Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 24 No. 4
Article ID B4295
2025

Original Research Paper
https://doi.org/10.46488/NEPT.2025.v24i04.B4295
Open Access Journal

Health Risk Assessment Among Biogas and Conventional Cooking Fuel Users in Different Socioeconomic Conditions of Rural West Bengal

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Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com
Received: 10-12-2024
Revised: 05-02-2025
Accepted: 14-02-2025

Key Words:

Household air pollution
Exposure load pattern
Health risk assessment
Biogas
Monte-Carlo simulation model

Citation for the Paper:

Bagdi, T., Koley, A., Das, N., Das, S., Gayen, S., Sarkar, A., Ghosh, S., Kumar, S., Chaudhury, S., Hazra, A. K., Ross, A. B., Chakraborty, D. and Balachandran, S., 2025. Health risk assessment among biogas and conventional cooking fuel users in different socioeconomic conditions of rural West Bengal. *Nature Environment and Pollution Technology,* 24(4), B4295. https://doi.org/10.46488/NEPT.2025.v24i04.B4295

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

In many rural areas of developing countries, solid fuel use is still widespread. The present study aims to investigate the Household Air Pollution (HAP) exposure effect from traditional biomass fuels and biogas on the health of rural women. The results revealed that nearly 93% of rural families utilize conventional fuels for daily cooking and heating purposes, whereas clean fuels like biogas were minimal. However, high-income, educated, elderly, well-structured houses (*Pucca*), and hierarchically more advanced families were observed to cook with biogas fuel. Further, the present study also used spatial HAP mapping and land use mapping models to analyze exposure load patterns and sources of solid fuel availability, respectively. The clean fuel biogas burning showed the lowest HAP concentration compared to traditional fuels, except for NO_2 (1.14 ± 0.05 ppm), which is also represented in the case of health risk estimation. The biogas users also observed the lowest COHb% (0.008 ± 0.01) than conventional fuels. The health risks associated with SO_2 and NO_2 for biogas users were revealed to be lowest in both acute and chronic instances. Monte-Carlo probabilistic model observed that coal cake may pose high health risks among traditional fuels when considering $PM_{2.5}$, SO_2, and NO_2, but in the case of COHb% %, cow dung users showed the highest health risk (0.39 ± 0.02). These findings have significant implications for public health, suggesting that promoting the use of cleaner cooking fuels, particularly biogas, which is less affected by muscular pain and eye irritation than biomass users, could lead to substantial health benefits for rural populations. This finding also indicates that government intervention should be required to enhance the utilization of cleaner cooking fuels in rural India for women's safety.

INTRODUCTION

Household air pollution (HAP) is the eighth most significant contributor to the global disease burden, and growing concern is caused by the combustion of solid fuels that pose a significant threat to human health (Manuel & Gautam 2023). About 2.6 billion people worldwide still cook with solid, unprocessed fuels (Mitra et al. 2023), making them vulnerable to the toxic effects of HAP. Recently, the World Health Organization (WHO) reported that HAP was responsible for a distressing global annual death toll of 3.2 million, including approximately 237,000 child fatalities in 2020 (WHO 2022). This exposure to HAP becomes a cause of low birth weight, pregnancy complications (Amegah et al. 2024), acute respiratory infections (Enyew et al. 2021), respiratory impairment (Pathak et al. 2019), cardiovascular disease (Mocumbi et al. 2019), and cognitive impairment (Krishnamoorthy et al. 2018), chronic obstructive pulmonary disease (COPD) (Wu et al. 2022). Most rural households mainly depend on solid biomass due to their lower socio-economic conditions, and women collect fuelwood for 5 to 8 hours a day, taking up 20% of their time and carrying 25–50 Kg of firewood for several miles (Matano 2022).

India, a country heavily dependent on agriculture, has a potential amount of biomass that may be processed using cutting-edge techniques to produce biogas energy. However, with the enormous emissions of greenhouse gases (GHGs) resulting from the combustion of fossil fuels, there is a growing need for alternative renewable fuels (Bagdi et al. 2023, Shane & Gheewala 2017). Methane gas yields about 802.29 $KJ.moL^{-1}$ of energy, while typical biogas (60% methane) produces 534.86 $kJ.moL^{-1}$ of energy (Mekonen et al. 2023). A small family-size biogas plant of one cubic meter capacity can save 0.43 kg of liquefied petroleum gas (LPG) daily (Aggarwal et al. 2021). To promote biogas technology in rural areas on large-scale applications for substitute cooking fuel, chemical fertilizer, and the generation of off-grid electricity, the government of India has initiated various initiatives, including the New National Biogas and Organic Manure Program, Biogas Power Generation (off-grid) and Thermal Energy Application Program, the Central Financial Assistant and the Sustainable Alternative Towards Affordable Transportation (Bharti 2019). The Ministry of New and Renewable Energy (MNRE) continues the National Bioenergy Program for FY 2021-22 to 2025-26, which recommended the implementation of NBP in two phases. Phase I, approved with a budget of INR ₹ 8580 million, includes around USD 12.5 million for the Biogas Program, supporting modest to medium-sized biogas plants. MNRE targeted the buildup 30795 number of small-scale biogas plants all over India by the financial year 2023-2024 (MNRE 2022). Despite the government of India's efforts to prioritize small-scale biogas plants in rural India, only 0.4% of rural Indian households use biogas as their primary energy source (Mottaleb 2019). According to a recent estimation in India, about 54% of households still rely on traditional solid biomass cooking fuels, likewise firewood, cow dung cake, charcoal, and agricultural residues, for cooking and heating purposes, which are prominent sources of indoor air pollution in developing nations (Sunil et al. 2021). Several scholarly investigations (Kumar et al. 2023, Shobande 2023, Zewdie et al. 2023) highlighted that the practice of burning solid fuels in inefficient stoves, attached with inadequate ventilation, can pose significant health risks. In addition, cooking with incomplete combustion of solid fuels, especially in unvented environments, can lead to elevated indoor levels of carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs) and polyaromatic hydrocarbons (PAHs) (Churchill & Smyth 2021, Nawaz 2021).

Recently, India announced at COP26 the targets to achieve larger goals within the allotted period as per COP21. India set a 40% non-fossil fuel energy goal as part of the Paris Agreement to combat climate change (Sawhney 2021). At the COP 26 summit in Glasgow, India's new objective has been revised to 500 gigawatts (GW) from renewable energy by the year 2030 to cut its carbon emissions by nearly a billion tons, aiming to have a carbon-neutral economy by 2070 (Singh et al. 2023). The installed capacity of bio-power in India has reached 10.16 gigawatts, which will account for 10.12% of the country's total capacity for renewable energy sources by the end of 2021 (Kulyal & Jalal 2022). Thus, there is a need to transform traditional energy into clean, modern, and sustainable energy to control climate change. Efficient, clean energy sources are linked to improved HAP, expanded opportunities for productive or recreational activities, and decreased dependence on biomass energy collection. In research conducted by Afridi et al. (2023), it was observed that women spend an average of 23 hours per week on cooking activities.

Additionally, when cleaner fuel was used for cooking, there was an 18% reduction in cooking time. In their study, Waris & Antahal (2014) observed that the average cooking time per meal decreased from 1.08 to 0.75 hours when using biogas stoves. Anderman et al. (2015) discovered that women who utilize biogas spend an average of 40 minutes less on cooking and 70 minutes reduction on collecting firewood per day compared to women in households that use solid biomass (Chowdhury et al. 2023). In order to mitigate the harmful effects of HAP and promote better health outcomes, various interventions have been proposed or tested. Among them, shifting towards cleaner cooking energy, for example, biogas (Koley et al. 2022a), electricity, LPG (Bagdi et al. 2022), or solar power is used. Another approach involves using improved cookstoves that generate more energy while producing less smoke (Chakraborty et al. 2021). In addition, interventions may focus on enhancing ventilation and optimising kitchens' design, as well as promoting changes in cooking behaviors (Chakraborty et al. 2022).

The 68th round report by the National Sample Survey Organization (NSSO) emphasised the significant dependence of rural families in India on traditional fuels. In 2011-12, it was found that 67.35% of rural households relied on firewood and chips as their primary cooking fuel source. The substantial reliance on firewood highlights rural communities' challenges in getting cleaner and more efficient energy sources. Using firewood poses health hazards due to indoor air pollution and contributes to environmental degradation by causing deforestation. The results emphasize the pressing necessity to advocate for alternative, sustainable energy options such as biogas. Biogas has the potential to boost health outcomes, mitigate environmental consequences, and improve the standard of living in rural regions. Moreover, the availability of huge potential of biomass resources in the village, like aquatic weeds (Koley et al. 2023, Koley et al. 2022b), algae (Koley et al. 2024b), agricultural residues, livestock resources (Dhungana et al. 2022, Bagdi et al. 2022), food waste (Nahar et al. 2024), etc., that may be used as feedstock for the biogas plant.

There are limited studies that have been conducted in the past on the comparison of health benefits from biogas over traditional cooking fuels under varying socio-economic conditions. This study investigated the relationship between socio-economic status, exposure load, and land use patterns. Additionally, the study analyzed the health risk assessment among rural women who are using traditional and biogas fuels. This study highlights the health and socio-economic benefits of biogas over traditional fuels, assesses health risks among rural women, and explores exposure assessments and land use patterns to provide policy insights for promoting clean energy and sustainability.

MATERIALS AND METHODS

Study Area

The present study was conducted in ‘Sehalai’ village (Lat 23.718238, Long 87.680435), located under Kasba gram panchayat in Bolpur-Sriniketan tehsils of Birbhum district, West Bengal, India (Fig. 1). The village covers 328.54 hectares of geographical area. As per the Census (2011), the reported total population of this village is 1408 people with 315 households. In Sehalai village, out of the total population, 386 (27.41%) and 616 (43.75%) belong to SC and ST communities. The primary occupation of the villagers is agriculture, with approximately 302.4 hectares of irrigated land and 2.4 hectares of forestland. Most villagers are engaged in agriculture (31%), while almost 60% rely on casual labor and other sectors. Sehalai village was chosen as the study region for this case study because it represents rural

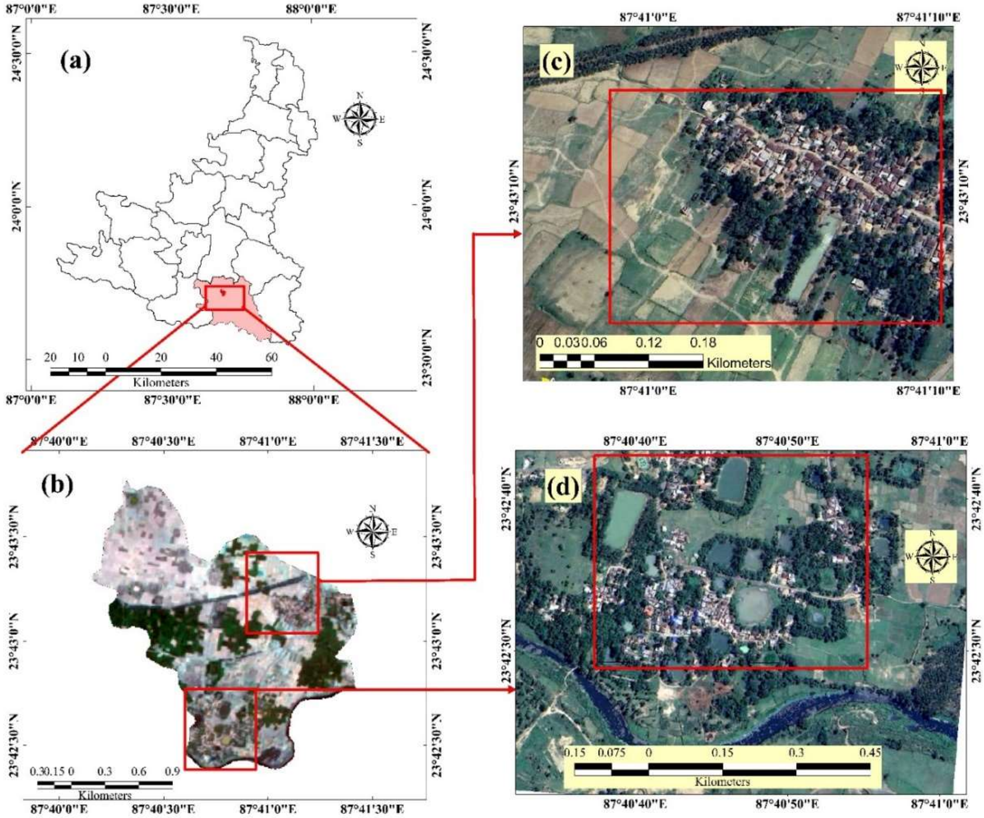


Fig. 1: Study Area (a) Birbhum District of West Bengal, (b) Sehalai Village of Birbhum District, (c) North Sehalai Village and (d) South Sehalai Village.

Bengal, as reported by the National Family Health Survey (NFHS) 2018, which found that 71% of rural families in West Bengal use firewood as their major cooking fuel. This heavy dependency reflects the region's broader rural environment, providing common concerns such as health risks from indoor air pollution and degradation of the environment caused by deforestation. By focusing on Sehalai hamlet, the study intends to gain insight into these prevalent concerns and assess the possible benefits of implementing sustainable energy options such as biogas. This selection assures that Sehalai's findings and recommendations may be applied to similar rural settings in West Bengal, providing an extensive comprehension of energy usage dynamics and the need for cleaner, more efficient cooking solutions.

Personal Interview and Data Collection

The study region was selected on the following basic criteria: (i) The village is at least 3 km from the major road to reduce other pollution (noise, vehicular pollution), (ii) no air polluting industries are present in the surrounding areas, (iii) the study areas have knowledge about biogas, and (iv) respondents aged 18 to 69 years were chosen. The inclusion criteria were non-smoking women who cooked using solid fuels or biogas for at least 2 h per day for the last 5 years, along with LPG as an emergency backup, and who had no chronic health conditions. Exclusion criteria include people who are entirely transitioning to LPG as their primary cooking fuel and women with chronic conditions.

The proposed research area's sample size is determined using a 95% confidence level and a 5% margin of error. According to the 2011 census report, the village has a total of 315 households. The proposed sample size is approximately 173 households out of the total number of households in the village. The recommended sample results are designed to ensure that they accurately represent the total population. The random sampling technique was employed to choose representative sample households from throughout the hamlet. The survey was conducted between July 2024 to September 2024. The questionnaire was originally developed in English and subsequently translated into Bengali, the native language of the study area. Participants were informed of the study's objective in Bengali, and informed consent was obtained before data collection. Participants who were literate provided written assent, while those who were unable to read or write confirmed their consent verbally. The authors surveyed to build rapport and enhance data gathering across the village. The questionnaire used a combination of open-ended, closed-ended, and multiple-response questions to collect both qualitative and quantitative data. A total of 173 households were surveyed through personal interviews to gather data on the households' demographic characteristics, such as the age of the head, head's education, primary occupation of the head, average family income, daily cooking hours, cooking experience, kitchen and fuel type, agricultural land holding, and housing structure. This information was collected using a standardized questionnaire with permission from the participating families, and recorded necessary information was recorded.

Measurement of Household Air Pollution

A total of 173 households were surveyed to gain insights into their socio-economic conditions and fuel usage patterns. Among these 173 households, a subset of 20 were selected from two different colonies that primarily relied on wood, cow dung cake, coal cake, and biogas to measure HAP indoors. During the monitoring, 5 households were excluded from the study due to non-compliance with the research protocol. The HAP was measured using a real-time 8-channel Indoor Air Quality (IAQ) Monitor (YESAIR) developed by Critical Environment Technologies in British Columbia, Canada. The real-time monitoring has been carried out for 24 hours, including cooking and non-cooking periods in selected households. The devices were set up at a breathing-level height and 1.5 meters away from the stove (in a sitting position) (Chakraborty et al. 2014).

Quality Assurance/Quality Control

Instruments were adequately charged and calibrated to maintain the data quality. The electrochemical sensors of CO (PNP-C), NO_2 (PNP-D), SO_2 (PNP-P), and CET-$PM_{2.5}$ were calibrated before each sampling session using the supplied calibration tube attached with one end to the cylinder full of 100% Nitrogen. The instrument has also been standardized in a controlled environment with an observation of ± 3% accuracy level.

Assessment of Household Air Exposure and Health Risk

$PM_{2.5}$ Exposure

The degree of exposure was determined by Chakraborty and Mondal (2018), using the total concentration of $PM_{2.5}$ emitted, the number of occupants, and the total amount of time spent in various circumstances while cooking. The exposure index was computed using Eq. 1. The $PM_{2.5}$ guideline value was taken from WHO (2021).

$$E_i = \sum_i^l \frac{C_i t_{ki}}{C_g t_a} \qquad \ldots (1)$$

Intake Concentration of $PM_{2.5}$

Mitra et al. (2022) determined the intake concentration by calculating the average concentration of $PM_{2.5}$. Eq. 2 was utilized to calculate the identical value (USEPA 1989).

$$IC = \frac{C_p \times E_t \times E_f \times E_d}{AT} \quad \ldots (2)$$

Intake Concentration of $PM_{2.5}$

The majority of cardiovascular diseases are linked to $PM_{2.5}$ intake. As a result, the toxicological risk of $PM_{2.5}$ was assessed using the Hazard Quotient (HQ) using Eq. 3 (USEPA 2005).

$$HQ = \frac{IC}{Rfc} \quad \ldots (3)$$

If the outcome values of HQ are more than 1, then there will be a chance to develop non-carcinogenic health risks among exposed groups.

Blood Carboxyhemoglobin Level Assessment

Applying the approach proposed by Peterson and Stewart, the blood COHb% levels were estimated (Eq. 4) for each fuel burned in this study (Chakraborty & Mondal, 2021).

$$\text{Log (COHb\%)} = [0.858 \times \log (\text{CO})] + [0.63 \times \log (t)] - 2.295 \quad \ldots (4)$$

Exposure Assessment for NO_2 and SO_2

Equation Eq. 5 was used to determine the non-carcinogenic exposure (average hourly dose for inhalation ($\mu g.kg.h^{-1}$)) to NO_2 and SO_2 (Basu et al. 2024).

$$\text{AHD} = \text{C} \times \text{IR/BW} \quad \ldots (5)$$

For exposure to non-carcinogenic pollutants (NO_2 and SO_2), the average daily dose of the pollutant of interest ($\mu g.kg.day^{-1}$) (Eq. 6) was calculated from the following formula:

$$\text{ADD} = (\text{C} \times \text{IR} \times \text{ED})/(\text{BW} \times \text{AT}) \quad \ldots (6)$$

Assessment of Non-Carcinogenic Risk Using Hazard Quotient (HQ)

The hazard quotient (HQ) was used to estimate the potential non-carcinogenic consequences of exposure to a known pollutant. The non-cancer likelihoods for cases of acute and chronic exposure were calculated using Eq. 7 and Eq. 8:

$$\text{Chronic HQ} = \text{ADD/REL} \quad \ldots (7)$$

$$\text{Acute HQ} = \text{AHD/REL} \quad \ldots (8)$$

Where REL (reference exposure level), as adopted from WHO (2021).

Statistical Analysis

The data were evaluated statistically utilizing SPSS 27 and Microsoft Excel 13. The ANOVA was applied to analyze the difference between concentrations of pollutants from different fuels burning at a 5% significance level. The independent variable in this study is the socioeconomic condition of households, which encompasses factors such as caste, occupational structure, housing pattern, and income group. On the other hand, the dependent variable is the pattern of primary fuel usage. The association between socioeconomic status and cooking fuel use was investigated using the Chi-square (χ^2) test at a 95 % significance level. To find out the uncertainty in health risk estimation, the Monte-Carlo simulation models were run for 10,000 simulations using Oracle Crystal Ball software version 11.

Analysis of Land Use/Land Cover

This study analyzed the spatial distribution of land use in the studied area. To examine the correlation between the use of traditional fuels, such as firewood gathered from local forests, and socio-economic status, considering the availability of land use factors like vegetation, forests, and agricultural land. This objective aims to understand how access to traditional fuel sources is influenced by land use and how these sources, in turn, reflect and impact socio-economic conditions.

Satellite Data

The present study involved the processing and analysis of a Sentinel-2A image acquired on 14th April 2023 at 11:54 a.m. UTC, as indicated in Supplementary Table 1. The imagery was obtained from the Copernicus open access hub (https://scihub.copernicus.eu/), a platform that offers unrestricted open access to the user products of Sentinel-2 Level-1C (L_1C). L_1C products, alternatively referred to as tiles, encompass spatially referenced images spanning an area of 100 square kilometers. These images are projected in the Universal Transverse Mercator (UTM)/ World Geodetic System 1984 projection-the tile designated as S2A_MSIL2A_20230414T043701_N0509_R033_T45QWG_20230414T081154.SAFE (Supplementary Table 1) was selected for subsequent analysis due to its inclusion in our designated study site. Moreover, to identify the land use pattern in the study area, bands with 10-meter resolution have been selected, namely Band-2, Band-3, Band-4, and Band-8 (Supplementary Table 1). Using a data management tool, all four bands have been composited in an Arc GIS environment (evaluation copy). The maximum likelihood classification method was applied to get the final output of the map. Five classes have been identified in the LULC map: water bodies, cultivated land, current fallow, built up and vegetation cover.

RESULTS AND DISCUSSION

Socio-Economic Condition and Fuel Use

In India, rural households mainly depend on solid biomass fuel for their daily cooking needs, which is the source of HAP in the indoor environment, leading to severe health and environmental hazards. In contrast, biogas will be an alternative solution for climate change, energy crises, and to fulfill the increased energy demand due to population growth. Moreover, in recent decades, due to increased price hikes of LPG, which is a financial burden for rural households where LPG is used as a secondary energy option. The majority of the households in rural areas in India still rely on solid fuel. Several factors are associated with the choice of clean cooking fuel, and only 0.4% of households used biogas as primary cooking fuel in India (Rajendran et al. 2012). In rural India, there are various types of biogas digesters, with most rural households using fixed dome biogas digesters. The Deenbandhu model, developed in 1984 by a voluntary organization, Action for Food Production, is a popular biogas digester among families due to its family-friendly design with various capacity options (Meena et al. 2024). Over time, KVIC has been actively promoting the Deenbandhu model as a biogas plant in rural areas of India, specifically at the community level (Singh et al. 2023). All the biogas plants in the study are fixed dome Deenbandhu model digesters with a capacity of 2 cubic meters. KVIC installed these digesters between 1994 and 1997. It is possible to generate one cubic meter of biogas per day, which is enough to meet the daily cooking energy needs of a family of 4-5 members (Aryal et al. 2022).

The socio-demographic characteristics of the village are provided in the Supplementary Table 1. The dominant economic status of the village (75%) households belongs to the lower-income group and the lower-middle-income group. The households mainly engaged in daily wage earners account for almost 55.5%, and a few households are engaged in the service sector (8%). The rest of the households engaged themselves in small businesses and other similar low-cost work. Hence, more than 66% of household heads were illiterate, and 76% of the household heads were male. In the village, most of the households are *pucca* (made up of brick and concreted roofs), and semi-*pucca* (made up of brick walls and asbestos or tin roofs) comprise almost 43%, and the rest of the households are *Kuccha* structures made by mud and thatched roofs (57%). Moreover, the village is covered by natural resources like trees, ponds, and agricultural land, but in the village, 38% of households are landless. The villagers belong to different social groups, i.e., General caste, Scheduled Caste (SC), and Scheduled Tribe (ST).

One of the key determinants of biogas as a primary fuel choice is the socio-economic conditions. In Table 1, chi-square statistics reveal the different cooking fuel types available based on the demographic characteristics of rural households. The present work discusses eight major socio-demographic characteristics that influence the choice of cooking fuel in rural households, such as social category, household head, age, gender, education, housing patterns, occupational structure, and income groups. In the study area, 68.21% of households use firewood as their main cooking fuel source, and only a very small percentage (4.62%) of households use biogas as a source of cooking fuel, while others use cow dung cake and charcoal cake (27.17%). In contrast, LPG is used as an optional or secondary option with other energy sources. Most significantly, people were still using conventional fuel (95.38%), and only 4.62% of households used biogas as a primary fuel. There is a significant relationship between access to cooking fuel types and the social groups of rural households, as measured by the chi-square statistic ($\chi^2 = 31.594$, $P < 0.01$). The results indicate that households from the general castes have the highest accessibility of biogas as a clean cooking fuel (17.95%), whereas only 1.52% of households access biogas. More interestingly, ST households do not use biogas as fuel. This is observed due to the caste inequality and lower economic status still considered major hindrances to adopting biogas energy that prevails in rural Indian society (Bagdi et al. 2022, Soni & Chatterjee 2023). However, most households in the study areas are still structured as *Kuccha* households (57%), which has significant relationship between housing pattern and access to cooking fuel ($\chi^2 = 28.241$, $P < 0.01$) was observed with the majority of *Kuccha* households using firewood (79.80%), while Pucca households' people still using biogas as their primary cooking fuel. Similar observations were reported by Baqir et al. (2019), Afridi et al. (2023), and Kalli et al. (2022), who found that most of the *Kuccha* households primarily depend on traditional fuelwood for their daily energy requirement. Some studies indicate that household structure influences the adoption of biogas technology (Yasmin & Grundmann 2019).

The household occupations are in the service sector (21.43%), and gardeners (52.94%) consume less firewood than those engaged in manual labour, driving, maid service, and small business. Households in the services category find it easier to afford cattle maintenance costs. However, livestock, particularly cattle, play an essential role in the livelihoods of rural populations, especially in developing countries. As a result, they often use cow dung cakes mixed with firewood as a substitute for cooking fuel. The findings indicate a strong association between cooking fuel types and the occupational structure of the village ($\chi2 = 39.260$, $P < 0.01$). The chi-square test results ($\chi2 = 45.779$, $P < 0.01$) reveal a significant relationship between income and access to cooking fuel. It was demonstrated that higher-income people had greater access to biogas as a clean and sustainable energy source. This suggests that higher-income households have a greater possibility of getting access to clean cooking

Table 1: Cooking energy using patterns among rural households by socio-demographic characteristics.

	Firewood	Cow dung cake	Charcoal cake	Biogas	Total	χ2
Occupational structure						**39.260*****
Daily wage earner	78.13	16.67	2.08	3.13	55.49	
Driver	84.62	15.38	0.00	0.00	7.51	
Gardener	52.94	23.53	23.23	0.00	9.83	
Maid	75.00	0.00	25.00	0.00	4.62	
Service	21.43	35.71	28.57	14.29	8.09	
Small business	56.00	16.00	16.00	12.00	14.45	
Social groups						**31.594*****
General caste	48.72	23.08	10.26	17.95	22.54	
Scheduled Caste (SC)	62.12	24.24	12.12	1.52	38.15	
Scheduled Tribe (ST)	85.29	8.82	5.88	0.00	39.31	
Housing pattern						**28.241*****
Kuccha	79.80	12.12	4.04	4.04	57.23	
Pucca	53.13	28.13	6.25	12.50	18.50	
Mixed	52.38	23.81	23.81	0.00	24.28	
Income Groups						**45.779*****
Lower Income Group	91.78	2.74	2.74	2.74	42.20	
Lower Middle-Income Group	55.93	30.51	10.17	3.39	34.10	
Upper Middle-Income Group	50.00	35.00	10.00	5.00	11.56	
Higher Income Group	38.10	19.05	28.57	14.29	12.14	
Education level						**66.570*****
Illiterate	81.74	13.91	3.48	0.87	66.47	
Primary level	56.67	26.67	13.33	3.33	17.34	
Secondary level	38.89	27.78	22.22	11.11	10.40	
Higher secondary level	0.00	20.00	40.00	40.00	5.78	
Household's Head Age						**17.199*****
Below 30	62.50	22.50	15.00	0.00	23.12	
30 years – below 60 years	73.86	19.32	4.55	2.27	50.87	
60 years and above	62.22	11.11	13.33	13.33	26.01	
Household's kitchen pattern						**13. 5*****
Kuchcha	74.02	16.54	7.87	1.57	26.58	
Pucca	52.17	21.74	13.04	13.04	73.42	
Household's agricultural land						**14.222*****
Agriculture landless	59.09	28.79	12.12	0.00	38.15	
Agriculture landowner	73.83	11.21	7.48	7.48	61.85	
Total households	68.21	17.92	9.25	4.62		

Source: author's calculation from household survey (percentage)

Significance level: *** $p < 0.01$, **$p < 0.05$,

fuels like biogas than lower-income households. Multiple studies concluded that households with higher incomes are more likely to switch and adopt biogas as a greener energy source than households with lower incomes (Ghosh et al. 2020). It also demonstrates that the tendency of changing patterns towards biogas adoption is highly related to household income level, which decreases firewood use and shifts towards renewable energy resources or clean energy.

Moreover, the level of education of the households is one of the significant factors for the adoption and access to clean fuel. The results also demonstrate a significant relationship between the education level of the Head of household and access to clean cooking energy ($\chi2 = 66.570, P < 0.01$). This indicates that increasing education levels will significantly impact access to clean cooking energy. Although the analysis indicates a significant relationship between the age of the household head and access to cooking fuels in rural households, as measured by the chi-square statistic ($\chi2 = 17.199, P < 0.01$). It implies that the choice of clean cooking fuel increases with the household member's age due to concern about the family benefits of clean energy over traditional energy, where HAP is one of the major issues. The majority of the households have a *kuchcha* kitchen structure (73.42%), which is mainly made of bamboo and mud-made walls with roofs covered by rice straw, while *pucca* kitchens are made of bricks with concrete roofs, mainly inside the main building. The study found there is a strong association ($\chi2 = 13.5, P < 0.01$) between kitchen structure with fuel use. The pattern found that biomass user households generally used the *kuchcha* pattern.

In contrast, biogas user groups mainly used a *pucca* structure. This might be due to their lower economic status and lack of proper knowledge about the effects of indoor air pollution. Finally, the result found a significant association between access to cooking fuel types and the availability of agricultural land, as measured by the chi-square statistic ($\chi2 = 14.222, P < 0.01$). This implies households with agricultural land are interested in clean energy, particularly biogas, as they can use the bio-slurry as an organic fertilizer for their agricultural land and clean cooking fuel. The fertilizer that the biogas plant produces can replace 15-20% of chemical fertilizer with organic fertilizer, which will sustain agricultural productivity (Show et al. 2023, Karmakar et al. 2024, Koley et al. 2024a). Therefore, households with biogas plants profit more by utilizing biogas as cooking energy and bio-slurry as fertilizer. Numerous studies proposed that a household biogas plant benefits from all aspects of household needs and is also environmentally friendly (Sarker et al. 2020, Singh & Kalamdad 2021).

Indoor Air Quality and Health Risk Assessment

Status of indoor particulate matter ($PM_{2.5}$) and carbon monoxide (CO) concentration: The concentrations of PM2.5 and CO are presented in Table 2. The inhalation of exceeded mass concentrations of particulate matter (PM) (Chakraborty & Mondal 2021) and gaseous pollutants (Basu et al. 2024) compared to WHO-prescribed indoor air quality standards is responsible for both chronic and acute health effects. The degree of exposure and health risk in rural women increases, particularly those who have used biomass fuel as a cooking fuel for a long duration of time, due to inhalation of PM (PM10, PM2.5) and gaseous pollutants, a byproduct of biomass burning. Previous studies show that PM2.5 penetrates deep into the alveolar area while PM2.5-10 mainly accumulates in the tracheobronchial airways in the human respiratory system (Schroeter et al. 2006). Hypoxia affects organs with higher oxygen use, including the developing fetus (Hutter & Jaeggi 2010). In the present study, the PM2.5 concentration was observed to be highest for coal cake (293.53 ± 11.75 µg.m-3), followed by cow dung (205.83 ± 9.47 µg.m-3) > wood (185.06 ± 6.45 µg.m-3) > biogas (1.11 ± 0.16 µg.m-3). The ANOVA analysis also showed a significant ($p < 0.001$) difference in PM2.5 concentrations among different fuel user groups. The same trend in the output of ANOVA analysis was also observed for carbon monoxide (CO). However, the highest concentrations were monitored for cow dung users (6.46 ± 0.28 ppm), followed by coal cake (4.79 ± 0.21 ppm) > wood (4.48 ± 0.21 ppm) > biogas (0.01 ± 0.01 ppm) (Table 2). The result of the present study shows that biogas has significantly lower emissions for both PM2.5 and CO, which may be a positive aspect for efficient fuel use for rural and urban households.

Health risk assessment from indoor particulate matter ($PM_{2.5}$): The present study results of PM2.5 exposure index and intake concentration (Table 3) were observed almost 170-274 times and 167- 268 times higher than the biogas users. The median exposure index calculated for wood, cow dung, coal cake, and biogas were 2.05, 2.26, 3.29 and 0.012, respectively. At the same time, median intake concentrations were 118.71, 132.2, 190.07 and 0.707, respectively. A higher level of PM2.5 in traditional cookstoves is possibly due to inefficient biomass combustion in poorly designed traditional stoves. The PM emission from traditional biomass cookstoves is well-documented (Mitra et al. 2023). A meta-analysis was conducted by Atkinson et al. (2014), who highlighted that every 10 µg.m-3 increase of PM2.5 leads to a 1% increase in hospital admission. The hazardous quotient was calculated for PM2.5 exposure via the inhalation route, and the results demonstrated that it exceeded greater than one for every traditional fuel except biogas. The representable HQ values were 7.91, 8.81, 12.67 and 0.047 for wood, cow dung, coal cake and biogas, respectively (Table 3). An elevated hazard

Table 2: The concentration of $PM_{2.5}$ ($\mu g.m^{-3}$) and CO (ppm) from different fuel burning.

Pollutant	Wood	Cow Dung	Coal Cake	Biogas	F value	*P* value
$PM_{2.5}$	185.06 ± 6.45	205.83 ± 9.47	293.53 ± 11.75	1.11 ± 0.16	3363.59 (R-Sq = 99.45%)	< 0.001
CO	4.48 ± 0.21	6.46 ± 0.28	4.79 ± 0.21	0.01 ± 0.01	2682.43 (R-Sq = 99.31%)	< 0.001

Table 3: Exposure Index, Intake Concentration, and Toxicological Risk from $PM_{2.5}$ concentration among different fuel user groups.

	Wood	Cow Dung	Coal Cake	Biogas
Exposure Index (EI)				
Median	2.05	2.26	3.29	0.012
1st quartile	2.02	2.26	3.19	0.012
3rd quartile	2.08	2.33	3.36	0.013
Intake concentration (IC)				
Median	118.71	132.2	190.07	0.707
1st quartile	117.08	131.01	184.93	0.707
3rd quartile	120.36	134.81	194.14	0.771
Hazard Quotient (HQ)				
Median	7.91	8.81	12.67	0.047
1st quartile	7.81	8.73	12.33	0.047
3rd quartile	8.02	8.99	12.94	0.051

quotient level for biomass users may be due to the excessive deposition of particles in the respiratory tract (Chalvatzaki et al. 2019). Thus, a higher intake of PM2.5 can induce the early symptoms of cardiovascular diseases (Mitra et al. 2022).

Status of indoor particulate matter ($PM_{2.5}$) and carbon monoxide (CO) concentration: Blood carboxyhemoglobin percentage (COHb%) may be used to estimate the amount of carbon monoxide present in a person's body. According to the Commission of the European Communities' research in 1991, myocardial infarction (MI) could have been linked to greater levels of carbon monoxide inhalation. According to earlier clinical studies, blood COHb concentrations above the 3% threshold can cause carbon monoxide poisoning, which can eventually be lethal (ATSDR 2009). The blood COHb% was recorded highest for cow dung cake users (0.39 ± 0.02%), followed by Coal cake (0.28 ± 0.02%) > Wood (0.25 ± 0.02%) and least for biogas users (0.008 ± 0.01%). The COHb% values showed a significant ($p < 0.001$) difference among the biogas and other fuel user groups (Table 4). Chakraborty and Mondal (2021) found comparable calculated blood COHb% results across regular cooks who were using biomass cooking fuel. Thom (2008) states that blood COHb% varies from 0.2% to 0.85% in non-smokers and is elevated in smokers (10%) and heavy smokers (4%). Mitra et al. (2022) discovered comparable research findings and health consequences of CO when they evaluated the physical condition of women from the same region who were exposed to wood smoke.

Concentration of indoor Nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) and Health risk assessment: The concentrations of NO2 emitted from different fuel burning were used to calculate HQ (Table 5). The HQ calculated for acute and chronic exposures showed no immediate and prolonged adverse health effects for women (HQ < 1.0). However, cooking with biomass fuels may show some long-term chronic health risks, as evidenced by our analysis. The highest mean NO2 concentration was found for coal (1.42 ± 0.16 µg.m-3), followed by cow dung (1.31 ± 0.15 µg.m-3) > wood (1.20 ± 0.12 µg.m-3) > biogas (1.13 ± 0.04 µg.m-3). The NO_2 concentration showed a significant ($p < 0.001$) difference among the biogas and other fuel user groups except wood fuel. Present risk evaluation found that acute exposure to indoor NO2 posed a minimal risk. Recent research, however, has indicated that modest amounts of NO2 exposure can cause acute and obstructive lung illnesses. Some investigations also discovered a link between NO2 levels and acute ischemic stroke. However, several research studies have found no statistically significant links between NO2 exposure and human health (Andersen et al. 2012, Chen et al. 2012).

Table 4: Percentage of blood Carboxyhemoglobin (COHb) of different fuel user groups.

Stove categories	Mean ± SD	t value	CI (95%)	*p*-value
Wood	0.25 ± 0.02	41.35	0.23, 0.26	< 0.001
Cow Dung Cake	0.39 ± 0.02	74.11	0.37, 0.39	< 0.001
Coal Cake	0.28 ± 0.02	85.97	0.26, 0.28	< 0.001
Biogas	0.008 ± 0.01			

This study is 1st of its kind, which seeks to explore the health risk assessment from SO_2 concentration from burning biomass and biogas fuels in the indoor microenvironment. The concentrations of SO_2 emitted from different fuel burning were used to calculate HQ (Table 6). The HQ calculated for acute and chronic exposures showed no immediate and prolonged adverse health effects for women (HQ < 1.0). The highest means SO_2 concentration was found for coal (0.055 ± 0.008 $\mu g.m^{-3}$), followed by wood (0.015 ± 0.004 $\mu g.m^{-3}$) > cow dung (0.008 ± 0.002 $\mu g.m^{-3}$) > and biogas (0.002 ± 0.001 $\mu g.m^{-3}$). The SO_2 concentration showed a significant ($p < 0.001$) difference among the biogas and other fuel user groups. Chakraborty et al. (2014), as well as Mondal and Chakraborty (2015), also observed similar results. In contrast to biomass, many coals include

Table 5: Hazard quotients for acute and chronic exposure health risk from nitrogen dioxide (NO_2, $\mu g.m^{-3}$) among different fuel user groups.

Fuel types	Mean ± SD	Acute HQ	Chronic HQ	*p*-value
Wood	1.20 ± 0.12	1.05×10^{-3}	4.64×10^{-2}	< 0.073
Cow dung	1.31 ± 0.15	1.15×10^{-3}	5.09×10^{-2}	< 0.001
Coal	1.42 ± 0.16	1.24×10^{-3}	5.51×10^{-2}	< 0.001
Biogas	1.13 ± 0.04	9.88×10^{-4}	4.38×10^{-2}	

Table 6: Hazard quotients for acute and chronic exposure health risk from Sulphur dioxide (SO_2, μg.m^{-3}) among different fuel user groups.

	Mean ± SD	Acute HQ	Chronic HQ	*p*-value
Wood	0.015 ± 0.004	8.20×10^{-6}	3.63×10^{-4}	< 0.001
Cow dung	0.008 ± 0.002	4.29×10^{-6}	1.90×10^{-4}	< 0.001
Coal	0.055 ± 0.008	3.01×10^{-5}	1.33×10^{-3}	< 0.001
Biogas	0.002 ± 0.001	1.02×10^{-6}	4.51×10^{-5}	

inherent pollutants such as lead, mercury, silica, fluorine, sulfur, and arsenic. These pollutants are not eliminated by combustion; they are discharged into the atmosphere in their unaltered or oxidized state. For instance, sulfur dioxide (SO_2) pollution has a local or regional impact on outdoor and interior air quality in homes that burn sulfur-rich coal since coal burns at a significantly higher temperature than biomass combustion, which produces more NO_2 emissions than biomass combustion (Zhang et al. 2000).

Health risk assessment and Monte-Carlo probabilistic simulation: There is always a chance of having uncertainties in health risk estimation. The uncertainty may be present among the concentrations of pollutants, variables used for risk estimation, and/or other environmental factors. The median value of H.Q for wood PM2.5 was found 5.10 with a certainty range from 4.13 to 6.28 at a 95% level of confidence interval during the use of biomass cookstove (Fig. 2A). Whereas the median value of HQ for cow dung PM2.5 was observed at 5.67 with a certainty range from 4.53 to 7.04 at a 95% level of confidence interval in case of biomass users (Fig. 2B). However, the highest median value of HQ for coal cake PM2.5 was found 8.08 with a certainty range from 6.54 to 10.00 at a 95% level of confidence interval during the use of traditional coal cookstove (Fig. 2C) and the median value of HQ for biogas PM2.5 was found 0.03 with a certainty range from 0.02 to 0.04 at a 95% level of confidence interval during the use of biogas cookstove (Fig. 2D). Monte-Carlo sensitivity analysis has revealed exposure time and exposure duration were the two most important factors to represents in the health risk estimation for wood, cow dung and coal cake users, however, for biogas users PM2.5 showed the highest contribution (Fig. 3A-3D). The above results may be due to high or low ventilation present in the particular households. The present study has observed that traditional cookstove users are more prone to non-carcinogenic health risks, whereas biogas represents a clean and safer cooking fuel.

The study's major contribution is the incorporation of self-reported health-related data related to household air pollution across various user groups, along with a comparative analysis of biogas user groups. Presently, due to energy shortages and environmental protection, biogas is an alternative solution to mitigate these upcoming threats. However, the study design has some limitations, such as the smaller sample size of biogas users compared to solid fuel user groups. The study only focused on a single village; it could be conducted in different parts of the location with regional variation. Thus, further study will provide more significant results. The study does not include other relevant socio-economic factors such as religion, livestock, gender,

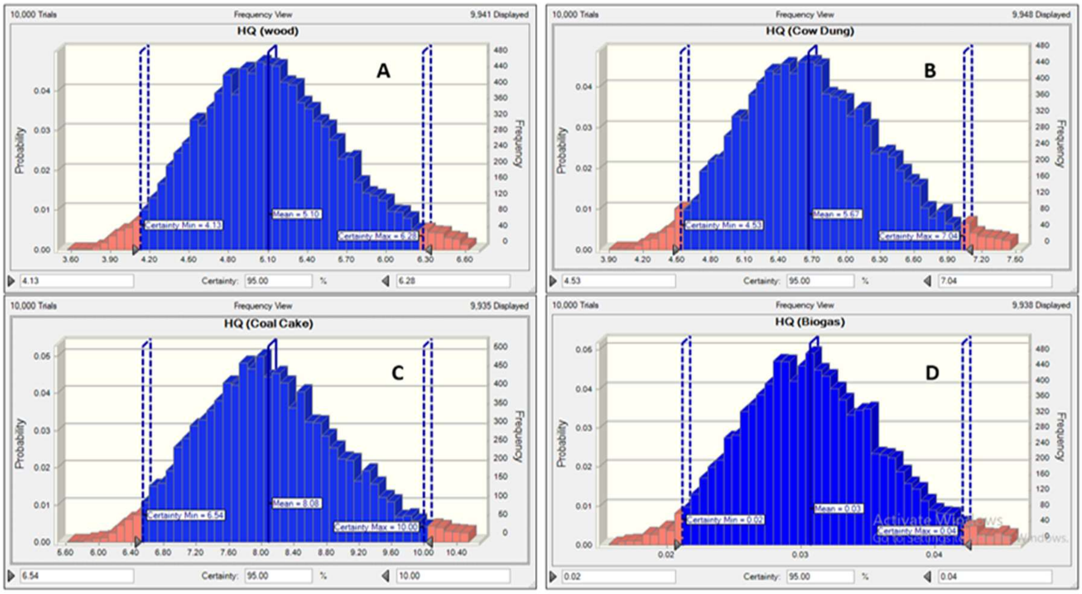


Fig. 2: Monte-Carlo probabilistic distribution of the Hazard Quotient (HQ) for wood $PM_{2.5}$ (A), for cow dung $PM_{2.5}$ (B), for coal cake $PM_{2.5}$ (C) during the use of a traditional biomass cookstove and for biogas $PM_{2.5}$ during the use of a biogas cookstove (D).

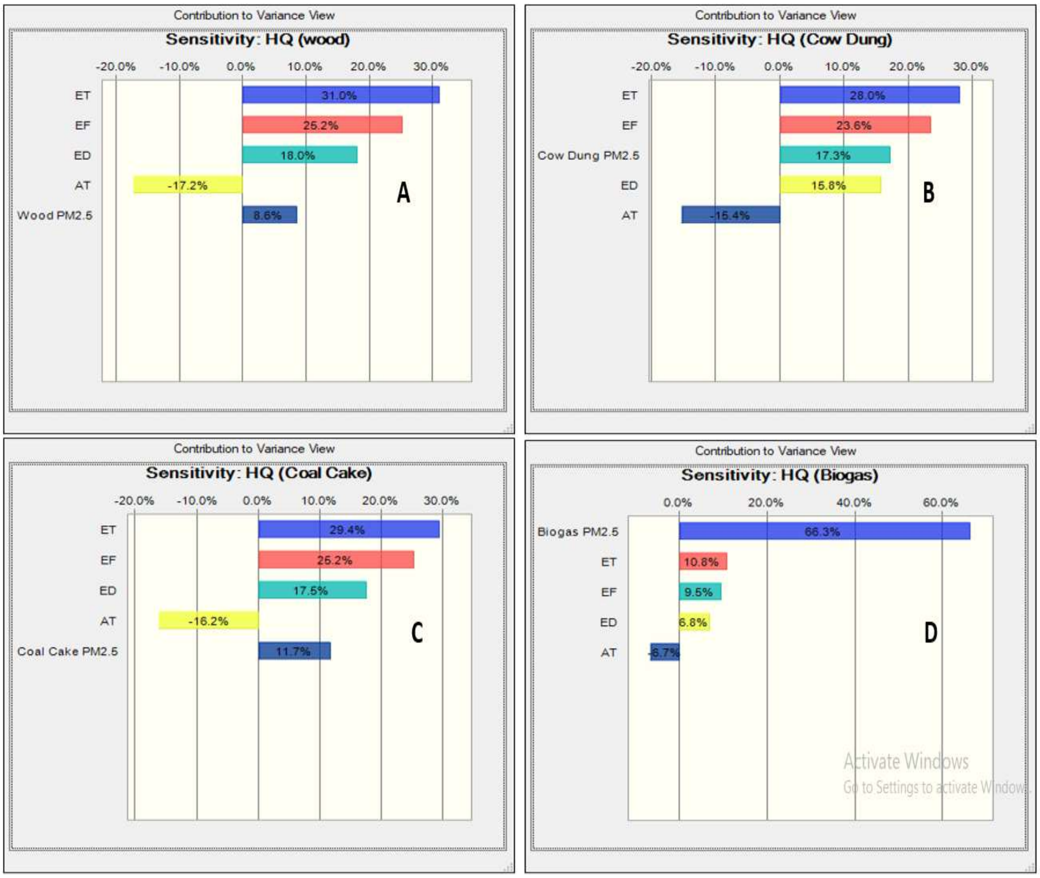


Fig. 3: Sensitivity factors after running Monte-Carlo probabilistic distribution of the Hazard Quotient (HQ) for wood users (A), for cow dung users (B), for coal cake users (C), and for biogas (D) users.

food habits, and household size. Future studies might carefully address other unmeasured pollutants like PAHs and benzene, along with other health-related parameters like BMI status, nutritional status, blood pressure, and heart rate.

Self-reported Symptoms of Health-Related Issues Among Different Fuel User Groups

Table 7 presents the self-reported health problems faced by households with different fuel user groups. Table 7 reveals that solid fuel biomass user groups primarily experience eye irritation, breathlessness, wheezing cough, and muscle pain; conversely, only a small proportion of biogas users experience headache, sneezing, chest pain, and arthritis. The current study emphasized that muscle pain is a significant issue for fuelwood users, particularly women who handle loads of firewood exceeding 20 kg for extended periods. This issue affects 17% of women who use solid fuel, excluding those who use biogas.

According to the women's self-reported health problems, firewood users reported the highest percentage of headaches (50%) among the different fuel types. In comparison, biogas users had a significantly lower incidence (11.8%), with 18 individuals (10.4%) overall reporting headaches across all fuel types. Eye irritation was most common among firewood users (70%), with no cases reported among biogas users, indicating a strong association between traditional biomass fuels and eye irritation, as 20 individuals (11.6%) reported this symptom. Breathlessness was reported by 61.5% of firewood users and 26.9% of cow dung cake users, with no cases among biogas users, suggesting a health benefit of biogas use by 26 individuals (15%) who reported breathlessness. Cough was also most prevalent among firewood users (79.2%), with no cases among biogas users, contributing to the 24 individuals (13.9%) who reported this condition. Chest pain was reported by 61.1% of firewood users, with the lowest incidence among biogas users (5.6%), making up 18 cases (10.4%) overall. Muscle pain was highly prevalent among firewood users (77.4%) and absent among biogas users, with 31 individuals (17.9%) reporting this symptom. Sneezing was reported by 70.6% of firewood

Table 7: Classification of self-reported health status symptoms among different biomass user and biogas user groups.

Types	Firewood	Cow dung cake	Coal cake	Biogas	Total
Headache	50.0 (9)	16.7 (3)	22.2 (4)	11.8 (2)	10.4 (18)
Eye Irritation	70.0 (14)	20.0 (4)	10.0 (2)	0.0 (0)	11.6 (20)
Breathlessness	61.5 (16)	26.9 (7)	11.5 (3)	0.0 (0)	15 (26)
Cough	79.2 (19)	16.7 (4)	4.2 (1)	0.0 (0)	13.9 (24)
Chest pain	61.1 (11)	22.2 (4)	11.1 (2)	5.6 (1)	10.4 (18)
Muscle pain	77.4 (24)	12.9 (4)	9.7 (3)	0.0 (0)	17.9 (31)
Sneezing	70.6 (12)	11.8 (2)	11.8 (2)	5.9 (1)	9.8 (17)
Arthritis	68.4 (13)	15.8 (3)	10.5 (2)	5.3 (1)	11 (19)

users (12 individuals) and less frequently by biogas users (5.6%), with a total of 17 cases (9.8%). Lastly, arthritis was reported by 68.4% of firewood users, contributing to the 19 cases (11%) overall.

Matinga & Clancy (2020), as well as Koyuncu et al. (2021), observed that women were burdened with a significant burden of muscle pain and back pain. Women who use solid fuel primarily report eye irritation issues. This is possible due to the absence of proper ventilation and smoke generation from the burning of solid fuel biomass, which will sometimes enhance the risk of cataracts. A recent study by Kumar et al. (2023) and Mandell et al. (2020) highlighted that cataracts are common among solid fuel biomass user women in China. The issue doesn't impact biogas user groups because they burn biogas fuel without emitting smoke. Arthritis, also commonly known as joint pain symptoms, was highly preventable among solid fuel user groups. Liu et al. (2022) highlighted that exposure to $PM_{2.5}$ increases the risk of arthritis among solid fuel biomass user groups. The questionnaire-based survey results revealed that solid fuel user groups experience more common respiratory issues, such as whooping cough, breathlessness, and sneezing.

In contrast, only a few biogas user women reported experiencing sneezing problems. This observation aligns with a previous study, which found that upper and lower respiratory systems affect 50.9% and 70.9% of premenopausal biomass-using women in India, respectively. Similarly, Wang et al. (2023) found a significant correlation between exposure to $PM_{2.5}$ and respiratory infection due to the air pollutant. Similarly, Pathak et al. (2020) found a higher prevalence of respiratory symptoms among biomass user groups compared to clean fuel user groups. The study demonstrates a correlation between biomass exposure and an elevated risk of respiratory system issues. Therefore, the current study indicates that households using solid fuels experience more health-related issues than those receiving biogas.

Health Risk and Socioeconomic Condition

Socioeconomic conditions severely influence the health risks associated with traditional fuel use in rural areas. Traditional fuels like firewood, cow dung cake, and coal cake are prevalent in lower-income households due to their affordability and accessibility, but they pose significant health risks. These fuels emit high levels of particulate matter ($PM_{2.5}$) and carbon monoxide (CO), which are linked to severe respiratory and cardiovascular diseases. For instance, the exposure to $PM_{2.5}$ in households using these fuels is drastically higher compared to those using biogas, leading to increased incidences of chronic health conditions.

The reliance on traditional fuels is often a result of socioeconomic factors such as income, education, and social status. In rural communities, where a large proportion of households fall into lower-income groups and depend on daily wage labour, the financial burden of cleaner fuels is often too high. Moreover, households from marginalized social groups, such as SC and ST, and those living in *kuccha* (mud) houses are more likely to use traditional biomass fuels. These groups often lack access to information about the health benefits of cleaner fuels and the economic resources needed to adopt them. Conversely, higher-income households, those with better education, and those living in pucca (brick) houses are more likely to use biogas, which significantly reduces health risks by emitting negligible amounts of harmful pollutants. However, despite the health and economic benefits of biogas, its adoption remains low in many rural areas due to persistent socioeconomic barriers.

Dependency on Traditional Fuels

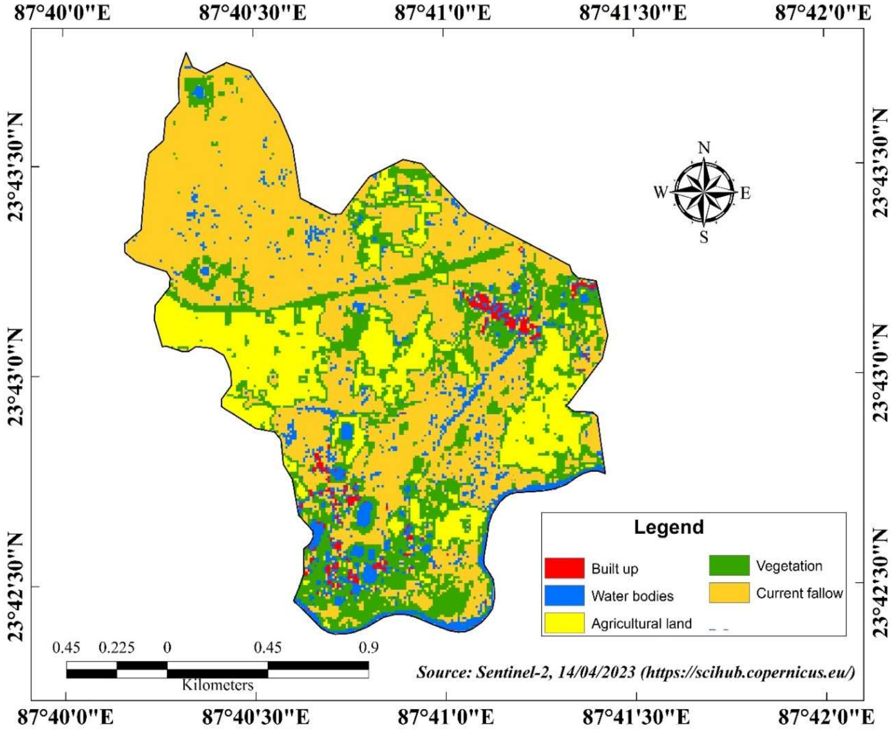
In rural India, women still rely on biomass fuels like firewood, manure, and agricultural residues, even though biogas is a more sustainable and eco-friendly energy source. Rural women face many challenges when implementing biogas, including a reduced reliance on male household members for labor-intensive cooking fuel collection, which is often seen as an integral part of their domestic responsibilities. Cultural preferences, like as the taste of meals prepared over an open fire or firewood, are sometimes the cause of resistance to the adoption of biogas. Although biogas facilities need a large initial investment and continuous maintenance, financial restrictions are also a major factor. Furthermore, biomass is a reliable and readily stored energy source that ensures fuel security for rural women in areas where firewood is easily accessible.

In the study area, Sehalai village exhibits a dispersed settlement pattern (Fig. 4), with sample households covering an area of about 0.0494 km². The findings reveal evident spatial segregation of social groups, with the ST population located in a specific northern settlement. In contrast, SC and general caste households are situated in closer proximity to other groups. The village consists of 0.227 km² of waterbodies, which include ponds and canals, while a river flows through its southern area, providing sufficient water resources for agricultural activities. The area covered by homestead trees and woodlands is 0.6749 km², whereas the estimated cultivable land area is 2.0316 km². The presence of these natural resources plays an essential role in shaping household energy decisions, as the accessibility of firewood supports the practice of fuel stacking. Women, who predominantly control cooking responsibilities, rely upon readily available biomass resources because alternative energy sources are often too expensive or scarce, thus continuing the reliance on traditional fuels.

In addition, the production of biogas frequently exhibits variability, especially during periods of limited feedstock supply or colder temperatures, causing households to shift back to biomass fuels to meet their energy requirements. Moreover, women residing in rural regions frequently encounter constraints in their decision-making control, especially when it comes to financial investments in clean cooking technologies. The transition to biogas is further hindered by a lack of awareness regarding the health benefits of cleaner fuels, alongside insufficient understanding of the health risks linked to biomass combustion, which include cough, eye irritation, and respiratory illnesses.

Policy Recommendations

To effectively involve the community in the implementation and upkeep of the biogas adoption, particularly in rural areas, by increasing awareness of the advantages of biogas, focusing on the effects on the environment and human health. To encourage government organizations, community-based organizations, non-governmental organizations, and other stakeholders to take effective actions to implement biogas-related schemes and policies.



Source: Sentinel-2, 14/04/2023 (https://scihub.copernicus.eu/)

Fig. 4: Land Use Pattern of the North and South Sehalai village.

Implementing biogas schemes in collaboration with income and employment-generating government programs, such as the Mahatma Gandhi National Rural Employment Guarantee Act, will have a more direct impact on the community. This will lead to reduced dependence on traditional cooking fuels. Even though there were subsidies for India's SC and ST population, they still had less biogas adoption due to a lack of subsidies, so the government focused more on subsidizing marginalized and disadvantaged groups, especially the women members of economically and socially weaker sections of society.

CONCLUSIONS

The present study results revealed that rural households using traditional fuel showed a higher risk of health hazards directly and indirectly, particularly for women, due to the generation of household air pollution. Biogas is one of the feasible solutions to reduce HAP concentration, workload, health risks, and environmental threats by replacing traditional fuels. The present study found that biogas has emerged as a less polluting energy source (in terms of particulate matter and gaseous pollutants emission) than other traditional cooking energy sources. However, most of the population used it due to its easy availability and low cost. Moreover, factors such as income, age, education, occupation and social categories may play a significant role in choosing biogas as their primary energy source. Moreover, the highest biomass smoke user groups observed increased muscle pain, eye irritation, cough and breathlessness when compared to biogas users. However, due to a lack of awareness about the technology used, rural people are still not ready to accept the biogas fuel, although it has great potential. Though the Government of India promote several schemes related to installing family-type biogas plants by MNRE in rural households, several drawbacks (e.g. technological barriers, fuel stacking, lack of supply chain and network system, unavailability of trained professional and awareness among SC and ST people) of the schemes which are required to take into consideration for policy formulation to achieve UN-SDG by 2030. The Government of India should facilitate proper initiatives to implement the schemes regarding the biogas plant at the household level to increase biogas adoption. The study mainly focuses on the women user group, while for future studies, a comparative study with health status in men among marginalized groups is needed. The perceptual barriers to biogas adoption and certain health indicators like heart rate, blood pressure, and body mass index are not well covered in this study. Future studies should examine long-term advantages, include scientific evaluations of health effects, and concentrate on sociocultural elements impacting the use of biogas. Research on gender dynamics, the efficacy of policies, and supply chain constraints is required, as are comparisons with other clean energy sources. Furthermore, evaluating the advantages of biogas adoption on the environment and climate could help shape sustainable energy legislation.

ACKNOWLEDGEMENTS

Tapas Bagdi, Apurba Koley and Sreya Ghosh are thankful to the BBSRC, United Kingdom, for receiving funding from the BEFWAM project: Bioenergy, Fertilizer and Clean water from Invasive Aquatic macrophytes [Grant Ref: BB/S011439/1] for financial support and research fellowship.

REFERENCES

Afridi, F., Debnath, S., Dinkelman, T. and Sareen, K., 2023. Time for clean energy? Cleaner fuels and women's time in home production. *The World Bank Economic Review*, 37(2), pp.283–304. [DOI].

Aggarwal, R.K., Chandel, S.S., Yadav, P. and Khosla, A., 2021. Perspective of new innovative biogas technology policy implementation for sustainable development in India. *Energy Policy*, 159, 112666. [DOI].

Amegah, A.K., Quansah, R. and Jaakkola, J.J.K., 2014. Household air pollution from solid fuel use and risk of adverse pregnancy outcomes: A systematic review and meta-analysis of the empirical evidence. *PLOS ONE*, 9(12), e113920. [DOI].

Anderman, T.L., DeFries, R.S., Wood, S.A., Remans, R., Ahuja, R. and Ulla, S.E., 2015. Biogas cook stoves for healthy and sustainable diets? A case study in southern India. *Frontiers in Nutrition*, 2, 28. [DOI].

Andersen, Z.J., Raaschou-Nielsen, O., Ketzel, M., Jensen, S.S., Hvidberg, M., Loft, S., Tjønneland, A., Overvad, K. and Sørensen, M., 2012. Diabetes incidence and long-term exposure to air pollution: A cohort study. *Diabetes Care*, 35(1), pp.92–98. [DOI].

Aryal, J.P., Chhay, P. and Sonobe, T., 2022. Ethnicity/caste-based social differentiation and the consumption of clean cooking energy in Nepal: An exploration using panel data. *Energy Economics*, 112, 106080. [DOI].

Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C. and Walton, H.A., 2014. Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: A systematic review and meta-analysis. *Thorax*, 69(7), pp.660–665. [DOI].

ATSDR (Agency for Toxic Substances and Disease Registry), 2009. *Toxicological profile for carbon monoxide*. Atlanta, Georgia: U.S. Department of Health and Human Services, Public Health Service. Available at: https://www.atsdr.cdc.gov/toxprofiles/tp201.pdf [Accessed 14 August 2025].

Bagdi, T., Ghosh, S., Sarkar, A., Hazra, A.K., Balachandran, S. and Chaudhury, S., 2022. Whose development counts? Adoption of biogas in the rural communities of India review. *International Journal of Renewable Energy Research*, 12(4), pp.2023-2042. [DOI]

Bagdi, T., Ghosh, S., Sarkar, A., Hazra, A.K., Balachandran, S. and Chaudhury, S., 2023. Evaluation of research progress and trends on gender and renewable energy: A bibliometric analysis. *Journal of Cleaner Production*, 712, p.138654. [DOI]

Baqir, M., Bharti, S.K., Kothari, R. and Singh, R.P., 2019. Assessment of an energy-efficient metal chulha for solid bio-mass fuel and evaluation of its performance. *International Journal of Environmental Science and Technology*, 16(11), pp.6773–6784. [DOI]

Bharti, V., 2019. India's programmes and incentives being implemented to support biogas systems. *Ministry of New and Renewable Energy, Government of India*. Retrieved March 28, 2024, from https://www.

ccacoalition.org/sites/default/files/resources/01_India%27s%20programmes%20and%20incentives%20being%20implemented%20to%20support%20biogas%20systems_Vijay%20Barthi_MNRE.pdf

Census, 2011. *Census of India*. Retrieved February 9, 2024, from https://www.census2011.co.in/data/village/317912-sehalai-west-bengal.html

Chalvatzaki, E., Chatoutsidou, S.E., Lehtomäki, H., Almeida, S.M., Eleftheriadis, K., Hänninen, O. and Lazaridis, M., 2019. Characterization of human health risks from particulate air pollution in selected European cities. *Atmosphere*, 10(2), 96. [DOI]

Chen, R., Samoli, E., Wong, C.M., Huang, W., Wang, Z., Chen, B. and Kan, H., 2012. Associations between short-term exposure to nitrogen dioxide and mortality in 17 Chinese cities: The China Air Pollution and Health Effects Study (CAPES). *Environment International*, 45, pp.32–38. [DOI]

Chowdhury, S., Pillarisetti, A., Oberholzer, A., Jetter, J., Mitchell, J., Cappuccilli, E., Aamaas, B., Aunan, K., Pozzer, A. and Alexander, D., 2023. A global review of the state of the evidence of household air pollution's contribution to ambient fine particulate matter and their related health impacts. *Environment International*, 107835. [DOI]

Churchill, S.A. and Smyth, R., 2021. Energy poverty and health: Panel data evidence from Australia. *Energy Economics*, 97. [DOI]

Dhungana, B., Lohani, S.P. and Marsolek, M., 2022. Anaerobic co-digestion of food waste with livestock manure at ambient temperature: A biogas-based circular economy and sustainable development goals. *Sustainability*, 14, 3307. [DOI]

Enyew, H.D., Mereta, S.T. and Hailu, A.B., 2021. Biomass fuel use and acute respiratory infection among children younger than 5 years in Ethiopia: A systematic review and meta-analysis. *Public Health*, 193, pp.29–40. [DOI]

Ghosh, S., Sarkar, A., Bagdi, T. and Hazra, A.K., 2020. Organic farming and digested biogas slurry for sustainable agriculture in India: A review. *Journal of Social Work and Social Development*, 12(2), pp.81–96.

Hutter, D. and Jaeggi, E., 2010. Causes and mechanisms of intrauterine hypoxia and its impact on the fetal cardiovascular system: A review. *International Journal of Pediatrics*, 401323. [DOI]

Kalli, R., Jena, P.R. and Managi, S., 2022. Subsidized LPG scheme and the shift to cleaner household energy use: Evidence from a tribal community of eastern India. *Sustainability*, 14(4), 2450. [DOI]

Karmakar, S., Koley, A., Thakur, R. G., Ghosh, A., Show, B.K. and Balachandran, S., 2024. Optimizing hydroponic growth by the liquid fraction of biogas digestate. In *Changing Scenario of Earth*, Rajesh Publications, New Delhi - 110002, ISBN: 978-93-91139-53-7

Koley, A., Mukhopadhyay, P., Show, B.K., Ghosh, A., Balachandran, S. and Santiniketan, V.B., 2022a. Biogas production potentiality of water hyacinth, pistia and duckweed: A comparative analysis. In *Proceedings of the National Symposium: "Recent Trends in Sustainable Technology-Techno-Commercial Developments"*, Kolkata, India, 9–10 September 2022.

Koley, A., Bray, D., Banerjee, S., Sarkar, S., Thahur, R.G., Hazra, A.K. and Balachandran, S., 2022b. Bioremediation of toxic metalloid. *CRC Press*, pp. 95–114. [DOI].

Koley, A., Ghosh Thakur, R., Das, K., Gupta, N., Banerjee, A., Show, B.K. and Balachandran, S., 2024a. Growth dynamics and nutrient removal from biogas slurry using water hyacinth. *Sustainability*, 16(11), p. 4450. [DOI].

Koley, A., Gupta, N., Singh, A., Ghosh Thakur, R. and Balachandran, S., 2024b. Application of microbial technology in wastewater treatment and bioenergy recovery. *Springer Nature Singapore*, pp. 359–384. [DOI].

Koley, A., Mukhopadhyay, P., Gupta, N., Singh, A., Ghosh, A., Show, B.K. and Balachandran, S., 2023. Biogas production potential of aquatic weeds as the next-generation feedstock for bioenergy production: A review. *Environmental Science and Pollution Research*, 30(52), pp. 111802–111832. [DOI].

Koyuncu, A., Bates, M.N., Petrin, Z., Cope, M., McCoy, S.I., Prata, N., Sijali, T.R. and Harris-Adamson, C., 2021. Heavy load carrying and musculoskeletal health: An exploratory study of biomechanical risk factors among sand miners in Pokhara, Kaski District, Nepal. *International Journal of Industrial Ergonomics*, 85, 103187. [DOI].

Krishnamoorthy, Y., Sarveswaran, G., Sivaranjini, K., Sakthivel, M., Majella, M. and Kumar, S., 2018. Association between indoor air pollution and cognitive impairment among adults in rural Puducherry, South India. *Journal of Neurosciences in Rural Practice*, 9, pp. 529–534. [DOI].

Kulyal, L. and Jalal, P., 2022. Bioenergy, a finer alternative for India: Scope, barriers, socio-economic benefits and identified solution. *Bioresource Technology Reports*, 17, 100947. [DOI].

Liu, Y.H., Lu, Y.K., Liu, X.T., Li, Y.L., Hu, L.K., Gao, H.Y., Yang, K. and Yan, Y.X., 2022. Association of household solid fuel use and long-term exposure to PM2.5 with arthritis in middle-aged and older population in China: A cohort study. *Ecotoxicology and Environmental Safety*, 230, 113104. [DOI].

Mandell, J.T., Idarraga, M., Kumar, N. and Galor, A., 2020. Impact of air pollution and weather on dry eye. *Journal of Clinical Medicine*, 9(11), 3740. [DOI].

Manuel, J.J. and Gautam, S., 2023. Household air pollution: A progress update by evaluation and scientometric analysis. *Water, Air, & Soil Pollution*, 234, 64. [DOI].

Matano, H., 2022. Clean energy for women, by women. Retrieved January 16, 2024, from https://blogs.worldbank.org/voices/clean-energy-women-women.

Matinga, M. and Clancy, J., 2020. Gender, firewood and health: The potential of ethnography to inform policy and practice. In *Engendering the Energy Transition*, pp. 33–57. [DOI].

Meena, P.K., Pal, A. and Gautam, S., 2024. Zone-wise biogas potential in India: Fundamentals, challenges, and policy considerations. *Environmental Science and Pollution Research*, 31(2), pp. 1841–1862.

Mekonen, E.A., Mekonnen, Y.T. and Fatoba, S.O., 2023. Thermodynamic prediction of biogas production and combustion: The spontaneity and energy conversion efficiency from photosynthesis to combustion. *Scientific African*, 26, e01776. [DOI].

Ministry of New and Renewable Energy (MNRE), 2022. Biogas Programme (Phase-I) for FY 2021-22 to 2025-26. Retrieved January 16, 2024, from https://biogas.mnre.gov.in/about-the-programmes.

Mitra, P., Chakraborty, D., Nayek, S., Kundu, S., Mishra, D., Dan, U. and Mondal, N.K., 2023. Biomass using tribal women exhibited respiratory symptoms, hypertensive risks and abnormal pulmonary function. *Chemosphere*, 311, 136995. [DOI].

Mocumbi, A.O., Stewart, S., Patel, S. and Al-Delaimy, W.K., 2019. Cardiovascular effects of indoor air pollution from solid fuel: Relevance to sub-Saharan Africa. *Current Environmental Health Reports*, 6, pp. 116–126. [DOI].

Mottaleb, K.A., 2019. Biogas adoption and elucidating its impacts in India: Implications for policy. *Biomass and Bioenergy*, 123, pp. 166–174. [DOI].

Nahar, G., Koley, A., Garai, S., Balachandran, S. and Ross, A.B., 2024. Enhancing biogas production through the co-digestion of fish waste (FW) and water hyacinth (WH) using cow dung as an inoculum: Effect of FW/WH ratio. *Applied Sciences*, 14(21), 9880. [DOI].

Nawaz, S., 2021. Energy poverty, climate shocks, and health deprivations. *Energy Economics*. [DOI].

National Family Health Survey (NFHS), 2018. *National Family Health Survey-5 India report*. Retrieved January 12, 2024, from https://iipsindia.ac.in/content/national-family-health-survey-nfhs-5-india-report.

Pathak, U., Gupta, C., Jagdish and Suri, C., 2019. Risk of COPD due to indoor air pollution from biomass cooking fuel: A systematic review and meta-analysis. *International Journal of Environmental Health Research*. [DOI].

Rajendran, K., Aslanzadeh, S. and Taherzadeh, M.J., 2012. Household biogas digesters—A review. *Energies*, 5(8), pp. 2911–2942. [DOI].

Sarker, S.A., Wang, S., Adnan, K.M. and Sattar, M.N., 2020. Economic feasibility and determinants of biogas technology adoption: Evidence from Bangladesh. *Renewable and Sustainable Energy Reviews*, 123, 109766. [DOI].

Sawhney, A., 2021. Striving towards a circular economy: Climate policy and renewable energy in India. *Clean Technologies and Environmental Policy*, 23, pp. 491–499. [DOI].

Schroeter, J.D., Kimbell, J.S. and Asgharian, B., 2006. Analysis of particle deposition in the turbinate and olfactory regions using a human nasal computational fluid dynamics model. *Journal of Aerosol Medicine*, 19(3), pp. 301–313. [DOI].

Shane, A. and Gheewala, S.H., 2017. Missed environmental benefits of biogas production in Zambia. *Journal of Cleaner Production*, 142, pp. 1200–1209. [DOI].

Shobande, O.A., 2023. Rethinking social change: Does the permanent and transitory effects of electricity and solid fuel use predict health outcome in Africa? *Technological Forecasting and Social Change*, 186, 122169. [DOI].

Show, B.K., Panja, S., Ghosh Thakur, R., Basu, A., Koley, A., Ghosh, A. et al., 2023. Optimisation of anaerobic digestate and chemical fertiliser application to enhance rice yield: A machine-learning approach. *Sustainability*, 15, 13706. [DOI].

Singh, K., Meena, R.S., Kumar, S., Dhyani, S., Sheoran, S., Singh, H.M., Pathak, V.V. et al., 2023. India's renewable energy research and policies to phase down coal: Success after Paris Agreement and possibilities post-Glasgow Climate Pact. *Biomass and Bioenergy*, 177, 106944. [DOI].

Singh, P. and Kalamdhad, A.S., 2021. A comprehensive assessment of state-wise biogas potential and its utilization in India. *Biomass Conversion and Biorefinery*, pp. 1–23. [DOI].

Soni, A. and Chatterjee, A., 2023. Not just income: The enabling role of institutional confidence and social capital in household energy transitions in India. *Energy Research and Social Science*, 8, 103020. [DOI].

Sunil, M., Agrawal, S., Jain, A. and Ganesan, K., 2021. State of clean cooking energy access in India: Insights from the India Residential Energy Survey (IRES) 2020. *Council on Energy, Environment and Water*, New Delhi.

Thom, S.R., 2008. Carbon monoxide pathophysiology and treatment. In: *Physiology and Medicine of Hyperbaric Oxygen Therapy*. Elsevier, St. Louis, MO, pp.321–347. ISBN 9781416034063.

USEPA, 1989. *Risk Assessment Guidance for Superfund I: Human Health Evaluation Manual (Part A)*. Office of Emergency and Remedial Response, Washington, DC.

USEPA, 2005. *Integrated Risk Information System*. Adherence to Long-Term Therapies: Evidence for Action. Retrieved 17 March 2024, from https://www.epa.gov/iris.

Wang, D., Dong, C., Xu, H., Xu, D., Cheng, Y., Shi, Y., Han, F., Chen, F., Qian, H., Ren, Y. and Sui, S., 2023. Association between air pollutants, sources, and components of PM2.5 and pediatric outpatient visits for respiratory diseases in Shanghai, China. *Atmospheric Environment*, 311, 119978. [DOI].

Waris, V.S. and Antahal, P.C., 2014. Fuelwood scarcity, poverty and women: Some perspectives. *IOSR Journal of Humanities and Social Science*, 19, pp.21–33.

World Health Organization (WHO), 2022. *Household air pollution*. Retrieved 2 April 2024, from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health#:~:text=Key/facts,Generates/harmful/household/air/pollution.

Wu, Y., Zhang, S., Zhuo, B., Cai, M., Qian, Z.M., Vaughn, M.G., McMillin, S.E., Zhang, Z. and Lin, H., 2022. Global burden of chronic obstructive pulmonary disease attributable to ambient particulate matter pollution and household air pollution from solid fuels from 1990 to 2019. *Environmental Science and Pollution Research*, 29, pp.32788–32799. [DOI].

Yasmin, N. and Grundmann, P., 2019. Adoption and diffusion of renewable energy—The case of biogas as alternative fuel for cooking in Pakistan. *Renewable and Sustainable Energy Reviews*, 101, pp.255–264. [DOI].

Zewdie, A., Degefa, G.H. and Donacho, D.O., 2023. Health risk assessment of indoor air quality, sociodemographic and kitchen characteristics on respiratory health among women responsible for cooking in urban settings of Oromia region, Ethiopia: A community-based cross-sectional study. *BMJ Open*, 13. [DOI].

Zhang, J., Smith, K.R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A. and Thorneloe, S.A., 2000. Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors. *Atmospheric Environment*, 34(26), pp.4537–4549. [DOI].