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Thermal Efficiency of Wood Burning Traditional Mud Cookstoves and Their Impact on Indoor Air Quality in North-Western Himalayas

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Abstract

The rural people use inefficient traditional mud cookstove for cooking and space heating in the hilly region due to severe winters resulting emission of pollutants inside the kitchen. A study was carried out to determine the altitudinal based thermal efficiency of wood burning traditional mud cookstoves and their emitted pollutants in Drang block of Mandi district. The calorific value of the preferred oven dried fuelwood species in study area ranged between 4282.52 kcal/kg for *Populus deltoids* and 5623.96 kcal/kg for *Quercus leucotrichophora* required for determining thermal efficiency. The average thermal efficiency of the mud cookstove was found to be 8.02% and power output was 0.43 kW. The distance travelled and time taken to collect fuelwood by the rural women had decreasing trend with increase in altitude. The daily fuelwood consumption increased with increase in altitude and per capita fuelwood consumption was found to be 4.57 Kg/day. The emission of particulate matter (PM_{10}) and volatile organic compounds increased with increase in altitude from 31.91 µg/m^3 and 2.52 ppb at lower altitude to 80.22 µg/m^3 and 5.81 ppb at middle altitude to 92.63 µg/m^3 and 8.71 ppb at higher altitude, respectively.

Key words: Calorific value, fuelwood, cookstove, efficiency, PM_{10}, VOCs.

1. Introduction

Climate change is a critical challenge facing humanity due to emission of greenhouse gases from burning of fossil fuels mainly responsible for global warming. Indoor air pollution is responsible for several health, environmental, and social issues that disproportionately and adversely affect women and children worldwide [1]. Intergovernmental Panel on Climate Change in 2007 recognized open fire cooking as a source of carbon emission as domestic biomass burning is the largest source of black carbon [2]. Half of the world's population uses traditional cookstove ([3], [4]) and around 3 billion people burn solid fuels as fuel for cooking and heating around the world [5]. Nearly three-fourth of Indian households use open fire or traditional mud cookstoves without a chimney and many times window inside the house, exposing women and children to high levels of toxic smoke from solid fuels.

Globally 4.3 million people die every year from the exposure to indoor air pollution ([6], [7]) and more than 1.45 million people, mostly women and children under five years old, die prematurely each year from household air pollution due to inefficient biomass combustion [8]. Due to low thermal efficiency of traditional wood burning mud cookstoves, the consumption of fuelwood increases resulting in increased deforestation and greenhouse gas emissions. These cookstoves are the source of black carbon which accounts for 18 % of greenhouse gas emissions globally. The average concentrations of black carbon in the range of 10-1000 µg/m^3 measured indoors in India may pose a serious threat to women and children subject to soot laden smoke from traditional stoves.

The per capita bio fuel consumption in Western Himalayan state (Himachal Pradesh) is the highest (firewood - 1.31 Kg per day, crop residue - 0.14 Kg per day, dung cakes - 0.22 Kg per day) when compared to other states of India [9]. The extent of indoor air pollution depends on the thermal efficiency of wood burning mud cook stove which in turn depends on the calorific values of different fuelwood species used. The calorific value depends on moisture content of the fuelwood used for cooking.

In Himachal Pradesh, people use wood, agro waste and forest waste, liquid petroleum gas, electricity and kerosene oil for cooking, room heating, water heating and lighting. The pattern of consumption of fuel for cooking in the state is firewood 72.2 % and 0.5 %, crop residue 1.2 % and 0.5 %, cow dung cake 0.1 % and 0.1 %, kerosene 3.6 % and 14.5 %, liquid petroleum gas 21.8 % and 76.6 %, electricity 0.2 % and 0.4 %, biogas 0.4 % and 0.3 % in rural and urban areas respectively [10]. People use wood burning traditional mud cookstove for cooking and heating, the wood is collected from nearby forests by the women and children. In the present study the calorific value of different fuelwood species being used in the study area has been determined to find out the thermal efficiency of traditional wood burning mud cookstoves and pollutants emitted in the kitchen.

2. Methodology

2.1. Study area

The study area lies in the Western Himalayas between 31°13′20″ to 32°04′30″ North latitude and 76°37′20″ to 77°23′15″ East longitude (Fig 1).

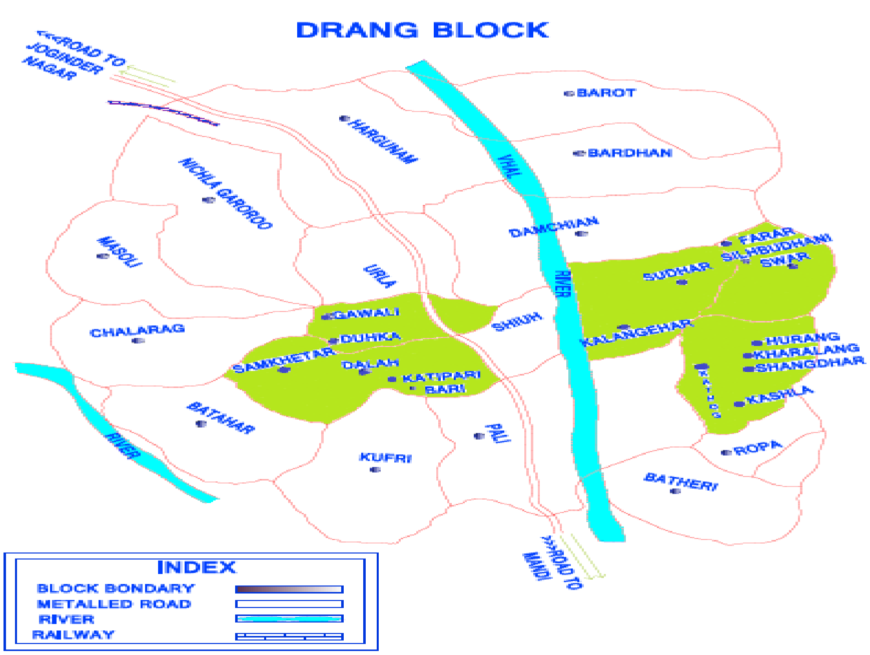

Fig. 1. Map of study area

It falls in the mid-hills sub-humid zone and high hills temperate wet agro climatic zone of Himachal Pradesh has 320 villages and there are total 17,982 families in this Block with total population of 82,407 [11]. Total geographical area of this district is 3950 km^2 with a density of 230 per km^2 and constitutes 7.095 per cent of the total geographical area of the state. Topographically, the district can be divided into two main categories: a) Shivalik or Outer Himalaya region, which varies from 651-1500 meter above mean sea level and b) Mid mountain or Inner Himalaya region, varying from 1500-4500 meter above mean sea level. The district receives annual average rainfall over the 15 years 1239.98 mm. Maximum (63 %) rainfall occurs in the month of June to September followed by January to March whereas least rainfall occurs in the month of November followed by December, October and April. Lower areas of the district experience hot summer (up to 40^0C) and cold winter with frost and fog. Hilly area experiences mild summer and cold winter with low to high snowfall and mist in rainy season.

The development block was divided into three altitudinal zones (<1000 meter, 1000-1500 meter and 1500-2000 meter). In each zone four villages were selected cluster wise. In each village two households were selected on the basis of income i.e. one above poverty line (APL) and one below poverty line (BPL) randomly. The households were classified on the basis of three categories viz. income, land holding and family size.

The calorific value of oven dried preferred fuelwood species available in the study area was calculated using bomb calorimeter. The calorific value of fuelwood having moisture content at field conditions used during water boiling test and actual cooking by households was also calculated to find out thermal efficiency of mud cookstoves. The calorific value of dried powder of wood samples was determined with bomb calorimeter, in which about 0.5 grams of oven dried wood was completely combusted under a pressurized to 425 psi with pure oxygen, and the rise in temperature of the cylinder allows the calculation of the calorific value when the exact weight of the sample is known. The bomb calorimeter was calibrated against benzoic acid standards before the analysis of samples [12]. The moisture content of the wood samples was calculated by using digital moisture meter.

Thermal efficiency of wood burning mud cookstove was calculated using Water Boiling Test [13]. The emission of pollutants (particulate matter and volatile organic compounds) was monitored during actual cooking time in the selected households using Environmental Perimeter Air Station (Automatic). In each selected household actual cooking was monitored only once a day. For the estimation of carbon dioxide emitted from burning of fuelwood in mud cookstoves, CO_2 analyzer was used. The data generated from present investigation were statistically analyzed using critical difference at 5% level.

3. Results and discussion

3.1. Kitchen Characteristics

The study identified that 20.83% households were having kitchens made up of cement and concrete and remaining 79.17 % kitchens were made up of stone and mud (Table 1).

Table 1. Characteristics of kitchen in selected households

Elevation	Social	Name of	Building	Kitchen type

(m)	Class	beneficiary	Material	Chimney	Ventilation	Height (ft)
<1000	APL	Tek Chand	Cement/concrete	Yes	Window	10
		Vijay Barwal	Cement/concrete	Yes	Window	10
		Ram chand	Cement/concrete	No	Window	8
		Suraj Kumar	Cement/concrete	No	Window	8
	BPL	Mast Ram	Stone/Mud	No	Window	8
		Khub Ram	Cement/concrete	**Yes**	Window	10
		Krishan Kumar	Stone/Mud	No	Window	8
		Prakash Chand	Stone/Mud	No	Window	8
1000-1500	APL	Chet Ram	Stone/Mud	No	No	8
		Dile Ram	Stone/Mud	No	No	8
		Mede Ram	Stone/Mud	No	No	8
		Bhadar Singh	Stone/Mud	No	No	8
	BPL	Shauju Ram	Stone/Mud	No	No	8
		Pawan Kumar	Stone/Mud	No	No	8
		Mani Ram	Stone/Mud	No	No	8
		Sanjay Kumar	Stone/Mud	No	No	8
1500-2000	APL	Tara Chand	Stone/Mud	No	No	8
		Kamar Singh	Stone/Mud	No	No	8
		Puran Chand	Stone/Mud	No	No	8
		Dina Nath	Stone/Mud	No	No	8
	BPL	Sukh Raj	Stone/Mud	No	No	7
		Duni Chand	Stone/Mud	No	No	8
		Raj Kumar	Stone/Mud	No	No	8
		Lal Singh	Stone/Mud	No	No	8

Only 12.5% households were having cookstoves with chimney and 33.33% households were having single window for ventilation in the kitchens and 66.67% households had no ventilation source in their kitchens. Only 12.5% households were found to have both chimney and window in their kitchens. The height of kitchen in the study area varied from 7-10 feet. The kitchens did not have proper ventilation resulting accumulation of pollutants inside the house can affect human healthy especially women and children.

3.2. Fuelwood characteristics

The study identified 15 preferred fuelwood species in the study area (Table 2). These preferred fuelwood species possessed good fuel characteristics like high calorific value with good and gradual flame and less smoke emission. The most preferred species in lower altitude was *Grewia optiva*. However, on the basis of calorific value, the preferred species at this altitude should have been *Pinus roxburghii having calorific value* of 5553.56 kcal/kg (table 2). In middle and higher altitude the most preferred species was *Quercus leucotrichophora* which has the highest calorific value (5623.96kcal/kg) among all the species available in both the altitudes. The fuelwood preference is based on the quality and availability of the fuelwood species. More preference is given to those fuels which is easy to use and require least effort on t he part of people to have access to that fuel and high calorific values per unit of given fuel, the results are in line with the findings of [14].

Table 2. Preferred fuelwood species and their ecological status in different altitudinal gradients in the study area

Altitude (m)	Species	Common Name	Family	Ranking (quality/ availability)	Calorific Value (kcal/kg)
<1000	*Celtis australis*	Khirak	Cannabaceae	3	4307.74
	Grewia optiva	Beul	Teliaceae	1	4908.16
	Morus alba	Shahtut	Moraceae	2	4764.73
	Mangifera indica	Mango	Anacardiaceae	5	4500.00
	Melia azadirach	Darek	Meliaceae	6	4707.32
	Pinus roxburghii	Chir	Pinaceae	4	5553.56
	Populus deltoides	Poplar	Salicaceae	8	4282.52
	Prunus padus	Paja	Rosaceae	7	4361.57
1000-1500	*Cedrus deodara*	Deodar	Pinaceae	2	5113.20
	Celtis australis	Khirak	Cannabaceae	5	4307.74
	Ficus palmata	Fegda	Moraceae	8	4421.99
	Grewia optiva	Beul	Teliaceae	4	4871.31
	Melia azadirach	Darek	Meliaceae	6	4707.32
	Pinus roxburghii	Chir	Pinaceae	9	5553.56
	Prunus padus	Paja	Rosaceae	7	4361.57
	Quercus leucotrichophora	Oak	Fagaceae	1	5623.96
	Rhododendron arboretum	Buransh	Ericaceae	3	5150.13
1500-2000	*Alnus nitida*	Kosh	Betulaceae	5	4593.81
	Cedrus deodara	Deodar	Pinaceae	4	5113.20
	Grewia optiva	Beul	Teliaceae	6	4871.31
	Celtis australis	Khirak	Cannabaceae	7	4307.74
	Myrica nagi	Kafal	Myricaceae	3	4785.00
	Pinus wallichiana	Kail	Pinaceae	8	4986.42
	Rhododendron arboretum	Buransh	Ericaceae	2	5150.13
	Quercus leucotrichophora	Oak	Fagaceae	1	5623.96

The fuelwood collection showed an increasing trend with increase in altitude (Table 4). The maximum fuelwood collection was 36.88 Kg/day observed at altitude of 1000-1500 meter which are in line with the findings of [15], [16], [17] and [18]. The fuelwood consumption showed an increasing trend with increase in altitude. The daily maximum fuelwood consumption was 30.0 Kg at altitude of 1500-2000 meter followed by 28.50 Kg at altitude of 1000-1500 meter and 20.00 Kg at altitude of <1000 meter which are similar with the findings of [19] and [20].

To collect the fuelwood from nearby forest the women and children have to travel about 1 km daily. There is decreasing pattern of daily distance travelled to collect the fuelwood with the increase in altitude. The average time taken to collect the fuelwood was 1.28 hours/day and was maximum (1.38 hours/day) at altitude of <1000 meter while minimum (1.16 hours/day) at altitude of 1500-2000 meter. The decreasing pattern observed in the distance travelled and time spent for the collection of fuelwood was due to low availability of preferred fuelwood species in the lower altitudes. So, the villagers from lower altitude travel more distance and spend more time in collection of preferred fuelwood species as compared to higher and middle altitudes, are in conformity with the findings of [21].

On the basis of social class, the low income families collect 37.50 Kg/day higher than the high income families (33.75 Kg/day). The fuelwood consumption was more (28.34 Kg/day) in low income families than high income families (24 Kg/day). The time spent by high income families was 1.25 hours/day which is less than low income families of 1.41 hours/day for the collection of fuelwood. The distance travelled to collect the fuelwood by high income families was 1.08 Km/day comparatively less than low income families (1.25 Km/day), for the collection of fuelwood.

The high income families have access to alternative energy such as electricity and liquid petroleum gas but low income families cannot afford these sources. They are solely dependent on fuelwood from nearby forest and are often compelled to spend more time collecting fuelwood from distant locations as resources decline [22].

3.3. Thermal efficiency and power output of traditional mud cookstoves

The thermal efficiency and power output of traditional mud cookstoves are based on number of pot hole, moisture content of fuelwood, and calorific value of fuelwood species determined using water boiling test (table 3).

Table 3. Thermal efficiency and power output of traditional mud cook stoves in selected households

Altitude (m)	Social Class	Species	Moisture content (%)	Calorific Value (kcal/kg)	No. of pot hole in cook stove	Efficiency (per cent)	Power output (kW)
<1000	APL	*Grewia optiva*	12.3	4183.36	1	9.60	0.47
		Grewia optiva	12.7	4177.97	2	8.31	0.40
		Morus alba	10.5	4613.46	1	7.90	0.42
		Prunus padus	10.3	4063.54	1	9.07	0.43
	BPL	*Grewia optiva*	11.7	4180.72	1	8.11	0.39
		Melia azaderach	10.2	4207.64	2	8.51	0.42
		Grewia optiva	12.5	4178.14	1	8.45	0.41
		Celtis australis	9.8	4193.17	1	8.28	0.40
1000-1500	APL	*Cedrus deodara*	12.6	4812.65	2	7.10	0.40
		Cedrus deodara	12.6	4812.65	2	6.93	0.39
		Quercus leucotrichophora	15.1	4781.91	1	8.79	0.49

		Quercus leucotrichophora	15.0	4784.59	2	7.14	0.40
	BPL	*Cedrus deodara*	12.6	4812.65	2	8.18	0.46
		Cedrus deodara	12.6	4812.65	2	8.80	0.49
		Rhododendron arboreum	11.2	4728.11	1	8.48	0.47
		Quercus leucotrichophora	15.0	4784.59	2	7.83	0.44
1500-2000	APL	*Quercus leucotrichophora*	15.0	4784.59	1	7.59	0.42
		Quercus leucotrichophora	14.7	4786.39	2	8.27	0.46
		Cedrus deodara	12.7	4811.21	1	7.30	0.41
		Quercus leucotrichophora	12.3	4790.42	2	7.64	0.43
	BPL	*Quercus leucotrichophora*	14.7	4786.39	2	6.77	0.38
		Quercus leucotrichophora	14.7	4786.39	2	8.48	0.47
		Cedrus deodara	12.7	4811.21	1	7.41	0.41
		Rhododendron arboreum	11.0	4729.91	2	7.50	0.41
Average						**8.02**	**0.43**

The highest thermal efficiency of mud cookstoves was 9.6% and lowest thermal efficiency of mud cookstoves was 7.9 % at altitude <1000 (Table 3). At altitude of 1000-1500 meter the highest and lowest thermal efficiency of mud cookstoves was 8.8% and 6.93%, respectively. The highest and lowest thermal efficiency of mud cookstoves at altitude of 1500-2000 meter was 8.48% and 6.77%, respectively. The average thermal efficiency of traditional mud cookstoves in selected households was found to be 8.02 % [23], [24] and [25].

The maximum power output of mud cookstove was 0.49 kW observed in altitude range of 1000-1500 meter while minimum power output of mud cookstove was 0.38 kW in altitude range of 1500-2000 meter. Low thermal efficiency of cookstove indicates flaws in design of cookstove as the calorific value of the fuelwood is quite high.

Table 4. Daily fuelwood collection and consumption pattern of selected households

Particular	Fuelwood collection (Kg/day)	Fuelwood consumption (Kg/day)	Distance travelled (Km/day)	Time spent to collect fuelwood (hrs/day)	Agro waste (Kg/day)
Altitude (m)					
<1000	33.13	20.00	1.50	1.38	1.25
1000-1500	36.88	28.50	1.19	1.31	2.50
1500-2000	36.88	30.00	0.88	1.16	3.69
Average	**35.63**	**26.17**	**1.19**	**1.28**	**2.48**
Social class					

APL	33.75	24.00	1.08	1.17	2.04
BPL	37.5	28.34	1.29	1.40	2.88
Average	**35.63**	**26.17**	**1.19**	**1.28**	**2.42**
Family size (no.)					
<4	35	20.00	1	1.00	3
4 to 6	35	25.88	1.31	1.33	2.5
7 to 8	38.75	28.00	0.75	1.10	2.4
>8	35	27.00	1.5	1.50	2.25
Average	**35.94**	**25.22**	**1.14**	**1.23**	**2.54**
Land holding (ha)					
<1	35	24.88	1.22	1.29	2.42
1 to 2	36.25	30.00	0.87	1.00	2.63
>2 to ≤ 4	40	30.00	1.5	1.75	2.75
Average	**37.08**	**28.29**	**1.20**	**1.35**	**2.60**

3.4 Indoor air pollution from wood burning mud cookstove

The emission of pollutants from wood burning mud cookstoves found statistically significant increasing pattern in the case of particulate matter (PM_{10}). The maximum emission of particulate matter was 92.63 µg/m^3 found at an altitude of 1500-2000 meter by the low income families and minimum (31.91 µg/m^3) was at an altitude of <1000 meter by the high income families, with an overall average of 68.25 µg/m^3. This increasing pattern is due to higher consumption of fuelwood, presence of inefficient cookstoves and inadequate ventilation in higher altitudes than in lower altitudes. The kitchen made of mud walls also increases the particulate matter (PM_{10}) concentration [26]. The concentrations of pollutant are in permissible limits as per United States Environment Protection Agency**.** However, the results are above permissible limits according to World Health Organization, except at an altitude of <1000 meter. The average particulate matter (PM_{10}) concentration was in conformity with the findings of [27], [28] and [29] and less than [30], [28] and Indian rural PM_{10} exposure standard: a 24-hour average of 100 µg per m^3 [26].

The maximum emission of volatile organic compound was 8.71 ppb found at an altitude of 1500-2000 meter and minimum (2.52 ppb) was at an altitude of <1000 meter, with an overall average of 5.68 ppb. The increase in emissions of pollutants with increase in altitude is statistically significant. The concentration of volatile organic compounds pollutants was in permissible limits as per United States Environment Protection Agency**.**

Table 5. Emission of pollutants from wood burning mud cookstove

Particular	**PM_{10} (µg/m^3)**	**VOC (ppb)**
Altitude (m)		
<1000	31.91	2.52
1000-1500	80.22	5.81
1500-2000	92.63	8.71

Overall average	**68.25**	**5.68**
Social class		
APL	60.42	5.1
BPL	76.08	6.26
Overall average	**68.25**	**5.68**
Family Size (No.)		
<4	95.73	9.11
4—6	65.33	5.58
7—8	68.89	5.42
>8	76.31	5.42
Overall average	**76.57**	**6.38**
Land holding (ha)		
<1	63.85	5.49
1—2	81.95	6.51
>2—3	80.49	5.71
Overall average	**75.43**	**5.90**

Permissible limit: For PM_{10} = 50 µg per m^3 for 24 hrs (WHO, 2009[b]) and 150 µg per m^3 for 24 hrs [40], for VOC **=** <200 µg per m^3 [31]

Endnotes:
USEPA= United States Environment Protection Agency
WHO= World Health Organisation
VOC: <200 µg per m^3 (Comfort zone), 200-3000 µg per m^3 (Multifunctional exposure), 3000-25000 µg per m^3 (Discomfort zone), >25000 µg per m^3 (Toxic)

3.4. Carbon dioxide (CO_2) emission and temperature during cooking

The emission of carbon dioxide was 252 ppm at an altitude of <1000 meter and 690.25 ppm at an altitude of 1500-2000 meter, this is due to higher consumption of fuelwood, presence of inefficient cookstoves and lack of adequate ventilation in higher altitudes than in lower altitudes which was statistically significant. The values are in permissible limit as per United States Environment Protection Agency. The temperature increased with increase in altitude with maximum rise of 7.9^{0}C during cooking in the kitchen and was statistically significant.

Table 6. **Carbon dioxide emission and increase in temperature during actual cooking**

Particular	**CO_2 (ppm)**	**Temperature increase (^{0}C)**
Altitude (m)		
<1000	252	3.63
1000-1500	470.75	5.24

1500-2000	690.25	7.93
Overall average	**471.00**	**5.60**
Social class		
APL	404.25	5.28
BPL	537.75	5.92
Overall average	**471.00**	**5.60**
Family Size (No.)		
<4	742	8.7
4—6	466.31	5.51
7—8	478	5.42
>8	355.5	5.15
Overall average	**510.45**	**6.20**
Land holding (ha)		
<1	456.78	5.61
1—2	536	5.8
>2—3	469	5.1
Overall average	**487.26**	**5.50**

Permissible limit: For CO_2 = <1000 ppm [32]
For Temperature = 20-27^{0}C [32]

Endnotes: ASHRAE= American Society of Heating, Refrigerating and Air Conditioning Engineers.

4. Conclusions

The study indicated that inspite of use of fuelwood of high calorific values the thermal efficiency of wood burning mud cook stove being used in rural areas of the state was low 8.02% which is well below the minimum requirement of 20% of improved cookstove. Due to this, more consumption of fuelwood was observed at higher altitudes in comparison to lower altitudes. The daily average per capita fuelwood consumption was found to be 4.57 kg in the study area. Due to low thermal efficiency and poor combustion of fuelwood the emission of pollutants viz. particulate matter (PM_{10}) and volatile organic compounds increased significantly with the increase in altitude but, were in permissible limit. The average value of particulate matter and volatile organic compound was found to be 68.25 µg/ $m^3$and 5.68 ppb, respectively. The average increase in carbon dioxide was found to be 471 ppm. The study revealed that the women are most affected right from the collection of fuelwood and indoor air pollutants of PM_{10}, CO_2 and VOCs. The indoor air pollutants in the kitchen affect the human health adversely particularly to the women and children which will be presented in following study.

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