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Adoption of improved biomass stoves in Kenya: a transect-based approach in Kiambu and Muranga counties

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**Abstract**

There is a wide consensus within policy, practice, and academic circles that the adoption of modern cooking options can benefit sub-Saharan Africa. Numerous studies have examined the various demographic, socioeconomic and institutional factors affecting the adoption of clean cooking options. However, most such studies did not properly consider how geographic and environmental factors and fuel availability can affect stove adoption. In this study we use a transect-based approach, from an area of high fuelwood abundance (a state forest) to an area of high fuelwood scarcity (the semi-arid interior of Muranga county) and a peri-urban area with many fuel options (the peri-urban area of Kiambu county). We survey 400 randomly selected households along the two transects from enumeration areas used in the Kenyan national census to understand how factors intersect to affect the adoption of improved biomass stoves as primary stoves. A probit analysis suggests that stove adoption depends not only on demographic and socioeconomic factors (e.g., income, education), but also on geographical and environmental factors that reflect biomass availability and accessibility, and market access. Female-headed households tend to have lower rates of improved biomass stove adoption, largely due to lower income and related enabling factors (e.g., education, land size). Through path analysis we identify that such households can improve their opportunities to adopt improved biomass stoves through better access to credit services and participation in social groups. Overall, this study suggests the need for non-uniform and spatially explicit stove promotion strategies informed by fuelwood availability and accessibility, and market access considerations. Such strategies that are conscious of local contexts could catalyze the large-scale adoption of clean cooking options in Kenya, and elsewhere on the continent.

1. Introduction

Access to modern and sustainable energy for cooking has moved to the forefront of international policy discourse and has been enshrined in Sustainable Development Goal 7 (SDG7) [1] and is linked to multiple other goals [2, 3]. Since 2010, international efforts led by the Clean Cooking Alliance and other international organizations have spurred the adoption of clean and improved cooking methods by 100 million households globally by 2020 [4, 5].

Kenya is one of the countries in sub-Saharan Africa whose population lack wide access to modern

and sustainable energy for cooking. Approximately 86% of Kenyans rely predominantly on traditional sources of cooking energy (i.e., fuelwood, charcoal, and agricultural residues) [3], of whom only 26% use improved biomass stoves [5]. According to a recent SDG7 progress report, only 14% of the Kenyan population has access to clean cooking technologies, ranking Kenya among the top 20 countries deficient in such access, in terms of population growth outpacing annual gains in clean cooking access in 2017 [3].

However, the use of traditional biomass fuels for cooking affects the health of millions of Kenyans, while having adverse environmental, economic and social

effects [6–11]. The adoption and sustained use of clean cookstoves presents a practical solution to many interconnected sustainability challenges associated with traditional methods of cooking, ranging from energy security or poverty to public health, rural livelihoods, food security, education, women's empowerment, and environmental conservation [11, 12].

Kenya has been striving to modernize its household energy system. For example, many efforts have been made in the promotion of clean cookstove and fuel options, but most such efforts have faced difficulties such as a lack of financing, slow technological progress, low consumer awareness, and lack of infrastructure for fuel and stove production and distribution [11–14]. The Kenyan government set a national target of seven million households to adopt clean stoves (e.g., liquefied petroleum gas (LPG), ethanol, electricity) and energy-efficient biomass stoves by 2020, coupled with the formulation of plans aiming to ensure the affordability and cost-efficiency of clean cooking options [5]. However, several studies identified the need to ensure sustainable financing within the clean cooking sector, which requires urgent reforms without curtailing the government's other sustainable development commitments [11, 15–17].

Stove promotion and dissemination programmes tend to focus more on stove technology than on the characteristics of their target adopters, and especially how these are mediated by the broader geographical and environmental context. For example, research on the determinants of stove adoption at the household level has concentrated on demographic and socio-economic attributes such as income, age, gender, and education [14, 18–22]. Although biomass dynamics and geographical and environmental factors have often been cited as key in stove adoption [22–25], information about the nature and magnitude of these effects is scanty within the literature. Furthermore, even though several studies have suggested that women tend to be disproportionately affected by traditional cooking practices in terms of time spent on fuelwood procurement and cooking, and health risks from indoor air pollution [26–29], there is a relative lack of information about the underlying factors that give rise to gender constraints towards stove adoption.

Furthermore, it has been advocated that in countries with very low clean cooking adoption rates, such as Kenya, there is a need to prioritize the promotion and dissemination of improved biomass stoves (often categorized as '*transitional cooking solutions*'). This is because such cooking options offer the most immediate pathway to improving universal access to clean cooking and at the same time providing substantial environmental benefits (and health benefits, to some extent), when compared to traditional three-stone stoves [3]. This is particularly true for rural communities, where there is limited infrastructure for the supply and distribution of modern cooking technologies and fuels such as LPG and electricity [12].

Considering the above, this study aims to delineate the factors influencing the adoption⁴ of improved biomass stoves as primary stoves in rural Kenya. We employ a transect-based approach from an area of high fuelwood abundance (a state forest) to an area of high fuelwood scarcity (the semi-arid interior of Muranga county) and a peri-urban area with many fuel options (the peri-urban area of Kiambu county). Fuelwood procurement practices vary widely across these transects due to the varying availability of and accessibility and market access to biomass and other clean cooking options.

In this respect, we partly hypothesize that proximity to areas of high fuelwood availability and easy accessibility (indications of biomass abundance) and market access can affect stove adoption. We believe that such a transect-based approach can enable us to identify how geographical and environmental factors of fuel abundance and market access can affect the adoption of clean stoves, which is a rather under-explored aspect in the literature (see above). Keeping in mind the important gender-differentiated aspects of cooking, we also pay particular attention to how the various factors in stove adoption intersect with income, and the stove adoption patterns of female-headed households. We focus on improved biomass stoves as this is considered to be a priority in achieving rapid sustainability benefits from clean cooking, as discussed above.

2. Methodology

2.1. Study sites

As outlined in section 1, we partly hypothesize that the geographical location and environmental context of households in areas of high fuelwood abundance (i.e., high availability and easy accessibility of biomass) can be an important determinant of stove adoption, and that a transect approach can help elicit the effects of geographical location and environmental characteristics.

We select two case study areas bordering the Aberdare Forest Reserve (a state forest): Kiambu County (1.1462 °S, 36.9665 °E) and Muranga County (0.7957 °S, 37.1322 °E). The two counties are among the rural 'hotspots' in Kenya that have experienced drastic land use change, periodic fuelwood shortages, and a threat of increasing scarcity of fuelwood [15]. They offer different environmental transitions, from forest to a semi-arid area (Muranga County) and from forest to a peri-urban area (Kiambu County). These environmental transitions result in varying abundance

⁴ There is no universally accepted definition of clean stove adoption [30]. In this paper we conceptualize stove adoption as the process of its acceptance and subsequent continuous use as the primary cookstove in terms of frequency of use, as self-reported by the surveyed households. This was done to reflect the possibility of stacking behaviour, which is rather common in Kenya and other regions of sub-Saharan Africa [31].

Table 1. Fuelwood supply–demand balances in Kiambu and Muranga counties. Source [15].

		Muranga	Kiambu	Kenya
Fuelwood Demand		631	1704	27 380
Supply (1000 t)	Total MAI	247	435	42 921
	Physically and legally accessible MAI	216	427	28 069
Balance (1000 t)	Total MAI	−415	−1277	689
	Physically accessible	−31	−8	−14 852
	Local	−411	−1254	349
	Commercial	−414	−1255	−2193

Note: All estimates are reported in 1000 t of oven-dry matter.

of fuelwood (i.e., availability and accessibility) and varying access to markets.

According to the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) exercise conducted in Kenya [15], there is a large discrepancy in the local supply of and demand for fuelwood, which causes large annual wood supply variability and deficits (table 1). Reportedly, the total estimated mean annual increment (MAI) of dendro-energy biomass (i.e., the woody fraction of above-ground biomass suitable for use as conventional fuelwood) is 0.435 Mt/year in Kiambu and 0.247 Mt/year in Muranga, which is the average fuelwood supply potential. However, about 2% and 13% of these resources cannot be accessed, possibly due to settlement expansion and land privatization (see table 1).

2.2. Data collection

A detailed explanation of the data collection and quality assurance procedures is available online at stacks.iop.org/ERL/15/024020/mmedia in section S1 of the supplementary electronic material. It is summarized below. In each county we collected data along an enumeration transect from the state forest to the semi-arid interior (Muranga County), and from the state forest to the peri-urban area of Nairobi (Kiambu County). This selection reflects fuelwood scarcity as experienced in most parts of rural Kenya, based on the availability and accessibility of forest resources and access to fuelwood markets [32] (section 2.1). We divided each transect into three broad zones that are a good approximation of the varying degrees of fuelwood abundance or scarcity (i.e., availability and accessibility), procurement practices, and market access (see below and section 3.1). These study zones include: (a) a close-forest zone, mid-zone, and semi-arid zone in Muranga; and (b) a close-forest zone, mid-zone, and peri-urban zone in Kiambu (see table 2)⁵. Communities in these zones have largely similar fuelwood procurement practices

⁵ We do not use an absolute distance to the forest (e.g., the straight-line distance) as a grouping parameter as: (a) it is not easy to know the actual distance to forest, considering the landscape geography (e.g., hilly terrain, seasonal roads), and; (b) the absolute distance to forest is not necessarily an actual measure of fuelwood scarcity or abundance [24].

that are relatively distinct between zones. Furthermore, fuelwood prices, which are used as an indication of market access, also vary substantially between zones (table 2).

In each zone, five enumeration areas (EAs) were randomly selected from the list of enumerator areas used for the Kenyan national census. According to the methodology of the Kenyan census, each EA contains about 100 households. We selected randomly a minimum of 15 households in each enumeration village through transect walks, as for reasons of confidentiality it is not possible to obtain a full list of residents in each EA (see section S1, supplementary material). The selected EAs were cross-referenced to a geographical information system (GIS) map. In order to ensure the reliable and unbiased identification of responding households, we identified on the GIS map the grid point of a road intersection. We used global positioning system (GPS) devices to locate the reference point as the start of the transect walk in each EA. We then surveyed every fifth household along the transect walk.

Data was collected through structured household surveys that were developed iteratively through multiple site visits and were captured on tablets (see section S1, supplementary material). The questionnaires elicited quantitative and qualitative information through closed-ended and open-ended questions employing fixed ranges that were coded appropriately. The questionnaire had three sections: (a) demographic and socioeconomic characteristics; (b) income, assets, and livelihood sources, and; (c) household energy and stove use patterns (section 2.2).

The interviews were conducted in person by trained enumerators in the local *kikuyu* language (see section S1, supplementary material). The target respondent was the main female decision-maker of the household (i.e., either the household head or spouse), or the closest household member that was conversant with the patterns of fuelwood procurement and stove use.

To obtain fuller information about stove adoption and use, and fuel procurement practices, we conducted 12 in-depth participant observation exercises (two per transect zone). In particular, we randomly identified these participants from the overall sample, and with their consent and permission we spent

Table 2. Characteristics of enumeration zones.

County	Transect zone	Sample size	Agroecological characteristics	Key livelihood activities	Local market fuelwood prices (KES/20 kg bundle)	
					Households	Local traders
Muranga	Close forest (TM-1)	70	Forest zone (humid)	Tea and dairy farming	42.60	50.00
	Mid-zone (TM-2)	65	Semi-humid	Coffee (rain-fed)	71.40	80.00
	Semi-arid (TM-3)	65	Semi-arid	Coffee (irrigated)	99.40	100.00
Kiambu	Close forest (TK-1)	70	Forest zone (humid)	Tea and dairy farming	51.20	50.00
	Mid-zone (TK-2)	65	Semi-humid	Coffee and dairy farming	77.00	70.00
	Peri-urban (TK-3)	65	Peri-urban	Subsistence farming, non-farm employment	102.60	120.00

Notes: Local market fuelwood prices were collected through the household survey and informal interviews with local fuelwood traders. Household prices denote the average price reported by all households in the respective zone. Prices for local traders were elicited through informal interviews with 1–2 fuelwood traders in each zone.

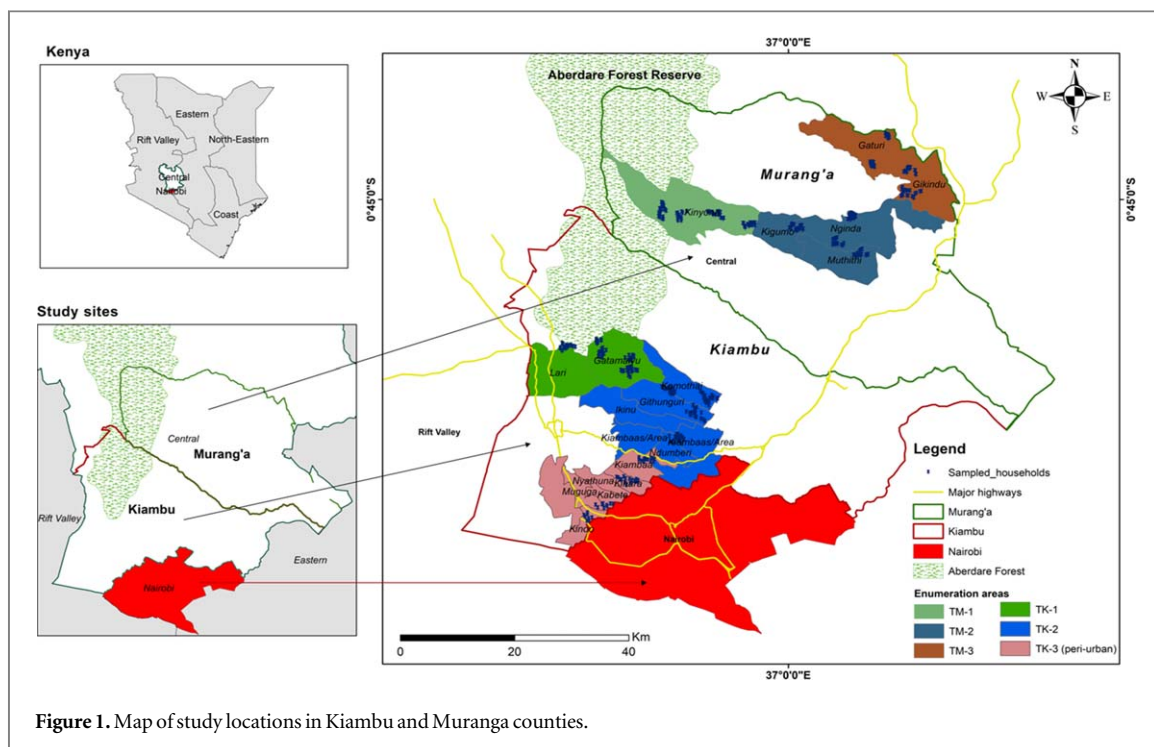


Figure 1. Map of study locations in Kiambu and Murang'a counties.

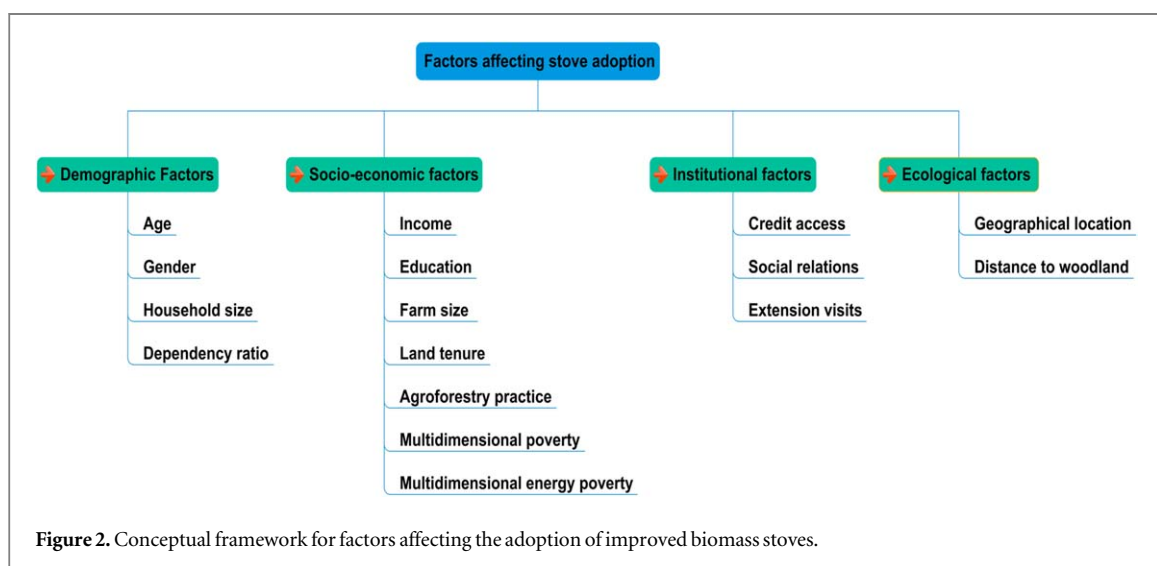


Figure 2. Conceptual framework for factors affecting the adoption of improved biomass stoves.

6–10 h over the duration of a single day in their homesteads and actively participated in fuelwood collection and cooking activities. During this time, in-depth discussions were held with the participants on issues related to fuelwood procurement and availability over time, cooking practices, and aspects of their livelihoods. Furthermore, 1–2 informal interviews were conducted with local traders to better understand the local fuelwood and charcoal markets. This mostly qualitative information is not formally analyzed in this paper, but it is used in some parts to put some results into perspective.

2.3. Data analysis

We include various factors that are commonly identified and/or hypothesized as affecting the

adoption of improved biomass stoves over traditional three-stone stoves (figure 2, table 3). We categorize these variables into four main domains: (a) demographic; (b) socioeconomic; (c) institutional, and; (d) geographical and environmental. These factors were identified through an extensive literature review [11], participant observation, and informal interviews and pilot studies in the study sites prior to the full-scale survey.

Table S1 (supplementary electronic material) offers a theoretical expectation about how the variables can affect the adoption of improved biomass stoves. Section S2 and tables S2 and S3 in the supplementary electronic material outline the calculation procedure for the two composite indicators used as adoption variables: the Multidimensional Poverty

Table 3. Description of the variables used in the estimation models.

Domain	Explanatory variables	Description	Type of measure
Demographic factors	Gender	Gender of the household head	1 if female; 0 if male
	Age	Age of the household head	Years
	Household size	The number of household members	Total number of household members
	Dependency ratio	Ratio of non-income earning members to income-earning members within the household	Household dependency ratio
Socioeconomic factors	Education	Education level of the household head	Attained education level
	Income	Household income in Kenyan shillings	Total household income
	MPI	A metric measure of multidimensional poverty	1 if household is multi-dimensionally poor; 0 otherwise
	MEPI	A metric measure of multidimensional energy poverty	1 if household is multi-dimensionally energy-poor; 0 otherwise
	Agroforestry	Planted trees on farm	1 if planted; 0 if not planted
	Farm size	Size of household farming land	Acres
	Land tenure	Legal regime of land ownership	1 if land is purchased or inherited; 0 if rented or leased
Geographical and environmental factors	Distance to woodland	Total distance to the most commonly used woodland for fuelwood collection	km
	Geographic location	Three dummy variables for transect zones:	1 if peri-urban, close forest or semi-arid; 0 if otherwise. (Note: the mid-transect zone is used as a control variable for location)
Institutional factors	Extension visits	Access to farm and/or home management extension services offered by government agencies	1 if households were visited by extension agents; 0 otherwise.
	Credit access	Access to credit from informal sources (e.g., table banking) or financial institutions (e.g., bank)	1 if have credit access; 0 otherwise
	Social group membership	Household members' participation in community-based organizations and groups	1 if participating in social groups; 0 otherwise

Index (MPI) [33] and the Multidimensional Energy Poverty Index (MEPI) [34].

In order to identify the factors influencing the adoption of improved biomass stoves, we conduct two specific analyses. Initially we conduct a probit analysis to establish how the identified variables (i.e., demographic, socioeconomic, institutional and geographical and environmental factors) affect the probability of adoption of improved biomass stoves. Subsequently we select the statistically significant variables from the probit analysis that are believed to affect household income (identified through literature review, and site and participant observation), and conduct a path analysis to identify their direct, indirect, and total effects on the adoption of improved biomass stoves [35]. For more information on the analytical procedure refer to section S2 in the supplementary electronic material.

3. Results

3.1. Stove adoption and fuelwood procurement

Tables 4, 5 present primary stove adoption characteristics across the two transects. Further descriptive

statistics for the sample are included in table S4 of the supplementary electronic material. Approximately 61.5% of surveyed households in Muranga (i.e., a rural interior transect) use traditional biomass stoves as their primary stove, while 38.5% have adopted improved biomass stoves as primary stoves. None of the surveyed households in the Muranga transect use non-fuelwood stoves as the primary stove. In Kiambu (i.e., a transect neighboring Nairobi city) there is a higher diversity of primary stove types, with 51.7% of the surveyed households using traditional stoves, 30.1% improved biomass stoves, and 18.3% another stove type as their primary stove.

A deeper scrutiny of adoption patterns across transects suggests there is broad variation in primary stove adoption. In the Muranga transect, the adoption of improved biomass stoves as primary stoves increases with increasing distance from the state forest towards the semi-arid interior. In particular, 44.6% of the surveyed population in the semi-arid interior use improved biomass stoves as their primary stoves, compared to 32.9% of the respondents close to the forest (table 4). This is perhaps due to the observed fuelwood scarcity and high fuelwood prices, which can

Table 4. Primary stove adoption patterns across transects.

Study area	Transect zone	Sample size	Traditional biomass stoves (%)	Improved biomass stoves (%)	Other stove types (%)		
					Charcoal	LPG	Electricity
Muranga	Close forest	70	67.1	32.9	0.0	0.0	0.0
	Mid-zone	65	61.5	38.5	0.0	0.0	0.0
	Semi-arid	65	55.4	44.6	0.0	0.0	0.0
	Total	200	61.3	38.7	0.0	0.0	0.0
Kiambu	Close forest	70	72.9	27.1	0.0	0.0	0.0
	Mid-zone	65	57.5	30.8	6.7	5.0	0.0
	Peri-urban	65	24.6	32.3	16.4	25.0	1.7
	Total	200	51.7	30.1	7.7	10.0	0.6

lead the local populations to adopt fuelwood-saving stoves.

Similarly, in the Kiambu transect, 32.3% of the peri-urban residents use improved biomass stoves as their primary stoves, compared to 27.1% of the households located close the forest (table 4). Notably, about 43.1% of the surveyed households in the peri-urban area primarily use non-fuelwood stove types such as LPG (25.0%), charcoal (16.4%), and electricity (1.7%). This is possibly attributable to extensive market infrastructure for modern cooking methods, including clean cookstoves, due to the proximity of Nairobi. Additionally, during the surveys and participant observation (see section 2.2), it was noted that the peri-urban area has limited open-access areas available for fuelwood collection.

Stove stacking or multiple stove use is a prevailing practice in most of the surveyed households. For instance, in the Kiambu transect, the use of LPG, kerosene, and improved charcoal stoves as secondary stoves increases with increasing proximity to the peri-urban area, while the prevalence of traditional biomass stoves reduces as the sole or the secondary stove along this transect (figure S2, supplementary material). Similar trends are observed in the Muranga transect, in that the adoption of improved biomass stoves as the sole stove option increases with increasing proximity to the semi-arid interior, while the adoption of traditional biomass stoves (as the sole or secondary stove) decreases (figure S1, supplementary material). Such stacking patterns most likely reflect fuel availability and prices in the respective zones, as discussed above.

Figure 3 illustrates the main fuelwood sources across the transect zones. It can be inferred that households' fuelwood procurement practices (e.g., where to collect it, how often, and how much time to spend on collection) varies by zone, and essentially reflects the availability of biomass resources within zones.

Households located in the vicinity of the state forest procure most of their fuelwood from trees on farms (i.e., agroforestry practices or woodlots) (45% in Muranga, 36% in Kiambu) and the state forest (25% in Muranga, 45% in Kiambu). Participant observation

and informal interviews suggest that 'legal' inaccessibility can significantly limit the availability of fuelwood, even for EAs located close to the state forest. Such households often require some form of official licensing, provided by the local forest office at a modest monthly fee of about KES 100 (USD 1.00), plus a commitment to maintain the forest tree nursery and participate in tree-planting activities (personal communication, Forest Officer, Gatare Forest Station, Muranga).

Conversely, as we move away from the state forest the fuelwood resources generally grow scarcer, and reliance on state forest resources and on-farm fuelwood sources tend to decrease (figure 3). Participant observation and observations during the household surveys suggest that natural barriers such as (a) the difficult landscape terrain, (b) the steep topography, and (c) climatic and seasonal variations often limit fuelwood availability and local market prices. According to the household survey, the estimated walking distance from homesteads to the main collection woodland for this location cluster is about 1.60 km (2.64 h per collection trip), which is about three times longer than that covered by communities close to the forest.

In the peri-urban zone close to Nairobi (Kiambu transect), different fuelwood procurement patterns are observed. Both the on-farm and off-farm fuelwood sources tend to decrease, and about 40% of households rely on the commercial fuelwood market. In this zone, participant observation, informal interviews with traders, and observations during the household surveys suggest that: (a) fuelwood is mostly supplied by the local furniture and construction workshops in the form of wood-cuts; (b) fuelwood is readily available in small, affordable quantities in the local market, and; (c) there is easy market access to cooking fuel alternatives such as LPG, charcoal, and kerosene, that can reduce or even substitute fuelwood for cooking.

Fuelwood procurement is a clear-cut gender-differentiated activity, with women and girls disproportionately responsible for its collection. We found that women and young girls bear 68% and 15% of the fuelwood collection burden, respectively.

Table 5. Household characteristics by primary stove and geographical and environmental characteristics in the two transects.

Study groups	Household head			Household		
	Gender	Education	Age	Family size	Farm size (acres)	Income (KES)
Total Kiambu	0.86 ± 0.35	3.49 ± 1.46	40.96 ± 12.27	4.14 ± 1.73	1.66 ± 1.36	20 240 ± 13 024.75
Close forest (<i>n</i> = 70)	Total average	3.06 ± 1.45	41.6 ± 13.07	4.39 ± 1.93	2.10 ± 1.67	19 382.86 ± 13 629.08
	Improved biomass (<i>n</i> = 19)	3.53 ± 1.31	35.26 ± 11.11	3.53 ± 1.07	1.36 ± 1.14	18 421.05 ± 9947.45
	Traditional stove (<i>n</i> = 51)	2.82 ± 1.41	41.12 ± 13.43	4.75 ± 2.08	1.67 ± 1.41	13 627.45 ± 6545.10
	t-test	n.s.	0.063	0.072	n.s.	0.022
Mid-transect (<i>n</i> = 55)	Total average	3.33 ± 1.41	41.77 ± 13.20	4.28 ± 1.55	1.54 ± 1.13	16 355 ± 9449.89
	Improved biomass (<i>n</i> = 22)	3.23 ± 1.57	41.91 ± 12.64	4.64 ± 1.61	1.78 ± 2.18	16 704.55 ± 13 241.04
	Traditional stove (<i>n</i> = 33)	3.12 ± 1.19	42.91 ± 14.20	4.06 ± 1.39	1.34 ± 0.96	13 787.88 ± 8087.44
	t-test	n.s.	n.s.	n.s.	0.084	0.036
Peri-urban (<i>n</i> = 35)	Total average	4.17 ± 1.28	39.42 ± 10.22	3.70 ± 1.59	1.27 ± 0.97	25 125 ± 14 014.71
	Improved biomass (<i>n</i> = 19)	3.32 ± 1.11	46.84 ± 11.47	4.63 ± 2.11	1.34 ± 1.07	18 736.84 ± 10 066.95
	Traditional stove (<i>n</i> = 16)	3.75 ± 1.18	46 ± 17.27	3.13 ± 1.25	2.02 ± 2.48	15 968.75 ± 8161.84
	t-test	0.003	n.s.	0.018	0.075	0.058
Total Muranga	0.82 ± 0.38	3.37 ± 0.93	41.18 ± 11.48	4.08 ± 1.13	1.79 ± 1.90	10 157.75 ± 6419.89
Close forest (<i>n</i> = 70)	Total average	3.37 ± 0.97	43.53 ± 11.76	4.11 ± 1.38	2.12 ± 2.63	14 276.43 ± 8448.30
	Improved biomass (<i>n</i> = 23)	4.00 ± 0.91	40.28 ± 9.58	3.80 ± 1.25	2.37 ± 3.89	12 900 ± 9 169.70
	Traditional stove (<i>n</i> = 47)	3.02 ± 0.81	45.33 ± 12.55	4.28 ± 1.44	1.36 ± 0.96	9485.56 ± 579.53
	t-test	n.s.	0.000	0.092	0.081	0.000
Mid-transect (<i>n</i> = 65)	Total average	3.26 ± 0.95	38.71 ± 10.58	3.66 ± 0.92	1.72 ± 1.44	9193.85 ± 4062.44
	Improved biomass (<i>n</i> = 25)	3.95 ± 0.84	37.95 ± 10.43	3.54 ± 0.83	2.11 ± 1.61	10 840.91 ± 5770.17
	Traditional stove (<i>n</i> = 40)	2.91 ± 0.81	39.09 ± 10.76	3.72 ± 0.95	1.49 ± 1.31	8351.16 ± 2520.42
	t-test	0.059	0.000	n.s.	0.079	0.018
Semi-arid (<i>n</i> = 65)	Total average	3.48 ± 0.87	41.12 ± 11.68	4.46 ± 1.71	1.51 ± 1.22	6686.15 ± 1721.09
	Improved biomass (<i>n</i> = 29)	3.86 ± 0.75	41.79 ± 12.58	4.00 ± 1.42	2.16 ± 2.71	7107.143 ± 1857.70
	Traditional stove (<i>n</i> = 36)	3.19 ± 0.84	40.62 ± 11.10	4.81 ± 1.82	1.39 ± 1.04	6367.57 ± 1560.64
	t-test	n.s.	0.002	0.012	n.s.	0.086

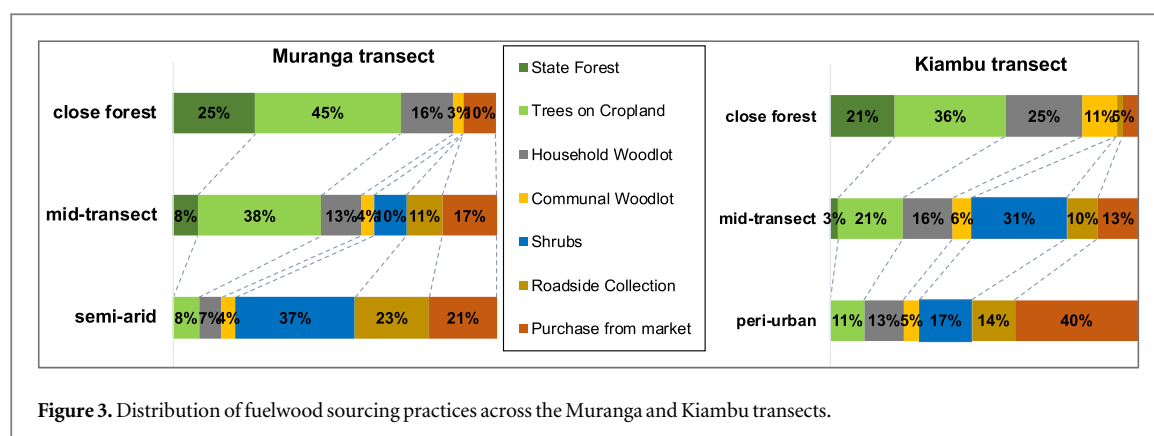


Figure 3. Distribution of fuelwood sourcing practices across the Muranga and Kiambu transects.

Table 6. Probit regression results of factors influencing the adoption of improved biomass stoves.

Domain	Variables	Coeff.	Robust standard error	p-value	dy/dx
Demographic factors	Gender	-0.309	0.210	n.s.	-0.063
	Age	-0.020	0.008	**	-0.004
	Household size	-0.455	0.227	**	-0.093
	Dependency ratio	-0.270	0.083	***	-0.055
Socioeconomic factors	Education	0.303	0.083	**	0.062
	Income	0.268	0.016	***	0.113
	Multidimensional poverty	-0.479	0.250	*	-0.098
	Multidimensional energy poverty	-0.692	0.411	*	-0.142
	Farm size	0.123	0.048	**	0.025
	Land tenure	0.028	0.207	n.s.	0.058
	Agroforestry	0.813	0.204	***	0.166
Institutional factors	Credit access	0.731	0.180	***	0.149
	Social group membership	0.602	0.205	***	0.123
	Extension visits	0.443	0.196	**	0.091
Geographic and environmental factors	Distance to woodland (km)	0.080	0.031	**	0.042
	Close forest: Muranga	-0.769	0.170	**	-0.207
	Mid-zone: Muranga	-0.188	0.310	n.s.	-0.0039
	Semi-arid zone: Muranga	0.307	0.044	*	0.063
	Close forest: Kiambu	-0.297	0.286	n.s.	-0.061
	Peri-urban zone: Kiambu	0.491	0.200	**	0.098
	Intercept	-1.047	0.270	*	—
	Pseudo R ²	59.47%			
	Observations	360			

Note. *: $p < 0.1$. **: $p < 0.05$. ***: $p < 0.01$.

3.2. Probit analysis of stove adoption factors

Below we discuss some of the most relevant results for probit estimation and the marginal effects (dy/dx) of variables determining the adoption of improved cookstoves (table 6).

Female-headed households have a lower likelihood of adopting improved biomass stoves as primary stoves, though this effect is not statistically significant. Participant observation suggests that although men are mostly responsible for household budget allocation, they do not directly undertake cooking tasks and fuelwood procurement. This implies that the negative outcomes of cooking with traditional fuels (e.g., drudgery, indoor pollution), are not necessarily reflected in cooking decision-making in such households.

A unit increase in household income significantly increases the probability of adoption of improved

biomass stoves as primary stoves, by 11.3% ($p < 0.01$). As for non-income poverty indicators, the results suggest that the incidence of multidimensional poverty and multidimensional energy poverty in households reduces significantly the probability of improved biomass stove adoption as the primary stove, by 9.8% and 14.2% respectively ($p < 0.05$).

Actively integrating and planting trees on farms (i.e., involvement in agroforestry) has a positive and significant effect on the adoption of improved biomass stoves, by a factor of 16.6%, compared to households that do not engage in agroforestry practices ($p < 0.01$). The coefficient for agroforestry was not only strongly significant, but the magnitude of its coefficient and marginal effects ranks the highest across the explored socioeconomic variables, emphasizing its relative importance for the adoption of improved biomass stoves as primary stoves.

Access to credit has a significant positive effect on the adoption of improved biomass stoves. The estimated marginal effects indicate that households with access to credit through formal and/or informal institutions had a 14.9% higher probability of adopting improved biomass stoves as primary stoves than households without access to credit ($p < 0.01$). Credit access enables households to finance the upfront costs of stove adoption, which are perceived to be quite high for most rural households, as indicated by participant observation.

Households participating in social groups also have a significantly higher probability of adopting improved biomass stoves, by 12.3%, compared to non-participating households ($p < 0.01$). It might be that belonging to a social group enhances social capital and information exchange. Participant observation reveals that women are often involved in local social groups referred to as 'table-banking', 'merry-go-round', or 'chamaas.' Women in such groups often pool modest amounts of money to support each other in rotations to purchase basic household assets, including clean, fuelwood-saving cooking technologies.

Household proximity to biomass resources has a significant effect on the adoption of improved biomass stoves as primary stoves. In particular, for households depending on self-collected fuelwood, the probability of improved biomass stove adoption increases by 4.2% with each additional kilometer walked from homesteads to the woodland most frequently used for fuelwood collection ($p < 0.05$). It can be inferred that local fuelwood scarcity leads households to adopt fuelwood-saving cookstoves, compared to households in areas of abundant biomass that can be easily collected.

Finally, household location along the transect has a significant effect on stove adoption. In Muranga, households located close to state forests have a significantly lower probability (by 20.7%) of adopting an improved biomass stove ($p < 0.05$). Conversely, households located at the vicinity of the urban center (i.e., the peri-urban zone in Kiambu transect) have a 9.8% ($p < 0.05$) higher probability of adopting an improved biomass stove.

3.3. Path analysis for female-headed households

During data collection and the first stages of analysis (i.e., descriptive statistic and probit analysis; sections 3.1–3.2) we made a series of important observations related to the adoption of improved biomass stoves as primary stoves. In particular, we noticed the following.

- (a) Paradoxically, female-headed households tend to have a lower probability of adopting improved biomass stoves, both for the pooled sample (probit analysis) and in most of the distinct zones (descriptive statistics). This is despite the fact that women disproportionately bear the drudgery and

burden of fuelwood procurement and cooking (participant observation, descriptive statistics).

- (b) Female-headed households have lower income throughout the study area; i.e., across all study zones (descriptive statistics).
- (c) Household income varies substantially across the zones (descriptive statistics) and is affected by various factors (participant observation), having eventually a significant effect on the adoption of improved biomass stoves (probit analysis).

In order to further explore the interface between gender, income, and environmental and geographical factors, we use a path analysis to estimate the direct, indirect and total standardized effects of the statistically significant income factors on stove adoption for female-headed households. We select a list of 10 predictors from table 6, to estimate the mediating effects of income on stove adoption and the magnitude of the standardized coefficients among the predictors. In order to better understand the dynamics between the gender of the household head and stove adoption, we estimate the correlation between the gender of the household head and the identified intra-household productive resources (table 7).

The standardized path coefficients and residual coefficients for the adoption of improved biomass stoves are shown in the path diagram (figure 4) along with their paths (arrow directions). The absolute magnitude of the standardized coefficients indicates the strength of the relationship. First, the results suggest that the selected variables included in the path model explain 60.40% of the variance on adoption, and 43.10% of the variance on income. With the exemption of forest remoteness, all coefficients for direct effects on the adoption of improved biomass stoves are statistically significant ($p < 0.01$ and $p < 0.05$).

The results in table 7 suggest that engagement with agroforestry practices (i.e., planting trees on farms) has the highest positive direct effect (0.303) and total effect (0.396, 23.5% mediated by income) on the adoption of improved biomass stoves. Ranked by decreasing magnitude of the coefficients of total effects, the other important variables influencing the adoption of improved biomass stoves include: female household headship (0.285, –13.5% mediated by income); household income level (0.255); education level (0.254, 22.5% mediated by income); credit access (0.225, 17.8% mediated by income); city proximity (0.221, 13.6% mediated by income); and social group membership (0.169, 18.3% mediated by income). On the other hand, energy poverty (–0.215) and multi-dimensional non-income poverty (–0.139) have negative total effects on adoption.

The estimation results for gender correlations with income factors as established in this path analysis

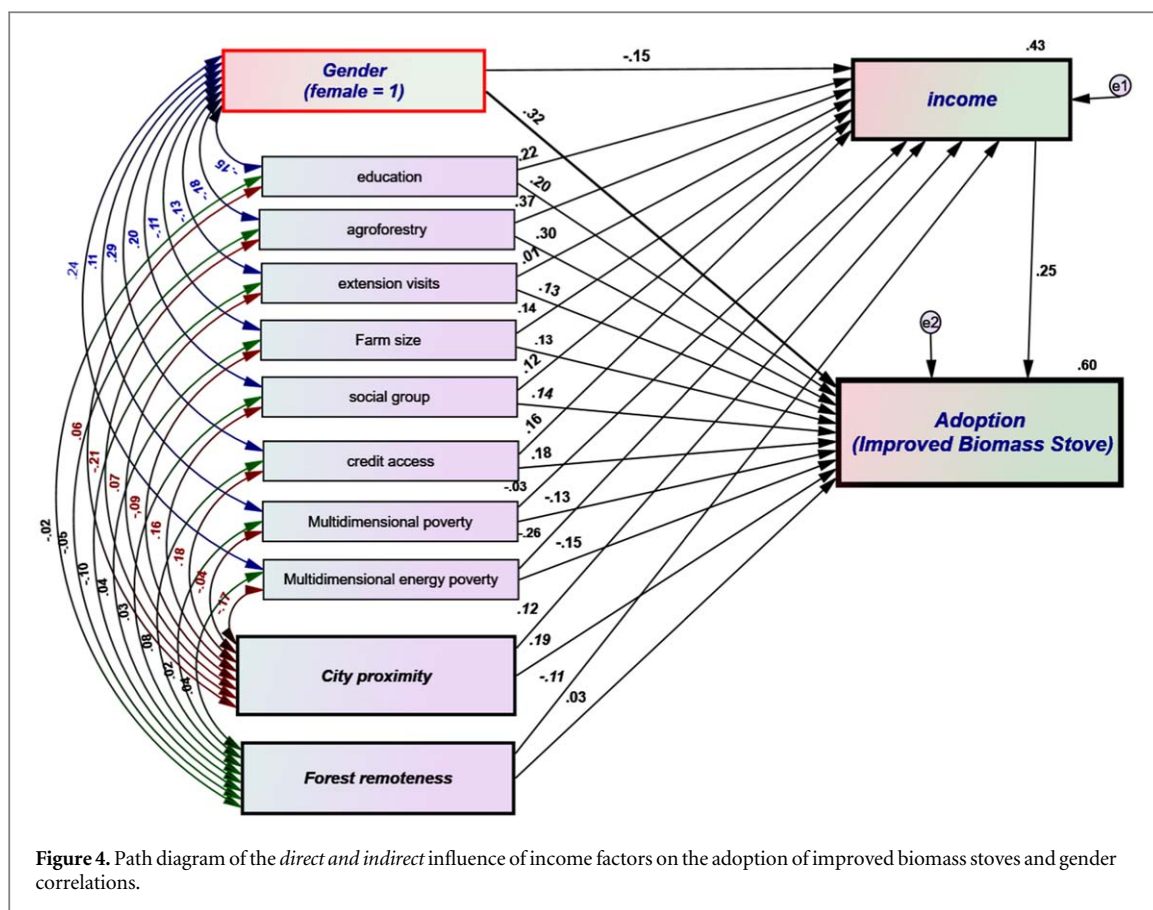


Table 7. Direct, indirect, and total effects of selected independent variables on the adoption of improved biomass stoves.

Variables	Correlations			Effects on adoption of improved biomass stoves		
	Female headship	City proximity	Forest remoteness	Direct effect (on adoption)	Indirect effect (via income)	Total effects
Agroforestry	-0.180	-0.213	-0.055	0.303	0.093	0.396
Gender (female head = 1)	—	—	—	0.323	-0.038	0.285
Income	—	—	—	0.255	—	0.255
Education	-0.151	0.059	-0.020	0.199	0.056	0.254
Credit access	0.292	0.183	0.081	0.185	0.04	0.225
City proximity (peri-urban)	—	—	—	0.191	0.03	0.221
Social group membership	0.205	0.161	0.026	0.138	0.031	0.169
Farm size	-0.107	-0.088	0.045	0.126	0.036	0.162
Extension visits	[-0.128]	0.069	-0.097	0.128	[0.001]	0.13
Forest remoteness (semi-arid)	—	—	—	[0.031]	-0.028	0.003
Multidimensional poverty	0.108	-0.036	0.024	-0.131	[-0.008]	-0.139
Energy poverty	0.238	-0.171	0.044	-0.148	-0.067	-0.215
e ₁	—	—	—	—	0.252	—
e ₂	—	—	—	0.073	—	—
Intercepts	—	—	—	-0.417	0.902	—
R ²	—	—	—	60.40%	43.10%	—

Notes. 1. Statistically insignificant coefficients are given in brackets. 2. e₁ and e₂ are error terms for unexplained variance.

suggest that female-headed households have a negative correlation with almost all of the identified income factors that positively affect the adoption of improved biomass stoves. These include agroforestry practice (-0.180), education (-0.151), farm size

(-0.107), and extension visits (-0.128). The results also show a significant and inverse association between female-headed households and household income, which reduces female total effects on the adoption of improved biomass stoves by 13.3%. Furthermore,

female-headed households are found to have positive correlations with multidimensional poverty (0.108) and multidimensional energy poverty (0.238), which are observed to have a significantly negative effect on the adoption of improved biomass stoves (section 3.2). On a more promising note, female-headed households are found to have a positive correlation with access to credit services (0.292) and participation in social groups (0.205), which are variables that have a significantly positive effect on the adoption of improved biomass stoves (section 3.2).

The correlation estimates for geographical factors suggest that households located close to the city have more access to credit services, social group participation, and extension visits. These factors are observed to have a significantly positive effect on the adoption of improved biomass stoves.

4. Discussion

4.1. Synthesis of findings

The probit estimation results identify that income increases significantly the probability of adopting improved biomass stoves as primary stoves (section 3.2) [36–38]. This is consistent both with previous studies across sub-Saharan Africa and the energy ladder theory that alludes to the fact that households tend to switch to modern cooking methods as their wealth increases [31, 39–41]. The income effects imply that any economic incentive improving the affordability of stoves could have an important effect on stove adoption by low-income households that have not yet made the transition from traditional to improved stoves [42–44]. However, such income effects are only part of the story, as the availability and accessibility of fuel and accessibility to markets can dictate fuel prices, which can have important ramifications for stove adoption [23–25]. For example, in Muranga, average incomes decrease with increasing proximity to the semi-arid interior, while improved stove adoption and fuel prices increase (table 2). In this sense, depending on the area, the incentives and subsidies towards fuel costs could have very different effects. However, further research will be necessary to elucidate these relationships between income, fuel prices and economic incentives, as they were beyond the focus of our study.

Second, the study identifies that the gender of the household head does not seem to have a significant effect on stove adoption (section 3.2), which is rather counter-intuitive, considering that females are disproportionately affected by fuelwood procurement and cooking in Kenya and other parts of sub-Saharan Africa [29, 45, 46]. However, the path analysis suggests that this is possibly due to the fact that female-headed households are less likely to benefit from critical factors that are positively associated with stove adoption (e.g., education, extension visits, engagement in

agroforestry, farm size), and tend to have lower income, which in turn reduces by 14% the total effects on adoption of improved biomass stoves (table 6) (section 3.3). More promisingly, the path analysis suggests that female-headed households are more likely to have access to credit and to participate in social groups, both of which increase their opportunity to adopt improved biomass stoves (section 3.3) [47–51].

Third, according to our results it is not only the intra-household factors such as income that affect the adoption of improved biomass stoves, but also broader geographical and environmental factors. In particular, biomass abundance in terms of local biomass availability (i.e., location in the close-forest zone and semi-arid area) and accessibility (i.e., distance to fuelwood collection areas), as well as availability of other fuels (i.e., location in the peri-urban zone) seem to have a significant effect on the adoption of improved biomass stoves as the primary cooking method (section 3.2). In particular, the probit analysis reveals that households located in the peri-urban zone have a significantly higher probability of adopting improved biomass stoves as primary stoves, while households located in the close-forest zone have a significantly lower probability of doing so (section 3.2). This is possibly due to the fact that urbanization increases the availability of (and access to) modern fuels (e.g., though improved market infrastructure) and awareness about modern products, including clean cookstoves [13, 14, 52, 53]. This, combined with the significantly higher income in this zone (table 5), possibly due to better employment and income diversification opportunities [52, 54], creates an environment conducive to the adoption of improved biomass stoves. On the other hand, fuel scarcity in the semi-arid zone (and the generally higher fuel prices), compounded with the lower household incomes (table 5), also result in a conducive environment for the adoption of improved biomass stoves as primary stoves (though this result is not statistically significant). It is worth mentioning that location, apart from affecting fuel and stove availability and prices, can also affect the availability of important services that can affect adoption, such as post-acquisition support (e.g., local capacity for stove repair and replacement of stove parts). Studies have found that a lack of such services can decrease stove adoption [55, 56], but this was beyond the focus of this study.

Biomass accessibility seems to be an equally important factor in biomass stove adoption. The probit model indicates that adoption increases significantly, by 4.2% ($p < 0.05$), with each additional kilometer walked from the homesteads to the most frequently used area of fuelwood collection (section 3.2). At the same time, both the probit and path analysis reveal that engagement with agroforestry practices significantly influences the adoption of improved biomass stoves (sections 3.2–3.3). This finding is consistent with previous studies that identified

the integration of trees on farms (either in the cropland or in dedicated woodlots) as being an opportunity for sustainable fuelwood production and consumption, and thus ready availability and accessibility [29, 57–59].

4.2. Policy implications and recommendations

According to our results, the adoption of improved biomass stoves depends on various factors, including: (a) geographical location and environmental characteristics, and how they intersect with fuel availability and accessibility and market access, and; (b) intra-household characteristics and their intersection with gender.

Factor (a) strongly suggests that stove dissemination programmes and projects should consider carefully, and factor into their strategies, how geographical and environmental factors intersect with local biomass dynamics, energy infrastructure, market access, and other factors in adoption. For example, households located in areas of fuelwood abundance have a lower disposition to adopt improved biomass stoves, even though income in such areas might not be the ultimate constraint (sections 3.1, 3.2). This possibly suggests the need to design non-uniform and spatially explicit stove promotion and dissemination strategies that consider the local relevance of differing stove technologies and biomass production practices (e.g., agroforestry, household woodlots), and offer differentiated incentives. Indeed, the simultaneous adoption of improved biomass stoves and sustainable biomass production practices could be a very promising strategy, considering the strong positive effect of involvement in agroforestry on stove adoption (section 3.2), but should be reflective of the context of the area. In any case, there is a need for significant further research on the effects of geography, environmental characteristics and biomass dynamics on stove adoption, as well as how to design optimal, spatially explicit stove promotion and dissemination strategies.

For (b), our results reveal a paradoxical situation where female-headed households have lower adoption rates, despite females being disproportionately affected by traditional cooking practices (section 3.2). This finding must be considered seriously in the face of current calls that gender aspects must permeate the entire process, from stove technology development and marketing, to adoption and customer support. Adoption in this case seems to be mediated through different pathways that often go beyond the stove sector itself, and reflect broader gender disparities (e.g., in education, income, and land tenure). It goes without saying that efforts should be made to increase women's access to and control of key productive resources. However, this might be a slow or slower social process, which might delay the adoption of clean cooking options. Interventions that are more rooted in the stove sector could capitalize on the large social capital embedded in

female groups through (a) improving access to finance through direct subsidies or micro-financing to enhance the affordability of clean cookstoves, and (b) marketing and awareness-raising campaigns about clean cookstove options and their health, economic, and environmental benefits over traditional cooking methods.

5. Conclusion

This paper explored how various demographic, socio-economic, institutional, geographic, and environmental factors affect the adoption of improved biomass stoves as primary stoves in rural Kenya. We followed a transect-based approach, starting from areas of high fuelwood abundance and moving towards semi-arid interior (Muranga County) and the peri-urban area of Nairobi (Kiambu County), where fuelwood procurement practices radically change.

Apart from the usual intra-household characteristics, such as income, our study finds that geographical and environmental factors also affect stove adoption. For example, households in peri-urban and semi-arid areas seem to have higher probabilities of adopting improved biomass stoves (but not statistically significant, in the latter case). Fuelwood availability is lower in both areas, suggesting a link between increasing biomass scarcity and the adoption of improved biomass stoves. However, this possibly happens through different mechanisms that require further exploration. Furthermore, the probability of adoption increases with increasing distance to the most frequently used fuelwood collection area, suggesting that accessibility also plays an important role.

Overall, this study suggests there is a need for non-uniform and spatially explicit stove promotion strategies that take into account fuelwood availability and accessibility, and market access. Such strategies that are aware of local contexts could catalyze the large-scale adoption of clean cooking options in Kenya, and elsewhere on the continent.

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Data availability statement

The underlying datasets are available from the corresponding author, upon reasonable request.

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