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Household-Level Determinants of Low-Carbon Cooking Technology Adoption in Rural Sierra Leone: Evidence from Bombali, Port Loko and Tonkolili

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Abstract

This study examined the household-level factors associated with the adoption of low-carbon cooking technologies using cross-sectional survey data from 600 households in Bombali, Port Loko and Tonkolili districts. Adoption was defined as the use of at least one improved biomass stove, liquefied petroleum gas, biogas, ethanol or electric cooking technology, while households relying exclusively on traditional three-stone fires or unimproved stoves were classified as non-adopters. The analysis employed descriptive statistics, chi-square tests, Welch mean-difference tests and a heteroskedasticity-robust linear probability model. The findings show that 38.0% of households had adopted at least one low-carbon cooking technology. Adoption rates were 39.2% in Bombali, 38.5% in Port Loko and 36.2% in Tonkolili, with no statistically significant differences across districts, $\chi^2(2) = 0.41$, $p = 0.817$. Household income, education, household size, female household headship, awareness, access to credit, stove cost, fuel price and market distance were not statistically significant predictors of adoption in the multivariable model. The model explained only 0.3% of the variation in adoption, suggesting that the measured household-level characteristics provided limited explanatory power. The findings indicate that low-carbon cooking adoption may be shaped more strongly by wider structural and institutional conditions, including technology availability, rural supply systems, distribution networks, programme design and maintenance support.

Keywords

Clean Cooking, Low-Carbon Technology, Rural Households, Technology Adoption, Sierra Leone, Linear Probability Model

1. Introduction

The continued reliance on traditional biomass fuels for cooking remains a major public health, environmental and socio-economic challenge in Sub-Saharan Africa. About 2.1 billion people still cook with open fires or inefficient stoves fuelled by kerosene, biomass, coal and other polluting fuels, creating harmful household air pollution [1]. The International Energy Agency also reports that more than 2 billion people lacked access to clean cooking in 2023, with Sub-Saharan Africa accounting for a large and growing share of the global access gap [2]. Conditions in Sierra Leone are particularly severe. World Bank data show that access to clean fuels and technologies for cooking remains very low in Sierra Leone, especially in rural areas [3]. As a result, many rural households continue to rely heavily on firewood and charcoal as their primary sources of cooking energy. This dependence reflects not only income poverty but also structural energy poverty, weak rural energy markets, limited transport infrastructure and restricted access to affordable alternatives [4]. Household air pollution associated with traditional cooking practices is a serious health risk. The World Health Organization links exposure to smoke from polluting fuels and inefficient stoves to diseases such as stroke, ischaemic heart disease, chronic obstructive pulmonary disease and lung cancer [1].

Women and children are particularly exposed because they spend more time around cooking spaces and because women are commonly responsible for cooking and fuel preparation. In rural contexts where access to health services is limited, these exposures deepen preventable illness and household vulnerability. The environmental implications are also significant. Traditional biomass use contributes to forest pressure where fuelwood is harvested unsustainably, while inefficient combustion releases greenhouse gases and short-lived climate pollutants, including black carbon [4] [5]. In Sierra Leone, forest resources are important for carbon sequestration, biodiversity conservation, soil protection and livelihood security. Continued dependence on firewood and charcoal therefore links household cooking practices to wider concerns around forest degradation, climate mitigation and rural ecological resilience. The socio-economic costs of traditional cooking practices are equally important. Women and girls often bear the primary responsibility for fuelwood collection, a task that can reduce time available for education, income-generating activities and community participation. Gender-sensitive energy research shows that energy poverty and cooking burdens are strongly connected to women's time poverty, health risks and limited economic opportunities [6]. These gendered burdens reinforce existing inequalities and undermine development goals related to education, health, poverty reduction and women's empowerment. Low-carbon cooking technologies, including improved biomass cookstoves, liquefied petroleum gas (LPG), biogas systems, ethanol stoves and electric cooking solutions, are promoted as alternatives to traditional cooking systems. These technologies can reduce household air pollution, lower fuel consumption, decrease pressure on forest resources and contribute to climate mitigation [4] [5]. However, their benefits depend on adoption, sustained use and compatibility with household cooking needs. Despite these potential benefits, the adoption of low-carbon cooking technologies in rural Sierra Leone remains limited. Some households adopt improved stoves or cleaner cooking options but continue to use traditional stoves alongside newer technologies. This pattern, often described as energy stacking, demonstrates that household energy transitions are rarely linear [7] [8]. Barriers such as high upfront costs, limited fuel and stove availability, weak infrastructure, cultural cooking preferences, limited access to credit and inadequate policy support continue to constrain widespread adoption. Although clean cooking adoption has been examined in several developing-country settings, household-level quantitative evidence from Sierra Leone remains limited. This research contributes by analyzing data from 600 respondents across Bombali, Port Loko and Tonkolili districts. The objective is to examine whether low-carbon cooking technology adoption is associated with household income, education, household size, gender of the household head, awareness, access to credit, stove cost, fuel price and market distance. The analysis also compares adoption rates across the three districts.

2. Literature Review

Access to clean and low-carbon cooking technologies has emerged as an important issue in global development, public health, gender equality and climate change mitigation. Clean cooking generally refers to the use of fuels and technologies that reduce household air pollution and greenhouse gas emissions compared with traditional biomass-based cooking systems such as firewood and charcoal [1] [4]. The 2030 Agenda for Sustainable Development places clean and affordable energy at the centre of inclusive development through Sustainable Development Goal 7, while also linking energy access to health, gender equality and climate action [9]. In developing-country contexts, household cooking practices are embedded in socio-economic realities, cultural norms and existing energy systems. Persistent reliance on traditional biomass fuels reflects not only low income but also structural barriers, including limited infrastructure, weak supply chains and the historical prioritisation of electricity access over cooking energy in national energy policies [4] [10]. In rural areas, households often depend on locally available biomass because it is perceived as affordable, accessible and suitable for traditional cooking practices. Low-carbon cooking technologies such as improved biomass cookstoves, LPG, biogas, ethanol and electric cooking are increasingly promoted as important pathways for achieving energy access, health improvement, gender equality, forest conservation and climate mitigation [2] [4] [5]. However, adoption remains uneven and context-specific. Evidence across developing regions shows that adoption is shaped by a complex interaction of economic, social, cultural and institutional factors [11] [12].

2.1. Theoretical Perspectives on Cooking Energy Transitions

The literature on household energy transitions is informed by several theoretical frameworks. The Energy Ladder Hypothesis argues that households move progressively from traditional fuels to modern energy sources as income increases [13]. Although influential, this framework has been criticised for assuming a linear transition and for failing to explain why households often continue using traditional fuels after adopting modern alternatives. The Energy Stacking Model provides a more flexible explanation. It argues that households use multiple fuels and technologies simultaneously to manage cost, availability, reliability, cooking needs and cultural preferences [7]. This framework is particularly relevant for rural settings where cleaner fuels may be unreliable, unavailable or unaffordable. In such contexts, adoption does not necessarily mean complete substitution of traditional fuels. Rogers' Diffusion of Innovations theory further contributes to understanding clean cooking adoption by emphasising perceived relative advantage, compatibility with existing practices, trialability, observability and social influence [14]. Applied to clean cooking, this theory suggests that households are more likely to adopt technologies when they perceive them as useful, affordable, culturally acceptable and successfully used by peers within their communities. Economic models of household choice frame adoption as a utility-maximisation decision constrained by income, prices, time and information. From this perspective, households compare the upfront and recurring costs of clean cooking technologies with expected benefits such as fuel savings, reduced cooking time, convenience, health improvements and environmental protection [5] [10].

2.2. Empirical Evidence on Determinants of Clean Cooking Adoption

Empirical studies consistently identify income as a key determinant of clean cooking adoption. Higher-income households are generally better able to afford the upfront cost of improved cookstoves, LPG cylinders and related equipment, as well as recurring fuel expenses. Studies on fuel choice and improved cookstove adoption also show that education and awareness increase the likelihood of adoption by improving information, risk perception and openness to new technologies

[8] [12] [15]. Gender dynamics are particularly important in cooking energy transitions. Although women are usually the primary users of cooking technologies, household financial control and major investment decisions may not always rest with women. Gender-sensitive energy research therefore emphasises that women's agency, access to finance and participation in household decision-making are critical for clean cooking adoption [6]. Affordability and market accessibility are widely reported barriers. High upfront stove costs, LPG cylinder costs and recurrent fuel costs discourage adoption among low-income households. Even when awareness of health and environmental benefits is high, liquidity constraints can prevent households from adopting cleaner technologies. Reviews of improved cookstove and clean fuel adoption show that adoption is influenced not only by technology performance but also by prices, credit, local supply chains, maintenance and user preferences [5] [11]. Cultural preferences and cooking practices also shape adoption. Some staple foods require long cooking times or high heat intensity, and households may perceive certain clean cooking technologies as unsuitable for traditional meals. Taste preferences, safety concerns, distrust of low-quality stoves and familiarity with traditional stoves can all contribute to continued energy stacking [7] [14]. Institutional and policy frameworks further influence clean cooking transitions. Weak coordination among government agencies, limited enforcement of quality standards, inadequate financing mechanisms and insufficient integration of clean cooking into national energy strategies can slow adoption. In Sierra Leone, clean cooking remains an urgent energy access challenge, as access to clean fuels and technologies for cooking remains very low, particularly in rural areas, according to World Bank data [3]. This study contributes to the literature by examining the combined effects of socio-economic, gender-related, informational, financial and infrastructural factors on low-carbon cooking adoption in rural Sierra Leone.

3. Methodology

This study used a cross-sectional household survey design to examine associations between observed household characteristics and low-carbon cooking technology adoption in rural Sierra Leone and low-carbon cooking technology adoption in rural Sierra Leone. The analysis combines descriptive statistics, bivariate tests and a heteroskedasticity-robust linear probability model. Because the data are observational and cross-sectional, all estimates are interpreted as associations rather than causal effects. The study covered rural households in Bombali, Port Loko and Tonkolili districts. Respondents were household heads or primary cooks who could report on household cooking technology, expenditure and access conditions. The final analytical sample contains 600 completed household interviews: 212 from Bombali, 192 from Port Loko and 196 from Tonkolili [16]. Primary data were collected through a structured, face-to-face questionnaire. The analytical dataset contains household income, years of education, household size, gender of household head, awareness score, access to credit, stove cost, fuel price, distance to market and low-carbon cooking technology adoption. Variable coding was as follows. Low-carbon cooking adoption equals 1 when the household reported using an improved biomass stove, LPG, biogas, ethanol or electric cooking technology, and 0 when it relied exclusively on a traditional three-stone fire or unimproved stove. Household income and stove cost were recorded in Sierra Leonean Leones (SLE) and divided by 1000 for regression estimation. Education is measured in completed years, household size as the number of household members, female-headed household as 1 for female and 0 for male, access to credit as 1 for yes and 0 for no, fuel price in SLE per reported unit, and market distance in kilometres. Awareness was recorded on a five-point scale ranging from 1 to 5, with higher values indicating greater reported awareness of clean-cooking benefits. Data collection was reported as occurring between March and April 2025. Informed consent was obtained from participants, participation was voluntary, and confidentiality was maintained. During data checking, one negative household-income value and one negative stove-cost value were identified as impossible values and treated as missing. The regression therefore uses complete cases (N = 598), while descriptive adoption and district comparisons use all 600 observations.

Empirical Model

Because the dependent variable is binary, logit and probit models are standard alternatives. The main analysis uses a linear probability model with HC1 heteroskedasticity-robust standard errors because coefficients are directly interpretable as changes in adoption probability. The specification is used as an associational model and not as a causal design.

$$\begin{aligned}\text{Adoption}_i = {} & \beta_0 + \beta_1 \text{Income}_i + \beta_2 \text{Education}_i \\ & + \beta_3 \text{Household Size}_i + \beta_4 \text{Female Head}_i \\ & + \beta_5 \text{Awareness}_i + \beta_6 \text{Credit}_i \\ & + \beta_7 \text{Stove Cost}_i + \beta_8 \text{Fuel Price}_i \\ & + \beta_9 \text{Market Distance}_i + \varepsilon_i\end{aligned}$$

The model contains exactly the predictors reported in the regression table. Income and stove cost are expressed in thousands of SLE. The remaining continuous variables retain their original units, while female household headship and credit access are binary indicators.

4. Results

4.1. Descriptive Statistics

Table 1 presents descriptive statistics for the household-level variables in the analysis. In total, 38.0% of households reported using at least one low-carbon cooking technology. The table excludes electrification coverage, poverty rate and forest cover because their sources and levels of measurement could not be verified as household-level observations.

Table 1. Descriptive statistics of retained household-level variables.

Variable	Mean	Std. Dev.	Min	Max
Low-carbon cooking adoption (1 = yes)	0.380	0.486	0	1
Household income (SLE)	3481.3	1218.7	74	6840
Education (years)	7.515	4.634	0	15
Household size (persons)	5.802	3.029	1	11
Female-headed household (1 = yes)	0.515	0.500	0	1
Awareness score (1 - 5)	3.040	1.441	1	5
Access to credit (1 = yes)	0.485	0.500	0	1
Stove cost (SLE)	2531.5	798.1	100	5296
Fuel price (SLE/unit)	25.352	7.989	2.252	46.475
Market distance (km)	7.749	4.119	0.513	14.934

Source: Authors' computation from the household survey dataset. Notes: N = 600 except household income and stove cost, where one impossible negative value in each variable was treated as missing (N = 599 for the affected descriptive statistic).

4.2. Adoption Differences across Districts

Adoption rates were 39.2% in Bombali (83 of 212 households), 38.5% in Port Loko (74 of 192) and 36.2% in Tonkolili (71 of 196). A Pearson chi-square test found no statistically significant association between district and adoption, $\chi^2(2) = 0.41$, $p = 0.817$.

4.3. Mean Difference Tests between Adopters and Non-Adopters

Welch independent-sample t-tests compared adopters and non-adopters across the continuous household variables. None of the mean differences was statistically significant at the 5% level. Table 2 reports group means, test statistics and p-values.

Table 2. Mean-difference tests: adopters versus non-adopters.

Variable	Adopters mean	Non-adopters mean	t statistic	p-value
Household income (SLE)	3416.4	3509.9	−0.900	0.369
Education (years)	7.597	7.465	0.338	0.736
Awareness score	3.000	3.065	−0.529	0.597
Market distance (km)	7.722	7.766	−0.129	0.898
Household size	5.746	5.836	−0.357	0.722
Stove cost (SLE)	2473.0	2560.1	−1.302	0.194
Fuel price (SLE/unit)	25.241	25.420	−0.265	0.792

Source: Authors' computation from the household survey dataset. Welch tests were used because equal variances were not assumed.

4.4. Adoption Rates by District

Table 3 reports the sample distribution and adoption rate by district. The descriptive differences are small and, as shown by the chi-square test, are not statistically significant.

Table 3. Sample distribution and adoption by district.

District	Households	Adopters	Adoption rate (%)
Bombali	212	83	39.2
Port Loko	192	74	38.5
Tonkolili	196	71	36.2
Total	600	228	38.0

Source: Authors' computation from the household survey dataset.

4.5. Econometric Results

Table 4 presents the results of the robust linear probability model. Income and stove cost are measured in thousands of SLE. The complete-case estimation sample includes 598 households.

Table 4. Robust linear probability model for low-carbon cooking adoption.

Variable	Coefficient	Robust Std. Error	p-value
Constant	0.5074	0.1297	<0.001
Income (1000 SLE)	−0.0104	0.0166	0.533
Education (years)	0.0011	0.0043	0.798
Household size	−0.0015	0.0066	0.827
Female-headed household	0.0024	0.0404	0.953
Awareness score	−0.0077	0.0140	0.583
Access to credit	0.0032	0.0403	0.936
Stove cost (1000 SLE)	−0.0238	0.0249	0.340
Fuel price (SLE/unit)	−0.0005	0.0025	0.856
Market distance (km)	−0.0001	0.0049	0.981

Source: Authors' computation from the household survey dataset. Notes: HC1 robust standard errors. Income and stove cost are measured per 1000 SLE. Dependent variable: adoption = 1; non-adoption = 0. N = 598; R-squared = 0.003. None of the household-level predictors is statistically significant at conventional levels. Female-headed household status has a small positive coefficient (0.002, $p = 0.953$), while education (0.001, $p = 0.798$) and credit access (0.003, $p = 0.936$) also have coefficients close to zero. Household income, measured in thousands of SLE, has a negative coefficient of −0.010 ($p = 0.533$), indicating that higher reported income is associated with a slightly lower probability of adoption, although the relationship is not statistically significant. Awareness, stove cost, fuel price and market distance are also not statistically significant. The model explains very little of the variation in adoption, with an R-squared value of 0.003.

5. Discussion

This study assessed the extent of low-carbon cooking technology adoption among

600 rural households in Bombali, Port Loko and Tonkolili districts. The results show that 38.0% of households had adopted at least one low-carbon cooking technology, indicating that adoption remains limited across the study areas. The similarity in adoption rates across the three districts suggests that the transition to cleaner cooking is a broader rural challenge rather than one confined to a particular district. The paper did not identify statistically significant household-level predictors of adoption. This means that the available evidence was insufficient to determine which household characteristics were most influential in shaping adoption decisions. The findings therefore point to the need for greater attention to the wider conditions surrounding access, availability and sustained use of low-carbon cooking technologies. Efforts to expand adoption should focus on making appropriate technologies more accessible, affordable and suitable for rural households. Policy interventions should also strengthen distribution networks, financing options, user support and coordination among government agencies, development partners and private-sector suppliers. The study contributes evidence on the current level of low-carbon cooking adoption in rural Sierra Leone and highlights important gaps for future research. Further studies should collect more detailed household, community and market-level data to support stronger explanations of adoption and guide more effective clean-cooking policies.

6. Conclusion

This research assessed the extent of low-carbon cooking technology adoption among 600 rural households in Bombali, Port Loko and Tonkolili districts. The results show that 38.0% of households had adopted at least one low-carbon cooking technology, indicating that uptake remains limited across the selected areas. Similar adoption rates across the three districts suggest that the transition to cleaner cooking represents a wider rural challenge rather than a problem confined to one location. The analysis did not identify any statistically significant household-level predictors of adoption. Consequently, the available evidence was insufficient to determine which household characteristics were most influential in shaping adoption decisions. Greater attention should therefore be given to the wider conditions affecting access, availability and continued use of low-carbon cooking technologies. Efforts to increase uptake should focus on making suitable technologies more accessible, affordable and compatible with rural cooking needs. Policy interventions should also strengthen distribution networks, financing options, maintenance services and coordination among government institutions, development partners, private suppliers and local communities. These findings provide evidence on the current level of low-carbon cooking technology adoption in rural Sierra Leone and identify important areas for further investigation. Future research should collect more detailed household, community and market-level information to support stronger explanations of adoption and guide effective clean-cooking policies.

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Ethics Statement

Informed consent was obtained from all study participants. Participation was voluntary, and confidentiality was maintained throughout the research process.

Author Contributions

Conceptualization, E.B. and H.M.S.; methodology, E.B.; formal analysis, E.B.; investigation, E.B. and H.M.S.; writing—original draft preparation, E.B.; writing—review and editing, E.B. and H.M.S. Both authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] World Health Organization (2025) Household Air Pollution. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

[2] International Energy Agency (n.d.) Access to Clean Cooking. International Energy Agency. https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking

[3] World Bank (2025) Access to Clean Fuels and Technologies for Cooking (% of Population)—Sierra Leone. World Development Indicators. https://data.worldbank.org/indicator/EG.CFT.ACCS.ZS?locations=SL

[4] World Bank (2020) The State of Access to Modern Energy Cooking Services. World Bank. https://openknowledge.worldbank.org/entities/publication/3b07067d-bd68-59fa-b1aa-1db2f4de9f07

[5] Jeuland, M.A. and Pattanayak, S.K. (2012) Benefits and Costs of Improved Cookstoves: Assessing the Implications of Variability in Health, Forest and Climate Impacts. *PLOS ONE*, **7**, e30338. https://doi.org/10.1371/journal.pone.0030338

[6] ENERGIA (2019) Gender in the Transition to Sustainable Energy for All: From Evidence to Inclusive Policies. ENERGIA International Network on Gender and Sustainable Energy, The Hague. https://energia.org/assets/2019/04/Gender-in-the-transition-to-sustainable-energy-for-all_-From-evidence-to-inclusive-policies_FINAL.pdf

[7] Masera, O.R., Saatkamp, B.D. and Kammen, D.M. (2000) From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development*, **28**, 2083-2103. https://doi.org/10.1016/s0305-750x(00)00076-0

[8] Heltberg, R. (2004) Fuel Switching: Evidence from Eight Developing Countries. *Energy Economics*, **26**, 869-887. https://doi.org/10.1016/j.eneco.2004.04.018

[9] United Nations General Assembly (2015) Transforming Our World: The 2030 Agenda for Sustainable Development. A/RES/70/1. United Nations. https://sdgs.un.org/2030agenda

[10] Pachauri, S. and Jiang, L. (2008) The Household Energy Transition in India and China. *Energy Policy*, **36**, 4022-4035. https://doi.org/10.1016/j.enpol.2008.06.016

[11] Lewis, J.J. and Pattanayak, S.K. (2012) Who Adopts Improved Fuels and Cookstoves? A Systematic Review. *Environmental Health Perspectives*, **120**, 637-645. https://doi.org/10.1289/ehp.1104194

[12] Jan, I. (2012) What Makes People Adopt Improved Cookstoves? Empirical Evidence from Rural Northwest Pakistan. *Renewable and Sustainable Energy Reviews*, **16**, 3200-3205. https://doi.org/10.1016/j.rser.2012.02.038

[13] Hosier, R.H. and Dowd, J. (1987) Household Fuel Choice in Zimbabwe: An Empirical Test of the Energy Ladder Hypothesis. *Resources and Energy*, **9**, 347-361. https://doi.org/10.1016/0165-0572(87)90003-x

[14] Rogers, E.M. (2003) Diffusion of Innovations. 5th Edition, Free Press.

[15] Karimu, A., Mensah, J.T. and Adu, G. (2016) Who Adopts LPG as the Main Cooking Fuel and Why? Empirical Evidence on Ghana Based on National Survey. *World Development*, **85**, 43-57. https://doi.org/10.1016/j.worlddev.2016.05.004

[16] Bryman, A. (2016) Social Research Methods. 5th Edition, Oxford University Press.

[17] Creswell, J.W. and Creswell, J.D. (2018) Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. 5th Edition, Sage Publications.