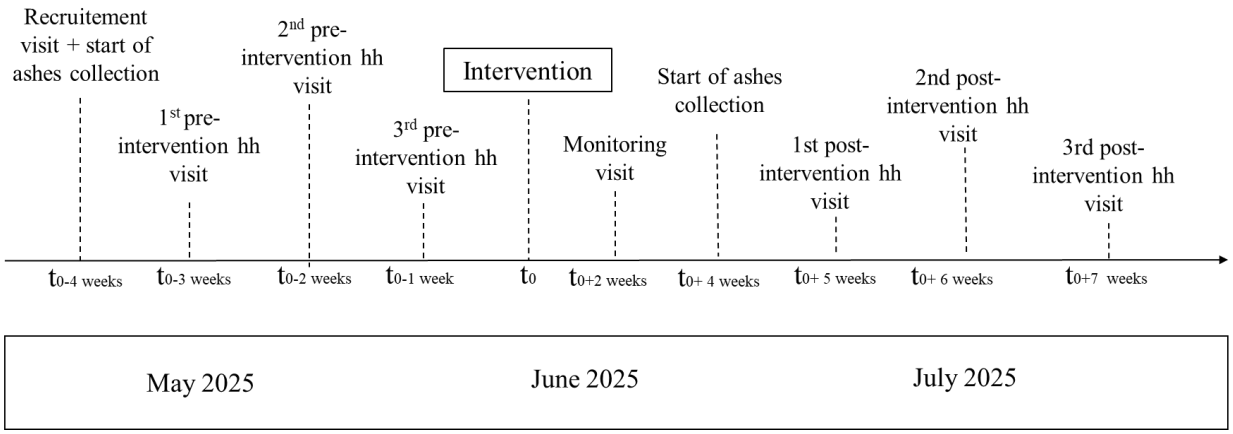
First, we conducted six in-person survey visits at approximately weekly intervals (three before the intervention and three after). During each visit, we collected data on cooking fuel purchases, the number of individuals regularly eating in the household over the previous week, and self-reported HRB usage over the same period. Second, following Berkouwer and Dean's protocol (2022), we measured charcoal consumption using a proxy based on ash production. During each visit, we weighed the charcoal ashes (stored by households in a designated bucket), recorded the number of collection days to calculate average daily ash weight, and emptied the buckets. Third, we collected high-frequency usage data using stove use monitors (SUMs) sewn into the HRBs. We used the EXACT Pro Stove Use Monitor from Climate Solutions – previously employed in several studies (e.g. Thivillon et al, 2024) – which recorded temperature every two minutes throughout the study period.

Fourth, we conducted a focus group discussion (FGD) after the final post-intervention survey. The FGD included five high-frequency users and five low-frequency users, defined based on average weekly HRB usage. The discussion lasted approximately two hours and aimed to explore usage patterns, constraints to adoption, and the extent to which the technology aligned with users' needs. The session was facilitated by one of the authors in Swahili, using a flexible discussion guide (see Appendix B).

iv. Timeline

The study involved a total of nine household visits over a period of roughly three months. Following the recruitment survey, three pre-intervention survey visits were conducted at weekly intervals. The intervention was then implemented, followed by a support visit. Finally, three post-intervention survey visits were conducted, approximately five, six and seven weeks after the HRB distribution. The full timeline is illustrated in Figure 2.

Figure 2: Timeline



Note: Following a recruitment survey to assess eligibility and obtain consent, the 40 selected households began collecting charcoal ashes. Three pre-intervention survey visits were conducted at weekly intervals. The HRB and pot bundle was then distributed, followed by a monitoring visit. Three post-intervention surveys were conducted approximately four, five, and six weeks after distribution.

III. Empirical Strategy

i. Primary outcomes

The intervention is expected to increase HRB usage and, through reduced stove use, decrease fuel consumption and expenditures. Accordingly, we define five primary outcomes, as specified in the pre-analysis plan.

The first outcome is the number of weekly HRB usage events, measured using SUM data. A usage event is defined as a period during which the temperature inside the HRB exceeds 40°C. Lower thresholds may generate false positives from ambient heat, sunlight, or human contact, while higher thresholds may underestimate usage duration and reduce sensitivity to lower-temperature uses such as keeping food warm (see Appendix C)[8]. We aggregate these usage events over the seven days preceding each survey visit. The second outcome is the self-reported number of weekly HRB usage events, collected during survey visits. The third outcome is average daily HRB usage time. We compute total weekly usage time as the cumulative duration during which the temperature exceeds 40°C over the previous seven days and divide by seven to obtain a daily average. The fourth outcome is charcoal consumption, proxied by the daily weight of charcoal ashes. We measure total ashes collected since the previous visit and divide by the number of days between visits. Lastly, the fifth outcome is weekly cooking fuel expenditure (in US dollars),

[8] Appendix C provides a comparison of alternative thresholds and shows that the results are sensitive to this choice: lower temperature thresholds (30°C) lead to a greater number of detected usage events and higher average daily usage time, whereas higher thresholds (50°C) yield fewer detected events and lower estimated usage time.

computed as the sum of daily fuel expenditures reported for the seven days preceding each survey visit.

Our main explanatory variable is a binary indicator equal to one for observations collected after the distribution of the HRB, pot, and lid bundle.

ii. Main specification

Because all households received the intervention, identification relies on within-household variation over time. Each household serves as its own control in a common shock interrupted time series design (Penfold & Zhang, 2013), using three pre-intervention and three post-intervention survey rounds.

We estimate the following fixed-effects model:

$$y_{i,t} = \beta 0 + \beta 1 \cdot T_{i,t} + \gamma \cdot N_{i,t} + \alpha_i + \varepsilon_{i,t}$$

where $y_{i,t}$ denotes the outcome of interest for household *i* at week *t,* and $T_{i,t}$ is a binary variable equal to one after the intervention. N_{it} captures the number of individuals regularly eating in household *i* at time *t*. Household fixed effects α_i absorb all time-invariant unobserved heterogeneity, and $\varepsilon_{i,t}$ is a idiosyncratic error term. Standard errors are clustered at the household level and computed using wild cluster bootstrap methods (Cameron et al, 2008), to account for the small number of clusters (N = 40). [9]

iii. Exploratory analyses & Robustness

We conduct several analyses to assess the robustness of our findings. First, we estimate dynamic specifications for daily ash production and fuel expenditures by survey week to assess pre-treatment trends and the evolution of treatment effects over time. Second, we examine the relationship between HRB usage intensity and fuel outcomes by estimating the marginal effects of additional usage, which allows us to capture dose-response effects along the intensive margin. Third, we estimate pooled models, without household fixed effects, to exploit both within and between variation in usage (Appendix D).

[9] While the pre-analysis plan specified a Poisson model for count outcomes (measured and self-reported HRB usage events), estimation produced implausible coefficients due to the pre-post design of this study. We therefore report estimates from a linear fixed-effects model (assuming Gaussian errors).

IV. Results

i. Main results

We present our main results in Table 2. We first examine HRB adoption and usage. Post-intervention, we observe 2.07 weekly HRB usage events based on SUM data (Column 1) and 3.03 events based on self-reports (Column 2). On average, households use their HRB 90.81 minutes per day (Column 3). Differences between self-reported and sensor-based measures, including potential over-reporting in survey data, are discussed in Appendix E.

Table 2: Primary outcomes

	(1) Measured weekly HRB usage events (nb. events)	(2) Reported weekly HRB usage events (nb. events)	(3) Daily HRB usage time (min)	(4) Daily ashes (g)	(5) Weekly expenditures (USD)
HRB, pot & lid bundle	2.07***	3.03***	90.81***	-41.37***	-1.47***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.003)*
Nb of people eating in the household (last 7d)	0.180	0.300**	6.213	2.00	0.23
	(0.193)	*(0.049)*	*(0.261)*	*(0.357)*	*(0.339)*
N	240	240	240	240	240
Pre-intervention average	0	0	0	93.95	3.77
Change from pre-intervention				-44%	-39%

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include household fixed effects and wild cluster bootstrapped standard errors clustered at the household level. Outcomes in columns 1 and 3 are measured with stove use monitors. Those in columns 2 and 5 are measured with survey data. Finally, daily ashes (column 4) are measured during a task in which households were requested to put all their post-combustion charcoal ashes in a 10L bucket.*

We next turn to fuel outcomes. Prior to the intervention, households generated on average 94 grams of charcoal ashes per day and spent $3.77 per week on cooking fuels. Following the intervention, daily ash production decreases by 41.37 grams[10] ($p < 0.01$), corresponding to a 44% reduction, while weekly fuel expenditures decline by $1.47 ($p < 0.01$), or 39% (Columns 4 and 5). These findings indicate that HRB adoption is associated with substantial reductions in fuel use. Results are robust to estimating the model without household fixed effects (Appendix D).

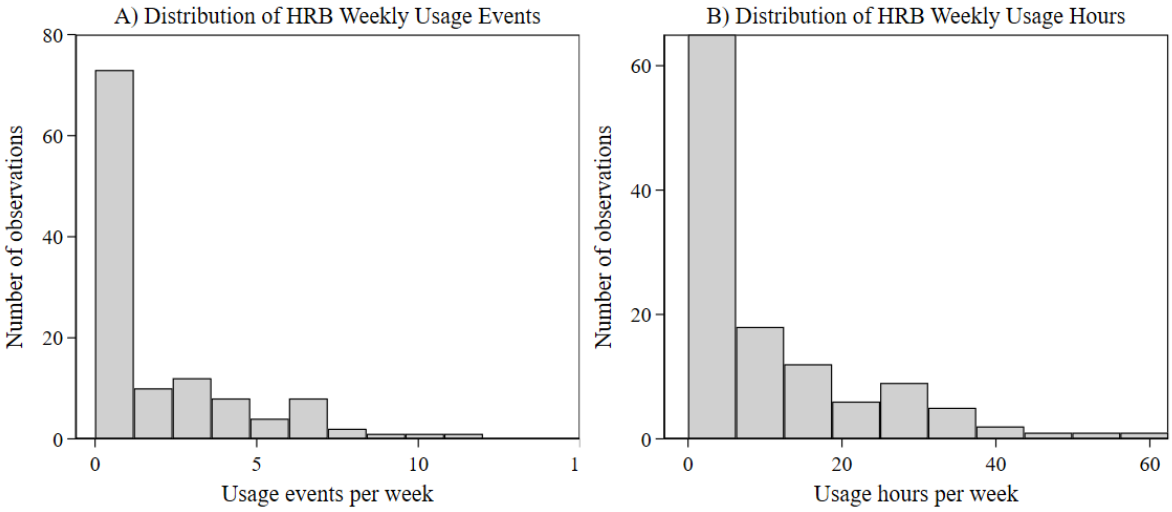
Controlled cooking tests conducted prior to the intervention suggested that HRBs can reduce active cooking time per meal by up to 68% (see Appendix A), but the extent to which such savings

[10] In another study in Goma, Desbureaux et al. (2025) report a charcoal-ashes conversion factor of 4.16%. Under this assumption, a 41gr reduction in ashes corresponds to a 0.985kg reduction in charcoal.

translate into lower overall household fuel consumption was ex-ante unclear. Our results (Columns 4 and 5 of Table 2) provide evidence that these efficiency gains materialize at the household level, with a decrease in charcoal consumption of approximately 40%.

Next, we explore heterogeneity in HRB usage of the HRB. Figure 3 illustrates the distribution of usage across post-intervention household-week observations (N = 120). Most observations are concentrated between 0 and 5 usage events per week and between 0 and 20 weekly usage hours, but the distribution is right-skewed, with some households reaching more than 10 usage events and 60 hours per week. A substantial share of observations (39%) exhibit zero usage in a given week; however, this reflects irregular use rather than non-adoption, as only five out of 40 households never used the HRB. This heterogeneity in usage patterns suggests that households differ in their ability and willingness to use the HRB, a question we explore further using qualitative evidence in Section IV.v.

Figure 3: Post-Intervention HRB Usage



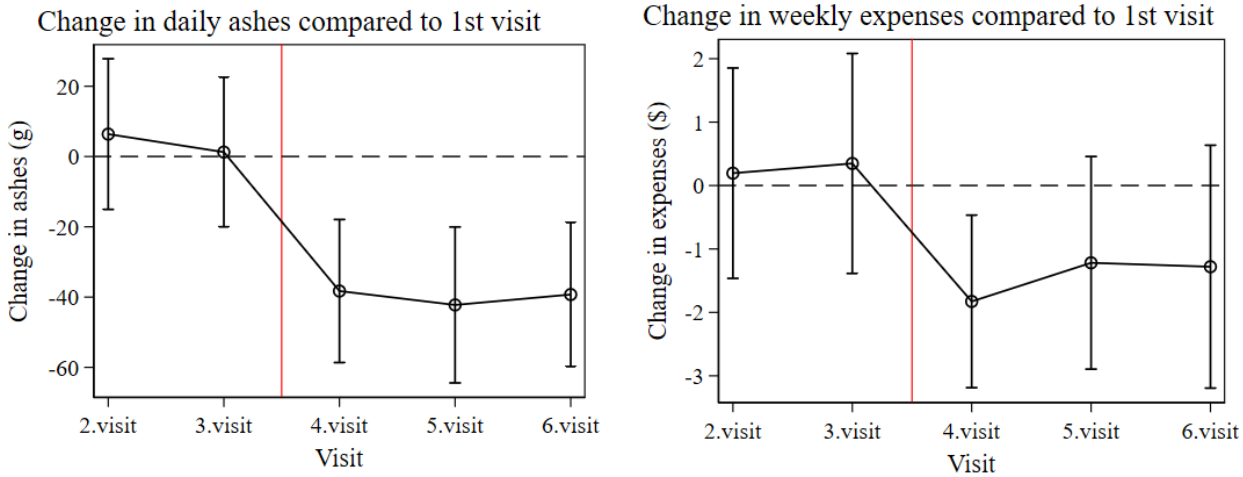
Note: Distribution of HRB usage across post-intervention household-week observations (N = 120). Panel A shows weekly usage events; Panel B shows total weekly usage hours. Each household contributes three observations.

ii. Dynamic Model

Figure 4 plots changes in daily ashes and weekly expenditures by survey week, relative to the first pre-intervention visit. In the pre-intervention periods, estimated coefficients for both outcomes are statistically indistinguishable from zero, providing no evidence of differential pre-trends. Following the intervention, we observe a significant reduction in daily ash production of 38 to 42 grams, consistent with our main results.

Results for expenditures follow a similar pattern: weekly spending decreases by $1.20, to $1.83, in the immediate post-intervention periods. In later periods, however, estimates are no longer statistically distinguishable from zero. Given the small sample size, this may reflect limited statistical power.

Figure 4: Change in main outcomes between the 1st pre-intervention visit and subsequent visits

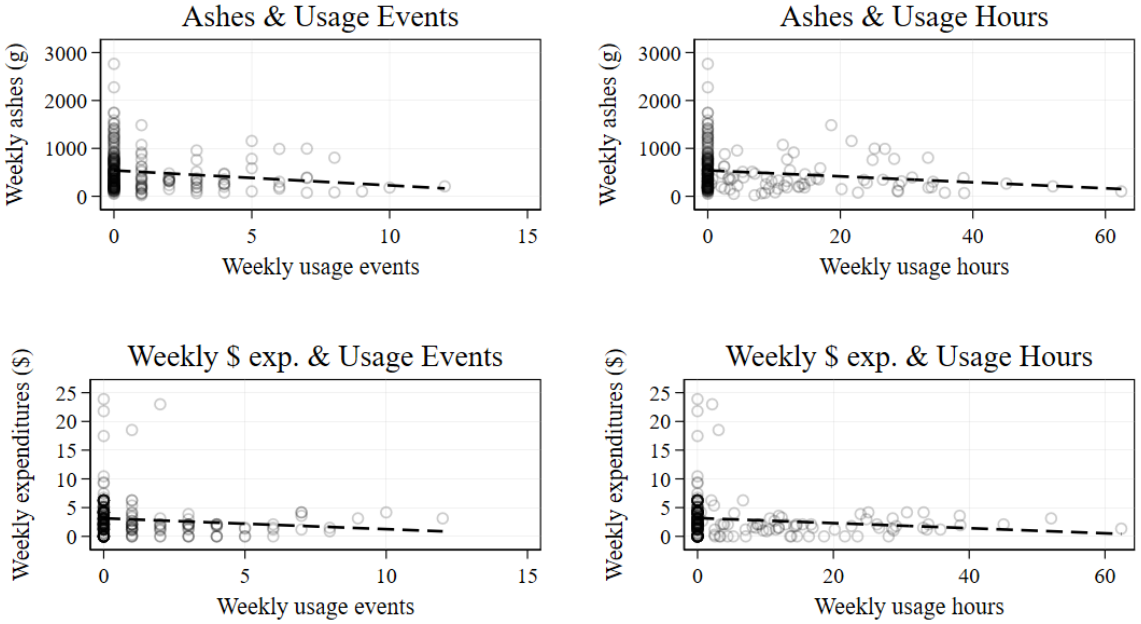


Note: Change in primary outcomes compared to 1st pre-intervention visit. Vertical line corresponds to the intervention (HRB, pot and lid distribution). We report 95% CI.

iii. Usage Intensity

To better understand how outcomes vary with usage intensity, we examine the relationship between HRB use and fuel consumption. If reductions in fuel use are indeed driven by adoption of the treatment bundle, higher HRB usage should be associated with larger reductions in charcoal consumption and expenditures. Figure 5 plots HRB usage intensity - measured in weekly usage events and usage hours - against charcoal ashes and fuel expenditures. The scatterplots reveal a negative relationship between HRB usage and both outcomes.

Figure 5: Relationship between HRB usage intensity and fuel outcomes



Note: Weekly HRB usage events and usage hours are plotted against weekly charcoal ashes and fuel expenditures.

We formalize this relationship by estimating fixed-effects regressions of charcoal ashes and expenditures on HRB usage intensity. To limit the influence of high-leverage observations, we top-code both usage variables at the 90th percentile, capping 7.5% and 10% of observations at six weekly usage events and 29 weekly usage hours, respectively. [11]

Table 3: Usage intensity

	(1) Daily ashes (g)	(2) Weekly expenditures (USD)	(3) Daily ashes (g)	(4) Weekly expenditures (USD)
Nb. of usage events	-6.852***	-0.443***		
	(0.001)	*(0.000)*		
Total weekly usage in hours			-0.984***	-0.089***
			(0.002)	*(0.000)*
N	240	240	240	240
Pre-intervention average	93.95	3.77	93.95	3.77

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include household fixed effects and wild cluster bootstrapped standard errors clustered at the household level. All models also account for household size. Weekly usage data are capped at a maximum of 6 events. Values above this threshold are re-coded to 6. Weekly usage hours are capped at a maximum of 29 hours. Values above this threshold are re-coded to 29.*

Table 3 reports the results. We find a negative and statistically significant relationship ($p < 0.01$) between HRB usage and both fuel outcomes across all specifications. An additional usage event is associated with a reduction of 6.85 grams of daily ashes and $0.44 in weekly expenditures

[11] HRB usage intensity is right-skewed (Figure 3), with a few observations exhibiting very high usage, which may disproportionately influence estimates given the small sample size.

(Columns 1-2). Similarly, an additional hour of HRB use is associated with reductions of 0.98 gram of daily ashes and $0.089 in weekly expenditures (Columns 3-4). Results are robust to alternative specifications, including using uncapped data and alternative top-coding thresholds (Appendix F), as well as modeling usage events as categorical variables (Appendix G).

Back-of-the-envelope calculations based on observed usage levels (e.g., two usage events or ten usage hours) imply reductions in charcoal consumption that are smaller than the average treatment effects reported in Table 2. Variation in SUM measured usage includes all forms of HRB use, including low-productivity uses such as keeping food warm - a common practice (54 out of 120 post-intervention observations) - and leaving food in the HRB longer than necessary (Section IV.v). As a result, increases in measured usage do not translate one-for-one into reductions in fuel consumption.

iv. Focus Group Discussions

While our quantitative results are robust across specifications, they raise two questions regarding underlying usage patterns. First, the magnitude of fuel savings - approximately 40%, even among households using the HRB only twice per week - is substantial. Second, we observe considerable variation in usage across households: 39% of post-intervention household-week observations (47/120) show no HRB use, while 21% (25/120) indicate intensive use (more than three weekly usage events). To better understand these patterns, we turn to evidence from focus group discussions.

Focus group discussions reveal that variation in HRB usage is closely linked to households' ability to plan meals in advance. Because HRBs require longer cooking times, food must be purchased several hours before consumption. However, many low-income households in the DRC cook immediately after purchasing food - typically when liquidity becomes available - leaving limited scope for advance planning. As one respondent noted, "[…] *cooking with the bag takes a long time, and we don't always have food supplies at home, so it is difficult to plan and organize our meals. Those who have more food supplies at home use the bag more than us!*" Another mentioned that *"the low food stocks we have at home are the main reason why we cannot use the bag".* These findings suggest that HRBs may be most effective for households with more predictable food access and greater capacity to plan meals.

Importantly, the charcoal savings generated by HRB use are not sufficient to relax these constraints – at least over our six weeks study period. As one respondent explained, "[…] *if we save money with the bag, we can maybe purchase salt or sugar to make the food taste better, or school supplies*

for the children, but the savings are not enough to purchase much food." This highlights that liquidity constraints remain binding, limiting the extent to which households can adjust cooking practices.

Even among households that make limited use of the HRB for cooking, the technology still provides value through alternative uses. Several respondents reported using the HRB to keep food warm rather than to cook. This is consistent with survey data, which indicate that households used the HRB for this purpose at least once in 45% (54/120) of post-intervention household-week observations. One respondent explained: "*In my home, we often eat fufu.*[12] *Usually, I cook it in the afternoon, but it is cold when we eat it in the evening. You cannot prepare fufu with the bag, but I use it to keep the fufu warm until my husband comes home from work*." While this use generates utility, it has little impact on charcoal consumption.

The relatively large fuel savings observed in the main results, despite limited usage frequency, can be explained by the type of meals prepared. Savings are most pronounced for beans, a highly fuel-intensive staple typically cooked in large batches two to three times per week. Survey data indicate that HRBs were used to prepare beans in 52% of post-intervention household-week observations. This was corroborated by focus group discussions, where respondents emphasized that the benefits of using the HRB for such dishes clearly outweigh the additional time and planning required. As one respondent noted, "*It takes a very long time to cook with the bag so it is not very practical for the small everyday meals. But for the beans and the sombe,*[13] *it is great, it consumes less charcoal and the taste is also good, so we only use the bag when we cook these recipes*". Another respondent highlighted that: "*it is easier to digest the beans when they are prepared with the bag*". This frequent use for fuel-intensive dishes helps explain why relatively limited HRB usage can still generate substantial reductions in fuel consumption.

Beyond these fuel-intensive meals, additional usage appears to yield smaller marginal savings. This reflects both the lower fuel intensity of other dishes and uncertainty about optimal HRB usage. Some respondents reported leaving food in the HRB longer than necessary to ensure it was fully cooked, which increases recorded usage without proportionally reducing fuel consumption. As one respondent explained: "*We are not always sure how long a certain dish must stay in the bag to be fully cooked. So, we cook it on the fire, then put the pot in the bag for a long time, at*

[12] Local staple recipe, comparable to Ugali consumed in East Africa. It consists in a sticky paste prepared from manioc or corn flour.

[13] Cassava leaves.

least several hours, to make sure it is really cooked and safe to eat. In some cases, the food is overcooked and does not have much taste." [14]

Finally, some respondents highlighted time-saving benefits associated with HRB use. For instance, one respondent noted: "*It takes a long time to cook the beans. But now I put them on the fire in the evening, then I leave the beans in the bag during the night, and in the morning they are ready. So, I can do other tasks in the house".* This suggests that, beyond fuel savings, HRBs may generate additional welfare gains through improved time allocation.

V. Discussion & Conclusion

Using high-frequency panel data on household fuel consumption and expenditures (N = 40 households, 240 observations), SUM data on HRB usage, and qualitative evidence, we provide the first evidence on the adoption and impact of HRBs in a low-income setting.

We document substantial adoption, with 60% of post-intervention household-week observations (N=72/120) indicating HRB use. On average, participants use the device approximately twice per week, corresponding to about 10 hours of weekly usage. We find that receiving the HRB bundle (HRB, pot, and fitted lid) is associated with substantial statistically significant reductions in charcoal consumption and expenditures of 44% and 39%, respectively. Dynamic estimates confirm these findings.

i. Limitations

This study has several limitations. First, our estimates capture short-term adoption and usage in a context where households were regularly visited, which may have induced behavioral responses. At the same time, usage and impacts could increase over time as households become more familiar with the technology and adjust their cooking practices. Assessing longer-term adoption and sustained impacts remains an important avenue for future research. However, our common shock interrupted time series design, in the absence of a control group, would restrict our ability to rule out the influence of time-varying confounders in a longer-term follow-up study. Importantly, no significant shocks occurred during the relatively short duration of this study, supporting the credibility of our estimates.[15]

[14] Not leaving food in the HRB for more than 6 to 7 hours was a key guideline communicated during the demonstration session. Prolonged use increases the risk of bacterial growth, as the temperature in the bag drops below 60°C roughly six hours after cooking. This risk is higher if food is placed in the HRB after it has already cooled.

[15] A particularly relevant shock would be a change in charcoal prices. In a related study in the same area, we monitored charcoal prices throughout the study period. We plot the evolution of charcoal prices in Appendix H and find no evidence of a price shock during our study period.

Second, our measure of fuel expenditures relies on self-reported data and is subject to desirability bias, as the topic of the study was communicated to participants ex-ante. This could affect reported fuel expenditures in two ways: participants might either under-report expenditures post-intervention if they perceive that doing so aligns with the study's objectives, or over-report expenditures if they believe this positions them as eligible for additional assistance. However, behavioral results derived from ashes collection are consistent with self-reported expenditures estimates, supporting the credibility of our results.

Third, the bundled nature of the intervention prevents clean identification of the individual contributions of the HRB and the pot-lid components. The relatively small sample size (N = 40 households) limits statistical power to detect heterogeneous effects with respect to previous fitting lid ownership,[16] despite the large number of repeated observations per household. While existing evidence suggests that fitted lids may independently improve fuel efficiency by reducing heat loss and evaporation (Opadokun, 2019; Berick, 2006), empirical evidence remains scarce. Future work should disentangle these effects, particularly given the low cost and potential scalability of improved lids.

Lastly, our data do not allow us to capture potential changes in diet composition or meal frequency post-intervention. Future research should examine whether HRB adoption affects food security levels, which is especially relevant amongst vulnerable households – many of whom are food aid recipients.

ii. Policy implications

Our results highlight the importance of targeting. While HRBs can generate substantial fuel savings, their effective use requires the ability to plan meals in advance. As shown by our qualitative findings, many highly vulnerable households cook immediately after acquiring food, limiting their capacity to adopt the technology. HRBs therefore appear best suited for energy-constrained but relatively food-secure households with predictable access to food and the ability to plan meals. They may be less appropriate for the most vulnerable populations, such as displaced households or those facing severe food insecurity.

At the same time, HRBs can generate meaningful reductions in energy expenditures, which may help relax liquidity constraints at the margin. This suggests that their impact could be enhanced

[16] We tried to estimate a model in which we interact the treatment variable with prior lid ownership but find no statistically significant heterogeneity. However, this analysis is limited to a subsample (N = 32/40) of respondents which we could locate after the end of the study to collect information on prior lid ownership. This analysis is likely underpowered, so results should be interpreted with caution and are, therefore, not reported in this article.

when combined with complementary interventions that improve households' ability to plan meals, such as cash transfers, food assistance, or savings mechanisms that smooth food purchases over time.

Participants also emphasized the importance of compatibility with local cooking practices. HRBs were particularly valued for preparing fuel-intensive staple dishes such as beans, highlighting the importance of aligning clean cooking technologies with local cuisines and habits (Bielecki & Wingenbach, 2014; Akintan et al, 2018; Adem & Ambie, 2017; Njau & Matto, 2024). Future research should assess the applicability of HRBs across different cultural and geographic contexts.

Looking beyond the study setting, Africa's urban population is projected to double from 700 million to 1.4 billion by 2050 (OECD, 2025), with much of this growth occurring in low-income urban settlements. The constraints faced by households in our study—limited access to clean fuels, liquidity constraints, and reliance on biomass—are likely to remain widespread, underscoring the relevance of our findings in rapidly growing urban contexts.

At the same time, the potential of HRBs is not limited to low-income populations. Given rising energy prices and growing environmental concerns, this technology can generate energy savings across a wide range of settings. Its compatibility with existing stoves and fuels further enhances its scalability.

Beyond considerations of targeting and scalability, the cost-effectiveness of HRBs is central for policy design. We therefore turn to an assessment of their cost-effectiveness.

iii. Cost-effectiveness of HRBs

The full intervention cost, including implementation, amounts to approximately $33 per household,[17] while reducing charcoal expenditures by 39%, corresponding to annual savings of up to $76 – assuming sustained usage at the observed rate. Based on a very conservative one-year lifespan, this translates into an internal rate of return (IRR) of approximately 230% when accounting for full intervention costs, and 308% when considering only the cost of the HRB and pot - consistent with existing studies that base IRR calculations on appliance costs alone (e.g. Berkouwer and Dean, 2022). The break-even usage rate is 0.89 uses per week when including full

[17] In this pilot, HRBs were procured at a manufacturing cost of $16, with no margin for the Virunga Foundation. Retail prices are likely to be somewhat higher, although unit costs are expected to decline as production scales up. Pots and lids were procured for $8, and the demonstration sessions cost roughly $11 per participant.

implementation costs ($33), or 0.65 uses per week when only accounting for appliances cost ($24). Both thresholds lie well below the observed usage rate of 2.065 uses per week, indicating that the positive returns are robust to reductions in adoption intensity.

These estimates are likely conservative. HRBs are expected to last several years and can be easily repaired, implying substantially higher lifetime returns. Moreover, they do not account for additional benefits such as reduced exposure to indoor air pollution, time savings, and environmental gains, implying that total welfare effects are likely larger.

In sum, compared to existing clean cooking interventions, HRBs appear highly competitive in terms of both impact and cost-effectiveness. They deliver substantial fuel savings at low cost, without requiring changes in fuel type or cooking infrastructure.

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VII. Appendix

A) Appendix A: Preparatory studies

We conducted three exploratory studies to assess the potential of HRBs in Eastern DRC, all of which were implemented in Goma between January and August 2024.

Study 1: Suitability for Local Cuisine

In the first exploratory study, we assessed whether HRBs were suited to the local cuisine. Our team conducted over 300 controlled cooking tests across a range of commonly prepared dishes. Results indicate that HRBs are well suited to recipes requiring prolonged boiling—such as beans, *sombe*, and rice—but not appropriate for fried foods or dishes that require evaporation to achieve the desired consistency.

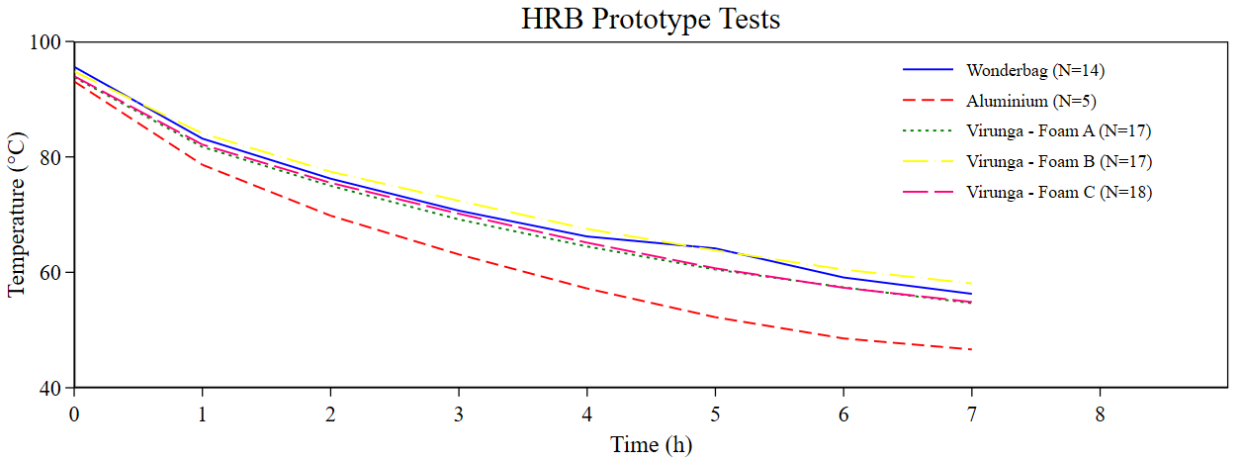
Study 2: Local Production and Performance

The second exploratory study evaluated whether HRBs could be produced locally at lower cost while maintaining performance comparable to existing commercial products, such as the *Wonderbag*, sold at a retail price of $30[18]. Prototypes manufactured locally by our partner at a unit cost of $16 proved as effective as the Wonderbag, maintaining temperatures above 60°C for approximately six hours after placement in the HRB (Figure A.1).

A key design difference concerns the filling material. While the Wonderbag uses shredded foam, our prototype uses solid foam blocks. This adaptation reflects local cooking conditions: as many low-income households cook directly on the floor, fabric-based devices are prone to tearing. In such cases, shredded foam can spill out, reducing insulation performance. The use of foam blocks mitigates this risk and facilitates maintenance.

[18] A shipping fee of roughly ~ $20 per unit must be added to the retail price of $30.

Figure A.1: Heat retention bag prototypes



Note: Temperature inside a pot of boiling water after placement in the HRB. "Wonderbag" refers to HRBs from the South African brand Wonderbag. "Aluminum" refers to a circular insulated aluminum food container.[19] "Virunga HRBs" were manufactured in Goma by the widows' organization affiliated with the Virunga Foundation[20], using three types of mattress foam (A, B & C). Foam B offered the best price–insulation ratio and was selected for subsequent studies.

Study 3: Stove Use Time

The third exploratory study aimed to quantify stove use time with and without the HRB across a range of typical recipes. We distributed HRBs to ten enumerators in Goma, along with mobile phones and weighing scales. For each cooking event, enumerators recorded the type and quantity of food prepared, the type and amount of fuel used, stove usage time, time spent in the HRB, and the estimated time required to prepare the same dish without the HRB.

In total, we collected over 230 cooking observations. We estimate the impact of HRBs by comparing stove usage time with and without HRB across recipes. Results in Table A.1 indicate that HRBs reduce active cooking time by 68% on average per meal, and by 72% for beans. These estimates are consistent with manufacturers' claims that HRBs can reduce fuel use by up to 70%.[21]

[19] The aluminum HRB has notable drawbacks, including durability concerns (e.g., zipper failure after limited use) and fixed dimensions that limit compatibility with different pots.
[20] https://virunga.org/fr/support-us/donate/fallen-rangers-fund/
[21] The South African company *Wonderbag* claims the following on their retail webpage: "*Invest in a Wonderbag and reduce your energy consumption by up to 70%.*"

Table A.1: Heat retention bag prototypes test

	Obs.	Mean	Sd. Dev.	Min	Max
Ratio of active stove usage time with HRB to normal stove usage time	230	0.321	0.167	0.067	1.10
Ratio of active stove usage time with HRB to normal stove usage time - Beans only	35	0.281	0.185	0.067	1

B) APPENDIX B: Focus Group Discussion Guide

In this section, we describe the discussion guide used in the focus group discussion conducted after the end of the study, in August 2025. The FGD lasted around two hours and aimed to shed more light on usage patterns, constraints to adoption, and the extent to which the technology aligned with users' needs. The FGD was facilitated by our team in local Swahili and took place in Goma town. We invited five non-adopters and five households that regularly use the HRB (as measured through SUM data). Participants were rewarded for their participation with a portion of kidney beans and compensated for transportation costs.

Questions asked to all participants:

- *Have you changed your cooking habits since you received the HRB? For instance regarding the time at which you cook, or who in the household cooks?*
- *Are there features of the HRB that need to be improved? For instance the handles, the closing system, the shape, the type of foam, the construction, the fabric?*
- *How much do you think a HRB like this can cost, in $?*
- *How much would you be willing to pay for a HRB at the market here in Goma, in $?*
- *Have you noticed any interest from your neighbors and friends regarding the HRB?*
- *Would you recommend the HRB? To whom would you recommend it or not recommend it?*
- *Do you also use the HRB to keep food warm, as a thermos?*
- *Do you also use the HRB for other uses (pillow, crib, etc)?*

Questions asked to active users:

-*Why do you use the HRB, what are the advantages?*

- *Why do you not use the HRB more often? What limits its usage?*

- *For how many meals would you say you use the HRB each week?*

- *Have you noticed any change in your use of Makala since you received the bag?*

- *Does the HRB allow you to save time during the day? Why?*

- *For which recipes is the HRB well suited? For which meals is it not appropriate?*

Questions asked to non-users:

- *Why do you not use the HRB?*

- *Is it because the recipes you like cannot be cooked in the HRB, or taste bad? Or because of the way the HRB functions, with a lot of planifications? Or some other reason?*

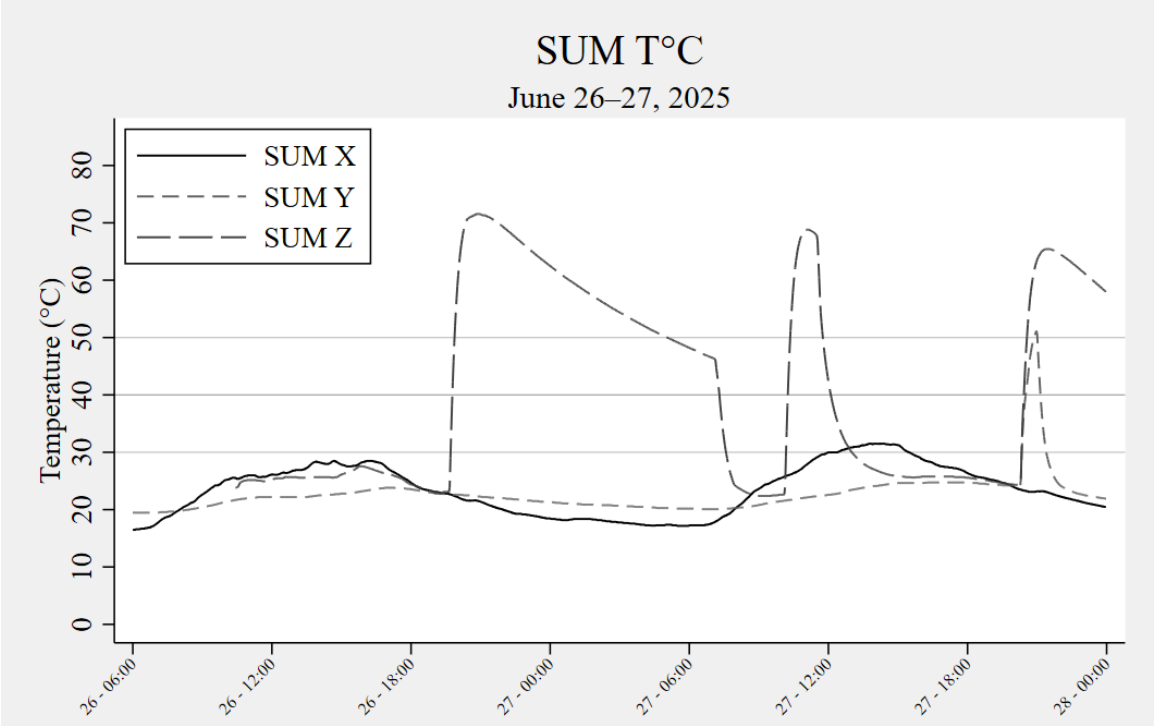
C) APPENDIX C: Usage event temperature threshold

We compare alternative temperature thresholds to define HRB usage based on SUM data. In the main specification, we use a 40°C cutoff to identify usage events.

Lower thresholds (e.g., 30°C) risk false positives, as the HRB may be warmed by ambient heat, sunlight, or human contact. Higher thresholds (e.g., 50–55°C) more reliably capture active cooking but underestimate usage duration, as SUM devices require time to register gradual temperature increases. Higher thresholds also reduce sensitivity to lower-temperature uses such as keeping food warm. The 40°C threshold provides a compromise between these concerns: it is sufficiently high to limit false positives while remaining sensitive to both cooking and warming uses, and better captures the duration of usage events.

Figure C.1. provides examples motivating the 40°C threshold. On June 27th, SUM X reaches 31°C through midday ambient heat alone, rendering a 30°C cutoff unreliable in the DRC climate. Conversely, applying a 50°C threshold to SUM Z reduces a 690-minute cooking event (taking place in the night of June 26th to June 27th) to 548 minutes, removing over two hours of recorded cooking time for a single event.

Figure C.1: T°C evolution - SUMs



As expected, measured usage decreases with higher temperature thresholds. Table C.1 shows that both the number of usage events and usage duration are highest with a 30°C threshold and lowest with a 55°C threshold.

Table C.1: Usage based on different temperature thresholds

	Average measured weekly usage events	Average daily usage minutes
55° usage cutoff	1.43	59.3
40° usage cutoff	1.94	86.6
30° usage cutoff	2.36	117.3

Table C.2: Main Results – 30°C threshold

	(1) Measured weekly usage events (SUM)	(2) Reported weekly usage events	(3) Measured daily usage (min)	(4) Daily ashes (kg)	(5) Weekly fuel expenditures ($)
HRB	2.485***	3.030***	121.774***	-0.041***	-1.468***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)
Pre-intervention mean	0	0	0	93.95	3.77
Observations	240	240	240	240	240

* p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses . All specifications include household fixed effects and wild cluster bootstrapped (999 reps) standard errors clustered at the household level. All models also account for household size.

Table C.3: Main Results – 50°C threshold

	(1) Measured weekly usage events (SUM)	(2) Reported weekly usage events	(3) Measured daily usage (min)	(4) Daily ashes (kg)	(5) Weekly fuel expenditures ($)
HRB	1.758***	3.030***	63.740***	-41.134***	-1.468***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)
Pre-intervention mean	0	0	0	93.95	3.77
Observations	240	240	240	240	240

* p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses . All specifications include household fixed effects and wild cluster bootstrapped (999 reps) standard errors clustered at the household level. All models also account for household size.

D) APPENDIX D: Main results without fixed effects

In this section, we report our main model (reported in Table 2) without household fixed effects. As shown in Table D.1, results are similar when household fixed effects are omitted, suggesting that time-invariant household characteristics do not materially bias our estimates.

Table D.1: Main results – no household fixed effects

	(1) Measured weekly usage events (SUM)	(2) Reported weekly usage events	(3) Measured daily usage (min)	(4) Daily ashes (g)	(5) Weekly fuel expenditures ($)
HRB, pot & lid bundle	2.03***	2.90***	89.34***	-38.10***	-1.41***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.004)*
Nb of people eating in the household (last 7d)	0.13*	0.11	4.06	6.41***	0.32***
	(0.075)	*(0.156)*	*(0.140)*	*(0.000)*	*(0.000)*
Pre-intervention mean	0.00	0.00	0.00	93.95	3.77
Observations	240	240	240	240	240

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include wild cluster-bootstrapped (999 reps) standard errors at the household level.*

E) APPENDIX E: SUM vs. Survey Measures of HRB Usage

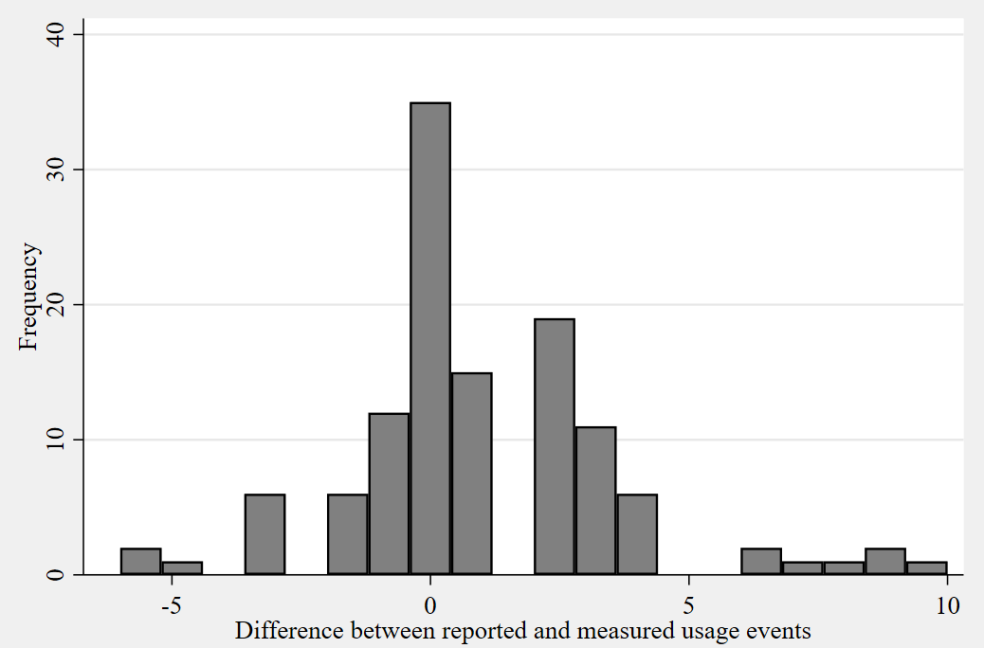
We compare the two measures of HRB usage used in the analysis: self-reported usage from survey data and measured usage derived from SUM data. The correlation between the two measures is 0.5, indicating moderate alignment. On average, self-reported usage exceeds SUM-measured usage by 0.88 events per week when using a 40°C temperature threshold to identify usage (Table E.1). Consistent with this, in the main specification (Table 2), the coefficient on self-reported usage is approximately 50% larger than that based on SUM data (3.030 vs. 2.065 weekly usage events). The difference between self-reported and measured usage is smaller when using a lower temperature threshold (30°C) to detect usage.

Table E.1 Difference between reported (survey) and measured (SUM)usage per T°C threshold

	Average difference: reported – measured usage events
55° usage cutoff	1.39
40° usage cutoff	0.88
30° usage cutoff	0.23

Figure E.1 plots the distribution of the difference between self-reported and SUM-derived weekly usage events. Self-reported usage exceeds measured usage in 58 out of 120 (48%) post-intervention household-week observations, while it is lower in 27 observations (22.5%). The fact that self-reported usage is higher on average suggests the presence of over-reporting, likely driven by social desirability bias.

Figure E.1 Distribution of the difference between reported (survey) and measured (SUM, 40°C threshold) weekly usage events (N = 120)



F) APPENDIX F: Marginal effects estimates

Table F.1 reports the marginal effects of an additional weekly HRB usage event on daily ashes (Column 1-3) and weekly fuel expenditures (Column 4-6). Table F.2 reports the marginal effects of an additional weekly HRB usage hour on daily ashes (Column 1-3) and weekly fuel expenditures (Column 4-6). In both tables, column 1 and 4 report raw data estimates, column 2 and 5 report estimates using explanatory variables top-coded at the 90th percentile (as in the main body of the paper), while column 3 and 6 report estimates based on usage variables top-coded at the 75th percentile.

Table F.1: Weekly usage events (SUM)

	(1) Daily ashes (g) raw data	(2) Daily ashes (g) 90th perc.	(3) Daily ashes (g) 75th perc.	(4) Weekly exp. ($) raw data	(5) Weekly exp. ($) 90th perc.	(6) Weekly exp. ($) 75th perc.
Usage events	-5.359***	-6.852***	-12.183***	-0.397***	-0.443***	-0.600***
	(0.005)	(0.001)	(0.000)	(0.000)	(0.000)	(0.002)
N	240	240	240	240	240	240
Pre-intervention avg.	93.95	93.95	93.95	3.77	3.77	3.77

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include household fixed effects and wild cluster bootstrapped standard errors clustered at the household level. All models also account for the number of people eating in the households in the last 7d.. Column 1 and 4 report raw data estimates, column 2 and 5 report estimates for usage events top-coded at the 90th percentile, as shown in the main body of this paper, while column 3 and 6 report estimates based on explanatory variables top-coded at the 75th percentile.*

Table F.2: Weekly usage hours

	(1) Daily ashes (g) raw data	(2) Daily ashes (g) 90th perc.	(3) Daily ashes (g) 75th perc.	(4) Weekly exp. ($) raw data	(5) Weekly exp. ($) 90th perc.	(6) Weekly exp. ($) 75th perc.
Usage hours	-0.762***	-0.984***	-1.819***	-0.071***	-0.089***	-0.139***
	(0.003)	(0.003)	(0.001)	(0.001)	(0.000)	(0.000)
N	240	240	240	240	240	240
Pre-intervention avg.	93.95	93.95	93.95	3.77	3.77	3.77

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include household fixed effects and wild cluster bootstrapped standard errors clustered at the household level. All models also account for the unmber of people eating in the households in the last 7d. Column 1 and 4 report raw data estimates, column 2 and 5 report estimates for usage hours top-coded at the 90th percentile, as shown in the main body of this paper, while column 3 and 6 report estimates based on explanatory variables top-coded at the 75th percentile.*

G) APPENDIX G: Categorical variable - Usage events

To assess whether the marginal 'effect' of HRB usage on our main outcomes is non-linear, we estimate a model in which weekly usage events (derived from SUM data) are coded as categorical rather than continuous. Because a small number of households occasionally account for unusually high numbers of usage events[22] - which could disproportionately influence estimates in our relatively small sample - we also recalculate the weekly usage count by top-coding all values above six usage events (top-coding at the 90th percentile, affecting 7.5% of post-HRB household-week observations), then all values above three usage events (top-coding at the 75th percentile, affecting 20.8% of post-HRB household-week observations). We then re-estimate the model using adjusted binary usage variables.

[22] Observations with more than four weekly usage events are sparse: we observe 4 household-week observations each for five, six, and seven weekly usage events, 2 for eight events, and 1 observation each for nine, ten, and twelve events.

We find that, relative to households with no HRB usage, two or three weekly usage events are associated with sizeable reductions in daily ashes production of 33 to 43g per day ($p<0.01$), corresponding to reductions in ashes of 35 to 45% (see Table G.1, column 1-3). These findings are robust even when capping outlier usage values (at the 75th and 90th percentile). The relationship between HRB usage and weekly fuel expenditures follows a similar pattern: while estimates for one or two usage events are imprecisely estimated, households reaching three weekly usage events exhibit reductions in expenditures of about \$1.43 to \$2.11, equivalent to approximately 38 to 56% less than their pre-intervention expenditures (\$3.7) (see Table G.1, column 4-6). The coefficients of the binary variables for two and three weekly usage events are very similar in magnitude to the treatment bundle estimate in our main specification (Table 2), consistent with the predominant usage pattern in our sample, whereby households use the HRB two to three times per week to prepare staple foods. Coefficients of binary variables above four weekly usage events are imprecisely estimated but also suggest a negative relationship between HRB usage and charcoal consumption.

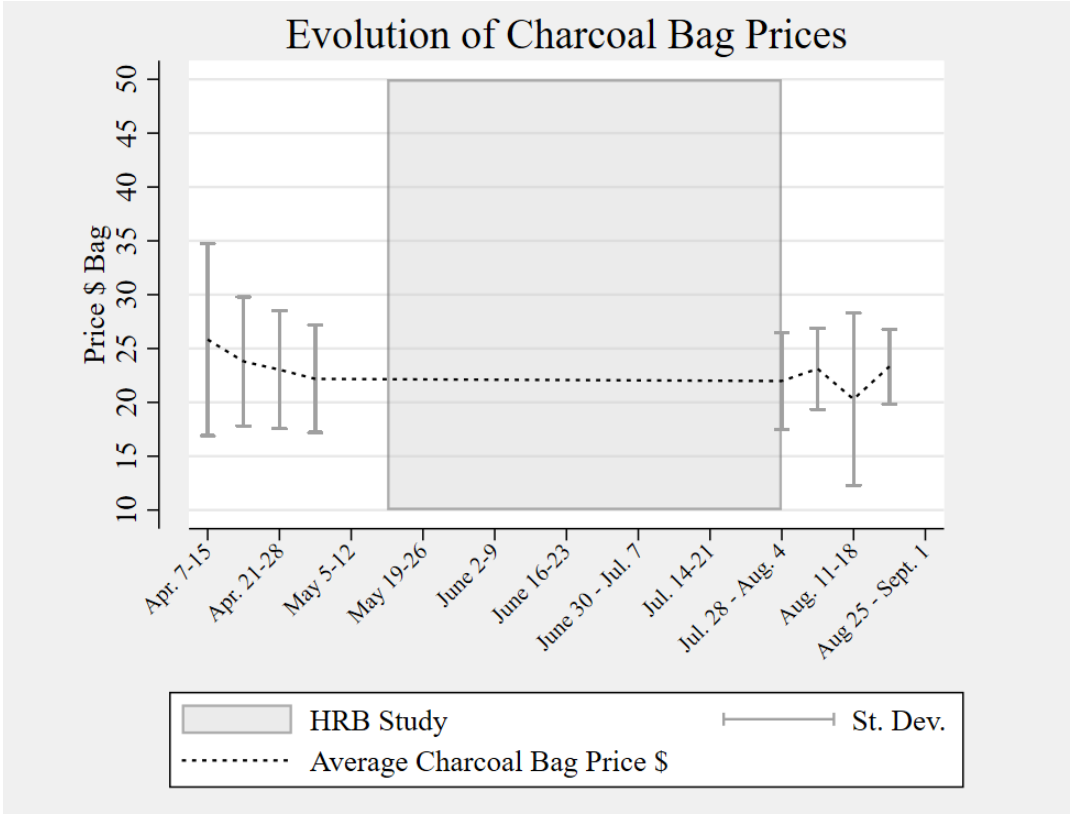
Table G.1: Categorical usage events

	(1) Daily ashes (g) raw data	(2) Daily ashes (g) 90th perc.	(3) Daily ashes (g) 75th perc.	(4) Weekly exp. (\$) raw data	(5) Weekly exp. (\$) 90th perc.	(6) Weekly exp. (\$) 75th perc.
1 usage/week	-19.569*	-19.508**	-18.872*	-0.262	-0.305	-0.329
	(0.053)	(0.049)	(0.052)	(0.767)	(0.728)	(0.705)
2 usage/week	-41.775***	-41.715***	-41.122***	0.438	0.375	0.352
	(0.003)	(0.003)	(0.002)	(0.863)	(0.881)	(0.887)
3 usage/week	-42.546***	-42.439***	-32.550***	-1.428***	-1.476***	-2.113***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
4 usage/week	-36.385**	-36.655**		-2.060**	-2.196***	
	(0.050)	(0.046)		(0.012)	(0.005)	
5 usage/week	-29.976***	-28.087***		-2.710***	-2.819***	
	(0.000)	(0.000)		(0.002)	(0.001)	
6 usage/week	-15.204	-19.969		-1.863***	-2.569***	
	(0.620)	(0.157)		(0.000)	(0.002)	
N	240	240	240	240	240	240
Pre-intervention avg.	93.95	93.95	93.95	3.77	3.77	3.77

** p<0.10, ** p<0.05, *** p<0.01. p-values in parentheses. All specifications include household fixed effects and wild cluster bootstrapped standard errors clustered at the household level (999 reps). All models also account for household size. For column 1 and 4, we report coefficients of binary variables equal to one for one to six weekly usage events, but the model accounts for more usage events categories. In column 2 and 5, we top-coded the number of usage events at six (90th percentile). We replicate the same procedure in column 3 and 6, using a different threshold (75th percentile ~three usage events)*

H) APPENDIX H: Charcoal Prices

Figure H.1: Evolution of Charcoal Prices over the Study Period



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