From the Hearth to the Farm: Experimental Evidence on Improved Cookstoves and Women's Economic Empowerment

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Abstract

We present experimental evidence on the impact of improved cookstoves on household biomass management and women's economic empowerment in rural Ethiopia. Households were randomly assigned to receive a Mirt improved cookstove—shown to reduce fuelwood consumption by 50% and indoor air pollution by 90% under laboratory conditions—or a value-equivalent bag of wheat flour. Fifteen months after distribution, treated households reduced monthly firewood consumption by 35.5% and fuelwood collection time by 40.8%. We document a novel resource substitution effect: treated households applied 108% more animal dung as manure and 135% more crop residue as livestock fodder, reallocating organic inputs from the hearth to the farm. Women in treated households—who bear near-exclusive responsibility for fuel collection and cooking—were 12.5 percentage points more likely to participate in farming and 27.6 percentage points more likely to engage in poultry and livestock management. We find no significant effects on men's time allocation, confirming that the productivity gains are gender-specific. These results suggest that the social returns to clean cooking technologies significantly exceed their private returns, and that standard cost-benefit analyses omit important productivity gains accruing to women.

JEL Classification: D12, O12, O13 Q53, Q54.

Keywords: Improved cookstoves, women's empowerment, time allocation, biomass reallocation, randomized controlled trial, energy poverty.

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1. Introduction

Women in low-income settings bear a disproportionate and well-documented burden of unpaid domestic labor. A large body of empirical evidence shows that, relative to men, women in developing countries spend substantially more time on household chores—including fetching water and fuel, cooking, and caring for children—while facing systematic disadvantages in access to assets, education, and economic opportunity (Duflo, 2012; Jayachandran, 2015; Alonso et al., 2019). In rural sub-Saharan Africa in particular, women's lower socioeconomic status is reinforced by entrenched gender norms that restrict land ownership, inheritance rights, and participation in household financial decisions (Harari, 2019; Goldstein and Udry, 2008). Time-use studies consistently reveal that women in developing countries devote two to three times as many hours per day as men to unpaid domestic work, with the burden particularly acute in rural areas where access to labor-saving infrastructure is limited (Charmes, 2019; Hyde et al., 2020). Because the opportunity cost of this domestic drudgery is foregone market and agricultural production, this "time poverty" represents a significant constraint on women's economic agency and household welfare more broadly (Asian Development Bank, 2014; Khanna and Thomas, 2024). Technologies that reduce the time and effort demands placed on already overburdened women therefore have the potential to generate welfare gains that extend well beyond the direct user—to children, the household, and the community at large. Studying the impact of such technologies on women's time allocation is, consequently, a matter of considerable global importance, precisely because the social return on investment will typically exceed the private return.

In this paper, we investigate the impact of a household durable technology with significant private returns for women and households, and social returns in the form of environmental improvement. We distributed improved cookstoves (ICS) to a randomly assigned treatment group of rural households in the Tigray region of Northern Ethiopia and measure their impact on biomass fuel consumption, fuel reallocation, and women's time allocation 15 months after distribution. To ensure that our results are driven by the technology itself rather than a simple income effect, the control group received a bag of wheat with a comparable market value. In the study context, almost all households cook over a traditional three-stone open fire, which wastes nearly 90% of the heat energy it generates (Plan and Finance, 2011; Mekonnen et al., 2022). Cooking over an open flame exposes women to burns and chronic smoke inhalation, while trapping them in a cycle of domestic drudgery that limits their economic agency. The improved stove we distributed—the "Mirt" stove—primarily used to bake *injera*, the key staple consumed in the region reduces fuelwood consumption by 50%, protects the cook from direct flame exposure, and reduces indoor smoke and particulate matter by 90%.[1] Because it reduces the fuel required for cooking and features a side chamber for the simultaneous preparation of sauces or coffee, the stove saves both fuelwood collection time and cooking time. As in Ethiopia nearly 100% of cooking and the large majority of fuelwood collection are performed by women, these gains accrue disproportionately to them.[2]

[1]See `http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm` for a technical description of the Mirt stove. At the time of the fieldwork, the stove sold for 150 Ethiopian Birr (ETB), approximately USD 7.50, at regional markets; however, households in the study area had no prior knowledge of or exposure to the technology. See Figure 9 in Section 4.4 for a picture of the stove taken during the field demonstration.

[2]In many developing countries, children also benefit from reduced collection time and lower indoor air pollution, as they are frequently present in the kitchen during cooking and girls, in particular, participate

Our results reveal a transformative shift in household resource management. First, the treatment group consumed 35.5% less firewood than the control group fifteen months after the stoves have been distributed. More strikingly, the ICS generated a novel *resource substitution effect*: as firewood demand fell, households diverted organic fuels—specifically animal dung and crop residues—away from the hearth and toward their highest-value agricultural uses. Treatment households applied 108% more manure to their farms and utilized 135% more crop residue as animal fodder compared to the control group. These findings represent a "double dividend": the technology simultaneously reduces toxic indoor emissions and promotes soil fertility and livestock productivity, two outcomes not previously documented together in the ICS literature.

Second, we test the hypothesis that liberating women from the hearth enables them to reclaim their time for productive pursuits. Consistent with this hypothesis, we find that women in the treatment group were 12.5 percentage points more likely to participate in farming and 27.6 percentage points more likely to participate in poultry and livestock management. We find no significant effects on wage labor, handicraft production, or small business participation. We argue that this "time windfall" is channeled into farming and livestock because these activities utilize the household's existing assets and carry low barriers to entry—in contrast to thin and rationed local labor markets, where participation in off-farm employment and non-agricultural enterprise requires access to capital, specialized skills, and established markets that most sample households lack (Berhane et al., 2014; Debela et al., 2015; Alem and Broussard, 2017). Crucially, we find no significant effects on men's time allocation across any activity category, confirming that the direct productivity gains of this technology are gender-specific. The results on time allocation of women pass multiple hypothesis testing (MHT) corrections and remain robust.

The key mechanisms explaining the large effects on women's time allocation are time savings in fuelwood collection and cooking. Because of its superior combustion design, the Mirt stove reduced fuelwood consumption among the treatment group by 35.5%, directly reducing collection time as households require less fuel to bake the same quantity of staple food. Consistent with this, treatment households spent 40.8% fewer hours per month on fuelwood collection. Beyond fuel efficiency, a key attribute of the stove is its ability to facilitate multi-tasking: while baking *injera*, the cook can simultaneously prepare sauces or boil coffee on the side chamber, generating substantial reductions in total cooking time. Consistent with this mechanism, women in the treatment group reduced their daily cooking time by 19.9% relative to women in the control group.

This paper contributes to two strands of the economics literature. We speak first to the growing body of work on technology adoption and its welfare consequences in low-income settings. A substantial experimental literature documents that improved and modern cooking technologies reduce household biomass consumption (Bensch and Peters, 2015; Gebreegziabher et al., 2018) and, in some settings, cooking time (Krishnapriya et al., 2021). However, a landmark randomized study by Hanna et al. (2016) found that stove usage declined sharply over time in rural India, as households failed to maintain the technology and reverted to open-fire cooking—a reminder that field impacts can diverge substantially from laboratory performance. Our study contributes to this debate by documenting sustained impacts 15 months post-distribution in an Ethiopian context, and by showing that the Mirt stove's purpose-built design for *injera* baking—the dominant cooking task in the region—is central to sustaining high usage intensity. More importantly, by showing that

in fuelwood collection at the expense of time in school (WorldBank, 2011).

ICS adoption leads to increased application of animal dung as manure and crop residue as fodder, we provide, to the best of our knowledge, the first experimental evidence on the productive reallocation of secondary biomass resources—a benefit entirely absent from existing cost-benefit frameworks for clean cooking technologies.

We also contribute to the broader literature on women's empowerment and intra-household resource allocation. In many developing regions, women face systemic barriers to economic agency, including lower bargaining power over household financial decisions and restricted access to productive assets (Duflo, 2012; Jayachandran, 2015). Experimental evidence shows that men, who often control household finances, may under-invest in technologies that primarily benefit women (Miller and Mobarak, 2013; Alem et al., 2023)—a distortion with significant implications for household welfare and technology diffusion. By demonstrating that the Mirt stove enables women to shift time from domestic drudgery to productive agricultural roles, we show that clean energy technology can serve not only as an environmental solution, but as a direct vehicle for gender equity and rural development. This finding reinforces calls to integrate energy interventions with agricultural extension programs and targeted female empowerment initiatives, so that the labor liberated by technological efficiency can be channeled into the highest-return productive activities available to rural households.

The rest of the paper is organized as follows. Section 2 lays out a theoretical framework that motivates the experiment and the empirical hypotheses. Section 3 presents the experimental design, descriptive statistics, and tests of covariate balance. Section 4 presents the main treatment effects, the mechanisms through which the intervention affects the outcome variables, and the scope for future research. Section 5 concludes.

2. Conceptual Framework

To motivate our empirical analysis, we formulate a microeconomic framework that captures the trade-offs in time and resource allocation following a technological shock. Following the convention, we model the farm household as a utility-maximizing unit in a setting characterized by "missing" or thin markets, where production and consumption decisions are non-separable (de Janvry et al., 1991). The household maximizes utility derived from consumption (C), leisure (L), and the health status of its members (H):

$$U = U(C, L, H) \tag{1}$$

Consistent with the gendered division of labor in low income setups (Cooke et al., 2008; Ashraf, 2009; Charmes, 2019; Hyde et al., 2020), the woman (wife) is the primary agent responsible for domestic activities, such as fuel fetching and food preparation. Her total time endowment T is divided across four activities: cooking time (T_c), fuelwood collection time (T_f), productive household and income-generating activities (T_O), and leisure (L):

$$T = T_c + T_f + T_O + L \tag{2}$$

The introduction of the Mirt improved cookstove (ICS) represents a labor-saving and fuel-saving technological shock (τ). Compared to the traditional three-stone fire, the ICS improves thermal efficiency by a factor $\gamma \in (0, 1)$, which reduces the time required per meal. If a household prepares N meals, the time saving in cooking is:

$$\Delta T_c = T_c^{3S} - T_c^{ICS} = \gamma N t_c \tag{3}$$

Furthermore, since fuelwood requirements are proportional to cooking duration ($F = \mu T_c$) and collection time is a function of fuel volume ($T_f = \eta F$), the ICS generates a secondary "time windfall" in fuel procurement:

$$\Delta T_f = \eta\mu\gamma N t_c \tag{4}$$

In a setting with perfectly competitive labor markets, this liberated time ($\Delta T = \Delta T_c + \Delta T_f$) would be supplied as wage labor at the prevailing market wage w. However, given the high transaction costs and rationing in off-farm employment in the study context (Bhatta and Årethun, 2013; Berhane et al., 2014), the household reallocates this labor into activities with the highest internal marginal productivity. Following de Janvry et al. (1991), the household intensifies production on its primary existing assets—land and livestock—where labor elasticity is high and entry barriers are minimal:

$$\Delta T \rightarrow \Delta T_O + \Delta L \tag{5}$$

Beyond time, we hypothesize a novel *resource substitution effect*. As the ICS reduces the demand for firewood, the household can divert alternative biomass—animal dung (D) and crop residues (R)—away from the hearth and toward their most productive agricultural uses: dung as manure for soil fertility and crop residues as animal fodder. Consequently, household agricultural income (Y) increases:

$$Y = P \cdot f(T_O, D, R) \tag{6}$$

where P is the price of output. Finally, by reducing exposure to indoor air pollution (A), the ICS improves health outcomes (H), where $\partial H/\partial A < 0$ (Duflo, 2012). Taken together, the model predicts that $U^{ICS} > U^{3S}$ because the technology relaxes the woman's time constraint, increases agricultural productivity through biomass reallocation, and improves welfare through health and leisure.

3. Experimental Design

3.1. Context

The study was conducted in the Tigray region of Northern Ethiopia, encompassing three primary agro-ecological zones: *Dega* (highland), *Woynadega* (midland), and *Kola* (lowland). These zones exhibit significant spatial variation in biomass availability and forest density, creating a natural gradient in the shadow price of fuelwood. In areas of high scarcity, women—who bear near-exclusive responsibility for fuel collection and cooking—often travel up to 30 km per trip, a task frequently performed alongside childcare. In contrast, households in high-access zones travel an average of 6 km (Plan and Finance, 2011). This environmental variation provides a robust setting to analyze how the elasticity of women's time-use responds to a labor-saving technological shock across differing resource constraints.

The institutional landscape for clean cooking in Ethiopia has been characterized by several cycles of dissemination efforts since the 1980s. However, adoption has historically been hindered by technical durability issues and negative household perceptions regarding stove utility (Plan and Finance, 2011). We focus on the "Mirt" stove, a second-generation biomass technology specifically designed for baking *injera*, a process that accounts for over 50% of household primary energy demand (World Bank, 2015). While laboratory trials indicate that the Mirt stove reduces fuelwood consumption by 50% and particulate matter by 90%, field-based adoption remains puzzlingly low, with rates in the Tigray region estimated at less than 1% (Plan and Finance, 2011; Bluffstone et al., 2019; Mekonnen et al., 2022). At the time of the baseline survey (July 2013), the stove was priced at 150 Ethiopian Birr (ETB), or approximately 7.50 USD. This low take-up, despite high theoretical returns to efficiency, presents a classic development puzzle regarding the barriers to adopting welfare-enhancing technologies.

3.2. Sampling, Treatments, and Data Collection

Our experimental sample consists of 295 households drawn from six villages (*kushets*) in the Tigray region: Boye, Hergbeda, Adimengesha, Teklehaimanot, Barsale, and Hadiskignt. These villages were selected because the second-generation "Mirt" stove technology had not yet been introduced. To ensure balance across local environmental and market conditions, we employed a stratified randomization strategy at the village level. Within each village, households were randomly assigned to either the treatment group ($N = 147$) or the control group ($N = 148$). An additional six villages in the region were assigned to a separate purchase experiment using the Becker-Degroot-Marschak (BDM) mechanism; however, these villages are geographically distant from our RCT sites, effectively ruling out cross-village spillovers or information contamination.

Prior to implementation, the research protocol was evaluated and approved by the Environment for Development (EfD) Network's Research Committee.[3] To isolate the technological impact of the stove from a pure wealth effect, we utilized an active control group: while the treatment group received the Mirt stove (valued at 150 ETB or 7.50 USD), the control group received a bag of wheat of equivalent market value. This design ensures that any observed shifts in labor allocation are driven by the stove's technical efficiency rather than a positive income shock.

The baseline survey was conducted between July and October 2013, followed by a follow-up survey 15 months later (January–February 2015). We focus on three sets of outcomes: (i) biomass consumption; (ii) the application of organic fertilizers; and (iii) participation in five productive activities (farming, wage labor, handicrafts, livestock, and small business). Given the challenges of recall reliability for labor hours in rural subsistence settings, these productive activities are measured as binary outcomes (participation over the previous 12 months). However, for the primary mechanisms of interest—fuelwood collection and cooking—we collected continuous daily hour data to quantify the specific labor-saving potential of the technology.

3.3. Statistical Power Analysis

The randomization for this study was implemented at the household level. To determine the required sample size to detect meaningful shifts in energy consumption and time-use, we conducted power calculations based on a one-month pilot study of 25 households in the Tigray region. In the pilot, the control group exhibited a mean monthly fuelwood consumption of 140 kg ($\sigma = 45$), while the treatment group consumed 120 kg ($\sigma = 55$).

Under the assumptions of 80% power and a 5% significance level, the sample size required to detect a 20% reduction in fuel consumption is 202 households (101 per treatment arm). This 20% target is a conservative threshold; for context, Gebreegziabher et al. (2018)

[3]Following committee approval, the project was registered and hosted on the EfD initiative website: `https://www.efdinitiative.org/projects`.

find that improved stoves in Ethiopia reduce fuel consumption by 22% to 31% in similar field settings. Our final experimental sample of 295 households ($N_T = 147, N_C = 148$) exceeds this requirement, providing a sufficient buffer to identify the hypothesized effect size and accounting for the potential higher variance often found in time-use data compared to physical fuel measurements.

3.4. Descriptive Statistics and Randomization Balance

Table 1 reports the baseline summary statistics for the 295 households in our experimental sample. The data reveal a setting characterized by significant human capital and resource constraints, typical of rural subsistence communities in Northern Ethiopia. The average household head is 45 years old with only 1.6 years of formal schooling, suggesting limited outside labor market opportunities. Households are moderately sized, with an average of 4.1 members, and rely heavily on livestock (6.8 TLU) and small-scale landholding (3.2 tsimads or 0.8 ha) for their livelihoods.[4] Of particular importance to our research hypothesis is the baseline time-use burden: women spend an average of 39.5 hours per month collecting fuelwood and over 3.4 hours per day on cooking-related tasks. This substantial labor allocation to domestic energy procurement confirms that the study population faces significant "time poverty," providing a meaningful context for testing the impact of a labor-saving technological intervention.

The internal validity of our experimental design is supported by the randomization balance results presented in the final column of Table 1. We find no statistically significant differences between the treatment and control groups across any of baseline covariates, including demographic characteristics, asset holdings, and—most crucially—baseline levels of the primary outcome variables. For instance, the difference in monthly firewood consumption between groups is negligible (1.5 kg, $p > 0.10$), and the baseline participation rates in productive activities such as wage labor and handicrafts are nearly identical. To ensure the robustness of these results, we performed both two-tailed t-tests for equality of means and Wilcoxon rank-sum tests to account for potential non-normality in skewed variables like asset value and fuel consumption; both approaches yield consistent results. The lack of significant differences across all measured dimensions suggests that the randomization was successful and that the control group—which received a value-equivalent bag of wheat to isolate income effects—provides a valid counterfactual for the treatment group.

Table 1 also presents descriptive statistics on stove use among treatment households, which serve as an important indicator of compliance with the intervention. Compliance is of particular relevance in our context, as the stoves were distributed free of charge — a design feature that, while maximizing uptake, also raises the possibility that some households may have accepted the stove without integrating it into their regular cooking practices. The results are reassuring: on average, treatment households report having used the stove for 7.6 months at the time of the endline survey. The binary stove use indicator confirms that 84% of treatment households used the stove for at least one month, with the remaining 16% classified as non-compliant. Taken together, these statistics suggest a high level of sustained engagement with the technology, consistent with the Mirt stove's purpose-built design for *injera* baking — the dominant and most time-intensive cooking task in the study context — which provides a strong functional incentive for continued use. As our primary estimates are based on an Intent-to-Treat (ITT) framework, the presence

[4] 1 tsimad = 0.25 ha

of 16% non-compliers implies that the ITT estimates represent a lower bound of the true technological impact among households that fully adopted the stove.

Table 1: Baseline Summary Statistics and Randomization Balance

Variable	Full Sample (N=295)	Treatment (N=147)	Control (N=148)	Difference (T − C)
Panel A: Individual and Household Covariates				
Age (years)	45.37	44.86	45.87	−1.01
	(12.01)	(11.84)	(12.19)	(1.40)
Years of Schooling	1.62	1.74	1.51	0.23
	(2.28)	(2.10)	(2.45)	(0.26)
Works Off-farm (binary)	0.35	0.32	0.37	−0.05
	(0.48)	(0.47)	(0.49)	(0.06)
Household Size	4.09	4.17	4.01	0.16
	(1.50)	(1.51)	(1.50)	(0.17)
Asset Value (1,000 ETB)	33.11	33.11	33.11	0.00
	(31.63)	(30.85)	(32.49)	(3.69)
Livestock (TLU)	6.84	6.60	7.07	−0.47
	(3.87)	(4.05)	(3.69)	(0.45)
Land Size (Tsimad)	3.22	3.36	3.08	0.27
	(2.07)	(2.11)	(2.04)	(0.24)
Log of Trees	1.38	1.40	1.35	0.06
	(1.53)	(1.37)	(1.68)	(0.18)
Panel B: Baseline Fuel Consumption (Monthly) and Stove Use				
Firewood Consumed (kg)	129.80	129.10	130.60	−1.50
	(48.55)	(50.49)	(46.70)	(5.66)
Dung Applied as Manure (kg)	1.86	2.02	1.69	0.33
	(3.44)	(3.39)	(3.49)	(0.40)
Crop Residue as Fodder (kg)	23.85	24.67	23.04	1.63
	(14.52)	(12.23)	(16.48)	(1.69)
Months Stove in Use	—	7.57	—	—
		(4.53)		
Any Stove Use (binary)	—	0.84	—	—
		(0.37)		

Continued on next page...

Table 1 *(Continued)*

Variable	Full Sample (N=295)	Treatment (N=147)	Control (N=148)	Difference (T − C)
Panel C: Baseline Women's Time Allocation				
Firewood Collection (hrs/month)	39.45	40.21	38.70	1.51
	(32.49)	(35.19)	(29.68)	(3.78)
Daily Cooking Time (hrs/day)	3.44	3.46	3.41	0.05
	(0.76)	(0.71)	(0.80)	(0.09)
Farming (binary)	0.23	0.25	0.22	0.03
	(0.42)	(0.43)	(0.42)	(0.05)
Wage Labor (binary)	0.21	0.20	0.21	−0.01
	(0.41)	(0.40)	(0.41)	(0.05)
Handicrafts (binary)	0.10	0.09	0.11	−0.02
	(0.30)	(0.29)	(0.31)	(0.03)
Poultry & Livestock (binary)	0.11	0.11	0.11	0.00
	(0.31)	(0.31)	(0.31)	(0.04)
Small Business (binary)	0.06	0.06	0.06	0.00
	(0.24)	(0.24)	(0.24)	(0.03)

Notes: This table reports baseline summary statistics for the 295 households, stratified by treatment assignment. Column (1) presents means for the pooled sample. Columns (2) and (3) report means for the treatment and control groups, respectively, with standard deviations in parentheses. Column (4) displays the difference in means (T − C) with standard errors in parentheses. Statistical significance is based on two-tailed t-tests. To address potential non-normality in continuous variables, p-values from Wilcoxon rank-sum (Mann-Whitney) tests were also computed; results are consistent across both methods for all covariates. Stove use statistics are reported for the treatment group only, as these variables are not applicable to the control group. 1 Tsimad = 0.25 ha. TLU = Tropical Livestock Unit. ETB = Ethiopian Birr. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4. Results

4.1. Empirical Strategy

To identify the causal impact of the clean cooking intervention, we utilize an **Intent-to-Treat (ITT)** framework. All treatment households adopted the stoves (with zero non-compliance). The 100% adoption is understandable given the study context: the households in our sample are from a low-socioeconomic-status rural community, and the Mirt stove—which carries a meaningful market value, is technically superior to the traditional three-stone fire, and was offered free of charge—provided a compelling incentive for uptake. However, as shown in Table 1, only 84% of the treatment households used the stove, with the remaining 16% not using it at all. Since randomization was conducted at the household level and there is some non-compliance to treatment, the ITT estimator provides an unbiased estimate of the average effect of being offered the technology.

We estimate the primary treatment effect using the following specification:

$$Y_{i,v,1} = \alpha + \beta T_{i,v} + \mathbf{X}'_{i,v,0}\gamma + \eta_v + \epsilon_{i,v} \tag{7}$$

where:

- $Y_{i,v,1}$ is the outcome of interest for household i in village v measured at follow-up.
- $T_{i,v}$ is a binary indicator equal to 1 if the household was randomly assigned to the treatment group and 0 otherwise.
- $\mathbf{X}_{i,v,0}$ is a vector of household-level baseline covariates included to improve the precision of the estimates.
- η_v represents **village fixed effects**, which control for unobserved time-invariant village-level characteristics, effectively ensuring that the treatment effect is identified through within-village comparisons.
- $\epsilon_{i,v}$ is the idiosyncratic error term.

The coefficient of interest is β, representing the average treatment effect. Since randomization was performed at the household level, we utilize **robust standard errors** to account for potential heteroskedasticity in the error terms.

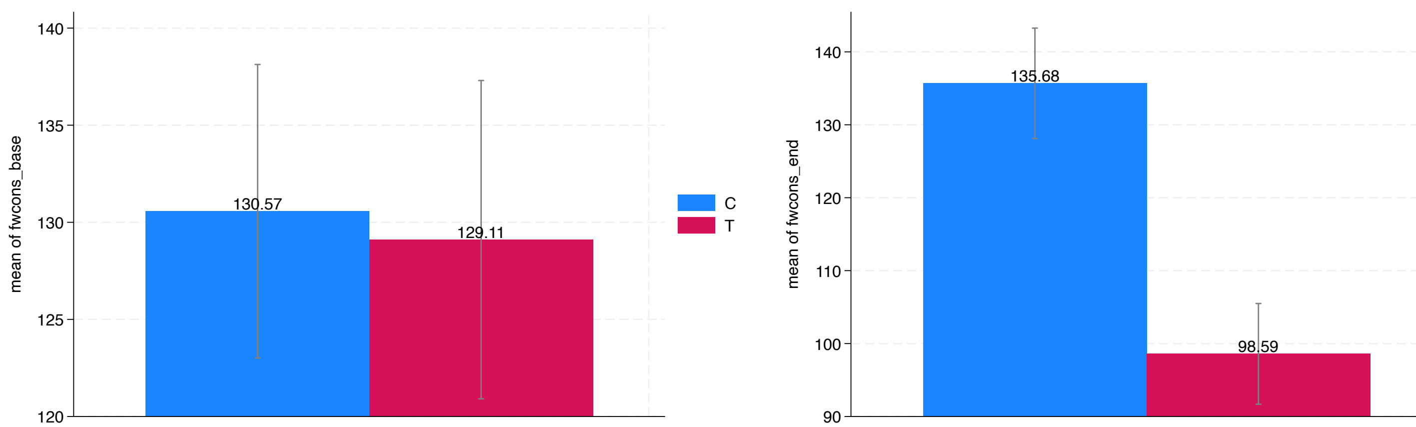
Multiple Hypothesis Testing. When a study tests many outcome variables simultaneously, the probability of rejecting at least one true null hypothesis by chance alone increases rapidly with the number of hypotheses tested—a problem known as familywise error rate inflation. In such settings, it is standard practice to apply multiple hypothesis testing (MHT) corrections to guard against spurious discoveries (Benjamini and Hochberg, 1995; Anderson, 2008). Our analysis examines outcomes across three families: biomass consumption and reallocation (Table 2), women's time allocation (Table 3), and the mechanisms of fuelwood collection and cooking time (Table 4). We do not apply MHT corrections to the biomass outcomes or the mechanism outcomes for two reasons. First, these outcomes are *primary* and *pre-specified*: the central hypothesis of the study is that the Mirt stove reduces firewood consumption, and the collection and cooking time variables are the direct mechanical pathways through which this reduction occurs. Testing a small number of pre-specified primary outcomes does not generate the multiple comparisons problem that MHT corrections are designed to address (List et al., 2019). Second, the direction and magnitude of the expected effects on these outcomes are tightly disciplined by the conceptual framework in Section 2, further reducing the risk of spurious discoveries. In contrast, we test five women's time allocation outcomes simultaneously in Section 4.2, where the concern about false discoveries is more relevant. We therefore apply the Benjamini-Hochberg false discovery rate correction (Benjamini and Hochberg, 1995) to this family of outcomes, following standard practice in randomized experiments (Anderson, 2008). The adjusted q-values are reported alongside the unadjusted p-values.

4.2. Firewood and Other Fuel Use

We begin the presentation of results with a mean comparison of firewood consumption and the agricultural application of animal dung (manure) and crop residue (fodder) between treatment and control groups at baseline and endline. The primary hypotheses tested are: (i) whether access to an improved cookstove (ICS) reduces firewood consumption; and (ii) whether households redirect solid fuels—specifically animal dung and crop residue—from the kitchen to the farm once firewood demand is reduced.

Figure 1 illustrates the monthly mean comparisons for firewood consumption. At baseline, randomization successfully yielded balanced groups, with the control and treatment groups consuming 130.57 kg and 129.11 kg, respectively. By the endline, a significant divergence emerged: while the control group's consumption remained relatively stable at approximately 135.68 kg, the treatment group reduced consumption to 98.59 kg—a descriptive reduction of roughly 27.3%.

Figure 1: Firewood Consumption: Baseline and Endline



Notes: This figure presents monthly mean firewood consumption in kg for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Column 1 of Table 2 reports the formal intent-to-treat (ITT) estimates for firewood consumption. The specification includes baseline covariates, village fixed effects, and robust standard errors. The results show that treated households reduced firewood consumption by 35.4% ($p < 0.01$). This reduction is consistent with the findings of Gebreegziabher et al. (2018), who documented savings of 22%–31% for the "Mirt" stove in similar Ethiopian contexts. Notably, our field-based estimates are more conservative than the 50% reduction typically reported in laboratory settings, likely reflecting the real-world usage intensity and "stacking" behaviors described in our conceptual framework. Consistent with recent longitudinal evidence, we find that these fuel savings represent a significant shift in household energy dynamics (Mekonnen et al., 2022).

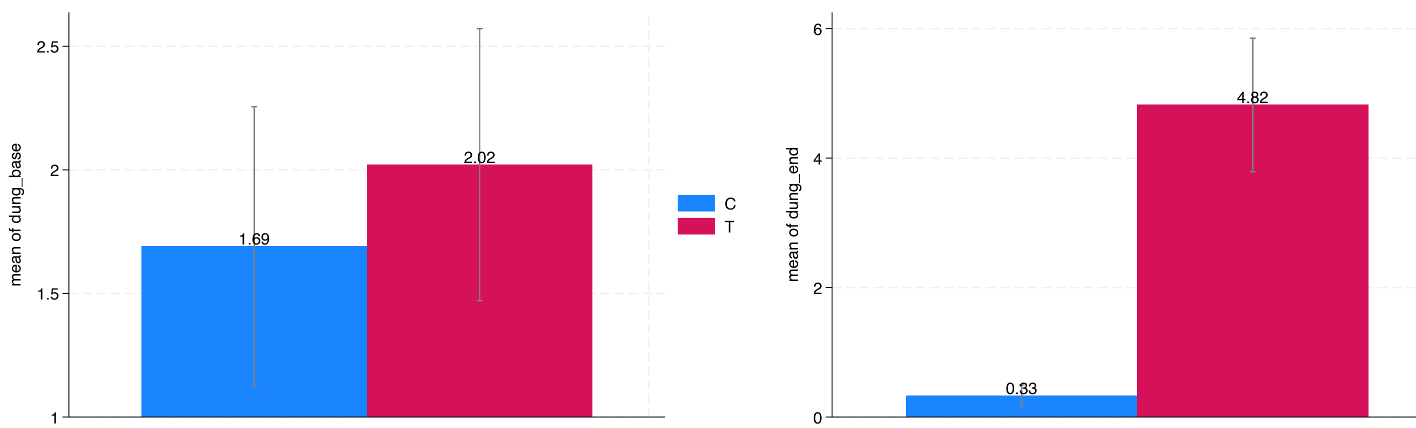
The Energy-Agriculture Nexus: Biomass Redirection. Beyond primary woodfuel, rural households in Ethiopia frequently rely on other solid fuels, particularly in woodfuel "hotspots" where the fraction of non-renewable biomass (fNRB) is high.[5]

To track the redirection of these organic materials to the farm, we present descriptive shifts in Figures 2 and 3. At baseline, dung application and fodder use were low and balanced across groups. By the endline, however, the treatment group's manure application rose to 4.82 kg, while the control group's use fell to 0.33 kg. Similarly, the use of crop residue for fodder increased from approximately 24 kg at baseline to over 50 kg for the treatment group at endline.

[5]The fNRB represents the ratio of wood harvested in excess of the incremental growth rate to the total harvest. In Ethiopia, high scarcity often necessitates the use of dung and crop residues as fuel supplements (Bailis et al., 2015; Alem et al., 2014).

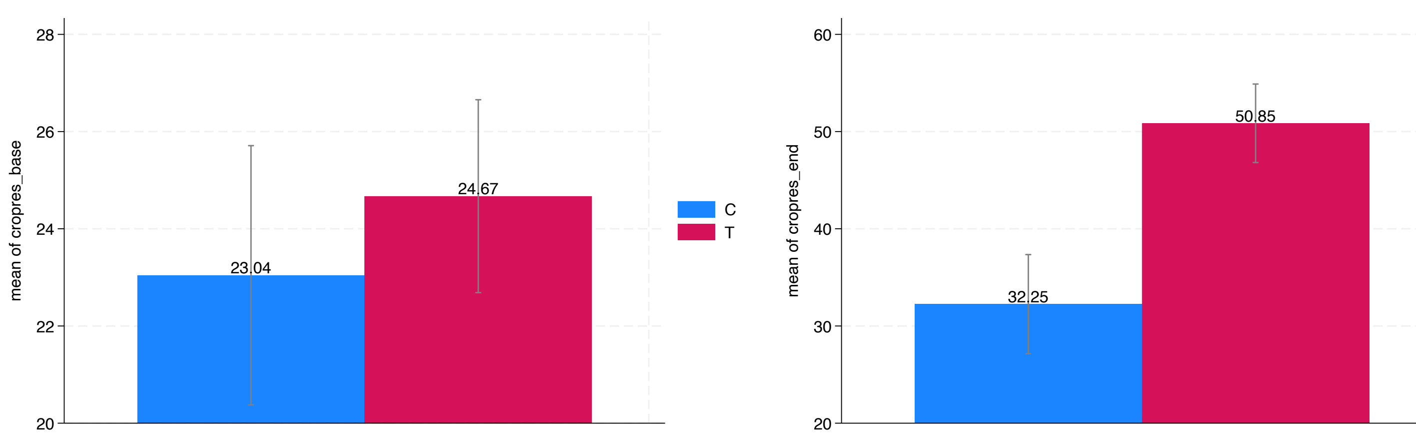
Columns 2 and 3 of Table 2 provide the formal econometric evidence for this redirection. The ITT results suggest that the treatment group applied 108.2% more manure on their farms ($p < 0.01$) and utilized 135.5% more crop residue for fodder ($p < 0.01$) compared to the control group. These findings have profound implications for sustainable agriculture. By reducing the need to burn dung and residues for energy, the Mirt stove effectively acts as a productivity-enhancing input. This "positive stacking" allows households to improve soil fertility and livestock quality—indirect benefits that significantly bolster the social return on investment for clean cooking technologies.

Figure 2: Animal Dung Use on Farm: Baseline and Endline



Notes: This figure presents monthly mean dung use in kg for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 3: Crop Residue Use for Animal Feeding: Baseline and Endline



Notes: This figure presents monthly mean crop residue use in kg for animal feeding for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Table 2: Impact on Household Fuelwood Use - ITT Effects

	(1) Fuel Cons	(2) Manure	(3) Fodder
Treated	-0.354***	1.082***	1.355***
	(0.048)	(0.099)	(0.186)
Controls	Yes	Yes	Yes
Village fixed effects	Yes	Yes	Yes
R-squared	0.21	0.33	0.19
Observations	295	295	295

Notes: This table presents Intent-to-Treat (ITT) estimates of the impact of the Mirt improved cookstove (ICS) on household biomass consumption and fuel allocation. Column (1) reports the effect on the log of monthly firewood consumption. Columns (2) and (3) estimate the impact on the log quantities of animal dung applied as manure and crop residues used as animal fodder, respectively. All specifications include village fixed effects to control for time-invariant local characteristics and the suite of baseline household covariates reported in Table 1. Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4.3. Impact on Women's Time Allocation

A central hypothesis of this study is that adoption of an improved cookstove (ICS) generates a substantial "time windfall" for women by reducing the labor-intensive requirements of fuelwood collection and cooking. Because gendered divisions of labor in many rural low-income communities, such as Ethiopia typically assign the responsibility for energy procurement and food preparation to women and girls (Ashraf, 2009; WorldBank, 2011; Duflo, 2012; Miller and Mobarak, 2013; Alem et al., 2023), any technological efficiency gain should theoretically be reflected in a reallocation of their time toward other activities.

To measure these shifts, we focus on participation in five categories of productive work: farming, wage labor, handicrafts, poultry and livestock management, and small business. To minimize measurement error and survey fatigue—common challenges in recalling precise labor hours in subsistence settings—we utilize binary indicators of participation over the preceding year rather than continuous hour data.

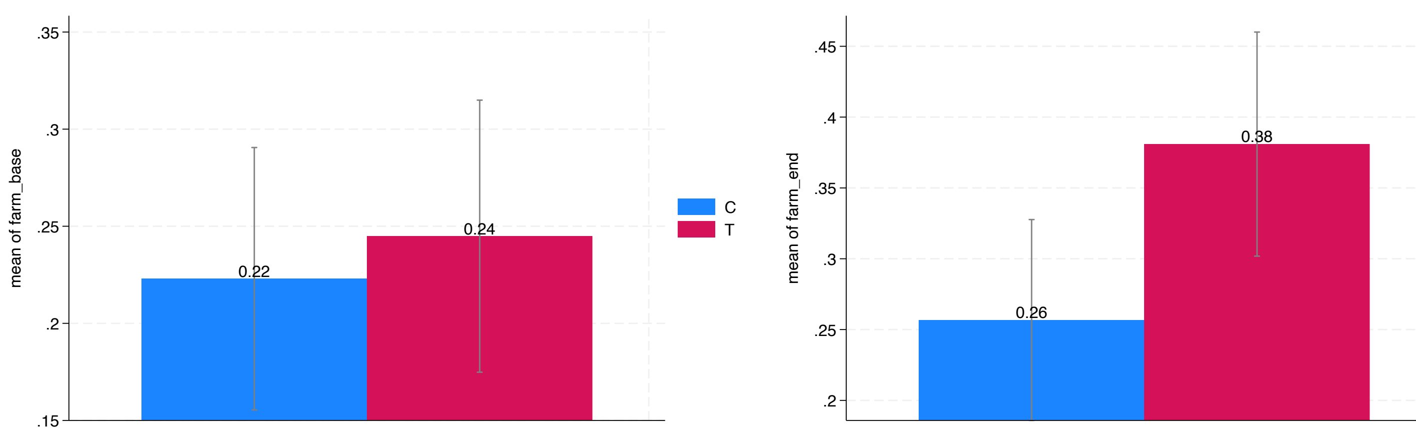
Figures 4 through 8 illustrate the mean comparison tests for these activities at both baseline and endline. At baseline, participation rates across all five categories are statistically indistinguishable between the treatment and control groups, further validating our randomization. However, a significant divergence emerges at endline. As shown in Figure 4, while baseline participation in farming stood at 24% for the treatment group and 22% for the control group, by the 15-month follow-up, the proportion of women in the treatment group engaged in farming rose to 38%. A similarly robust shift is observed for poultry and livestock management, which increased to 40% among treatment households (Figure 7).

Table 3 provides the formal ITT estimates, which confirm these visual trends. Controlling for baseline covariates and village fixed effects, the results suggest that ICS adoption leads to a 12.5 percentage point increase in the likelihood of participating in farming ($p < 0.05$) and a 27.6 percentage point increase in the likelihood of livestock and poultry management ($p < 0.01$). We find no statistically significant treatment effects for the other three categories: wage labor, handicrafts, and small business. This selective reallocation suggests that women are primarily channeling their saved time into home-based agricultural production rather than off-farm labor markets. In the following section, we explore the specific mechanisms—including local labor market thickness and activity complementarity—that may explain why the impact is concentrated in these specific domains.

To address potential concerns about multiple hypothesis testing across the five women's time allocation outcomes, we apply the Benjamini-Hochberg false discovery rate (FDR) correction (Benjamini and Hochberg, 1995), following standard practice in randomized experiments (Anderson, 2008). The BH procedure controls the expected proportion of false discoveries among all rejected hypotheses—known as the False Discovery Rate (FDR)—rather than the probability of making even a single false rejection, as in classical Bonferroni-type corrections (Benjamini and Hochberg, 1995). The procedure works by ranking the p-values of all hypotheses within a family from smallest to largest, and comparing each ranked p-value against a scaled critical threshold of $(k/M) \times \alpha$, where k is the rank of the hypothesis, M is the total number of hypotheses in the family, and α is the chosen significance level. A hypothesis is rejected if its p-value does not exceed this threshold. By scaling the critical value proportionally to the rank, the BH procedure is less conservative than Bonferroni correction—which divides α by M uniformly for all hypotheses—while still providing a meaningful statistical guarantee against spurious rejections.

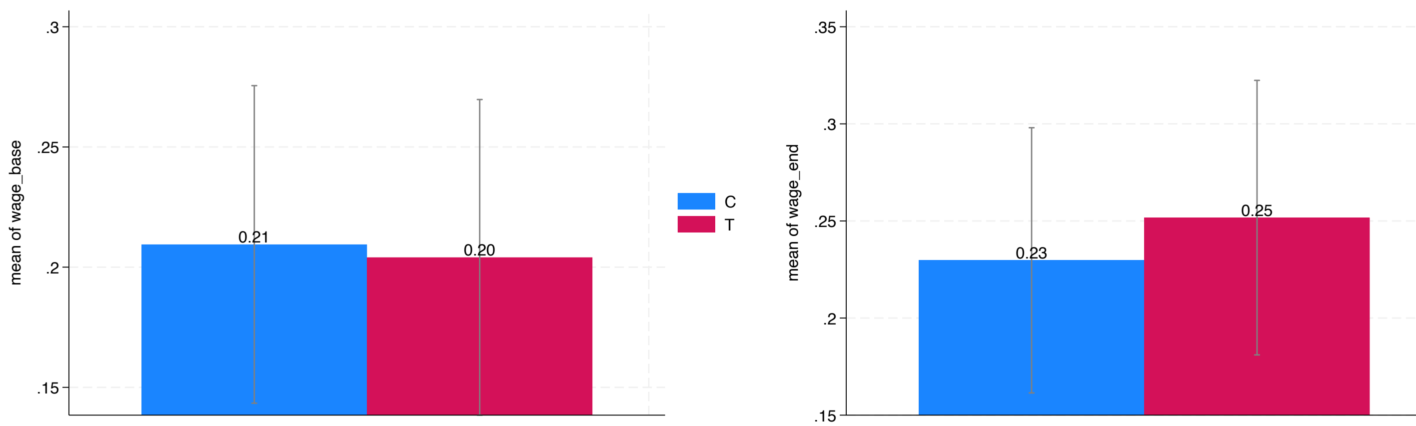
In our setting, we apply the BH procedure to the family of $M = 5$ women's time allocation outcomes at the $\alpha = 0.05$ significance level, yielding the adjusted q-values reported in Table 3. The adjusted q-values, reported in the bottom row of Table 3, confirm that the treatment effect on poultry and livestock management remains highly significant after correction ($q < 0.001$). The farming result, significant at the 5% level before correction ($p = 0.023$), remains marginally significant at the 10% level after adjustment ($q = 0.058$), consistent with a positive but more modest effect on this outcome. The null results for wage labor, handicrafts, and small business are robust to the correction across all specifications.

Figure 4: Time Allocation on Farming: Baseline and Endline



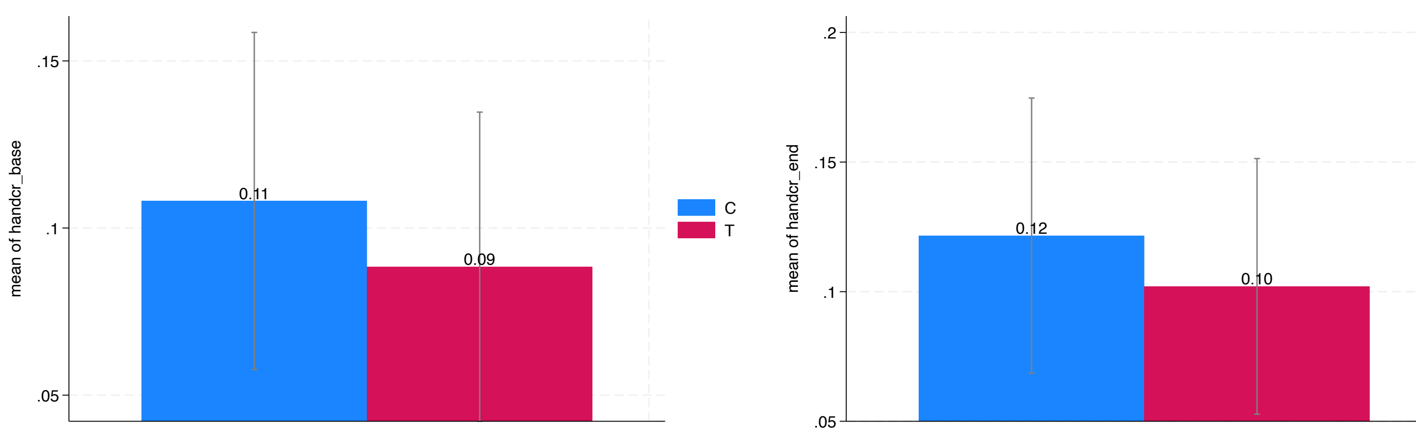
Notes: This figure presents mean likelihood of allocating time for farming of women for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 5: Time Allocation on Wage Work: Baseline and Endline



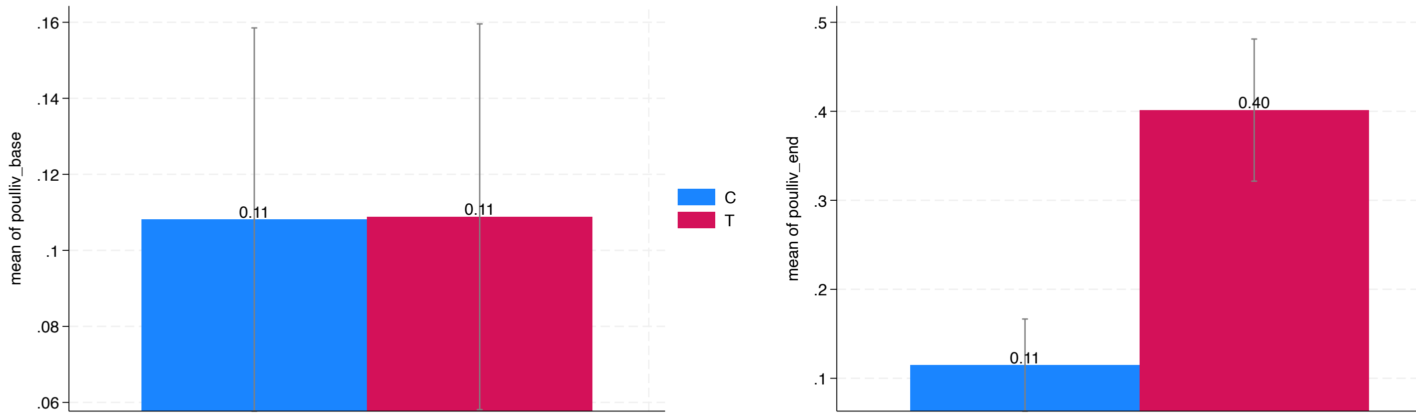
Notes: This figure presents mean likelihood of allocating time for wage work by women in the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 6: Time Allocation on Handcraft: Baseline and Endline



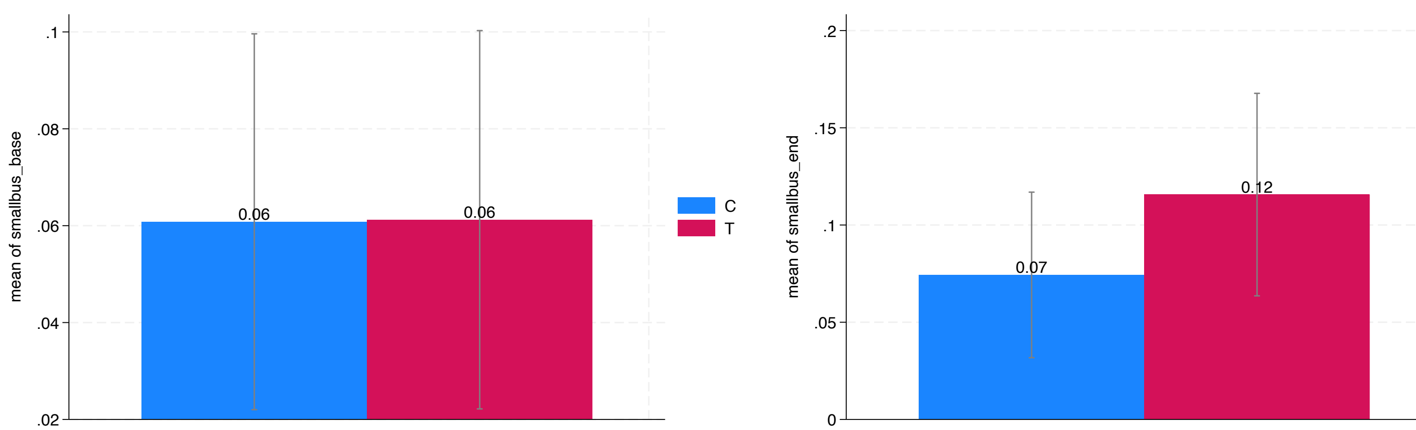
Notes: This figure presents mean likelihood of allocating time for handcraft by women in the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 7: Time Allocation on Poultry and Livestock Keeping: Baseline and Endline



Notes: This figure presents mean likelihood of allocating time on poultry and livestock keeping by women in the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 8: Time Allocation on Small Business: Baseline and Endline



Notes: This figure presents mean likelihood of allocating time on small business by women in the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Table 3: Impact on Time Allocation of Women - ITT Effects

	(1) Farming	(2) Wage Labor	(3) Handcraft	(4) Poultry & Livestock	(5) Small Business
Treated	0.125**	0.023	-0.024	0.276***	0.040
	(0.055)	(0.050)	(0.039)	(0.049)	(0.035)
p-value	[0.023]	[0.637]	[0.537]	[<0.001]	[0.257]
BH-adjusted q	[0.058]	[0.637]	[0.637]	[<0.001]	[0.428]
Controls	Yes	Yes	Yes	Yes	Yes
Village FE	Yes	Yes	Yes	Yes	Yes
R^2	0.078	0.067	0.040	0.147	0.047
Observations	295	295	295	295	295

Notes: This table presents Intent-to-Treat (ITT) estimates of the impact of the Mirt improved cookstove on time allocation of women. Columns (1)–(5) report the effect on the likelihood of engaging in farming, wage labor, handcraft, poultry and livestock, and small business. All specifications include village fixed effects to control for time-invariant local characteristics and the suite of baseline household covariates reported in Table 1. Robust standard errors are reported in parentheses. Unadjusted p-values are reported in the first set of brackets. Benjamini-Hochberg false discovery rate adjusted q-values (Benjamini and Hochberg, 1995) are reported in the second set of brackets. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively, based on unadjusted p-values.

4.4. Mechanisms

What are the specific pathways through which access to improved cookstoves affects biomass reallocation and women's time allocation? In this section, we investigate the underlying mechanisms. We begin by reviewing the technical attributes of the stove and the baseline division of labor within our sample.

The Mirt improved cookstove (ICS) distributed to treatment households is a purpose-built technology designed specifically for baking *injera*, the regional staple. Constructed from locally available sand and cement, the stove features a fixed, two-part cylindrical design tailored to the traditional *mitad* (griddle). Its enclosed combustion chamber and optimized airflow reduce fuel consumption while maximizing heat transfer, offering a significant upgrade over traditional three-stone open fires. Laboratory tests suggest the Mirt reduces fuelwood consumption by up to 50%, while reducing smoke and indoor air pollution by 90%.[6]

Beyond fuel efficiency, a key attribute is the stove's ability to facilitate multi-tasking; while baking *injera*, the cook can simultaneously prepare sauces or boil coffee on the side of the stove. Figure 9 displays the stove as installed in the study area. Given these superior technical specifications, a significant reduction in firewood demand is expected. Furthermore, we argue that the observed reallocation of animal dung to farms and the use of crop residue as fodder (Section 4.2) represent novel secondary impacts not typically documented in the ICS literature.

[6]See `http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm`. At the time of intervention, the stove retailed for approximately 150 ETB (USD 7.50); however, households in the study area had no prior exposure to the technology.

Figure 9: The Mirt Improved Cookstove Distributed to the Treatment Group

The labor-saving potential of the Mirt stove is hypothesized to explain the shift in women's time toward farming and livestock management. In rural Ethiopia, women and girls bear the near-exclusive responsibility for fuel collection and cooking (Cooke et al., 2008; Alem et al., 2023). At baseline, women in our sample spent an average of 39.5 hours per month on fuelwood collection and 3.4 hours per day on cooking. Given these stylized facts, the benefits of the ICS should accrue primarily to women.

Figures 10 and 11 present the mean comparison tests for these time-intensive tasks. While baseline participation was balanced, a sharp divergence emerges at endline. In the treatment group, monthly fuelwood collection time fell from 40.2 hours to 17.6 hours (a 56% reduction in levels). Similarly, cooking time decreased from 3.46 hours per day to 2.69 hours per day.

Table 4 presents the formal ITT estimates. Controlling for baseline covariates and village fixed effects, the results in Column [1] indicate that ICS adoption leads to a 40.8% reduction in monthly fuelwood collection time ($p < 0.05$). Correspondingly, Column [2] shows a highly significant 19.9% reduction in cooking time ($p < 0.01$). These efficiency gains are a direct result of the stove's high heat retention and its capacity to support simultaneous cooking tasks.

Table 4: Mechanisms: Fuelwood Collection and Cooking Time of Women

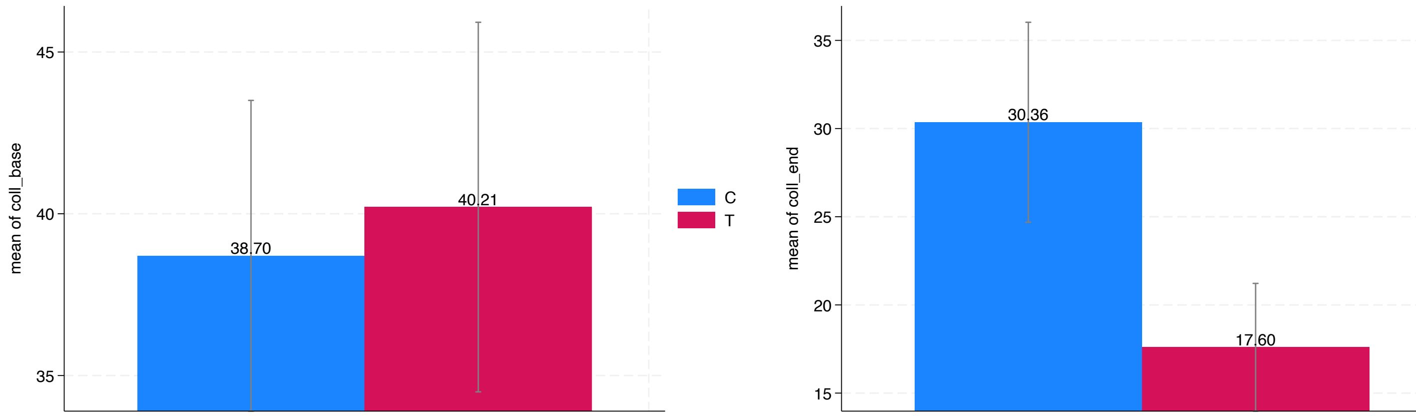
	(1) Collection Time	(2) Cooking Time
Treated	-0.408**	-0.199***
	(0.185)	(0.023)
Controls	Yes	Yes
Village fixed effects	Yes	Yes
R-squared	0.088	0.287
Observations	295	295

Notes: This table presents Intent-to-Treat (ITT) estimates of the impact of the Mirt improved cookstove on women's fuelwood collection and cooking time. Column (1) reports the effect on the log of monthly fuelwood collection time, and column (2) presents the effects on daily cooking time. All specifications include village fixed effects to control for time-invariant local characteristics and the suite of baseline household covariates reported in Table 1. Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

A key question arises: why did the resulting "time windfall" translate only into increased farming and livestock management, rather than wage labor or small business activities? We argue this is a function of pervasive market constraints in remote rural areas. Engaging in wage labor requires a thick labor market; in Northern Ethiopia, off-farm employment is largely limited to the Productive Safety Net Program (PSNP), where participation is conditional on specific vulnerability criteria rather than labor supply (Berhane et al., 2014; Debela et al., 2015; Alem and Broussard, 2017). Engaging in activities such as handicrafts and small businesses requires initial investment, such as specialized skills acquisition, access to start-up capital, and established markets (Fafchamps and Quinn, 2017; Nagler and Naudé, 2017), which sample households are unlikely to possess. In contrast, participation in family farming and livestock management requires no additional capital outlay and utilizes the primary productive assets already available to the household (de Janvry et al., 1991).

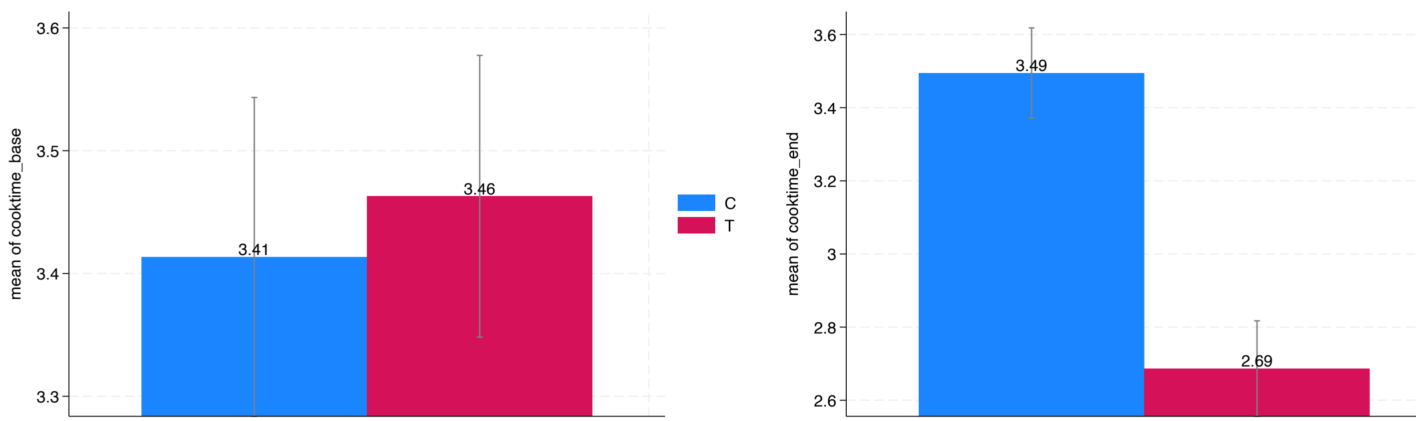
Finally, we test for potential impacts on men's time allocation as a placebo check. Table 5 reports the ITT estimates for male household members. We find no statistically significant effects on men's time across any activity category. These results are expected, given that men are rarely involved in domestic energy procurement or food preparation. This reinforces our conclusion that the welfare gains of ICS technologies are gender-specific, and suggests that social cost-benefit analyses must explicitly account for these productivity gains among women.

Figure 10: Firewood Collection Time: Baseline and Endline



Notes: This figure presents monthly mean firewood collection time of women for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

Figure 11: Cooking Time: Baseline and Endline



Notes: This figure presents daily mean cooking time of women for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

4.5. Caveats and Limitations

While our results demonstrate a robust and novel impact of the Mirt improved cookstove on biomass consumption and women's time allocation, we acknowledge several limitations inherent in the study design and sample size that should be considered when assessing the external validity of our findings.

Experimental Design and Spillovers: Owing to resource constraints, the randomized controlled trial was implemented among 295 households across six villages. Randomization was conducted at the household level rather than the cluster (village) level. While this approach maximizes statistical power for a sample of this size, it introduces the potential for spillovers or "contamination" of the control group. Since

Table 5: The Impact of ICS on Time Allocation of Men - ITT Effects

	(1) Farming	(2) Wage Labor	(3) Handcraft	(4) Poultry & Livestock	(5) Small Business
Treated	-0.014	0.082	0.014	-0.002	-0.006
	(0.023)	(0.059)	(0.024)	(0.033)	(0.037)
Controls	Yes	Yes	Yes	Yes	Yes
Village fixed effects	Yes	Yes	Yes	Yes	Yes
Robust SE	Yes	Yes	Yes	Yes	Yes
R-squared	0.036	0.064	0.081	0.065	0.055
Observations	295	295	295	295	295

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table presents Intent-to-Treat (ITT) estimates of the impact of the Mirt improved cookstove on time allocation of men. Columns (1)-(5) report the effect on the likelihood of engaging in farming, wage labor, handcraft, poultry and livestock, and small business. All specifications include village fixed effects to control for time-invariant local characteristics and the suite of baseline household covariates reported in Table 1. Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

treatment and control households reside in the same villages, members of the treatment group may have shared the use of their Mirt stove with neighbors in the control group. To address this, we collected detailed endline data on stove ownership and usage among the control group; we found no statistically significant increase in the use of improved technology among control households compared to baseline. However, if unobserved sharing did occur, our ITT estimates would represent a *lower bound* of the true treatment effect, as the difference between groups would be artificially compressed.

Precision and Clustering: Because the intervention was randomized at the household level and involves a limited number of clusters (six villages), we report robust standard errors rather than clustering at the village level. While outcome variables within the same village may be correlated due to local ecological or market conditions, the small number of clusters prevents the use of standard cluster-robust variance estimators, which rely on a larger number of groups for asymptotic validity (Cameron and Miller, 2015). We address this potential correlation by including village-level fixed effects in all specifications to absorb time-invariant local characteristics.

Measurement of Time Use: Our primary outcome variables for women's time allocation are measured at the extensive margin (binary participation) rather than the intensive margin (labor hours). While a continuous time-log approach would provide more granular data, we opted for binary indicators to mitigate respondent fatigue and minimize recall bias, which is particularly prevalent in subsistence settings where labor tasks are fragmented throughout the day (Arthi et al., 2018). While this prevents us from calculating the exact magnitude of the "time windfall" in minutes, the significance of the shift in participation across 295 households suggests a substantial reallocation of labor. Future research utilizing larger samples and high-frequency time-use data could further illuminate the transition from domestic to productive labor.

5. Conclusions

This study provides empirical evidence on the impact of an improved cookstove (ICS) intervention on biomass consumption and women's time allocation in rural Ethiopia. Using a randomized controlled trial, we document a significant "double dividend" resulting from the adoption of the Mirt stove. First, the technology successfully fulfills its primary technical objective: it reduces the household's reliance on traditional biomass, leading to a 40.8% reduction in monthly fuelwood collection time and a 19.9% reduction in cooking duration. Beyond firewood, we find that the intervention leads to a novel reallocation of other biomass resources, such as animal dung and crop residues, away from fuel and toward soil fertility and animal fodder.

Second, our results demonstrate that the time saved from domestic chores is reallocated into home-based productive activities. Specifically, ICS adoption leads to a 12.5 percentage point increase in the likelihood of women participating in farming and a 27.6 percentage point increase in participation in poultry and livestock management. The absence of similar impacts on wage labor, handicrafts, or small business suggests that in the presence of thin local labor markets and capital constraints, the "time windfall" generated by labor-saving technologies is primarily channeled into existing household production functions where labor elasticity is high and barriers to entry are low.

The gendered nature of these impacts is particularly striking. Our findings indicate that the direct benefits of the Mirt stove—both in terms of time savings and subsequent productive reallocation—accrue exclusively to women. Placebo tests on men's time allocation show no statistically significant changes, underscoring the fact that energy poverty is a deeply gendered experience in the Ethiopian highlands.

From a policy perspective, these findings suggest that traditional cost-benefit analyses of clean energy interventions significantly underestimate their social returns by ignoring the value of women's time. By reducing the opportunity cost of engagement in agriculture, improved cookstoves serve as a catalyst for local productivity and rural development. To maximize these gains, future energy interventions should be integrated with agricultural extension services or micro-credit programs, ensuring that the labor liberated by technological efficiency can be invested in the most high-return productive pathways available to rural households.

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