Khan *et al. Energy, Sustainability and Society* (2024) 14:18
https://doi.org/10.1186/s13705-024-00448-1

Energy, Sustainability
and Society

RESEARCH **Open Access**

Spatial and temporal patterns of fuelwood consumption and its associated CO_2 emissions in Muzaffarabad division, a western Himalayan region

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Abstract

Background In the Himalayan region, fuelwood serves as a critical energy source for rural communities. Being vital for meeting energy needs, fuelwood combustion is a source of carbon dioxide (CO_2) emission and, consequently, global warming, as well as deforestation and public health damage. Therefore, quantifying fuelwood consumption patterns and its associated CO_2 emissions is essential to understand the environmental impact and promote sustainable resource management.

Methods This research conducts an evaluation of fuelwood burning patterns and the associated CO_2 emissions in Azad Jammu and Kashmir (AJK), situated within the western Himalayan region. The study entails an extensive survey of 24 villages representing 240 households, equally distributed between the subtropical and temperate regions, each comprising 120 households. Data collection was executed through a combination of direct queries and the weight survey method, following standard protocols.

Results In the study area, the mean annual fuelwood comsumption per household amounts to 24.28 ± 3.1 Mg (or 3.195 ± 1 Mg capita^{-1}). A variance was observed between subtropical and temperate zones, with the latter exhibiting higher consumption rates. The consequential CO_2 emissions were assessed as 41.88 ± 4.5 Mg per household (5.51 ± 0.6 Mg capita^{-1}). On a daily basis, households consumed an average of 66.52 ± 6.4 kg of fuelwood (8.75 ± 1.5 kg capita^{-1}), resulting in a daily CO_2 release rate of 114.745 ± 8.6 kg (15.095 ± 2 kg capita^{-1}). The findings unveiled seasonal variations, indicating increased fuelwood consumption and emissions during the winter season. Statistical analysis shed light on the significance of altitude and family size in shaping the patterns of fuelwood use.

Conclusions The results revealed the importance of prioritizing forest conservation and strategically implementing sustainable practices, including reforestation, afforestation, responsible harvesting, and actively promoting sustainable fuel sources. This research highlights the vital role of well-designed policies focused on preserving ecosystems and improving energy management. Policy intervention can ensure the sustainable stewardship of local and regional forest resources.

Keywords Climate change, Biomass, Himalayas, Altitude, Sustainability, Fuelwood, Energy

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Background

Global warming poses substantial risks to human health and the environment. Increasing environmental degradation urges stakeholders to address these challenges with sustainable policies [1, 2]. Scientific consensus confirms that factors such as financial development, trade, globalization, natural resource exploitation, and the extensive combustion of fossil fuels are drivers of greenhouse gas (GHG) emission, which is a driver of global warming [3, 4].

The latest IPCC 2021 climate scenarios indicate that global warming can surpass 1.5–2 °C by the end of the century and may cause more frequent heatwaves, impacting food crop productivity and contributing to heightened global food insecurity [1, 5]. The Sustainable Development Goals (SDGs) of the United Nations address economic, environmental, and climate-related concerns in a sustainable manner by adopting green production technologies to increase productivity and reduce reliance on those fuels that emit large amount of CO_2 [6, 7].

Pakistan, classified as an energy-deficient developing economy, has long been suffering by a substantial energy crisis resulting from an imbalance between demand and supply. Mitigating energy poverty aligns with the objectives of SDGs. Due to the significant shortage of energy (particularly in the form of electricity), rural communities have come to rely on biomass-based fuels for their energy needs [8–10]. Rural and urban households in Pakistan primarily rely on woody fuel sources, where 67% of energy is obtained from fuelwood. A literature survey revealed that about 95% of rural households use fuelwood for cooking and heating due to lower income and higher energy prices in the region [6, 11].

The burning of fuelwood not only emits GHGs but also contributes to indoor and outdoor air pollution, leading to health issues [6, 10, 12]. Fuelwood-mediated deforestation also poses a complex challenge with far-reaching ecological and climatic consequences including local biodiversity loss, habitats depletion, soil erosion, loss of sequestered carbon, and disruption of local ecosystems, which needs a sustainable management [13, 14]. To effectively address this environmental challenge, it is required to implement sustainable practices in forestry, energy, and carbon management [15].

In countries such as Pakistan, progress toward sustainable goals is hindered by factors such as population growth and high energy costs, which make adopting clean energy difficult [16]. To address climate vulnerabilities and prevent adverse environmental changes, securing access to clean energy becomes pivotal in promoting economic advancement, elevating living standards, and mitigating health hazards. To tackle this issue, a transition to cleaner energy sources such as solar, wind, and tidal power at the household level is essential [8–10, 17]. Research reveals that the environment can benefit from using innovative and conservative energy strategies as it is crucial to balance economic growth with environmental concerns [18]. The households in Pakistan support the transition to renewable energy [19]. The choice of alternative energy sources for lighting and cooking is shaped by intricate interactions among socioeconomic, demographic, and infrastructural factors, particularly in rural areas where understanding and awareness are still inadequate [8–10].

Identifying the interplay among fuelwood consumption, CO_2 emissions, and biodiversity threats in the western Himalayan region is crucial from an environmental perspective, as supports preserving ecosystems, mitigating climate change impacts, and improving the socioeconomic welfare of local communities [20, 21]. This region was chosen for investigation due to its unique biodiversity, susceptibility to climate change, fragile nature, and rich cultural significance, supporting diverse, interdependent species. Local communities are here highly vulnerable to environmental shifts, as their traditional lifestyles play a pivotal role in adapting to climate change [22]. However, these valuable local perspectives are often underrepresented in policy discussions [22, 23].

This study fills critical knowledge gaps in the biodiverse region of the western Himalayas, where previous research lacks detailed insights into fuelwood consumption patterns and the associated CO_2 emissions. This research aims to provide information about effective strategies for addressing fuelwood-related environmental issues in this region, facilitating targeted mitigation efforts by providing a comprehensive evaluation of fuelwood consumption at both household and individual levels. This study explores often neglected seasonal and altitudinal variations in fuelwood consumption and the consequent CO_2 emissions, aiming to improve understanding of the environmental consequences linked to traditional energy sources, shedding light on distinctive challenges and opportunities in the Himalayan regions. The study reveals that fuelwood is a significant energy source in the area, but its combustion contributes substantially to CO_2 emissions, particularly during the winter season on an individual and household scale. In addition, it provides an inventory of fuelwood species that are under constant threat of decline due to continuous deforestation in the region. These research findings underscore the urgent need for conservation efforts to protect preferred fuelwood species and promote sustainable fuelwood use in the area. It also lends support to policy initiatives for environment, natural resource management and climate change mitigation by providing insights into fuelwood mediated CO_2 emissions.

Methods

Study area

The study was carried out in three districts of the Muzaffarabad division in the state of AJK (Fig. 1). The study area is situated within the western Himalayan region and is typified by steep, mountainous slopes, hilly topography, and deep valleys, resulting in an uneven and undulating landscape [24]. Muzaffarabad division can be divided into distinct vegetation zones on the basis of climate. The lower region experiences a humid subtropical climate in the area around 700 m above sea level where summers are hot and winters are mild to cold. The upper region has a temperate and subarctic climate with cold winters and mild summers. The area above 1200 m experiences a harsh climate in the winter and receives heavy snowfall.

The average temperature in the study region fluctuates between −3 °C and 27 °C in winter (December and January). Climate records from 1957 to 2022 show that the temperature in the summer season (May to September) varies between 7 °C in the upper region to 40 °C in the lower region. Monthly heaviest rainfalls remain 188.1 mm in dry months and may exceed 720 mm in monsoon season [25]. The population of Muzaffarabad division was 1.08 million in 2020 with approximately 50.1% male and 49.9% female inhabitants. The rural and urban population in the division is 62% and 24%, respectively [24].

Data collection

A combination of stratified random and purposive sampling methods was used [26, 27] after conducting preliminary field surveys in the study area. The hybrid sampling strategy was employed to secure a representative sample of the population of the Muzaffarabad division. The use of stratified random sampling recognizes the ecological diversity within the area, resulting in the division of the region into distinct subtropical and temperate ecological zones. Within each ecological zone, an equal number of 120 households from 12 villages were selected to minimize the potential sources of sampling bias.

Purposive sampling was incorporated to diversify the sample by intentionally choosing households with varying socioeconomic backgrounds and demographic

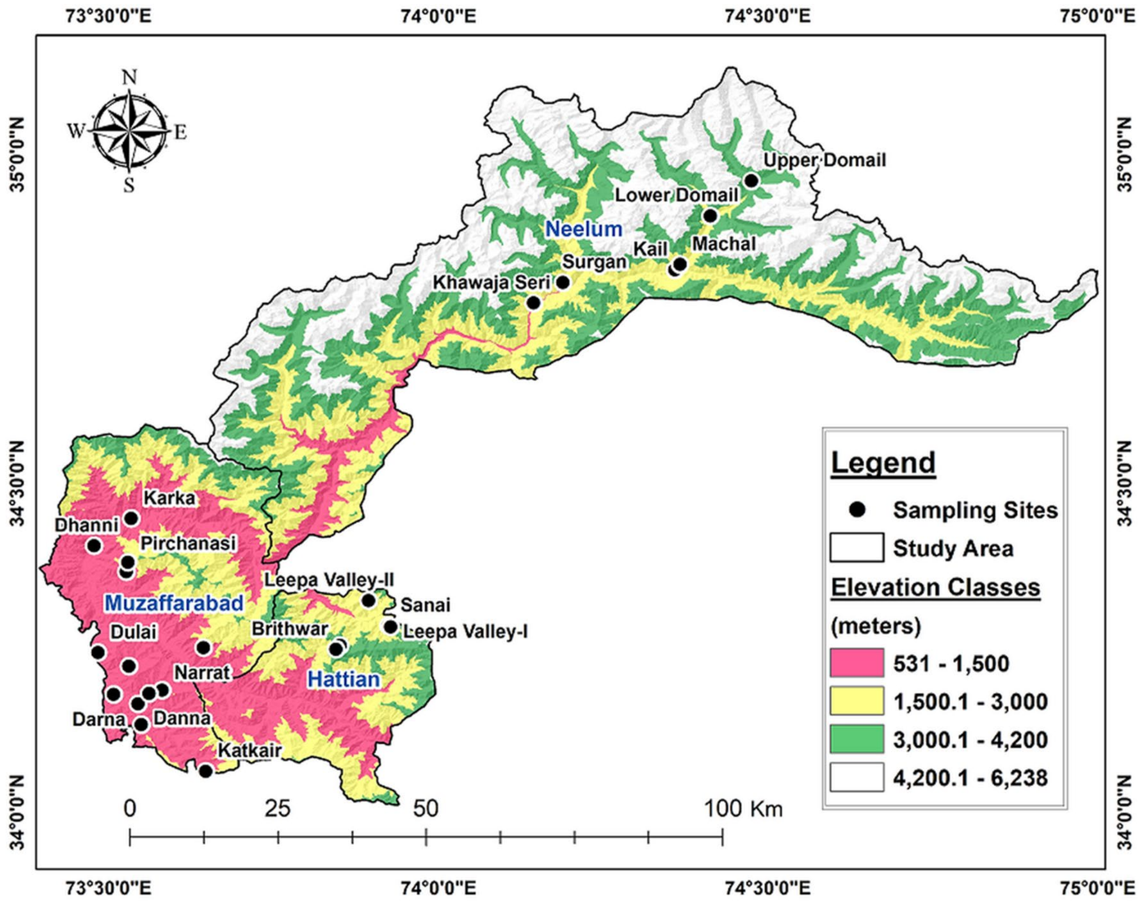

Fig. 1 Map of the study area indicating the sampling sites

characteristics [26, 28, 29]. The purposive sampling technique ensures that categories or cases that hold significance for the research study are intentionally included in the final sample [30, 31]. This methodological synthesis aimed to provide a comprehensive representation to enhance understanding of fuelwood usage patterns across various ecological contexts and household profiles [32].

Field surveys were carried out for data collection between March 2021 and September 2022. Forests and vegetation zones in the study area were classified through ecological surveys, vegetation characters and composition of plant communities [33], and input from local ecologists and botanists familiar with the local climate and ecosystems. This approach ensured a thorough and accurate categorization of vegetation zones. We selected 12 study villages in the subtropical region of the Muzaffarabad district (Fig. 1). These villages span an altitudinal range from 860 to 1845 m, and the site elevations were determined using a GPS device. Samples and photographs of the plant species used as fuel were gathered and identified at the University of Azad Jammu and Kashmir Herbarium (UAJK-AKASH) herbarium, located within the botany department of the University of Azad Jammu and Kashmir.

Plant species found in the subtropical region are combustible thin canopy pine forests, occasionally with a covering of dry and evergreen shrubs, while dry and deciduous subtropical broad-leaved or mixed forests are also found in the region. Scrub formation is prevalent and abundantly intermingled with grasses in subtropical mixed forests [34, 35]. Out of the remaining 12 study villages situated near temperate forests, we chose 6 from Neelum Valley, 4 from Jhelum Valley, and 2 from the Muzaffarabad district based on the diversity of temperate climatic conditions (Fig. 1). Our temperate study villages were located within an elevation range of 1940–2890 m above sea level (Table 1). The area is characterized by Himalayan moist and dry temperate forests with the dominance of conifers followed by broad-leaved tree species and dense undergrowth flora comprising both evergreen and deciduous species [35, 36].

Table 1. Sampling villages, district, vegetation zone, individuals per household, and elevation

Site no.	Sites name	District	Vegetation zone	Average number of individuals per household	Elevation (m)
1	Dulai	Muzaffarabad	Subtropical	6	860
2	Dhanni	Muzaffarabad	Subtropical	8	875
3	Namhoter	Muzaffarabad	Subtropical	7	1155
4	Darna	Muzaffarabad	Subtropical	6	1175
5	Narran	Muzaffarabad	Subtropical	8	1335
6	Narrat	Muzaffarabad	Subtropical	9	1410
7	Karka	Muzaffarabad	Subtropical	7	1450
8	Dumbi	Muzaffarabad	Subtropical	5	1510
9	Danna	Muzaffarabad	Subtropical	10	1585
10	Niazpura	Muzaffarabad	Subtropical	8	1705
11	Katkair	Muzaffarabad	Subtropical	6	1750
12	Awan Patti	Muzaffarabad	Subtropical	7	1845
13	Khawaja Seri	Neelum Valley	Temperate	7	1940
14	Surgan	Neelum Valley	Temperate	7	1960
15	Kail	Neelum Valley	Temperate	8	2080
16	Lower Domail	Neelum Valley	Temperate	7	2315
17	Sanai	Jehlum Valley	Temperate	7	2320
18	Machal	Neelum Valley	Temperate	8	2335
19	Leepa Valley-I	Jehlum Valley	Temperate	8	2395
20	Leepa Valley-II	Jehlum Valley	Temperate	9	2400
21	Leepa Valley-III	Jehlum Valley	Temperate	9	2420
22	Pirchanasi	Muzaffarabad	Temperate	9	2765
23	Brithwar	Jehlum Valley	Temperate	9	2810
24	Upper Domail	Neelum Valley	Temperate	9	2890

Quantification of fuelwood and CO_2 release

The selected (at least 10%) households in each village were approached and informed about the research objectives and their consent was obtained. Socioeconomic data including family size and local preference for wood fuel species was collected through direct queries and face-to-face conversations. The approximation of daily fuelwood use for cooking and heating in selected households was accomplished through a weight-survey technique. The air-dried fuelwood bundles were weighed using a spring balance. Household members were instructed to use only the firewood from these weighed bundles. The calculation of daily consumption was determined by measuring the remaining firewood and determining the weight difference on the next day [37].

$$\mathrm{DFWD} = W_i - \mathrm{W}_f.$$

where DFWD stands for daily fuelwood consumption (kg), W_i is the initial weight of the air-dried fuelwood bundle in household i and W_f stands for the final weight of the remaining air-dried fuelwood after daily usage.

Off-season biomass fuel requirements were also acquired from respondents to establish an annual wood use paradigm. Primarily, the daily fuelwood quantity was chronicled in kilograms (kg) at each household (kg hh^{-1}) and then converted to megagrams per household (Mg hh^{-1}) and finally to megagrams per capita (Mg $capita^{-1}$).

$$FWD_{Mghh} = \frac{FWD_{Kghh}}{1000}$$

$$FWD_{MgCap} = \frac{FWD_{Mghh}}{\text{No. of individuals at each household } i}$$

where FWDMghh stands for fuelwood combusted in Mg hh^{-1}, FWDkg hh for fuelwood combusted in kg hh^{-1} and FWDMgCap stands for fuelwood combusted in Mg $capita^{-1}$.

Average temperature variations between seasons can significantly affect fuelwood requirements. To address this variability, the magnitude of average daily and annual fuelwood consumption was calculated by considering the daily average values for both prevalent seasons (summer and winter). The obtained values, which were adjusted to nullify the impact of both summer and winter variations, were then multiplied by the total number of days in a year (365). This allowed to represent a typical daily requirement that accounts for neither the excesses of summer nor the demands of winter, providing a standardized estimate of fuelwood consumption. The calculation for the average daily and annual fuelwood requirements was determined as follows:

$$DFWD = \frac{DFWD\ in\ summer\ season + DFWD\ in\ winter\ season}{2}$$

$$AFWDC = DFWD\,x\,365$$

where DFWD stands for daily fuelwood combustion (Mg $capita^{-1}$), AFWD stands for annual fuelwood combustion (Mg $capita^{-1}$) and 365 specifies the number of days in a year.

Total daily and annual carbon loss through the combustion of woody biomass fuel was considered equal to previously sequestered biomass carbon content and was calculated by multiplying the respective combusted woody biomass value to 0.47, a biomass to carbon conversion factor [38–41] and was estimated by using following formulae:

$$TDCL = BCC = DFWDC\,x\,0.47$$

$$TACL = BCC = AFWDC\,x\,0.47$$

where TDCL stands for total daily carbon loss (Mg $capita^{-1}$), BCC for biomass carbon content (Mg), DFWDC for daily fuelwood combustion (Mg $capita^{-1}$), TACL for total annual carbon loss (Mg $capita^{-1}$), AFWDC stands for annual fuelwood combustion (Mg $capita^{-1}$), and 0.47 designates the default value for biomass to carbon conversion.

The numerical value of carbon loss associated with fuelwood combustion was converted to released CO_2 by multiplying with a CO_2 equivalent value of 3.67 [42–45].

$$DCO_2R = TDCR\,x\,3.67$$

$$ACO_2R = TACR\,x\,3.67$$

where DCO2R stands for daily CO_2 release (Mg $capita^{-1}$), TDCR for total daily carbon release (Mg $capita^{-1}$), ACO_2R for annual CO_2 release (Mg $capita^{-1}$), TACR stands for total annual carbon release (Mg $capita^{-1}$) and 3.67 is CO_2 equivalent.

Data analysis

Eight parameters were included in the analysis comprising independent variables such as site elevation and family size, as well as dependent variables related to fuelwood and emission parameters, including summer DFWD (kg hh^{-1}), winter DFWD (kg hh^{-1}), average DFWD (kg hh^{-1}), summer DFWD (kg $capita^{-1}$), winter DFWD (kg $capita^{-1}$), and average DFWD (kg capita-^{1}). All the variables used were quantitative in nature. Statistical tests were used to examine how two independent variables affect fuelwood consumption and its associated CO_2 emissions. The selection of independent variables in this study exhibited both representativeness and innovation in the assessment of fuelwood consumption and its associated CO_2 emissions within the study region [37, 46]. Altitude was chosen to reflect the climatic and ecological diversity in the region, allowing for an exploration of its impact on fuelwood consumption patterns. In parallel, the family size served as a proxy for assessing household energy demand. These variable choices collectively enhance the comprehensiveness of the analysis concerning environmental issues linked to fuelwood usage in this distinct geographical context [20, 37, 39].

The collected data were analyzed using principal component analysis (PCA) to identify the underlying factors that influence fuelwood consumption in the study population. PCA has been widely applied in different studies related to fuelwood and other wood resource usage studies [20, 21, 47, 48]. The values for each variable were used to extract the principal components. The biplot and scree plot were generated to visually represent the relationships between the variables and the principal components and to determine the number of significant principal components included in the analysis [49, 50]. The resulting data were then interpreted to gain a deeper understanding of the factors that contribute to fuelwood consumption patterns in the study region. The Wilks lambda and *F*-tests were employed to evaluate the statistical significance of the independent variables. The significance of statistical analysis was tested using an *F*-test, while the goodness-of-fit of the model was assessed using R^2 values. The analysis also included the computation of regression coefficients, standard errors, *t*-values, and *p*-values to establish the strength and direction of the relationship between the variables.

Results

Fuelwood consumption and its associated CO_2 emissions at the household level

The use of fuelwood as a primary energy source for households was examined in the study region, where an average amount of 24.28 ± 3.1 Mg hh^{-1} was consumed annually. TACL associated with fuelwood combustion was found to be 11.41 ± 1.8 Mg hh^{-1}, with an ACO_2R rate of 41.88 ± 4.5 Mg hh^{-1}. A comparison of the subtropical and temperate regions revealed lower rates of AFWDC and ACO_2R in the former, at 20.67 ± 4.3 and 35.65 ± 3.8 Mg hh^{-1}, respectively, as opposed to the latter, which had AFWDC requirements of 27.89 ± 3 Mg hh^{-1} and ACO_2R of 48.11 ± 5.2 Mg hh^{-1}.

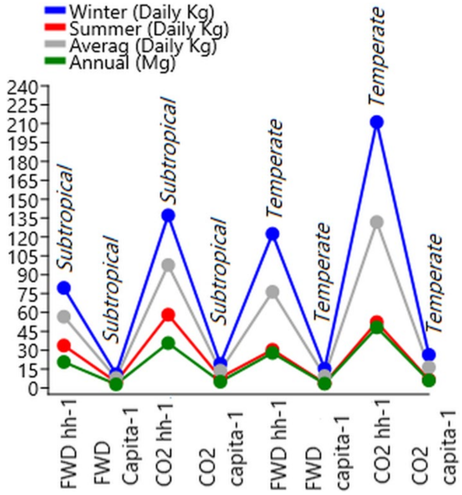

Fig. 2 Fuelwood consumption and associated CO_2 emissions estimates in the study area

The mean DFWD in the study area was 66.52 ± 6.4 kg hh^{-1}, which resulted in a TDCL of 31.26 ± 2.7 kg hh^{-1}. The average DCO_2R was estimated to be 114.745 ± 8.6 kg hh^{-1}. In the subtropical region, DFWD and DCO_2R were lower, at 56.63 ± 6.5 and 97.68 ± 8.4 kg hh^{-1}, respectively, while the temperate region showed higher values of DFWD and DCO_2R at 76.41 ± 6.4 and 131.81 ± 7.6 kg hh^{-1}.

The highest DFWD of 101 ± 7.6 kg hh^{-1} was recorded in winter, while the lowest rate of 32.045 ± 2.7 kg hh^{-1} was observed in summer. The maximum DCO_2R of 174.215 ± 9.3 kg hh^{-1} was found in winter, while the minimum of 55.27 ± 6.5 kg hh^{-1} was recorded in summer. In the subtropical region, DFWD rates were 79.52 ± 9.4 kg hh^{-1} in winter and 33.74 ± 5.2 kg hh^{-1} in summer, resulting in DCO_2R ranging from 137.16 ± 9.7 kg hh^{-1} in winter to 58.2 ± 5.5 kg hh^{-1} in summer. In the temperate region, DFWD ranged from 122.48 ± 8.8 kg hh^{-1} in winter to 30.35 ± 4.2 kg hh^{-1} in summer, resulting in DCO_2R of 211.27 ± 6.8 kg hh^{-1} and 52.34 ± 5.6 kg hh^{-1} in winter and summer, respectively (Fig. 2).

Fuelwood consumption and its associated CO_2 emissions at the individual level

AFWDC was recorded as 3.195 ± 1 Mg $capita^{-1}$, resulting in a TACL count of 1.5 ± 0.3 Mg $capita^{-1}$ and ACO_2R of 5.51 ± 0.6 Mg $capita^{-1}$. The subtropical region had lower AFWDC and ACO_2R rates of 2.91 ± 0.6 and 5.02 ± 2.6 Mg $capita^{-1}$, respectively, compared with the temperate region's AFWDC of 3.48 ± 0.7 and 6 ± 1.5 Mg $capita^{-1}$.

The study showed that the average DFWD was 8.75 ± 1.2 kg capita^{-1}, causing a TDCL of 4.11 ± 0.7 kg capita^{-1} and an average DCO$_2$R of 15.095 ± 2 kg capita^{-1}. The subtropical region was recorded as having DFWD and DCO$_2$R of 7.96 ± 1.6 and 13.74 ± 2.4 kg capita^{-1}, respectively, while the temperate region had DFWD and associated DCO$_2$R of 9.54 ± 2.1 and 16.45 ± 3.1 kg capita^{-1}, correspondingly (Fig. 2).

DFWD varied with season, as high as 6.2 ± 1 kg capita^{-1} in winter and as low as 2.02 ± 0.4 kg capita^{-1} in summer. DCO$_2$R rates were totaled as a maximum of 22.765 ± 3.3 kg capita^{-1} in winter and a minimum of 7.42 ± 1.1 kg capita^{-1} in summer. In the subtropical region, DFWD in the winter season was 11.13 ± 2.1 kg capita^{-1} and 4.8 ± 0.7 kg capita^{-1} in summer, producing DCO$_2$R ranging between 19.19 ± 3.8 kg capita^{-1} in winter and 8.281.9 kg capita^{-1} in summer. In the temperate region, DFWD requirements ranged from 15.27 ± 2.3 kg capita^{-1} in winter to 3.8 ± 0.4 kg capita^{-1} in the summer season, triggering a daily DCO$_2$R of 26.34 ± 3.3 kg capita^{-1} and 6.56 ± 1.2 kg capita^{-1} in winter and summer, respectively (Fig. 2).

Fuelwood use along an elevation gradient

The mean DFWD (kg hh^{-1}) values were highest in the temperate region. The Upper Domail village, situated at an elevation of 2890 m above sea level (m a.s.l), had the highest average DFWD of 102.34 ± 8.8 kg hh^{-1}. It was followed by Brithwar (2810 m a.s.l) with a consumption rate of 98.5 ± 7.5 kg hh^{-1}, Leepa Valley-I (2395 m a.s.l) with 95.3 ± 7.8 kg hh^{-1}, Machal (2335 m a.s.l) with 85.17 ± 5.7 kg hh^{-1}, Khawaja Seri (1940 m a.s.l) with 83.17 ± 6.5 kg hh^{-1}, and Leepa Valley-II (2400 m a.s.l) with 80.9 ± 6.7 kg hh^{-1}. In the temperate region, all other study sites had DFWD consumption rates ranging from a maximum of 72.5 to a minimum of 47.61 kg hh^{-1}.

In the subtropical region, Danna (1585 m a.s.l), Niazpura (1705 m a.s.l), and Awan Patti (1845 m a.s.l) had higher average DFWD consumption rates of 82.75 ± 5.4, 76 ± 6, and 72 ± 6.4 kg hh^{-1}, respectively. The remaining villages in the subtropical region had DFWD consumption rates ranging from a highest of 70.5 to a lowest of 30.75 kg hh^{-1}.

In a similar manner, per capita consumption of DFWD was found to be higher in the temperate region compared with the subtropical region. The highest DFWD was recorded at Khawaja Seri (1940 m a.s.l) with a value of 12.6 ± 3.5 kg capita^{-1}, followed by Leepa Valley-I (2395 m a.s.l) with 11.91 ± 3.1 kg capita^{-1} and Machal (2335 m a.s.l) with 11.35 ± 2.7 kg capita^{-1}. Upper Domail (2890 m a.s.l) and Brithwar (2810 m a.s.l) showed similar DFWD values of 10.72 ± 2.4 and 10.36 ± 2.8 kg capita^{-1}, respectively. Other temperate villages exhibited an average DFWD range between 9.40 and 6.25 kg capita^{-1}. All the subtropical sampling villages (ranging from 1940 to 860 m a.s.l) demonstrated an average DFWD range of 9.5–4.07 kg capita^{-1}, except for the Katkair village (1750 m a.s.l), which displayed the highest value of 10.69 ± 3.7 kg capita^{-1}. The seasonal variations in DFWD are depicted in Fig. 3.

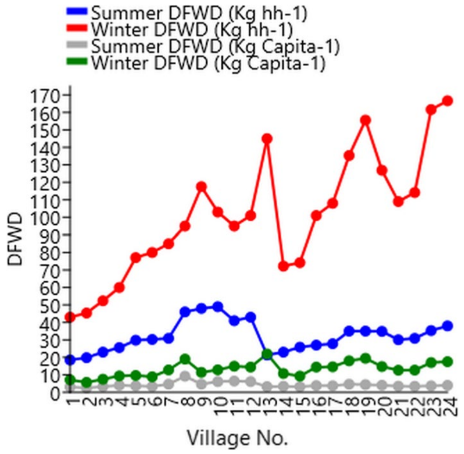

Fig. 3 Seasonal variations in the fuelwood consumption patterns at the study sites

Preferred species for fuel

According to the survey conducted, a total of 75 plant species belonging to 39 different plant families were identified as preferred sources for combustion. These plants included 37 trees, 33 shrubs, 4 small trees or shrubs, and 1 herb. Rosaceae was found to be the most dominant family providing 11 species for fuel, followed by Fabaceae with 5 species. Other families such as Salicaceae, Moraceae, Pinaceae, and Sapindaceae were recorded with 4 species each, while Fagaceae and Lamiaceae were represented by 3 species each (Table 2).

Out of a total of all 75 plant species identified for use as a fuel, 37 were restricted to the subtropical region, while 23 were confined to the temperate region. Additionally, 15 plant species were commonly used as a fuel in both regions. The study revealed that *Broussonetia papyrifera*, *Dalbergia sissoo*, *Ficus palmata*, *Mallotus phillippensis*, and *Olea ferruginea* were the most prevalent species used as fuelwood in the majority of subtropical villages surveyed. For shrubs endemic to the subtropical area, *Dodonaea viscosa*, *Punica granatum*, *Justicia adhatoda*, and *Lantana camara* were the most used fuel sources (Table 2).

In the temperate region, *Abies pindrow*, *Acer caesium*, *Aesculus indica*, *Cedrus deodara*, *Picea smithiana*, and *Prunus padus* were identified as the most preferred

Table 2 Fuelwood species, family, habit, and habitat/region

No	Species name	Family	Habit	Habitat/region
1	*Plectranthus barbatus* Andrews	Lamiaceae	Herb	Subtropical
2	*Calotropis procera* (Aiton) Dryand	Apocynaceae	Shrub	Subtropical
3	*Colebrookea oppositifolia* Sm.	Lamiaceae	Shrub	Subtropical
4	*Cotinus coggyria* Scop.	Anacardiaceae	Shrub	Subtropical
5	*Debregeasia saeneb*(Forssk.) Hepper & J.R.I.Wood	Urticaceae	Shrub	Subtropical
6	*Dodonaea viscosa* Jacq.	Sapindaceae	Shrub	Subtropical
7	*Grewia optiva*J.R.Drumm. ex Burret	Malvaceae	Shrub	Subtropical
8	*Leptopus cordifolius* Decne.	Phyllanthaceae	Shrub	Subtropical
9	*Myrsine africana* L.	Primulaceae	Shrub	Subtropical
10	*Punica granatum* L.	Lythraceae	Shrub	Subtropical
11	*Woodfordia fruticosa* Kurz.	Lythraceae	Shrub	Subtropical
12	*Zanthoxylum armatum* DC.	Rutaceae	Shrub	Subtropical
13	*Justicia adhatoda* L.	Acanthaceae	Shrub	Subtropical
14	*Lantana camara* L.	Verbenaceae	Shrub	Subtropical
15	*Ziziphus jujuba* Mill	Rhamnaceae	Shrub/small tree	Subtropical
16	*Sapindus mukorossi* Gaertn.	Sapindaceae	Tree	Subtropical
17	*Senegalia modesta* (Wall.) P.J.H.Hurter	Fabaceae	Tree	Subtropical
18	*Vachellia nilotica* (L.) P.J.H.Hurter & Mabb	Fabaceae	Tree	Subtropical
19	*Bauhinia variegata* L.	Fabaceae	Tree	Subtropical
20	*Broussonetia papyrifera* (L.) Vent	Moraceae	Tree	Subtropical
21	*Celtis australis* L.	Cannabaceae	Tree	Subtropical
22	*Dalbergia sissoo* Roxb ex DC.	Fabaceae	Tree	Subtropical
23	*Diospyros lotus* L.	Ebenaceae	Tree	Subtropical
24	*Ficus palmata* Forssk.	Moraceae	Tree	Subtropical
25	*Mallotus phillippensis* (Lam.) Müll.Arg	Euphorbiaceae	Tree	Subtropical
26	*Malus domestica* (Suckow) Borkh	Rosaceae	Tree	Subtropical
27	*Morus alba* L.	Moraceae	Tree	Subtropical
28	Morus nigra L.	Moraceae	Tree	Subtropical
29	*Olea ferruginea* Wall. ex. Aitch	Oleaceae	Tree	Subtropical
30	*Pistacia chinensis* Bunge	Anacardiaceae	Tree	Subtropical
31	*Populus alba* L.	Salicaceae	Tree	Subtropical
32	*Populus nigra* L.	Salicaceae	Tree	Subtropical
33	*Prunus armeniaca* L.	Rosaceae	Tree	Subtropical
34	*Prunus domestica* L.	Rosaceae	Tree	Subtropical
35	*Prunus persica* L. (Stokes)	Rosaceae	Tree	Subtropical
36	*Pyrus communis* L.	Rosaceae	Tree	Subtropical
37	*Salix alba* L.	Salicaceae	Tree	Subtropical
38	*Berberis lycium* Royle	Berberidaceae	Shrub	Subtropical/temperate
39	*Daphne oleoides* Schreb	Thymelaeaceae	Shrub	Subtropical/temperate
40	*Elaeagnus parvifolia* Wall.	Elaeagnaceae	Shrub	Subtropical/temperate
41	*Indigofera heterantha* Wall. ex-Brandis	Leguminosae	Shrub	Subtropical/temperate
42	*Ricinus communis* L.	Euphorbiaceae	Shrub	Subtropical/temperate
43	*Rubus fruticosus* L.	Rosaceae	Shrub	Subtropical/temperate
44	*Sarcococca saligna* Müll.Arg	Buxaceae	Shrub	Subtropical/temperate
45	*Debregeasia salicifolia* (D.Don) Rendle	Urticaceae	Shrub/small tree	Subtropical/temperate
46	*Elaeagnus umbellata* Thunb.	Elaeagnaceae	Shrub/small tree	Subtropical/temperate
47	*Ailanthus altissima* (Mill.) Swingle	Simaroubaceae	Tree	Subtropical/temperate
48	*Azadirachta indica* A.Juss	Meliaceae	Tree	Subtropical/temperate
49	*Juglans regia* L.	Juglandaceae	Tree	Subtropical/temperate

Table 2 (continued)

No	Species name	Family	Habit	Habitat/region
50	*Pinus roxburghii* Sarg.	Pinaceae	Tree	Subtropical/temperate
51	*Quercus glauca* Thunb.	Fagaceae	Tree	Subtropical/temperate
52	*Quercus incana* W. Bartram	Fagaceae	Tree	Subtropical/temperate
53	*Berberis grandiflora* Turcz.	Berberidaceae	Shrub	Temperate
54	*Carissa spinarum* L.	Apocynaceae	Shrub	Temperate
55	*Desmodium elegans* DC.	Fabaceae	Shrub	Temperate
56	*Isodon rugosus* (Wall. ex Benth.) Codd	Lamiaceae	Shrub	Temperate
57	*Lonicera japonica* Thunb.	Caprifoliaceae	Shrub	Temperate
58	*Parrotiopsis jacquemontiana* (Dcne.) Rehder	Hamamelidaceae	Shrub	Temperate
59	*Phytolacca latbenia* H.Walter	Phytolaccaceae	Shrub	Temperate
60	*Rubus vestitus* Weihe	Rosaceae	Shrub	Temperate
61	*Salix flabillaris* Andress	Salicaceae	Shrub	Temperate
62	*Sorbaria tomentosa* (Lindl.) Rehder	Rosaceae	Shrub	Temperate
63	*Viburnum grandiflorum* Wall. ex DC.	Adoxaceae	Shrub	Temperate
64	*Cotoneaster microphyllus* Wall. ex Lind	Rosaceae	Shrub	Temperate
65	*Rosa webbiana* Wall. ex Royle	Rosaceae	Shrub	Temperate
66	*Juniperus communis* L.	Cupressaceae	Shrub/small tree	Temperate
67	*Abies pindrow* Royle	Pinaceae	Tree	Temperate
68	*Acer caesium* Wall. ex Brandis	Sapindaceae	Tree	Temperate
69	*Aesculus indica* (Wall.ex Cambess) Hook	Sapindaceae	Tree	Temperate
70	*Cedrus deodara* (Roxb. ex D. Don) G. Don	Pinaceae	Tree	Temperate
71	*Picea smithiana* (Wall.) Boiss	Pinaceae	Tree	Temperate
72	*Prunus padus* L.	Rosaceae	Tree	Temperate
73	*Quercus robur* L.	Fagaceae	Tree	Temperate
74	*Taxus wallichiana* Zucc.	Taxaceae	Tree	Temperate
75	*Betula utilis* D.Don	Betulaceae	Tree	Temperate

fuelwood species. Prominent shrubs for fuel in the temperate region comprised *Salix flabillaris*, *Sorbaria tomentosa*, and *Viburnum grandiflorum*. While *Ailanthus altissima*, *Azadirachta indica*, *Juglans regia*, *Pinus roxburghii*, *Indigofera heterantha*, *Ricinus communis*, *Rubus fruticosus* and *Sarcococca saligna* were among the major species used as fuelwood in both subtropical and temperate regions in the study area (Table 2).

Principal component analysis (PCA)

PCA analysis revealed the extraction of eight principal components (PCs) as per the data input. The first three PCs explained much of the variance in the data, with PC1 accounting for 59.8%, PC2 for 24.4%, and PC3 for 12.5%. The remaining PCs accounted for very little variance, with PC8 explaining almost no variance at all. Loading analysis showed that PC1 had high positive loadings for elevation, family size, and all three fuelwood consumption variables (summer DFWD, winter DFWD, and average DFWD) in both kg hh^{-1} and kg $capita^{-1}$ units (Fig. 4).

PC1 represents a general measure of fuelwood consumption, with higher elevation values indicating higher levels of wood combustion as a fuel. PC2 showed insignificant loadings for the fuelwood consumption variables apart from average DFWD kg hh^{-1} and winter DFWD kg hh^{-1} suggesting the family size as a measure of socioeconomic status was larger at higher elevation and does not significantly impact the overall fuelwood consumption patterns in the study area. To further explore the relationship between the extracted PCs and the original variables, a scatter plot was generated showing the correlation between each variable (Fig. 4).

To assess the reliability of the extracted PCs, a scree plot was generated. This plot shows the eigenvalues of each PC, plotted in descending order with a clear break after the first three PCs, indicating that these PCs account for most of the variance in the data, and suggesting that they are the most reliable PCs to interpret (Fig. 5). The analysis revealed that elevation, family size, and fuelwood consumption variables were strongly related to overall fuelwood consumption, while socioeconomic status and

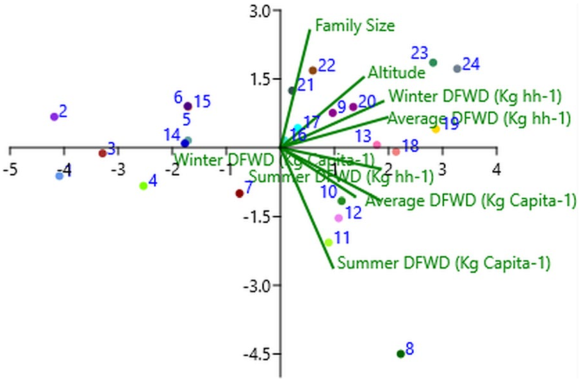

Fig. 4 PCA scatter plot of the fuelwood usage trends and influencing factors

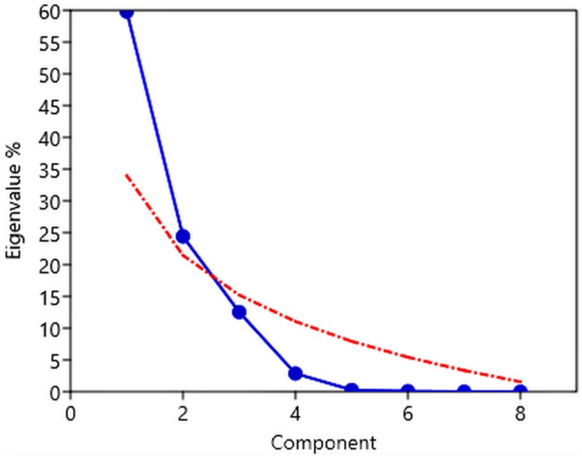

Fig. 5 Correlation analysis between PCA component and eigenvalue

seasonal variation in fuelwood consumption were also important factors. These findings have important implications for the development of effective energy policies and programs aimed at reducing fuelwood consumption and promoting sustainable energy use in the region.

Discussion

The requirement for energy to facilitate societal and economic advancement depends on locally available resources, notably fuelwood obtained from local forests. Fuelwood represents a prevalent and widely adopted energy source among the rural Himalayan communities, predominantly for cooking and heating purposes [26, 51]. Nonetheless, the extensive usage of fuelwood has played a fundamental role in the depletion of forests in various developing countries, accompanied by the emission of substantial volumes of GHGs into the atmosphere [27, 37, 52].

Fuelwood consumption rates vary across different regions. The current study recorded dissimilar AFWD (hh^{-1}) values when compared with reported figures of 3.06 Mg in Dolakha District, Nepal [53] and 2.08 Mg in the Shiwalik Himalayas [54]. DFWD (kg hh$^{-1)}$ values in the region are also found to be varying, reported as 8.4 kg in the Dolakha District of Nepal [53] and 5.4 kg in the Indian East Himalayas [55]. Likewise, DFWD (capita^{-1}) stands at 1.9–2.2 kg capita^{-1} in South Asian countries [56], 1.7–2.5 kg capita^{-1} in East Asian countries [57], 1.23 kg capita^{-1} in Nepal [58], and 3.90 kg capita^{-1} in Meghalaya, India [59], while the western Himalaya exhibited a DFWD consumption rate of 3.56 capita^{-1}) [60]. In the Garhwal Himalaya, DFWD ranged from 1.49 to 3.14 kg capita^{-1} [61, 62] and in the Central Himalaya, 1.49 kg capita^{-1}, while in Southern India, DFWD was reported as 1.632 kg capita^{-1} [63].

The mean DFWD values in this study exhibited significant variations when compared with findings from other studies in the region, such as 2.97 kg capita^{-1} in Bagh district of Kashmir [20] and 1.7 kg capita^{-1} for Dolakha District, Nepal [53]. In the lower Indian Himalayas, DFWD from agroforestry was 2.05 and 0.63 kg capita^{-1} in winter and summer, respectively, while from alternative sources, it was 1.16 and 0.34 kg capita^{-1} in winter and summer [63]. These variations underscore the importance of considering local factors and regional contexts in understanding fuelwood consumption patterns [2, 3, 8–10].

Fuelwood consumption trends are generally shaped by variables such as family size, altitude, seasonal variations, and the qualitative and quantitative characteristics of locally available firewood. A primary contributing factor to escalated fuelwood utilization, deforestation, and the consequent release of CO_2 emissions has been attributed to population growth. Countries having significant rural populations exhibit elevated rates of fuelwood extraction [5, 39, 64]. The impact of these factors varies depending upon the specific bioclimatic zones and socioeconomic circumstances of the communities under consideration [13, 14, 65]. Furthermore, the choice of stoves employed by the households plays a significant role in influencing CO_2 emissions resulting from fuelwood use. Adopting clean and efficient cooking technologies has the potential to mitigate CO_2 emissions, decrease fuelwood consumption, and reduce cooking duration [19, 27].

This study has some limitations, including its limited geographic scope, small sample size, focused variables, and socioeconomic factors. In addition, the absence of long-term data prevented a species-wise analysis to fully explain temporal trends and variations for the generalizability of outcomes. However, the study observed that fuelwood consumption and carbon emission rates were higher in the temperate region compared with the subtropical region. This divergence can be attributed to variations in site elevation, which influence fuelwood consumption through numerous factors including fuelwood species availability, energy requirements according to the climatic conditions, technological interventions, infrastructure, and socioeconomic factors [3, 20, 62].

The statistical analysis examined the effects of elevation and family size on average daily fuelwood combustion (ADFWD) separately for kg hh^{-1} and kg $capita^{-1}$. The Wilks lambda statistical test of the overall significance of the independent variables suggested that both elevation (Wilks lambda = 0.4428) and family Size (Wilks lambda = 0.08203) have a significant effect on DFWD. Similarly, the F-test endorsed the significance of each independent variable individually. The results showed that both elevation ($F = 12.59$, $p < 0.001$) and family size ($F = 111.9$, $p < 0.001$) have a significant effect on DFWD (Table 3). Site elevation had a direct effect on firewood consumption when comparing firewood consumption in different countries because residents at high altitude locations need more fuel for heating. Higher elevations typically have colder weather leading to increased fuelwood consumption [66].

The findings (dependent variables) of the current study were tested using several statistical techniques including the calculation of the R^2 value and application of the F-test. R^2 is a measure of how well the independent variables explain the variance in the dependent variables. The results showed that the independent variables (elevation and family size) explain 62.44% and 47.75% of the variance in mean DFWD per household and per capita, respectively. Similarly, the F-test for the overall significance of the data analysis suggested that the model is significant for both DFWD (hh^{-1}) having an F-value of 17.46, $p < 0.001$) and DFWD ($capita^{-1}$) having an F-value of 9.596 and $p < 0.01$ (Table 3). Socioeconomic factors such as population density, income, and education level also influence fuelwood consumption patterns. The consumption of fuelwood is greatly influenced by climate and seasons, with higher consumption in winter months due to low temperatures and prolonged winter. Therefore, sustainable energy policies should consider the impact of altitude on fuelwood consumption patterns for effective implementation [60, 67].

The regression coefficients for each independent variable in each model were also computed. The coefficient for the elevation in the model predicted that DFWD (hh^{-1}) is 0.024448, which suggests that for every unit increase in elevation, the predicted value of DFWD (hh^{-1}) increases by 0.024448 kg. The R^2 value as a coefficient of determination for each model represented the proportion of variance in the dependent variable that is explained by the independent variables. The R^2 value of 0.61297 predicts that the independent variables in the model can explain 61.297% of the variation in DFWD (hh^{-1}) meaning that the model is a better fit for the data (Table 3).

Rural Himalayan communities predominantly rely on nearby forest resources for obtaining fuelwood for cooking and heating due to the ease of access, cost-effectiveness (as firewood is often freely available), and the convenience it offers in the absence of readily available alternative energy sources [11, 51]. The combustion of wood results in continuous GHG emissions that contribute to climate change. In areas that are distinguished by severe climate conditions and prolonged winter season,

Table 3 Tests on variables with regression coefficients and statistics

Tests on independent variables	**Wilks lambda**	***F*-value**	**df_1**	**df_2**	***p*-Value**	**R^2**
Altitude	0.4428	12.59	2	20	0.0002895	–
Family size	0.08203	111.9	2	20	1.38E−11	–
Tests on dependent variables	–	***F*-value**	**df_1**	**df_2**	***p* -Value**	**R^2**
ADFWD (kg hh^{-1})	–	17.46	2	21	3.42E−05	0.6244
ADFWD (kg $capita^{-1}$)	–	9.596	2	21	0.001096	0.4775
Regression coefficients and statistics	–	**Coefficient**	**Standard error**	***t*-Value**	***p*-Value**	–
ADFWD (kg hh^{-1})	*Constant*	5.816	16.412	0.35437	0.72659	–
	Altitude	0.024448	0.0050676	4.8245	9.08E−05	0.61297
	Family size	1.9003	2.3745	0.80029	0.4325	0.20814
ADFWD (kg $capita^{-1}$)	*Constant*	10.401	2.4366	4.2685	0.00034187	–
	Altitude	0.0032091	0.00075235	4.2654	0.00034446	0.27474
	Family size	− 1.0064	0.35253	− 2.8548	0.0094859	0.024846

the extraction of fuelwood can result in the overexploitation of forests and their resources [5, 39, 51].

The seasonal variations in fuelwood consumption are due to the increased demand for space heating in the winter months, when temperatures are lower, and fuelwood is used as heating source. In contrast, fuelwood is primarily used only for cooking in the summer months, when temperatures are higher and there is less need for space heating [20, 68]. The availability of alternative fuels such as electricity and liquefied petroleum gas (LPG) can reduce fuelwood consumption during the summer months, when fuelwood is primarily used for cooking. However, due to their high costs and low availability in rural areas, fuelwood remains the primary source of energy for space heating during the winter months [69]. Traditional mud stoves, which are commonly used in the Himalayas, are inefficient and susceptible to winds, resulting in energy loss, higher fuelwood consumption, and increased smoke emissions [27, 48, 65].

Accessibility to forest resources and fuelwood species availability is another factor that affects fuelwood consumption in rural areas. Residents may not be aware of sustainability measures or energy needs due to the severity of the climate [64]. Numerous studies conducted on fuelwood species in the Himalayan region have yielded varying numbers of preferred fuelwood species i.e., 26 species in the North-Eastern Himalaya [70], 88 species in tourist-affected areas of Garhwal Himalaya [61], 19 species in the Eastern Himalaya [71], 14 species in the Shiwalik Himalayas [72], 14 species in the Takoligad Watershed of Garhwal Himalaya [73], 24 species in the Eastern Himalaya [74], 14 species in the Indian Himalayan region [68], 41 species in the Indian Eastern Himalayas [55], 12 species in the Western Himalaya [51] and 29 fuelwood species in Western Himalaya, India [75].

The use of wood for energy purposes represents a multifaceted phenomenon and is influenced by a multiplicity of factors, encompassing accessibility, energy efficiency, species abundance, climatic rigors, and closeness to forest resources [16, 22, 32, 55]. In regions with severe climatic conditions, the heavy reliance on fuelwood is further intensified by the absence of viable alternative energy sources and the prevalent low socioeconomic status of the residents [2, 5, 8, 9]. Recent estimates indicate that 90–95% of Himalayan rural households rely on fuelwood for cooking and heating, with occasional gas use in 60% of homes. About 75% primarily use fuelwood and brushwood for cooking. The high dependence on wood fuels is driven by the lower incomes and elevated energy prices as well as remoteness and inaccessibility to sustainable alternatives [6, 11, 76]. The continuous and accelerated depletion of Himalayan forests and forest products, especially preferred fuelwood species, can be accredited to deforestation and the selective felling of these preferred species, resulting in their gradual disappearance [36, 53, 77].

As the availability of fuelwood from the forest periphery diminishes, wood gatherers move further into the forest to selectively gather preferred fuelwood species. This practice not only intensifies deforestation but also leads to increased CO_2 emissions resulting from fuelwood harvesting [39, 77, 78]. The preference for specific wood species, along with the use of readily available fuelwood from deceased and deteriorated woody shrubs and trees, worsens the disparity between supply and demand [26, 63]. In the study region, several species such as *Cedrus deodara*, *Aesculus indica*, *Salix flabillaris*, *Betula utilis*, *Taxus wallichiana*, *Viburnum grandiflorum*, *Indigofera heterantha*, and *Berberis lycium* are under threat of being endangered due to extensive harvesting for burning. Apart from the carbon emissions caused by the wood combustion for fuel, the convenient availability of preferred fuelwood species in the study region poses a significant threat to the local biodiversity and human health [52, 76, 77]. These circumstances have resulted in the fragmentation of forest ecosystems, habitat degradation, and endangering certain fuelwood species that immediately need to be conserved in a sustainable manner [20, 23, 77].

Conclusions

This study examined fuelwood consumption patterns in a western Himalayan region and revealed that fuelwood consumption and CO_2 emissions are higher in temperate zones compared with subtropical regions. Elevation and family size have emerged as key determinants influencing fuelwood consumption and its associated CO_2, as higher altitudes and larger family sizes correlate with raised fuelwood usage. These patterns arise due to variations in climate, energy needs, resource availability, cultural factors, and availability of fuelwood species. Directives and subsidies can significantly influence fuelwood consumption, as they may promote or discourage its use. Additionally, economic conditions and income levels can also impact fuelwood consumption, with lower-income households often relying more on wood fuel due to cost considerations. The study recommends implementing sustainable energy policies encompassing a multifaceted approach to its address the challenges posed by fuelwood consumption and CO_2 emissions in the western Himalayan region. This emphasizes the need for clean and efficient energy technologies, afforestation and reforestation initiatives for sustainable fuelwood sources, and incentives for alternative energy adoption that can diversify energy options. Implementing sustainable forestry practices, fostering cooperation between the local communities and various departments, and promoting ecotourism strategies can play significant roles in achieving comprehensive solutions for regional energy and environmental sustainability. Awareness through educational initiatives and promoting socio-economic development can reduce reliance on fuelwood, while simultaneously enforcing strict measures against illegal logging. Future research should assess the effectiveness of policy interventions in reducing fuelwood consumption and greenhouse gas emissions. Upcoming research on fuelwood consumption in the Himalayan region should use an interdisciplinary approach, incorporating long-term data collection, species-specific consumption patterns and energy production, community engagement, and the complex interactions among fuelwood use, CO_2 emissions, and climate change. This comprehensive approach, supported by interdisciplinary methods and awareness campaigns, will provide a better understanding of the challenges associated with fuelwood consumption and foster the development of sustainable alternatives.

Author contributions

RWAK: Conceptualization, methodology, software, validation, visualization, supervision, project administration, writing—original draft. NN, SQ: Conceptualization, methodology, software, formal analysis, data curation. AM: Writing—review and editing. HS: Formal analysis, writing—review and editing. All authors read and approved the final manuscript.

Funding

This study is not funded by any organization.

Availability of data and materials

All the data obtained, and materials investigated in this research are accessible with the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 28 June 2023 Accepted: 8 February 2024

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