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Economic evaluation of household firewood consumption and carbon footprints in Pakistan: implication for climate change mitigations

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Controlling the carbon footprints of household firewood consumption is critical for promoting global sustainability and mitigating the impacts of climate change. This study aims to investigate the determinants of household firewood consumption and associated carbon footprint in Pakistan by employing the 2018–2019 data of Household Integrated Economic Survey (HIES), Heckman selection model, and Tobit regression method. On average, households consumed 1706 kg of firewood in Pakistan annually, which generated carbon emissions of 19.29 Gg per annum. The results of first stage of Heckman selection model reveal that household head's primary education, agricultural occupation, household size, rural residency, and KP region contribute to choosing firewood as an energy source, while head's higher education, household income, housing types, adoption of cooking range and clean stoves, and residency in Punjab and Sindh provinces discourage firewood use. Similarly, the results of the second stage of Heckman model demonstrate that head's age, household size, income, detached and semi-detached houses, and KP residency significantly account for household firewood consumption expenditure. Findings of Tobit regression uncover that illiterate head with agricultural occupation, household size, and rural residency in particular in KP province have a significant association with household carbon emissions. However, female-headed households, higher education, paid work, household income, and Punjab and Sindh residencies tend to generate lower carbon emissions. Therefore, the study suggests raising awareness among females about the harmful effects of firewood energy, expanding access to alternative cleaner energy sources, and promoting the use of clean and efficient stoves. In addition, increasing household income and decreasing household size could be other valid policy options for reducing household carbon footprints.
Keywords: Household consumption, carbon emissions, HIES, Heckman selection model, Tobit, Pakistan.

INTRODUCTION

Firewood is still a major source of energy for households living in the developing world. It is frequently the only available choice for cooking and space heating because alternative cleaner sources of energy, such as natural gas, solar and electricity, are either unavailable or unaffordable (Bishop *et al.*, 2015; Waswa *et al*., 2020). As a result, around 2.6 billion poor people from low-income countries rely on fuel wood, which corresponds to 55% of global wood harvest (Yousaf *et al*., 2021). Firewood is a renewable and inexpensive energy source, but its inefficient combustion in traditional stoves leads to the emissions of carbon dioxide (CO_2) gas. CO_2 is a major (60%) component of greenhouse gases (GHGs) instigating climate change. Therefore, the use of firewood for household energy consumption has significant implications for the sustainability of both the local and global environment (Ram and Bahadur, 2020). This has raised concerns among researchers and policymakers about the carbon footprints of household firewood consumption globally.

Access to clean energy is a critical issue for many countries in Asia. International Energy Agency (IEA) has reported that over 44% of the Asian population is without access to clean energy (IEA, 2019). However, in case of Pakistan, more than 66% of the country's population lacks access to clean cooking sources (Irena, 2019). Moreover, Pakistan is the third largest consumer of polluted fuels such as firewood, animal dung and crop residues, after Bangladesh and India (Janjua *et al.,* 2012). Around 73% of rural and 11% of urban population depends upon polluted fuels (NIPS, 2018). Rural households mainly consume firewood, which requires lots of time and effort to gather and prepare before consumption. Despite growing problems of air pollution, deforestation and climate change,

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this practice poses significant health risks to poor and vulnerable women and children, who are exposed to indoor air pollution from cooking with firewood (Bajželj *et al.,* 2014; Kouser *et al.,* 2022; Lee *et al.,* 2021). About 63% of total population (224.78 million) is residing in rural areas and has income constraints to improve living standards (GoP, 2022). Nonetheless, the government of Pakistan is encouraging households to switch from firewood to clean energy alternatives. In this regard, various programs such as alternative and renewable energy policy 2019, solar and wind system installation, and construction of dams for electricity generation have been initiated (GoP, 2020). Such efforts may help to modify current consumption patterns to limit the carbon footprints of society.

Existing literature has evaluated the determinants of household energy consumption such as socioeconomic status, cultural background, level of education (Ram and Bahadur 2020; Shahi *et al.,* 2020), family size (Bhatt and Sachan, 2004), availability of energy alternatives (Gladstone *et al.,* 2014; Sawadogo *et al.,* 2018; Waswa *et al.,* 2020), types of dwelling (Glasenapp *et al.,* 2019), and location (Ahmar *et al.,* 2022). Few studies have quantified carbon emissions from households' non-renewable and renewable energy choices (Bhatt and Sachan, 2004; Romanach and Frederiks, 2021; Shahi *et al.,* 2020; Waswa *et al.,* 2020). In the case of Pakistan, only two studies by Rahut *et al.* (2019) and Ahmar *et al.* (2022) have investigated the socioeconomic factors of cooking-fuel choices among rural households in Pakistan, while another study by Yousaf *et al.* (2021) has explored few factors of household energy consumption. They examined the carbon footprints of household energy consumption, but they did not investigate their determinants. Understanding the factors contributing to carbon emissions from household energy consumption is crucial for developing strategies to promote cleaner and more sustainable household energy practices, which can contribute to climate change mitigation and promote sustainable development.

To fill this research gap and contribute to the extant literature, this study has specified three major objectives: (1) to investigate the socioeconomic, demographic, and geographic determinants of household firewood consumption, (2) to quantify carbon emissions resulting from household firewood consumption, and (3) to identify household socioeconomic, demographic, and geographic factors, driving carbon footprints from firewood consumption. For estimating these objectives, study has employed 2018–2019 data from Household Integrated Economic Survey (HIES). While, Heckman selection model, and Tobit regression method were applied for analysis.

This article is structured as follows: after the introduction section, section 2 discusses the material and method used to estimate household firewood consumption expenditures, quantify carbon emissions from firewood consumption, and evaluates their determinates using the appropriate econometric method; section 3 presents results and discussions; and the last section concludes the study with policy recommendations and study limitations.

MATERIALS AND METHODS

Data and construction of variables: To investigate the determinants of household firewood consumption expenditure and associated carbon emissions, the study extracted data on socioeconomic (household size, employment types, income, and residence types), demographic (age, education, and marital status), gender, and geographic (provincial dummies) characteristics of households and firewood consumption as a cooking fuel from 2018-19 wave of HIES (PBS, 2019a), based on the existing literature.

To generate household firewood consumption expenditure (Y_i) variable, the study obtained firewood consumption quantities (C_i) for the ith household from HIES and multiplied with national firewood prices ($P_{firewood}$) estimated by the PBS (PBS, 2019b), which publishes monthly data of prices on a variety of energy sources including electricity, natural gas, gasoline, compressed natural gas (CNG), liquefied petroleum gas (LPG), and firewood as follows:

$$Y_i = C_i * P_{firewood}$$

To construct firewood carbon emission (E_i) variable, the study employed the Intergovernmental Panel on Climate Change (IPCC) conversion method (IPCC, 2018) to estimate firewood carbon emissions from household firewood consumption quantities (C_i) as follows:

$$E_i = C_i * Ce_{firewood} * Ox_{firewood} * \frac{44}{12}$$

Where, E_i represents the household carbon emissions from firewood consumption. C_i represents the quantities of firewood consumption by the ith households. $Ce_{firewood}$ represents the carbon emission factor for firewood, $Ox_{firewood}$ is the oxidation fraction of carbon that is completely oxidized during combustion, and the factor 44/12 is used to convert the resulting carbon emissions into carbon equivalent.

***Econometric Method Heckman Selection Model*:** The HIES data on firewood consumption indicate that 10,636 households consume firewood for cooking and heating purposes out of 24,809 households. This indicates that firewood consumption data are missing for 14,173 households due to natural exclusion restrictions. However, the Heckman selection model can correct for this selection bias and provides unbiased estimates, even when there are substantial missing observations (Heckman, 1976; Koné *et al.,* 2019). The Heckman method involves two stages. In the first stage, a selection model is estimated to identify the factors affecting the likelihood of firewood adoption in the sample, given a set of independent variables and firewood

exclusion restriction variables. The predicted probabilities from the selection model are lately used as an additional regressor in the second stage to control sample selection bias. The selection stage model is given as follows:

$$F_i = \alpha X_i + \beta Z_i + \varepsilon_i \quad (1)$$

Where, F_i represents the dichotomous firewood energy choice variable, where a value of '1" indicates that the i[th] household chooses firewood as the cooking fuel, otherwise '0'. X_i represents a vector of socioeconomic, demographic, and geographic characteristics of the surveyed households such as household head's age, gender, education, marital status, occupation, income, household size, and types of dwelling, as well as geographic characteristics such as region and province. The variable Z_i serves as the vector of exclusion restrictions for firewood consumption, indicating whether the i[th] household has access to firewood for cooking, measured by ownership of a clean cooking stove and cooking range. α and β are vectors of their respective coefficients. ε is a random error term.

In the second stage of Heckman selection model, we investigate the socioeconomic, demographic, and geographic determinants of firewood energy consumption expenditure (Y_i) of the i[th] household as follows:

$$Y_i = \alpha X_i + \gamma \hat{F}_i + \mu_i \quad (2)$$

Where, $\hat{F}_i$ represents the predicted probabilities of the firewood energy choice variable for the i[th] household from selection stage model and γ is its coefficient. μ is a random error term. Moreover, the inverse mills ratio obtained from the selection equation is as follows:

$$\lambda_i(y_i) = \lambda_i\,(-x_i - z_i * \beta/\sigma_v) \quad (3)$$

Tobit Regression Method: To identify household's socioeconomic, demographic, and geographic factors driving carbon footprints from firewood consumption, first, we quantify household firewood consumption quantities from household firewood expenditure; and then, we estimate carbon emissions resulting from household firewood consumption using the well-established carbon emission factors obtained from the Intergovernmental Panel on Climate Change (IPCC) Emission Factors Database (EFDB) (IPCC, 2018). Then, Tobit regression method was employed as the amount of firewood/carbon emissions (E_i) by the i[th] household is represented by the latent variable E_i^*. It is assumed that the data follow a normal distribution with a mean and standard deviation. E_i^* cannot be directly observed. Instead, we observe the censored values of E_i, which is defined as:

$$E_i = max(E_i^*, c) \quad (4)$$

Where, the censoring threshold is represented by c, which is the least amount of firewood carbon emissions that a household must create to be included in the sample. The Tobit regression equation, for estimating the relationship between firewood emissions and household characteristics, is given below:

$$E_i = \alpha_0 + \alpha_1 X_i + \sigma_i \quad (5)$$

Where, E_i represents the carbon emissions estimated from each household's firewood consumption. X_i represents a vector of household's socioeconomic, demographic, and geographic factors. α_0 is an intercept. α_1 represents a vector of coefficients for each independent variable. σ represents the error term.

This study employed the Tobit regression, which is a statistical technique to account for censoring nature of the household firewood consumption dependent variable. Censored variable either has an incomplete subset of observations or is truncated at a particular value. In our context, some households reported zero consumption of firewood fuel due to unobserved reasons (possible reasons could be unavailability of firewood or affordability of cleaner fuels etc). Hence, our dependent variable of firewood emissions (E_i) is left censored at zero value of emissions, representing those households who did not use firewood. The Tobit regression method has been used for modeling the consumption of firewood and electricity in previous studies (Gioda et al. 2022; Guta 2014). The Tobit regression helps estimate both the probability of observing a non-zero value and the level of consumption for households that consume firewood. In contrast, the use of ordinary least squares regression (OLS) method on truncated data leads to biased and inconsistent parameter estimates. However, the Tobit regression can provide consistent estimates of the model parameters for censored variables (Cameron and Trivedi 2010), which further reinforce its appropriateness for this study.

RESULTS

Descriptive Analysis: The descriptive statistics of the continuous and discrete explanatory variables of sampled households are presented in Table 1. For household heads, continuous variables include age, education, and profession. The average age of household heads was 45.84 years, and they had 8.40 years of schooling on average. In the sample, there were 6.45 people per family on average. Income is vital in the daily lives of households. The average annual household income is PKR 341,836. On average households consume firewood of 1705 kg/year with a worth of 7,526 kg/year, which generates carbon emissions of 19.29 Gg/year.

The descriptive statistics of explained and explanatory dummy variables for the present study are illustrated in Table 2. For household head, dummy variables include gender, education, marital status, and occupation. Most families are male-headed, with 90% of household heads are married. The average proportion of households with primary, secondary, and tertiary education in the sample is 43.0%, 43.61%, and 13.37%, respectively. Three types of dwellings, i.e., detached, apartment, semidetached are included in the analysis with other house types as a reference category.

Table 1. Summary Statistics of Sampled Households (n=24,809)

Variable	Mean	Std. Dev.	Min	Max
Household head age (years)	45.84	13.61	16	99.00
Household head education (years)	8.40	3.93	0	18.00
Income (Rs/year)	341,835.80	392,421.60	0	18,000,000.00
Household size (No.)	6.45	3.23	1	55.00
Household firewood expenditure (Kg/year)	1704.77	1457.04	60	48,000.00
Household firewood expenditure (Rs/year)	7,526.01	13,555.72	0	240,000.00
Household firewood carbon emissions (Gg/year)	19.29	34.75	0	615.26

Source: Estimated using 2018-19 HIES data.

Summary statistics represent that majority of households (76.94%) in Pakistan are living in detached dwellings. The ownership of cooking range and clean stove are the factors that discourage the usage of firewood.

Table 2. Summary Statistics of Explained and Explanatory Categorical Variables

Categorical variables	Categories	Proportion (%)
Gender of Head	Male=1*	90.54
	Female=0	9.46
Education of head	Illiterate=0*	43.61
	Primary education=1	27.95
	Secondary education=2	21.09
	Higher education=3	7.36
Marital Status	Married=1	90.73
	Unmarried=0*	9.27
Occupation	Employer=1	0.12
	Self Employed=2	4.12
	Paid Employee=3	19.86
	Agriculture=4	2.12
	Others=5*	73.61
Dwelling types	Detached=1	76.94
	Apartment=2	1.77
	Semi-detached=3	14.49
	Others=4*	6.80
Firewood availability	Yes=1	42.87
	No=0*	57.13
Cooking range ownership	Yes=1	1.66
	No=0*	98.34
Clean cooking stove	Yes=1	52.48
	No=0*	47.52
Region	Urban=0*	35.77
	Rural=1	64.23
Provinces	Khyber Pakhtunkhwa (KP)=1	18.08
	Punjab=2	47.49
	Sindh=3	25.06
	Baluchistan=4*	9.38

Reference categories are marked with an asterisk (*).
Source: Estimated using data from 2018-19 HIES survey

The majority of households that use firewood do not have a cooking range, whereas. 53% of households have a clean stove. The geographic location of households includes rural versus urban areas and four provinces Khyber Pakhtunkhwa (KP), Punjab, Sindh, and Balochistan. The regional comparison reveals that 64% of sampled households are living in rural areas, while 36% are living in urban areas. Similarly, 48% of surveyed households are selected from Punjab being major populated province, followed by Sindh (25%), KP (18%), and Balochistan (9%).

The distribution of household firewood energy expenditure and firewood carbon emissions across regions and provinces of Pakistan are illustrated in Figure 1. The comparison of bar charts across regions indicates that households in rural areas are consuming more firewood than those living in urban areas. Akin to this, the comparison of bar charts across provinces reveals that households living in KP are major consumers of firewood, followed by those living in Balochistan, Punjab and Sindh.

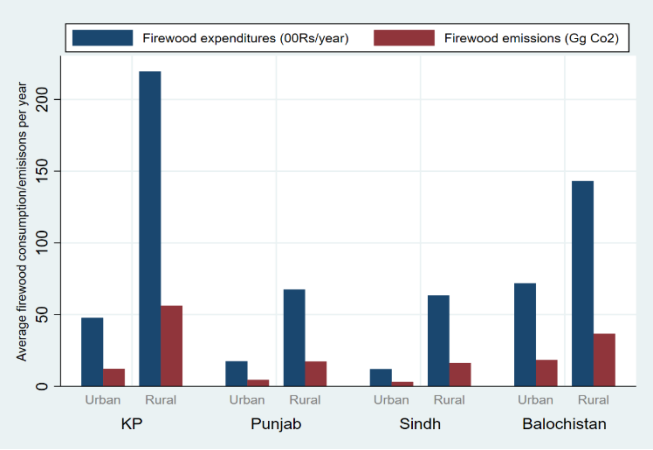

Figure 1. Distribution of Firewood Expenditure and Emission across Regions and Provinces
Source: Authors' creation using 2018-19 HIES data

Econometric Analysis

***Determinants of Household Firewood Consumption*:** To anticipate the determinants of household firewood consumption, this study used Heckman selection model as all households are not using firewood energy for cooking due to

natural exclusion restrictions. The results of the first and second stages of Heckman selection model are reported in columns 2 and 3 of Table 3, respectively. The coefficients of explanatory variables in the first selection stage (Probit model) reflect the direction and size of their effects on the probability of having access to firewood as cooking fuel. Among socioeconomic and demographic characteristics of household heads, the coefficients of age, gender, and marital status are statistically insignificant. The coefficient of primary education for household heads is positive and significant, implying that primary education does not inculcate households with the harmful effects of firewood use. However, the significant coefficients of secondary and higher education show that household heads with higher levels of education are less likely to use firewood as a cooking fuel compared to their illiterate counterparts. Among different occupation types, firewood accessibility increases if the household head is engaged in agriculture-related activities.

Among household and house characteristics, firewood accessibility is positively influenced by household size, as it is a cheaper source of energy to meet the needs of larger households. Although household income and dwelling types decrease their likelihood to access, polluted fuels like firewood. Moreover, households in rural regions are relying more on firewood energy than their urban counterparts. Similarly, the coefficients of provinces indicate that households in KP are using more firewood than those in Balochistan; while households in Punjab and Sindh are using more firewood than those in Balochistan.

Among exclusion restriction variables, ownership of a cooking range and clean cook stove decreases the likelihood of firewood accessibility by 75% and 93%, respectively. It is noteworthy that exclusion variables in the selection equation reveal a negative association between cooking appliances and firewood.

The coefficients of explanatory variables for the second stage of the Heckman model are presented in the last column of Table 3. The positive and significant coefficient of the household head's age suggests that as the age of the household head increases, household firewood consumption expenditure increases. However, the gender, education, and marital status of household head are not statistically significant, while household firewood consumption expenditures decrease with household head's self-employee and paid employee occupation types.

Keeping all other variables constant, an increase in household size increases household firewood consumption expenditures by Rs 736/year. Similarly, the significant coefficient of household income reveals a positive association between household income and firewood consumption expenditure. The influence of types of dwellings on firewood consumption expenditure is more significant in detached houses as compared to semi-detached, apartments as the coefficient for detached houses is substantially large.

Table 3. Results of Household Firewood Consumption using Heckman Selection Model

Factors	Firewood accessibility	Firewood consumption expenditure
Household head characteristics		
Age	-0.0005	50.385***
	(0.0007)	(10.590)
Gender	0.048	70.669
	(0.034)	(524.335)
Primary education	0.063**	-321.765
	(0.022)	(332.734)
Secondary	-0.047*	592.497
education	(0.026)	(410.119)
Higher education	-0.186***	177.783
	(0.044)	(754.144)
Married	0.0421	237.173
	(0.033)	(526.225)
Employer	-0.163	5142.163
	(0.209)	(4217.562)
Self-employee	0.051	-1376.607*
	(0.047)	(779.156)
Paid employee	-0.035	-877.583***
	(0.023)	(362.463)
Agriculture	0.233***	-352.072
	(0.058)	(876.540)
Household and house characteristics		
Household size	0.017***	735.766***
	(0.003)	(47.068)
Household income	-1.06e-07**	0.004***
	(3.52e-08)	(0.001)
Detached house	-0.303***	3889.473***
	(0.036)	(516.644)
Apartment	-0.925***	-225.641
	(0.110)	(2454.590)
Semi-detached	-0.459***	3345.292***
house	(0.042)	(614.054)
Household geographic characteristics		
Rural	0.818***	83.016
	(0.022)	(538.980)
KP	0.393***	5811.853***
	(0.036)	(490.905)
Punjab	-0.473***	-2985.852***
	(0.033)	(522.987)
Sindh	-0.231***	-9200.246***
	(0.035)	(510.245)
Exclusion restriction variables		
Cooking range	-0.750***	-
ownership	(0.110)	
Stove ownership	-0.931***	-
	(0.020)	
Constant	0.149**	10552.230***
	(0.07)	(1129.562)
Model Statistics		
Observations	24,809.000	
Rho	-0.312	
Sigma	14257.180	

Coefficients are reported with standard errors in parentheses. *= p <0.1, ** = p <0.05, *** = p <0.0

Source: Estimated using 2018-19 HIES data.

Among geographic characteristics, the coefficient of rural residency is insignificant, implying that both rural and urban regions are having similar firewood consumption expenditures. Similarly, the coefficients of provinces indicate that households in KP are spending more on firewood than those in Balochistan; while households in Punjab and Sindh are spending more than those in Balochistan.

Table 4. Results of Household Firewood Emissions using Tobit Regression.

Factors	Coefficients
Household head characteristics	
Age	-0.053*
	(0.032)
Gender	-6.63***
	(1.59)
Primary education	-3.25***
	(1.02)
Secondary education	-9.94***
	(1.205)
Higher education	-17.94***
	(2.081)
Married	1.09
	(1.584)
Employer	-10.620
	(10.163)
Self-employee	-1.797
	(2.263)
Paid employee	-1.828*
	(1.097)
Agriculture	5.903**
	(2.752)
Household and house characteristics	
Household size	2.458***
	(0.144)
Household income	-1.5E-05***
	(1.73E-06)
Detached house	-3.734**
	(1.638)
Apartment	-39.579***
	(5.579)
Semi-detached house	-9.550***
	(1.904)
Household geographic characteristics	
Rural	56.291***
	(1.069)
KP	18.025***
	(1.574)
Punjab	-30.303***
	(1.479)
Sindh	-24.681***
	(1.584)
Constant	-33.2469***
	(3.193)
Model Statistics	
Observations	24,809
Chi^2	8921

Standard errors are given in parentheses. * = p <0.1, ** = p <0.05, *** = p <0.01

Source: Estimated using 2018-19 HIES data.

Determinants of Household Firewood Emissions: Determinants of household firewood emissions estimated by Tobit regression are presented in Table 4. Household head's age and gender have significant and negative impacts on household firewood emissions. Similarly, the significant and negative coefficients of primary, secondary and higher education suggest that education has a considerable influence on reducing firewood emissions. However, higher education has much stronger and larger impacts in mitigating firewood emissions. Akin to this, the significant coefficient of paid employees suggests its negative relationship with firewood emissions. There could be due to several reasons such as paid work increasing household's affordability to cleaner energy sources. Nonetheless, household head's involvement in agriculture increases household's carbon footprints.

Among household characteristics, a positive and significant coefficient of household size suggests that higher household size is associated with increased emissions. However, household income has a negative and significant impact on firewood emissions. This could be due to various factors such as increased income improving household's access to clean energy sources or ventilation in the house.

All three types of dwellings have a negative and significant association with firewood emissions; indicating compared to reference category, the detached house has the smallest impact on firewood emissions followed by semi-detached house and apartment.

The location of residency also impacts household's carbonization. Rural households significantly generate more emissions than urban households because of their dependence on cheaper and readily available firewood as cooking fuel. Furthermore, households located in Khyber Pakhtunkhwa substantially produce more emissions compared to those located in Balochistan, while households in Punjab and Sindh release fewer emissions than their counterparts in Balochistan.

DISCUSSION

The results of the first stage of Heckman selection model suggest that age, gender and marital status of household head have an insignificant correlation with firewood availability. These results are in contrast with earlier studies, where experienced, married and female headed households prefer cleaner fuels for better health of their children and themselves (Kouser *et al.,* 2022). Our findings reveal that highly educated household heads prefer cleaner fuels, implying that higher education is making them better aware of the health and environmental risks associated with burning firewood. This is consistent with prior research, where the education level of the household head was found to have a significant and positive impact on the choice of modern energy sources over biomass (Imran and Ozcatalbas, 2020; Karimu, 2015; Rahut *et al.,* 2017, 2019). Overall, these findings suggest that

education plays a crucial role in promoting sustainable and healthy energy practices among households. However, if a household head is engaged in an agricultural profession, then household's accessibility to firewood increases due to the easy and free availability of crop residues for burning as cooking fuel.

The choice of firewood energy is positively associated with household size, while negatively associated with household income. This is consistent with the study of Biran *et al.* (2004), which explains that with higher income, households start demanding cleaner energy. The findings of the current study also validate that households residing in rural areas or KP province have greater access to firewood as compared to those in urban areas or Punjab, Sindh, and Balochistan. This finding is aligned with previous research conducted by Rahut *et al.* (2020) investigating the preferences for cooking fuel in different regions of Pakistan. Of particular significance, the exclusion variables in the selection equation uncovered a negative correlation between firewood and cooking appliances. This is because clean stoves and cooking ranges are commonly powered by natural gas, rendering firewood an improbable option for cooking fuel as reported by Hasan and Zhang, (2018) among Pakistani households and by Kulkarni *et al.* (2022) in India.

The results of Heckman second stage analysis reveal a significant and positive coefficient for household head age, indicating that as the head gets older household expenditure on firewood also increases. This could be attributed to a higher demand for firewood energy for heating and cooking purposes, particularly in households with elderly members. This result is consistent with the study conducted by Paudel *et al.* (2018). Akin to this, the positive correlation between household size and firewood consumption is in line with the findings of Gioda *et al.* (2022) for rural households in Brazil and of Ram and Bahadur (2020) in Nepal. The positive association between household income and firewood consumption expenditure in this study contradicts the findings of Gioda *et al.* (2022); Netshipise and Semenya (2022); and Rahut *et al.*(2019), where household firewood consumption decreases as income increases. The results of the present study suggest that the influence of firewood consumption is more pronounced in detached houses. This could be attributed to the fact that the larger size of detached houses leads to greater firewood consumption and insufficient ventilation in these houses may also contribute to higher energy usage. These results are supported by the previous research of Song *et al.,* (2012);Glasenapp *et al.* (2019); Zou and Luo (2019) and Romanach and Frederiks (2021). The findings of the present study indicate that in comparison to other provinces in Pakistan, households in KP utilize firewood as cooking fuel more frequently. This finding is aligned with a previous study by Rahut *et al.* (2020), which also reported higher usage of firewood for cooking in KP households as compared to other regions. This may be due to various factors such as easy access and availability of firewood, as revealed in the study conducted by Khan *et al.* (2022). Moreover, households in KP may have limited access to clean energy sources such as LPG due to underdeveloped infrastructure (Mosa *et al*., 2020).

The results obtained from Tobit model demonstrate that higher education is significantly contributing to reducing firewood emissions. These findings are aligned with Rahut *et al.* (2019), which also reported that higher education has a significant role in mitigating the use of firewood for cooking. The present study finds that large household size is linked to increasing emissions by burning more firewood. These results are consistent with prior research by Ram and Bahadur (2020) and Shahi *et al.* (2020), which also found a positive relationship between household size and emissions. Household income has a negative and significant impact on firewood emissions, Similar results were reported by Karimu (2015) and Rahut *et al*. (2017), who found that as household income increases, the likelihood of choosing clean cooking fuels over biomass fuels also increases. These findings suggest that improving household income could have a positive impact on promoting the adoption of cleaner energy sources for cooking (Mislimshoeva *et al.,* 2014). This is in line with the 7th United Nations' Sustainable Development Goal (SDG), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Therefore, policies aimed at reducing the use of biomass fuels for cooking purposes should consider targeting low-income households and promoting income-generating activities that can improve household economic conditions. According to the present study, detached houses have the least impact on firewood emissions as compared to other house types. This is in line with the findings of Paládi *et al.* (2014), who observed that households with joint family structures have significantly higher levels of emissions as compared to nuclear families. These differences could be attributed to various factors, including longer cooking times, greater demand for fuel, and limited access to clean energy sources. Rural households tend to emit more emissions due to the excessive use of firewood. This finding is consistent with earlier literature (Ram and Bahadur, 2020; Shahi *et al.,*2020; Romanach and Frederiks 2021; Netshipise and Semenya 2022). The factors contributing to this trend may include limited access to clean energy sources, and modern cooking technologies as well as a lack of awareness regarding the negative environmental and health impacts of using firewood as primary cooking fuel.

***Conclusions*:** Mitigating carbon footprints of household firewood consumption is a major concern globally. The inefficient combustion of firewood produces significant amounts of carbon dioxide (CO_2), which contributes to climate change and natural disasters. In developing countries like Pakistan, households often rely on traditional biomass fuels such as firewood for cooking and heating due to limited access to cleaner energy alternatives. In light of this

background, this study aims to investigate the determinants of household firewood consumption and associated carbon footprint in Pakistan by employing 2018–19 data of Household Integrated Economic Survey (HIES), Heckman selection model, and Tobit regression method.

The results of first stage of Heckman selection model reveal that household head's primary education, agricultural occupation, household size, rural residency, and KP region contribute to choosing firewood as an energy source, while head's higher education, household income, housing types, adoption of cooking range and clean stoves, and residency in Punjab and Sindh provinces discourage firewood use. The results of the second stage of Heckman model demonstrate that head's age, household size, income, detached and semi-detached houses and KP residency significantly account for household firewood consumption expenditure. Findings of Tobit regression uncover that illiterate head with agricultural occupation, household size, and rural residency in particular in KP province have a significant association with household carbon emissions. However, female-headed households, higher education, paid work, household income, and Punjab and Sindh residencies tend to generate lower carbon emissions.

The findings of the study suggest that higher education programs and awareness campaigns among women may help them to acquire knowledge about the harmful effects of using firewood energy and the benefits of alternative energy sources such as LPG or solar and to gain skills related to sustainable energy practices, such as the use of clean and efficient stoves. Compared to traditional stoves, clean stoves are generally more efficient by reducing the amount of firewood burned and minimizing emissions by boosting their use. By boosting household income and reducing family size, the government can further lessen the environmental impacts of firewood usage.

The data used in this study have limitations in terms of presenting a comprehensive picture of household behavior regarding firewood consumption. The findings show connections between some characteristics of households and firewood emissions but are not enough to identify the reasons for the observed behavioral changes. Future studies could use more detailed and diverse data sources such as surveys, interviews, or field observations, to acquire full knowledge of various characteristics that drive household firewood use behavior.

***Conflict of interest*:** The authors declare no conflict of interest.

Author's contribution statements: SH, A, and SK conceptualize the research work. SH conducted data cleaning, and econometric analysis, and prepared the initial draft of the paper, whereas A and SK supervised the analysis, and reviewed and edited the final draft.

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