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International Journal of Current Research
Vol. 10, Issue, 06, pp.70466-70473, June, 2018

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

HEALTH AND ENVIRONMENTAL IMPACT ASSESSMENT OF BIOMASS COOK STOVE USING INTEGRATED ENVIRONMENTAL PERFORMANCE SCORE

*Indira Parajuli

Tribhuvan University, Institute of Engineering, Pulchowk Campus, Department of Science and Humanities, Climate Change and Development Program, Pulchowk, Lalitpur, Nepal

ARTICLE INFO

Article History:
Received 18th March, 2018
Received in revised form
23rd April, 2018
Accepted 29th May, 2018
Published online 30th June, 2018

Key words:
Climate change,
Environmental Performance Score, Cook stoves, Health impact,
Environmental impact, TRACI.

***Corresponding author:**

ABSTRACT

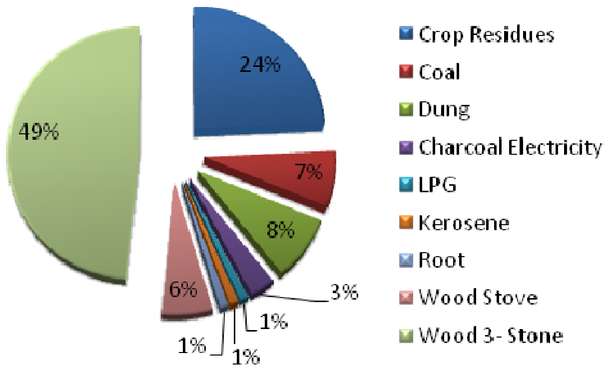
Around 3 billion people in the world cook and heat inside their homes using solid biomass fuel with simple stoves burning biomass and coal. Indoor Air Pollution (IAP) from inefficient cooking practices is a big environmental health problem worldwide (WHO, 2016). Climate forcing pollutants viz., Carbon dioxide (CO_2), Methane (CH_4) and Particulate Matters (PM) have an impact on the environment and human health. Use of biomass causes deforestation and environmental degradation as well as it contributes in Green House Gases (GHGs) (IPCC, 2007). This is vital to identify the lower emitting type of cook stove as a practical solution to lessen the impacts that ensure to save environemnt and human health. This study quantifies the Integrated Environmental Performance Score (IEPS) of five types of commonly used biomass cook stoves. Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) is used to derive performance scores for each of the stoves' potential contributions to impairment of climate, environment and human health. EPS of Three-stone stove is found 2.5 and 2.2 times higher than Rocket and Fan stoves, respectively. Rocket stove contributes the least impact on the environment and human health followed by Fan, Gasifier, and Charcoal stoves. The rate of energy consumption is also2.65, 1.20, 1.50 and 1.70 times less in rocket stove than in Three- Stone, Fan, Gasifier and Charcoal stove, respectively.

DOI: https://doi.org/10.24941/ijcr.30242.06.2018

Citation: Indira Parajuli, 2018. "Health and Environmental Impact Assessment of Biomass Cook stove using Integrated Environmental Performance Score", *International Journal of Current Research*, 10, (06), 70466-70473.

INTRODUCTION

Biomass such as wood, dung, crop residue or charcoal accounts about 88% of the fuel energy consumed for cooking among the total fuel consumption in cooking. The major cause of this trend of energy consumption is because of the excessive consumption of biomass, inefficient stove and low energy content of biomass as such. Out of the total energy consumption for cooking and heating, biomass account about 10%-15% of the global primary energy uses (World Health Organization, 2006). Biomass contributes over 90% of the households' energy consumption in most of the developing countries. While compared with primary energy demand of the world, developing countries accounts about 10% for the household's energy use. Out of which, 75% energy consumption is associated with the use of biomass energy (International Energy Agency and Organization for Economic Cooperation and Development (IEA/OECD), 2006). The predominance use of biomass in developing countries with inefficient appliances and unsustainable wood management (Grupp, Michael, 2004) has been causing emission of climate forcing pollutants. The policy intervention aiming to design the improved stove with more sophisticated cooking fuels is much cost – efficient as per the WHO computation. As per the cost – benefit analysis report, about US$ 100 billion could be saved within 10 years by switching people to cook in improved stove with sophisticated fuels (WHO, 2006). Generally, the efficiency is dependent on a type of appliances i.e. type of cook stove used while cooking and fuel used. In most of poor countries, there is a huge gap between open fire cooking (10%-15% efficiency with Three-stone fire) and modern stove technology (about 90% efficient induction hob). The levels of indoor pollution in developing countries have approximately 100 times higher than cities of the developed countries with serious outdoor air pollution (Dhakal, 2008). The smoke-filled kitchens exceed the guidelines for safe health value set by different agencies like WHO and USEPA in terms of exposure concentrations. The percentage share of global emission of cooking fuels (biomass) equivalent of CO_2 (CO_2e) is shown in fig. 1. Almost half percentage share is from cooking with animal dung followed by 24% from crop residues, 8% from three- stone firing and so on.



Source:http://timetable.cput.ac.za/_other_web_files/_cue/DUE/2004/PDF/26_M_Grupp.pdf (accessed 30 November 2012)

Fig. 1. Percentage shares of relative global emission of the different cooking fuels, in CO_2e.

Indoor Air Pollution (IAP) from inefficient cooking practices is a big environmental health problem world widely as almost half of world population relies on biomass as their cooking fuel and space heating (WHO, 2016). Two millions children under age of five die from Acute Lower Respiratory Tract Infection (ALRI) each year (Warwick and Doig, 2004).CO_2, Carbon monoxide (CO), CH_4 and PM contribute in climate change while they derived as the products of incomplete combustion (PICs). The simple stove used in cooking with solid fuels do not merely convert fuel carbon into CO_2 because of poor combustion condition in general and produce PICs, which have excessive contribution on Global Warming Potentials (GWPs) than CO_2 as such (Kirk R. Smith, 2000). The concentration of these pollutants observed in the kitchens highly exceeds guidelines value for the safe health. Moreover, the solid fuel use as such been identified as an important contributor to deforestation, environmental degradation and even for Greenhouse Gases (GHGs) (Intergovernmental Panel on Climate Change/ IPCC, 2007).Cook stove emits GHGs viz., CO_2, CH_4, Non- methyl Hydrocarbons, Nitrous Oxide (N_2O), CO, and oxides of nitrogen (NOx).Cook stoves are also emitting PM emissions from biomass burning, which have significantly strong effects on the climate. The clouds of pollution over the Indian Ocean appear to cause as much warming as GHGs released by human activity according to BBC News headline of 2007 (BBC News, 2007).The soot and Black Carbon (BC) particles are the primary components of the clouds. The cooking fires are the leading source of BC as per the Scientific American article (Biello, 2007).

Renewable source of energy viz., solar, wind, and biomass used for power generation are the major focussed areas of the clean development mechanism (CDM).CDM allows replacing the low- cost alternative with more expensive emission reductions strategy to the individual countries (UNFCCC/CDM, 2006). The wood burning cook stove in a households are categorized under the CDM category as it is a major contributor to global warming (Samson, 2007). Thus, the reliance on biomass fuels in developing nations has put considerable pressure both on human health and environment (deforestation and GHG emissions). If there is no compliance mechanism, the present 2.5 billion people relying on biomass fuel will increase to more than 2.7 billion by 2030 due to growing population. This accelerates the forcing on climate day by day excessively. Finding the way to health and an environment-friendly stove is the vital concern to save health and climate. The impact assessment of stove so far has done based on the emission extent only. However, merely air pollution concentration could not reflect the real impact on health and environment. One of the practical solutions to find not only the efficient but also environment-friendly cook stove is the vital concern to save both climate and health of the people. Therefore, it is urgent to explore the impact of different biomass stoves separately relating to environment and human health. This study aims to quantify total EPS as a penalty score of commonly used five types of biomass stoves as shown in fig. 2. Hence, it can be helpful to make people aware and facilitate them for replacing high impacting cook stove by less impacting one to reduce both environmental and health effect.

MATERIALS AND METHODS

Common stove types in world: Various types of stove are in use as a cooking means of almost half population in the world. The followings are commonly used stove types for the cooking purposes that are evaluated in this study.

- **Three –Stone Stove:** People put three stone in a tripod stand fashion and firewood burned directly under the pot. Usually, the pot being holds 22cm above the surface. Almost 2.2 billion people in the world use this type of stove or it is the most common method of traditional way of cooking practice prevailed in the world.
- **Rocket stove:** The stove made with well- insulation with rocket stove prototype having 10 cm diameter and combustion chamber of 30cm height. The stove was invented by Dr. Larry Winiarski and Aprovecho Research Center, USA. These technologies havebeen available in market for 25 years (Bryden *et al*., 2005). It costs around US$4 only. Almost half million people of the world are using this type of stove for their cooking purpose.
- **Karve Gasifier Stove:** The stove has a cylindrical combustion chamber and a batch of wood at the top lit. The combustion chamber is filled with 5cm long pieces of wood. The secondary air is passed from the top of the combustion chamber. The stove was invented by Dr. A.D. Karve, Appropriate Rural Technology Institute, India (Raj, 2007). The market price of this type of stove is around US$10.
- **Philips Prototype Fan:** The stove was designed and promoted by the Philips Company in the Netherlands (Philips, 2006). The combustion chamber of the stove is filled with pieces of wood having length 5cm.The better mixing of flame, gases and air can be ensured via a forced air jets into the combustion chamber in a space between the top of the stove and the pot with electric fan. The average market price of this type of stove is US$89.
- **Charcoal Jiko:** The bowl-shaped combustion chamber of stove is to be fed by the pieces of charcoal. The air get enter via holes around the stove to combustion zone and the amount of air controlled by a door below fire. This type of stove is famous in many African countries. It is available in a market costing around US$10.87. Enterprise Works/VITA in Uganda Since 1982 work for the designing and promotion of this type of stove. In overall, around 200,000 stoves are used by people in Ghana.

Three-stone stove

Rocket stove

Karve Gasifier stove

Philips PrototypeFan stove

Jiko Charcoal stove

Fig. 2.Various cook stove types prevailing in the world

As shown in Table 4, Single person requires the energy for cooking task equivalent to energy required to boil 10 liter of water on a daily basis (Nordica Mac Carthy, provecho Research Center, field study India, 2008).

Modelling methodology and tool: In this study, (TRACI, which is the modeling software prescribed by United States Environmental Protection Agency (USEPA),is used to calculate Integrated Environmental Performance Score (IEPS). It helps to compare environmental and health impact preferring ability of two or more products or processes. TRACI facilitates to characterize the potential impact viz. Ozone Depletion(OD), Global Warming (GW), Acidification (AC), Eutrophication (EU), Photochemical smog (P.Smog), Human Health Cancer (HHC), Human Health Non-Cancer (HHNC), Human Health Criteria (HHCR), Eco-toxicity (ET), Fossil Fuel Depletion (FFD), land use, and water use. This is a simple computational model to quantify the potential impacts (TRACI, 2002).

It helps to compute the environmental impact of products or process throughout the life cycle (Ciambron, 1997; B.W. Vigon, 1994). To measure the environmental performance, a "cradle to grave" process life-cycle assessment has applied. Each stage life of production process have impact on environment, which includes raw materials acquisition, product manufacturing, transportation, installation, operation and maintenance, and ultimately recycling and waste management (Lippiatt, 2002). Emission inventory derived from Water Boiling Test (WBT) for five common stove types utilized as an inventory data for this model referred from Nordica Maccarty *et al*., 2008 as mentioned in Table 2.

The modified WBT test protocol prescribed by University of California at Berkeley (UCB), 2003 (Bailis *et al*., 2007a) was followed by the referred study. WBT is the common process throughout the world to understand the energy transform from the fuel to cooking pot. The emission with different stoves in WBT is used as a baseline data for the sake of consistent result. Finally, the integrated impact of each pollutant is calculated individually that results the total penalty score of each stove types.

For every stage of life cycle, nine environmental impact categories viz., GW, AC, EU, ET, HHCR, HHC, HHNC, P.Smog and FFDP, caused by different pollutants derived from cooking are computed applying the inventory data and characterization factors. The total EPS are calculated using equation (1) – (3) to derive the environmental impact categories. Finally, the overall impact is calculated with the utilization of characterization factors as listed in BEES 3.0 (Lippiatt, 2002). The relative importance weight and normalization value are also utilized while computation as stated in previously published journal (Parajuli *et al*., 2017).

Environmental performance index (EPI): Analysis of the specific pollutants, Environmental Performance Index (EPI) Environmental impact of various pollutants calculated as per the effects of individual pollutants using TRACI, so it results the EPS as per the weight age effect of each pollutant.

$$IA_{jt} = \sum_{i=1}^{n} I_{ij} \times IA\ factor \qquad (1)$$

Where,

Env Scorej = environmental performance score for the building product alternative j,

$$IA\ Score_{jk} = \frac{IA_{jk} \times IVwt_k}{Norm_k} \times 100 \quad (2)$$

$$Env\ Score_j = \sum_{k=1}^{p} IAScore \quad (3)$$

where,

P	=	number of environmental impact categories,
IA Scorejk	=	characterized, normalized and weighted score for alternative "j" with respect to environmental impact "k",
IVwtk	=	impact category importance weight for impact k,
Normk	=	normalization value for impact k,
I	=	inventory flow,
n	=	number of inventory flows in impact category k,
Iij	=	inventory flow quantity for alternative "j" with respect to flow "I",
IA factori	=	impact assessment characterization factor for inventory flow I

RESULTS AND DISCUSSION

The total penalty score of common biomass cook stoves is computed using TRACI based on the amount of pollutants released from stoves with WBT. EPS of the stove is evaluated considering the associated environmental factors including GW, AC, EU, HHCR, HHC, HHNC, P. Smog, FFD and ET. Nine associated impact categories are considered for this analysis although TRACI has twelve-impact categories. EPSs for each impact categories are calculated and the total performance scores for each stove types are computed similar as our previously published article (Parajuli *et al*., 2017) using normalization values as guided by BESS 3.0 guideline (Lippiant, 2002) similar as previously published article (Parajuli *et al*., 2017).

The IEPS is estimated using the inventory based on the emission data as depicted in Table 3. A considerable difference is found in total EPS with various stoves. Integrated EPS penalty of Three-stone, Rocket, Fan, Gasifier and Charcoal stoves obtained as3.3E+02, 1.3E+02, 1.7E+02, 2.2E+02, and 2.2E+02, respectively as shown in Table 3. Integrated EPS share of five kinds of stoves found with higher Score sequence as Three-stone> Charcoal> Gasifier> Fan> Rocket as shown in Table 3. The EPS score of GWP of each type of stoves found to be noticeable among the other impact category.

While concerning GWP of various stoves, the percentage share of Three-stone, Rocket, Fan, Gasifier and Charcoal stove 89.87%, 85%, 91.34%, 91.92% and 89.85%, respectively as shown in fig.4. Likewise, AC potential calculated with the percentage share of 0.004%,0.012%, 0.008%, 0.004% and 0.007% and EU potential calculated with the percentage share of 1.81%, 5.27%,3.65%,1.85% and 3.19%, respectively of Three-stone, Rocket, Fan, Gasifier and Charcoal stove as in fig. 3. The HHC contribution of Three-Stone, Rocket, Fan, Gasifier and Charcoal stove 0.00002%, 0.0004%, 0.00001%, 0.00004%, 0.00003% and HHNC contribution 0.035%, 0.065%, 0.018%,0.067%,0.053%, respectively. Rocket stove has excessive contribution on HHCR i.e. about 3.983% followed by 2.734 % by Three- Stone, 1.28% by Charcoal, 0.87% by Gasifier and 0.11% by Fan stove as depicted in fig.4.

In a similar way, P. smog share is obtained as 0.016%, 0.019%, 0.005%, 0.02% and 0.03% respective of Three-stone, Rocket, Fan, Gasifier and Charcoal stove. The percentage share of ET is found as 0.40%,0.76%,0.20%,0.78%,0.61% respectively and FFD is found 5.11%,4.80%,4.65%,4.46%,4.96%, respectively of Three-stone, Rocket, Fan, Gasifier and Charcoal stoves cooking with a stove of individual type for a day. The integrated penalty score of Three- stone stove is found to be 3344.39 followed by Charcoal, Gasifier, Fan, and Rocket with respective IEPS penalty 2213.44, 2154.67, 1661.48, and 1340.10.

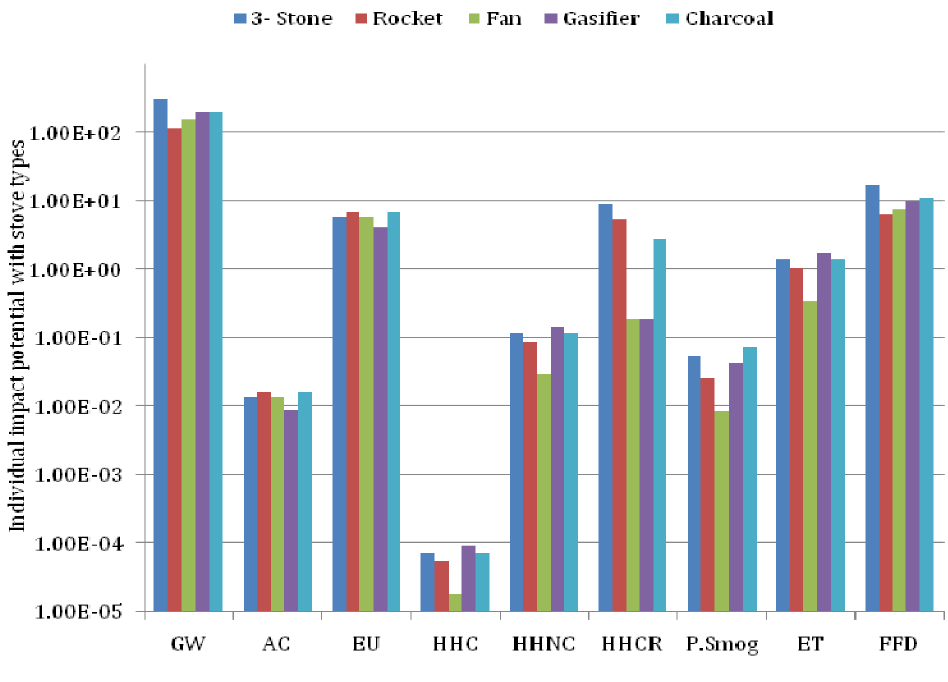


Fig. 3. Individual impact potential of five different Stoves prevailed in the world

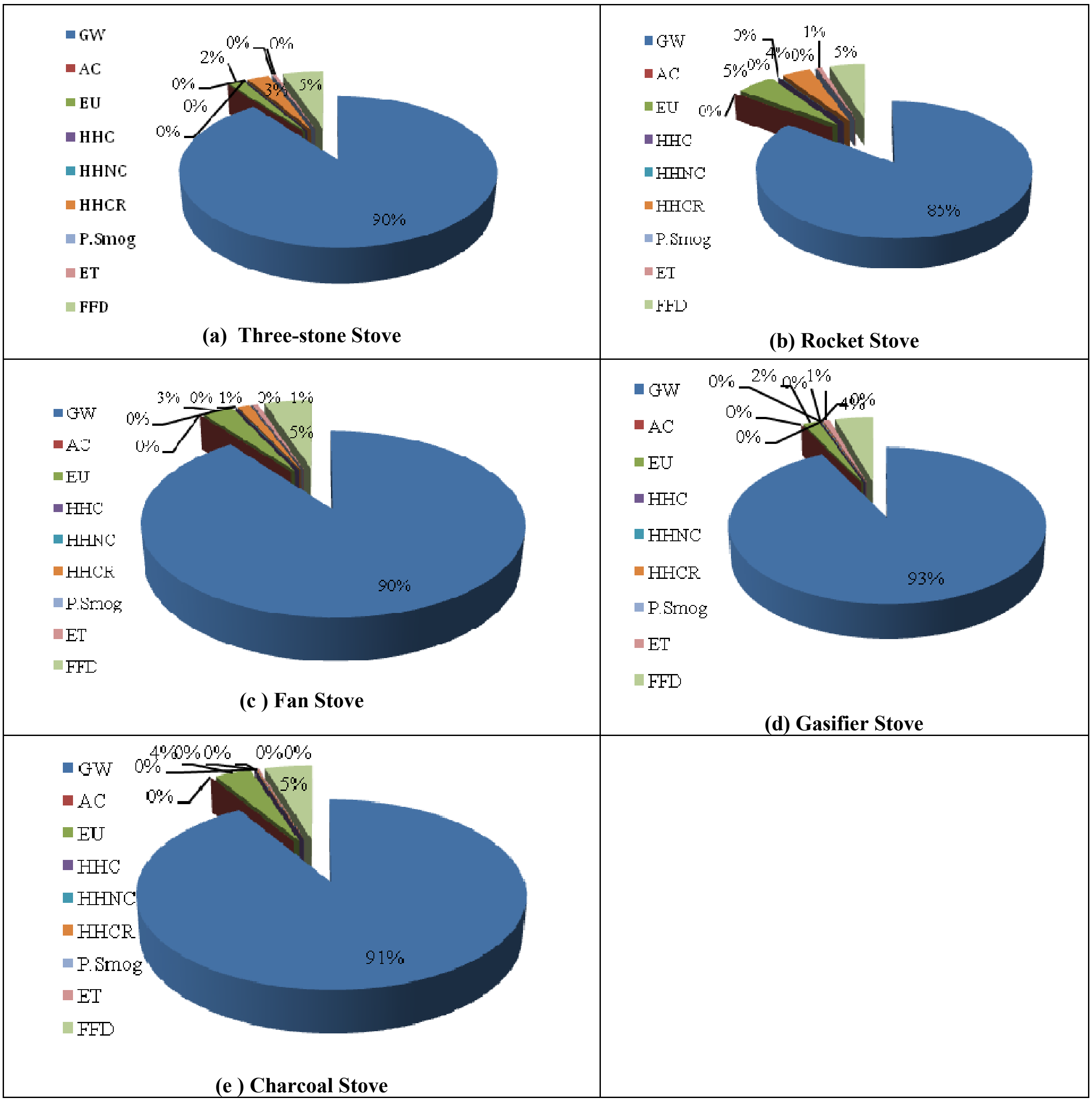


Fig.4. Percentage contribution of various potential impacts for various stove types (a) Three- Stone Stove (b) Rocket Stove (c) Fan Stove (d) Gasifier stove (e) Charcoal Stove

Table 1. Time Elapsed and Energy Consumption while boiling 1l of water and simmer it for 30 min with different cooking stoves in WBT

Stove Type	Time taken to boil & simmer for 30 min	KJ/lit (Sp. Energy consumption)	Remarks
Three- Stone	52	6553	Not required additional energy
Rocket	47	2470	Not required additional energy
Fan	37	2973	2.25KJ for 37min
Gasifier	55	3721	Not required additional energy
Charcoal	57	4216	Not required additional energy

Source: Nordica Maccarty *et al.*, 2008

Table 2. Emission categories and mass produced while boiling and simmering for 30 min (1lit water)

Emission Categories	Stove Types				
	Three- stone	Rocket	Fan	Gasifier	Charcoal
C_O2 (g/l)	536	206	277	356	300
Methane(g/l)	0.6	0.1	0	0.4	3
N20 (g/l)	0	0	0	0	0
C_O (g/l)	37	4	1	7	72
NOX (g/l)	0.5	0.7	0.6	0.6	0.7
Formaldehyde (g/l)	0.4	0.3	0.1	0.5	0.4
$PM_{2.5}$(mg/l)	240	140	5	50	75
NMHC (g/l)	1.4	0.3	0.4	1.5	2.5

Table 3. Comparison of Stove wise individual impact sharing on a daily basis

Impact Type	1 lit water for boiling and simmering for 30 mins					10l water/day				
	3- Stone	Rocket	Fan	Gasifier	Charcoal	3- Stone	Rocket	Fan	Gasifier	Charcoal
GW	3.01E+02	1.14E+02	1.52E+02	2.00E+02	1.99E+02	3.01E+03	1.14E+03	1.52E+03	2.00E+03	1.99E+03
AC	1.35E-02	1.57E-02	1.35E-02	8.98E-03	1.57E-02	1.35E-01	1.57E-01	1.35E-01	8.98E-02	1.57E-01
EU	6.06E+00	7.07E+00	6.06E+00	4.03E+00	7.07E+00	6.06E+01	7.07E+01	6.06E+01	4.03E+01	7.07E+01
HHC	7.34E-05	5.49E-05	1.83E-05	9.16E-05	7.34E-05	7.34E-04	5.49E-04	1.83E-04	9.16E-04	7.34E-04
HHNC	1.16E-01	8.72E-02	2.93E-02	1.45E-01	1.16E-01	1.16E+00	8.72E-01	2.93E-01	1.45E+00	1.16E+00
HHCR	9.14E+00	5.34E+00	1.90E-01	1.90E-01	2.85E+00	9.14E+01	5.34E+01	1.90E+00	1.90E+00	2.85E+01
P. Smog	5.26E-02	2.57E-02	8.38E-03	4.33E-02	7.32E-02	5.26E-01	2.57E-01	8.38E-02	4.33E-01	7.32E-01
ET	1.37E+00	1.03E+00	3.42E-01	1.71E+00	1.37E+00	1.37E+01	1.03E+01	3.42E+00	1.71E+01	1.37E+01
FFD	1.71E+01	6.44E+00	7.74E+00	9.69E+00	1.10E+01	1.71E+02	6.44E+01	7.74E+01	9.69E+01	1.10E+02
IEPS	3.3E+02	1.3E+02	1.7E+02	2.2E+02	2.2E+02	3344.39	1340.10	1661.48	2154.67	2213.44

Table 4. Energy consumption on a daily and yearly basis while cooking with various stoves type

Stove Type	Daily energy consumption/capita				Yearly energy consumption/capita			
	Time required For 10l/day	Time in hr	Energy consumed KJ/day/capita	Additional energy (KJ)	Time required/ year	Time in hr	Energy consumed KJ/year/capita	Additional energy (KJ)
3- Stone	520	8.67	65530		189800	3163.33	23918450	Not required additional energy
Rocket	470	7.83	24700		171550	2859.16	9015500	Not required additional energy
Fan	370	6.17	29730	22.5	135050	2250.83	10851450	8212.5
Gasifier	550	9.17	37210		200750	3345.83	13581650	Not required additional energy
Charcoal	570	9.50	42160		208050	3467.50	15388400	Not required additional energy

Relating with the energy consumption, the Three- Stone stove needs excess energy i.e. 6553 KJ/l for boiling 1lit water and simmer it for 30 minute followed by Charcoal, Gasifier, Fan, Rocket stove respectively of 4216KJ/l, 3721KJ/l, 2973 KJ/l and 2470 KJ/l as shown in Table 1. While concerning time to boil a lit. of water and simmer it for 30 min, the Charcoal stove takes more time among other i.e. 57min followed by 55min, 52min, 47min, 57min, 55min, 52min, 47 min and 37 min respectively in Gasifier, Three-Stone, Rocket and Fan stove as depicted in Table 1. Total EPS penalty percentage share with Three-stone stove is found to be higher i.e. 3.3E+02 followed by 2.2E+02, 2.2E+02,1.7E+02 and 1.3E+02, respectively of Charcoal, Gasifier, Fan and Rocket stove. The GWP has excessive contribution in the order as92%, 91%, 90%, 90%, and 85% respectively of Gasifier, Fan, Charcoal, Three-stone, Rocket while compared among their respective other impact categories contribution. The GWP computes with consideration of pollutants viz., CO_2, CH4, N_2O, Formaldehyde, $PM_{2.5}$ and Non-Methyl hydrocarbon (NMHC). In this way, GWP of Rocket stove is found lesser compared to other stove types. The similar result is found while compared with GWP of each stove type by Nordica Mac Carty *et al*., 2007 with vary in impact extent of individual stove types, derived from this study. The EPS of GWP of each stove type is found noticeable among other impact categories with a particular difference in an amount of CO, CO_2, CH_4, N_2O, NOx, NMHC, formaldehyde and $PM_{2.5}$ emisson.FFD, EU, and HHCR impacts cause by stoves are obtained comparatively more excessive than other impacts categories. This is because of use of fossil fuel for each type. The effect of FFD is due to NOx emission, and HHCRis due to $PM_{2.5}$, NOx, CO and CO_2 emission while burning stove. The HHCR impact is higher in Three–stone followed by Rocket as this stove produces excess amount of CO, CO_2, and $PM_{2.5}$. Based on a result of total EPS and its analysis, it has shown that Three-stone stove is found as the worst among other stoves for GWP, HHCR and FFD mentioned in Fig. 3. Rocket stove has more impact contribution for AC and EU. While concerning with HHC, HHNC and ET impacts, Gasifier stove contributes more than other stove types. Likewise, Charcoal stove contributes more impact on P. Smog among four other types.

While concerning with the total EPS, Three-stone is found to be 2.5, 2.01, 1.54 and 1.51 times higher than Rocket, Fan, Gasifier and Charcoal stove, respectively. From a result of impact computation, Rocket stove is found to be less impacting to environment and health followed by Fan, Gasifier, and Charcoal. Moreover, the use of Rocket stove adds more economic value as it is available with cheap cost as compared to other types of cook stoves. On the other way, Rocket stove requires less amount of energy although it takes additional 10min than Fan stove. Moreover, the Fan stove requires additional energy i.e. 2.25KJ for 37min to operate it.The energy consumption for the fan stove is also higher i.e. 80.35KJ/min than Charcoal, Gasifier and Rocket stove with the respective energy consumption of 73.96KJ/l, 67.65KJ/l and 52.55KJ/l. Hence, the Rocket stove is the most appropriate stove to use for cooking job as it is less polluting and consuming less energy among other stoves.Rocket stove is standing as an efficient stove as it consumes less energy to boil and simmer the water as compared to other stoves types as shown in Table 4.Rocket stove permits to transfer the energy from fuel to the cooking pot efficiently without unnecessary heat loss in surrounding.The energy consumption while cooking with the Rocket stove is also less as compared to other stove types. Hence, less firewood is required while cooking as compared to other stove that would also have contribution in reduction of rate of deforestation as well as savingthe climate. World widely, 2.2 billion people are user of the Three-stone cook stove which is standing as an inefficient and more polluting stove among other common types of stoves. With the current statistics with this study, the stove has 7.36E+12 impacts with the consumption of 1.44E+14KJ per day energy world widely. This is forcing on climate and human health and also in deforestation. More than half of the total use of the residential energy and 80% of households' energy is used for cooking respectively in developing countries and other poor countries (Goldemberg *et al*., 2000).Promotion of improved cook stoves are the cheapest and efficient way to save fuel input. Therefore, the policy interventions are required to target this group of biomass users. This helps to achieve the higher levels of energy efficiency with the reduction of pollution concentration that is harmful to the environment and human health. For this, the less impacting stove should be enforced legally and promote socially.

CONCLUSION

Out of five cook stoves, the highest EPS penalty is obtained with the Three-stone followed by Charcoal, Gasifier, Fan and Rocket stove. The integrated EPS of Three-stone traditional cook stove found 2.5 times higher than Rocket stove and 2.2 times higher than Fan stove. Based on the IEPS, this study concludes that the use of Rocket stove contributes in lowering the health and environmental impact followed by Fan, Gasifier and Charcoal. The market price of the Rocket stove, cheaper than other stove types, helps to save the economy as well. However, the Three-stone stove needs replacement legally to protect health and environment as well as to save the unnecessary loss of energy of the related country. The energy consumed by the Three- stone firing is 2.65, 2.20, 1.76, 1.55 times more than Rocket, Fan, Gasifier and Charcoal stove respectively. Hence, the traditional Three-stone stove is not only harmful for environment and health of the people but also inefficient. Therefore, this study recommends for the consideration of pollutants released while burning the stove as well as the amount of energy consumption while assessing the stove. Hence, it can easily be predicted health and environmental burden caused by stoves and its efficiency. Based on the valid scientific result, it is helpful to motivate the public for using less-polluting and efficient stove to reduce the adverse effect on environment and human health and reduce forced on climate.

Acknowledgement

Authors would like to thank Mrs. Jane Bare, National Risk Management Research Laboratory, United States EPA for her valuable suggestion during the modeling with TRACI.

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