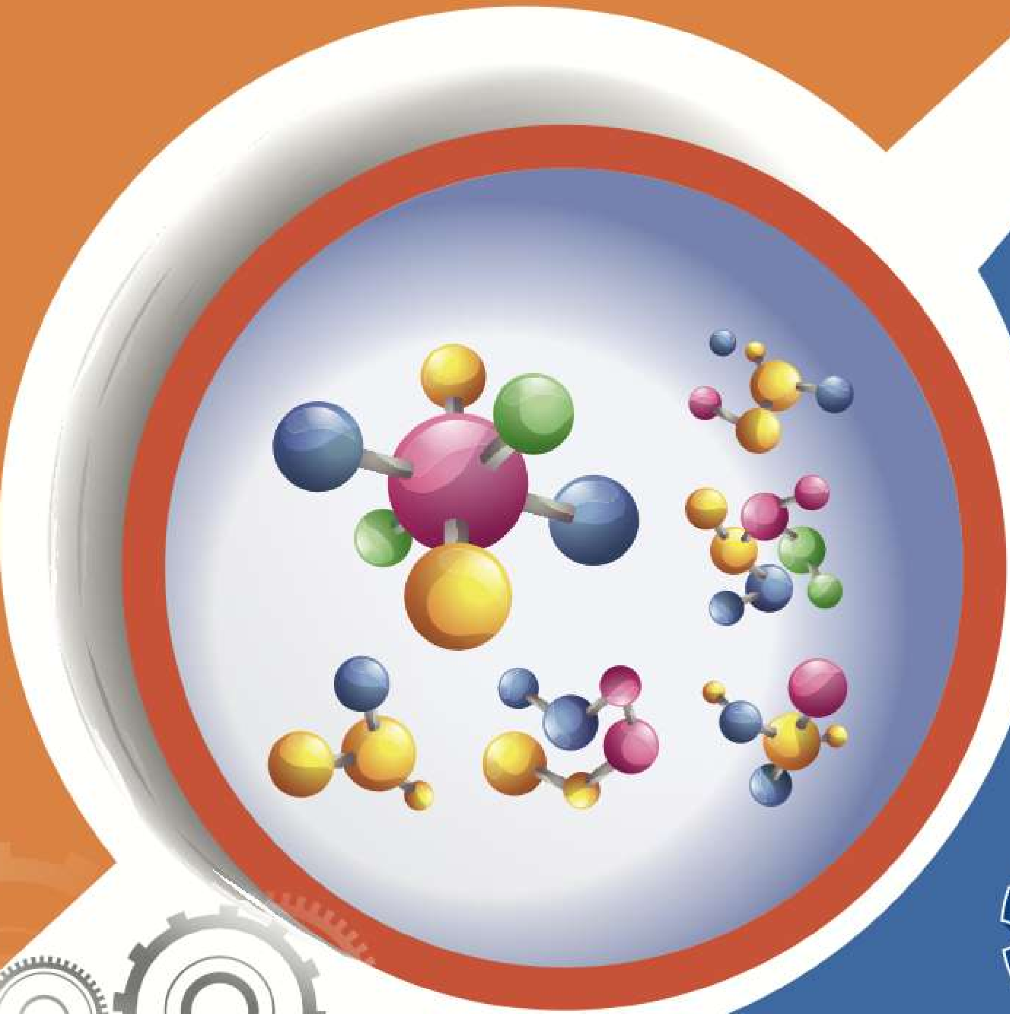
JOURNAL OF
CHEMICAL ENGINEERING



JOURNAL OF CHEMICAL ENGINEERING
The Institution of Engineers, Bangladesh
Vol.ChE 32, No. 1 , 2024

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Fuel Consumption Practices on Khulna Region: A Comparative Study on Traditional Fuel and Clean Fuel Use

Mahmudul Hasan Niaz*, Ahad Almahmood* Syda Wasy Yelmi, Mohammad Nahidul Islam and Sk. Yasir Arafat Siddiki

To cite the article:

Mahmudul Hasan Niaz*, Ahad Almahmood, Syda Wasy Yelmi, Mohammad Nahidul Islam and Sk. Yasir Arafat Siddiki, “Fuel Consumption Practices on Khulna Region: A Comparative Study on Traditional Fuel and Clean Fuel Use”, Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 1-7.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Journal of Chemical Engineering, IEB
Vol. ChE 32, No. 1, April 2024

Fuel Consumption Practices on Khulna Region: A Comparative Study on Traditional Fuel and Clean Fuel Use

Mahmudul Hasan Niaz*, Ahad Almahmood*, Syda Wasy Yelmi, Mohammad Nahidul Islam and Sk. Yasir Arafat Siddiki
Department of Chemical Engineering, Khulna University of Engineering & Technology, Khulna-9203, Bangladesh,
E-mail: niaz1829005@stud.kuet.ac.bd, ahad.mahmood1947@gmail.com

Abstract: The study involves fuel consumption practice on Khulna region of Bangladesh, to identify the determinants working behind the scenario and effects on environment as well as the socio-economic life of the people. To accomplish the motive, six rural villages Maheswarpasha, Telegati, Jabdipur, Mirerdanga, Shiromoni and Jogipol of Khulna district, located outside of city corporation on which fuel mapping is incomplete, have been considered as the study area. 60 family samples have been collected to understand the use of traditional fuel for household cooking, their impact on users and drawbacks, affordability and interest of using clean gases like LPG, LNG fuels. Traditional fuels cause indoor air pollutions which create severe impact on the users and environment. But according to this study 59% of the people use traditional fuel. The household of the rural people should use more alternate fuels than traditional one and better cooking methods like improved cook stoves for a better fuel consumption experience, saving cooking times, escaping health hazards and reducing air pollution.

Keywords: *traditional-fuel, alternate-fuels, pollutions, health hazard, improved cook stoves*

1. Introduction

Bangladesh is a densely populated country with a large amount of people living under the poverty line. At the national level of the economy, poverty rates are still relatively high which is close to 40%. More than 60 million people still live in poverty, with two thirds of them in the most terrible circumstances [1]. 4% of the population are covered with centralized gas connection and almost 80% people who lived out of metropolitans depend on traditional fuels for their household cooking. Biomass, wood, dried cow dunk, agricultural residue are the main types of fuels they use as their cooking fuels. Traditional fuels at rural areas are frequently used because of availability, low costs and long period practices in those areas [2]. The fuel consumption is scattering towards cleaner and user-friendly fuels like LPG which indicates the concern of cooking hours, pollution etc. At 2018 the demand for LPG in Bangladesh was about 750,000 MT, and by 2025 it will increase by 25 percent to be at 250,000 MT.LPG has already grabbed 16% of national fuel consumption for cooking. But the pricing of a 12KG LPG cylinder was almost 1200-1300 BDT which is very higher in terms of expenditure against fuel buying for the lower class and middle-class people as they want to spend as less as possible [3]. Various factors like the socio-economic structure of rural areas, monthly income of the family, family size, food taste variation on fuels, cooking hours, and age of person involved on cooking are behind the different practices on fuel consumption. Rice et al., reported that Bangladesh ranks eleventh best among the fifty-two developing nations that the World Bank evaluated in 2019 for their regulatory frameworks on clean cooking. In terms of energy efficiency, it scored only 44% while massive use of traditional fuels in undeveloped infrastructure causes huge energy loss [4]. Sagar & Kartha et al., have found that because inefficient fuel burning produces gases like methane and carbon monoxide that have a greater potential for global warming than carbon dioxide, cooking with traditional fuels and biomass can have an impact on the environment. Several socio-economic factors influence the use of traditional fuels that varies geographical area wise and behaviour of consumption [5]. Ahmed et al., has found biomass, wood etc. have major contribution on rural areas fuel necessity because of the availability and costs. At least 50% of the total consumption in these areas depend on wood and dried life [6].

Table 1. Wood cost per kilogram in Bangladesh on 2017

Types of Fuel	Dhaka (Taka per Kg)	Jessore (Taka per Kg)
Dried Wood	7.5/7	5
Wood from rice husk	10	9

The Table-1 shows that the price of traditional fuel is cheap on the rural areas, which influence users to consume it without thinking the health or environmental effect of it.

Kumar et al., reported that the health of those who use traditional stoves and their families is at risk because of the absence of vent pipes and poor home ventilation that allowed smoke to accumulate in the kitchen. Firewood is the most common type of cooking fuel in the world which claims at least 75% of total fuel use worldwide that indicates massive use of traditional fuels [7]. Aziz, et al., reported that due to diminishing domestic gas reserves, the government halted providing new natural gas distribution in 2016–2017. As of 2018, approximately 4 million households were linked to a natural gas pipeline which basically increases the demand of LPG cylinders for household cooking [8]. Ahmed et al., also found as no piped supply distributed on Khulna, Rajshahi, Barishal and Rangpur division, LPG plays a big role as cooking fuel on that region of Bangladesh. But the expenditure is very expensive for lower- and middle-class people as it costs on average 1000BDT and a family of five members need at least two cylinders per month and the government has no control on these markets as the private companies holding almost the whole stake of the market [6]. Miah, et al., have found 95% of households on Bangladesh use biomass and related mix-up fuels for household cooking where 40% of them are collected from nearby forests shows intends towards deforestation and pollution through incomplete combustion by using traditional fuels [9]. A literature gap on fuel consumption information and the potentiality of the market to use alternative fuels on the rural areas. This study is proposing to fill this gap selecting rural villages on Khulna district considering the socio-economic infrastructure of the users and various factors that influence the practice of fuel consumption behaviour. The major objectives of this study to explore the fuel consumption practice for cooking on Khulna region, estimation of average cooking hours and reasons behind the difference of cooking hours, and to understand the fluctuation of clean fuel uses over traditional fuels with the factors compensate the user behaviours.

2. Methodology

The primary data on which the study conducted has been collected from field survey. Six different villages were taken as the survey area considering the distance and time, affiliation with the local people and the cost on conducting the survey. The study area was taken outside of Khulna city corporation area to achieve variation in the socio-economic structure on the survey. 60 respondents, 10 from each village were taken by simple random sampling techniques and data was taken from all economical class. The person involved on cooking mostly the women of the household were taken as the respondents to achieve the actual data including fuels costs and sourcing, cooking hours, reasons behind choosing fuels, willingness of using better alternate fuels and the financial influence on the fuel consumption.

Two different methods were used to analyse the data. In inferential analysis method, amount of fuel consumption monthly, household income, cooking hours etc. were estimated by hypothesis testing. In descriptive analysis by using quantitative data analysis, costs of traditional and clean fuel users, number of users of the fuels individually have measured by verbal description and figures.

3. Result and Discussion

The data collected from six rural villages Maheswarpasha, Telegati, Jabdipur, Mirerdanga, Shiromoni and Jogipol of Khulna district, Bangladesh has been used to analyze and create a general model of fuel usage practices in rural Bangladesh. The cook who participated in the study had the purpose of cooking only for households. Almost all of the participant were women of different ages. No commercial fuel users were included. The study includes the comparison of fuel users on the basis of socio-economic factors and geological position. The study compares the cooking time fluctuation on the basis of fuel usage types.

3.1 Fuel usage difference on basis of geological position

Figure 1 shows that the fuel usage practice fluctuates from village to village. In Telegati 63% of the participants in the survey use traditional fuel and only 37% of the participants use clean fuel. In Jabdidpur, Mirerdanga, Jogipur the result is almost similar to that of Telegati where, respectively, 54%, 59%, and 60% of the participants use Traditional Fuel. These are almost the same as that of the overall fuel usage. In Mashwarpasha it is seen that the traditional fuel use has been raised up to 75%, which is the zenith of traditional fuel usage. It is a 26% jump in usage of traditional fuel usage compared to that of overall. In Shiromoni we see an exception to the trend where more participants of the study used clean fuel than that of the traditional fuel. Here, 58% use clean fuel, which is a 17% rise compared to that of the overall. The traditional fuel user is only 42%. So, it is clear that people's fuel choices differ with the variation of geological position.

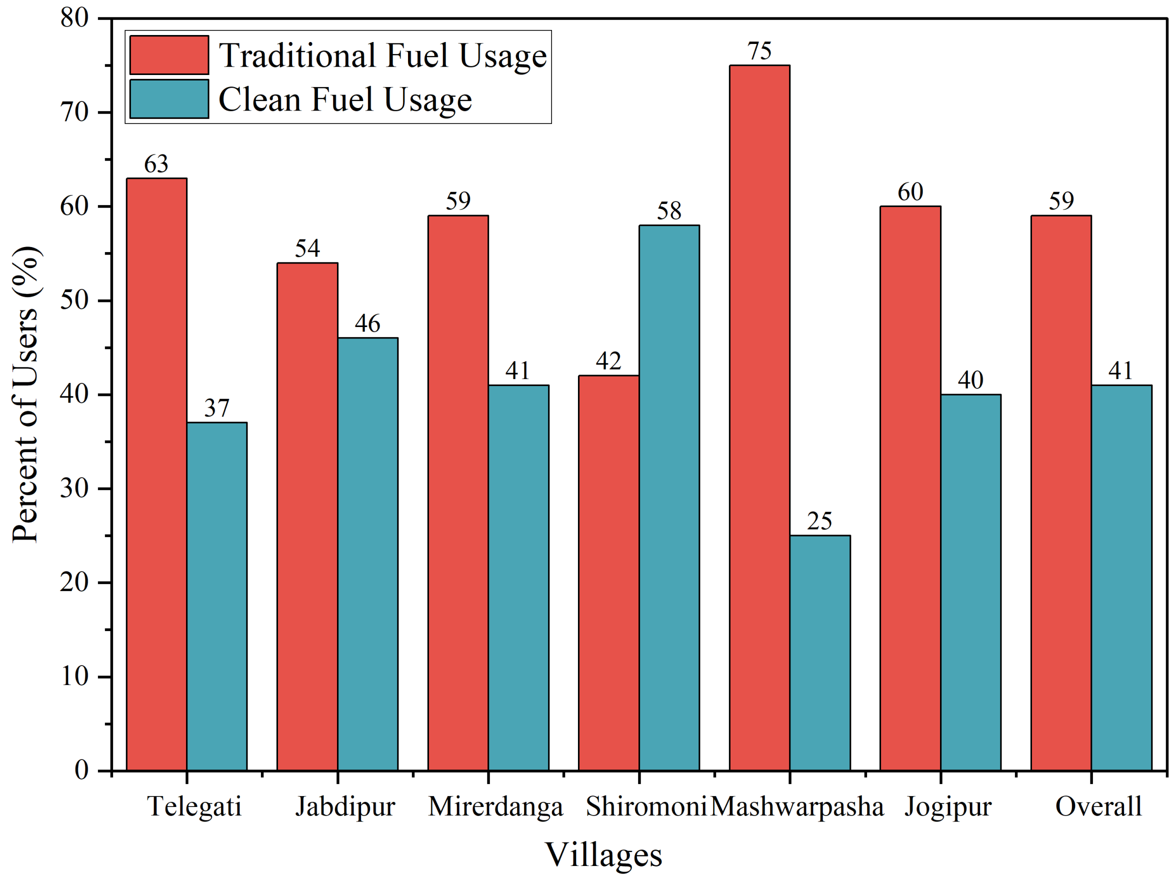


Figure 1. Comparison between Traditional and Clean fuel usage in different villages (Source: Authors' Estimation Based on Field Survey, 2019)

3.2 Average cooking time in different villages

Figure 2 projects the average cooking hour in different villages. Here the overall cooking time of the village is 2.85 hours, which is quite large in modern times. Here, the average cooking hour of Telegati is 3.2 and Mashwarpasha is 3.4, which are 0.35 and 0.55 hours greater than that compared to the overall respectively. Jogipur has cooking hours similar to that of overall, where, in Jabdipur, Mirerdanga, Shiromoni the average cooking hour has decreased by 0.20, 0.10 and 0.60 hours than that of the overall.

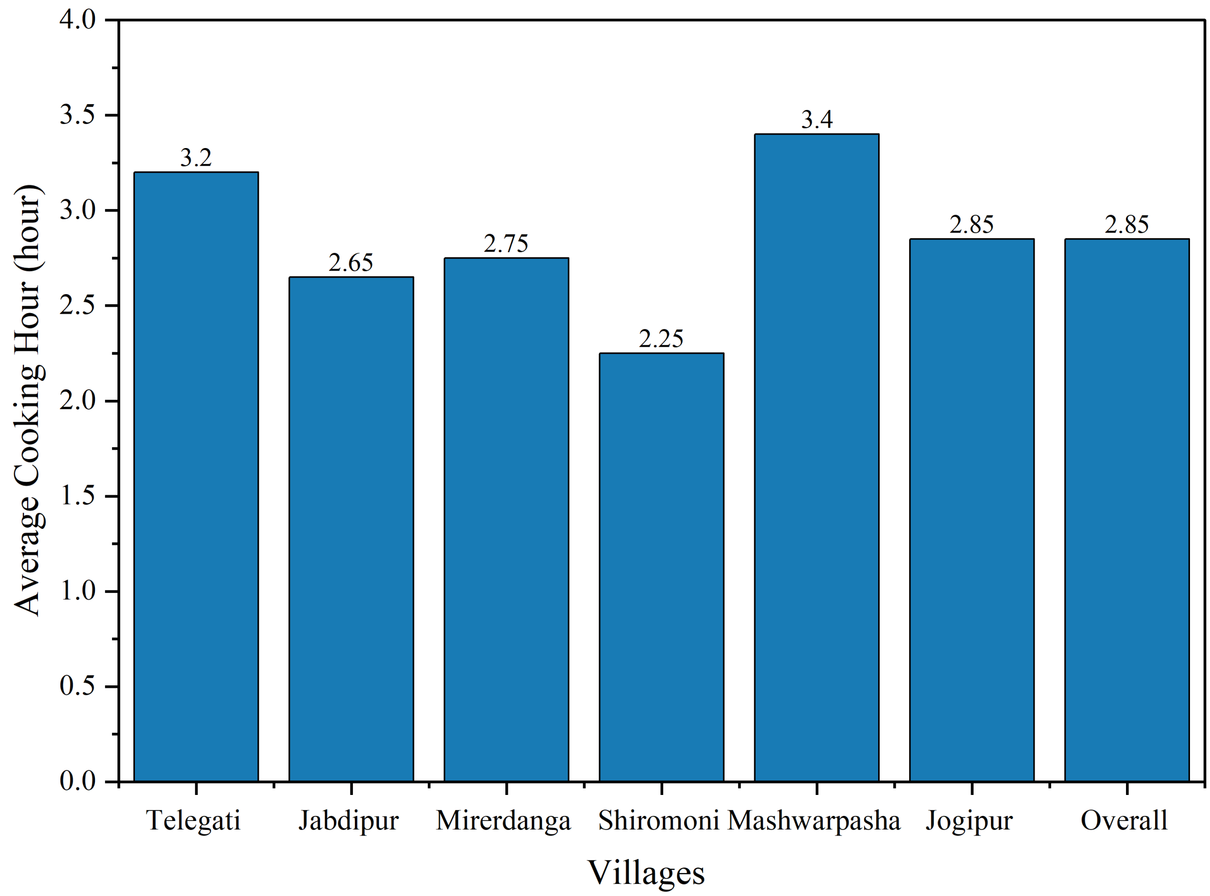


Figure 2. Average cooking time in different villages. (Source: Authors' Estimation Based on Field Survey, 2019)

Comparing Fig. 1 and Fig. 2 we can see that Telegati and Mashwarpasha have the largest cooking hours, where they have the largest traditional fuel usage also. Shiromoni had the least cooking hours and the largest clean fuel usage. Analysing the comparison between Fig. 1 and Fig. 2, a relationship can be established between the fuel choice and average cooking hour. The traditional fuel usage increases the cooking hour, the clean fuel usage decreases the average cooking hour.

4. Conclusions and Future Recommendation

This study focuses on the fuel usage by households in six villages of rural Bangladesh. The main focus was on mainly the two types of fuel: traditional fuel and clean. The study was conducted in the month of November, 2019, which is the winter season in Bangladesh, so the result may vary with that of the other seasons, since the resources and availability of the traditional fuel change with the change of weather. It was found that the fuel type does not vary much except in the village Shiromoni. Cooking time also does not vary much except Shiromoni and Mahshwarpasha. It was also found that the fuel type varies with the socioeconomic factors like monthly income.

Traditional fuel consumption causes more indoor air pollution, where using clean gases like LPG, LNG fuels causes less indoor air pollution. But according to this study 59% of the people use traditional fuel. Indoor air pollution directly affects human health. As the result of this study, we can suggest decreasing clean fuel prices to influence people to use clean fuel, since monthly income is related to clean fuel consumption, Das et al., also suggest Bondhu Chula [10], which is a locally invented, improved stove, which is also being suggested by the local agricultural department and by the agricultural ministry can also be an alternative to clean fuel. It is costs very low to install one, and also requires very low maintenance. So, Bondhu Chula is a good initiative to decrease indoor air pollution since, majority of people use traditional fuel. On the basis of this study, doing more research on fuel consumption practices in different regions, in different seasons, on the basis of family size, types of fuel availability, family education etc. is suggested to be done for generating an overall model of fuel consumption practice in rural Bangladesh.

5. Reference

1. Ali, E. & Talukder, D., 2010. Analysis of Poverty Dynamics: Bangladesh Perspective. *Journal of Third World Studies,* Volume 27(1), pp. 273-284.
2. LGED, 2006. *Bioenergy study - Bangladesh,* Bangladesh: Local Government Engineering Department.
3. Mehedi, M., Bhuiyan, M. & Jalal, M., 2021. Challenges of LPG Supply, Distribution and Pricing in Growing Market: Bangladesh Case Study. *American Journal of Agricultural Science, Engineering, and Technology,* Volume 5(2), pp. 11-25.
4. RISE, 2019. *Clean cooking. Retrieved from Regulatory Indicators for Sustainable,* s.l.: The World Bank Group.
5. Sagar, A. & Kartha, S., 2007. Bioenergy and sustainable development? *Annual Review of Environment and Resources,* Volume 32(1), pp. 131-137.
6. Ahmed, S., 2017. Fuel Options for Bangladesh-2017. *Journal of Chemical Engineering,* Volume 30(1), pp. 27-31.
7. Kumar, A., Prasad, M. & Mishra, K., 2013. Comparative study of effect of different parameters on performance and emission of biomass cook stoves. *International Journal of Research in Engineering & Technology,* Volume 1(3), pp. 121-126.
8. Aziz, S., Barua, S. & Chowdhury S.A., 2022. Cooking energy use in Bangladesh: Evidence from technology and fuel choice. *Energy,* Volume 250, p. 123696.
9. Miah, M., Al Rashid, H. & Shin, M., 2009. Wood fuel use in the traditional cooking stoves in the rural floodplain areas of Bangladesh: A socio-environmental perspective. *Biomass and bioenergy,* Volume 33(1), pp. 70-78.
10. Das, D. et al., 2021. Is there any demand for improved cooking stoves? Evidence from Bangladesh. *Journal of Environmental Management,* Volume 298, p. 113412.

6. Appendix A

"Energy Survey Questionnaires (Household)- November 2019

1. What is your name?
2. What is the size of your family?
3. How many earning members are there in the family?
4. What is the main source of income of your family?
5. What is the source of electricity at the house grid/solar/other?
6. What type of fuel do you use generally wood/loose biomass/kerosene/LPG?
7. What is your average consumption of fuels per month/week?
8. What is your preferred fuel? Please mention the reasons for preference.
9. How frequently do you purchase fuels? Please mention your typical purchase volume.
10. How much do you have to pay monthly to pay for purchasing fuels?
11. Is the fuel affordable?
12. What is the fuel used for cooking?
13. For what other purposes is the fuel used for in household lighting/vehicle/pumps & irrigations/others?
14. Are you satisfied with the fuel's quality that you are currently using?
15. How much time spent per day for cooking?
16. For what other purposes is the fuel used for in the household?
17. Are you willing to pay for reducing cooking time using better fuel/stove?
18. If there were any alternative fuel in the market, would you use it?
19. What is you expectation from an alternative fuel cheap/safe/after sales service/wide supply/easy to use environment friendly/commission on purchase/other?
20. Relative contribution in total earning by both male and/or female?
21. Have you borrowed money or taken out a loan?
22. For what purpose have you taken money/loan?
23. Do you participate in or are you a member of any social, political, or religious organizations?
24. How many children do you have?
25. Among the children who helps out in the household more?
26. What level of education would you like to see for your girl and/or boy?
27. If you could ensure more free time for them, what would you like to see them do?"

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Log Data-Driven Prediction of Rock Strength Using Least-Square Support Vector Machine Approach: Case Study of a Gas Well Reservoir

Mohammad Islam Miah[1*], and Mafruha Akhter Ovi[2]

To cite the article:

Mohammad Islam Miah[1*], and Mafruha Akhter Ovi[2], "Log Data-Driven Prediction of Rock Strength Using Least-Square Support Vector Machine Approach: Case Study of a Gas Well Reservoir", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 8-15.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Journal of Chemical Engineering, IEB
Vol. ChE 32, No. 1, April 2024

Log Data-Driven Prediction of Rock Strength Using Least-Square Support Vector Machine Approach: Case Study of a Gas Well Reservoir

Mohammad Islam Miah[1*], and Mafruha Akhter Ovi[2]

[1] Department of Petroleum and Mining Engineering, Chittagong University of Engineering & Technology, Chittagong- 4349, Bangladesh
[2]Department of Basic Sciences, Primeasia University, Dhaka- 1213, Bangladesh.
*Corresponding Author: islam.m@cuet.ac.bd

Abstract
An accurate estimation of uniaxial compressive rock strength (UCS) is crucial for wellbore failure analysis to protect a gas well blowout during drilling operation, sand protection, and safe reservoir management. The main objectives in this paper are a) to assess the suitability of machine learning-based connectionist model using geophysical log data and b) effects of predictor variable on rock strength estimation. The machine learning technique of least square support vector machine (LSSVM) is utilized to construct the data-driven connectionist model while predicting of UCS. The predictor variables are obtained gas reservoir log data of subsurface sandstone formation in the Bengal basin which utilized to obtain the output. For the evaluation of predictive model, statistical parameters such as correlation of determination (CC), and average absolute percentage relative error are applied in the study. According to the simulation study, it is found that the LSSVM-based model is performed excellent with the least error and high CC to predict UCS. The predictor variable of gamma-ray has major effects on UCS estimation rather than other input variables of formation bulk density, modules of elasticity and acoustic waves. These systematic research steps can be applied for connectionist model development and feature ranking to the petroleum industry such as predicting of reservoir rock and fluid properties, production optimization, and sanding potentiality of gas wells.

Keywords: Machine learning; Variable effects; Rock strength, Gas reservoir, Wellbore stability.

1. INTRODUCTION

An accurate estimation of uniaxial compressive rock strength (UCS) is crucial for wellbore failure analysis to protect a gas well blowout during drilling operation, sand protection, and safe reservoir management. The rock strength parameter of UCS can be measured through experimental measurements using standard core specimen. In general, an accurate rock (core sample) specimen preparation is very costly and time-consuming with keeping stress unloading and loading into the sample [1,2]. When the direct testing is not possible with capturing the subsurface gas reservoir environment to obtain sample collections for precise core specimens, the geophysical log data are the alternative option to obtain continuous profile of dynamic rock strength parameter of UCS. Accurate rock modeling and reliable rock strength parameters are important for evaluating of sanding potentiality and wellbore failure analysis during safe drilling operations. Several studies by different scholars have been done with a focus on the corresponding their research methods, limitations and scopes while obtaining rock geomechanically parameters and rock strength of which can be found available literature [3-6]. Based on the literature survey, it is revealed that a systematic comprehensive investigation is required to investigate the applicability of connectionist model with machine learning approach while obtaining rock strength, and effects of predictor log variables on UCS estimation for clastic sedimentary rock of gas reservoir in the Bengal basin.

The major objectives in this paper are a) to assess the suitability of machine learning-based connectionist model and b) effects of predictor variable to obtain rock strength of UCS using geophysical log data of a gas reservoir.

2. MATERIALS AND METHODS

The available field well logs data of formation gamma-ray (GR), bulk density (RB), compressional wave velocity (Vp), shear wave velocity (Vs) and modulus of elasticity (E) are adopted as predictor variables, while the target variable is the rock strength parameter of dynamic UCS, respectively. The process of geophysical log data quality is led to ensure the reliability of each log dataset variables. Furthermore, the machine learning technique is applied to develop the connectionist models using Mathlab and Python programming environment. In the project, hybrid connectionist tool of least square support vector machine (LSSVM) with coupled simulated annealing (CSA) is utilized to develop predictive model because of it is capable to handle high-dimensional complex relationships among real field core and log data variables [4,7,8]. In the study, the coupled-simulated annealing (CSA) optimization process applied which is proven to be more effective than multi-start gradient descent technique [9]. A typical methodological flowchart is shown in Figure 1, which will be adopted to assess the rock strength parameter using hybrid connectionist models using dynamic log data.

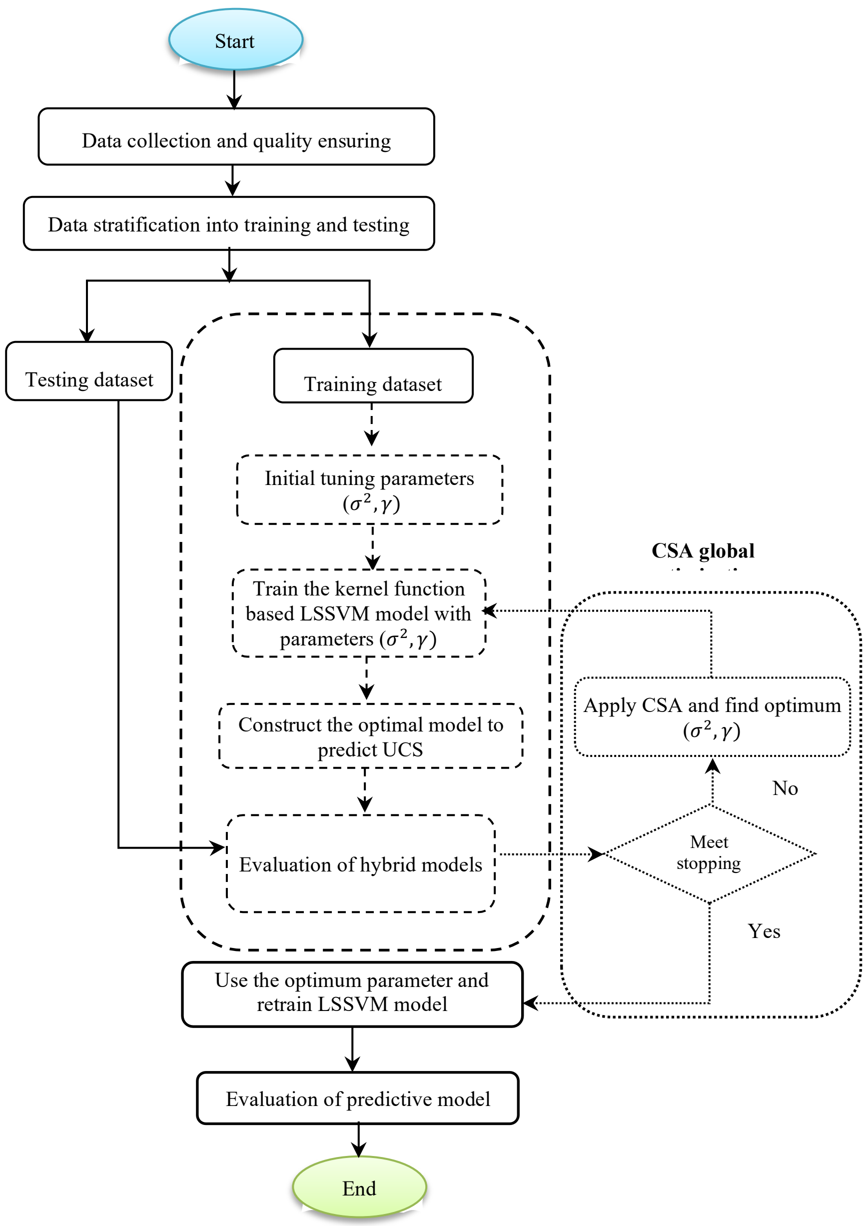


Figure 1: An illustration of hybrid connectionist model with LSSVM-CSA with major steps (Modified from [3]).

In the Gaussian radial basis kernel function (RBF)-based LSSVM model, the kernel and hyper-parameters of γ and σ^2 are tuned through a global optimization technique of CSA [10]:

$$K(x, x_i) = \exp\left(-\frac{(||x_i - x||)^2}{2\sigma^2}\right) \tag{1}$$

Additionally, the following mathematical model of LSSVM is applied to obtain output of rock strength parameter when b is the bias term and α is a weight factor, x is the training sample; and x_i refers to the support vector:

$$y(x_i) = \sum_{i}^{n} \alpha_i K(x, x_i) + b \tag{2}$$

In the study, the total samples will be categorized into two groups (such as, 65 % for training, and 35% for testing phases) in the LSSVM connectionist model with the CSA optimization approach. Additionally, the statistical performance indicators (SPIs) are used in this study to analyze the predictive model performance. In the study, the model is best for the higher value of CC and minimal error of AAPE using single-input and single-output strategy', approach and vice-versa. The mathematical equations for the SPIs to evaluate the model performance are mentioned below:

$$AAPE = \frac{1}{n}\sum_{i=1}^{n} \frac{(UCS_{t,i} - UCS_{p,i})}{RSP_{t,i}} \tag{3}$$

$$CC = 1 - \frac{\sum_{i=1}^{n}(UCS_{t,i} - UCS_{p,i})^2}{\sum_{i=1}^{n}(UCS_{t,i} - UCS_{t,mean})^2} \tag{4}$$

Where, n denotes the total number of data points, UCS_t denotes the target value of rock strength parameter UCS), $UCS_{t,\ mean}$ is the mean value of UCS_t, and UCS_p indicates the predicted output variable.

3. RESULTS AND DISCUSSION

3.1 Data Analysis

In this study, the geophysical log data samples are collected from a gas field of sandstone reservoir in the Bengal basin. In total, 183 samples of petrophysical log data adopted as the predicting variables, named gamma-ray (GR), bulk density (RB), sonic acoustic compressional velocity (Vp), shear wave velocity (Vs), modulus of elasticity (E) and the target variable of uniaxial compressive strength (UCS), respectively. The magnitudes of the geophysical log data samples under consideration differ significantly from one sample to the next as a result of formation depth, reservoir rocks' composition, and their diagenesis. The maximum and minimum values of UCS (MPa) over the entire lithology with sandstone formation are 42.60 and 26.57, respectively while the average value of UCS is 31.13. The following Table 1 depicts a summary of the statistical values of the predictor variables and target variable of dynamic rock strength, UCS.

Table 1: Summarized statistical values of studied variables in the study.

Statistical Values	GR (API)	RHOB (g/cm^3)	Vp (Km/sec)	Vs (Km/sec)	E (GPa)	UCS (Mpa)
Maximum	157.82	2.53	3.5506	1.9903	24.17	42.60
Minimum	76.28	2.30	3.1294	1.6498	17.02	26.57
Average	100.19	2.37	3.2893	1.7927	19.61	31.13
Standard deviation	13.84	0.04	0.0862	0.0702	1.47	2.76

The matrix of correlation between petrophysical log variables and uniaxial compressive strength and modulus of elasticity is shown in Figure 3 in order to represent the variable features.

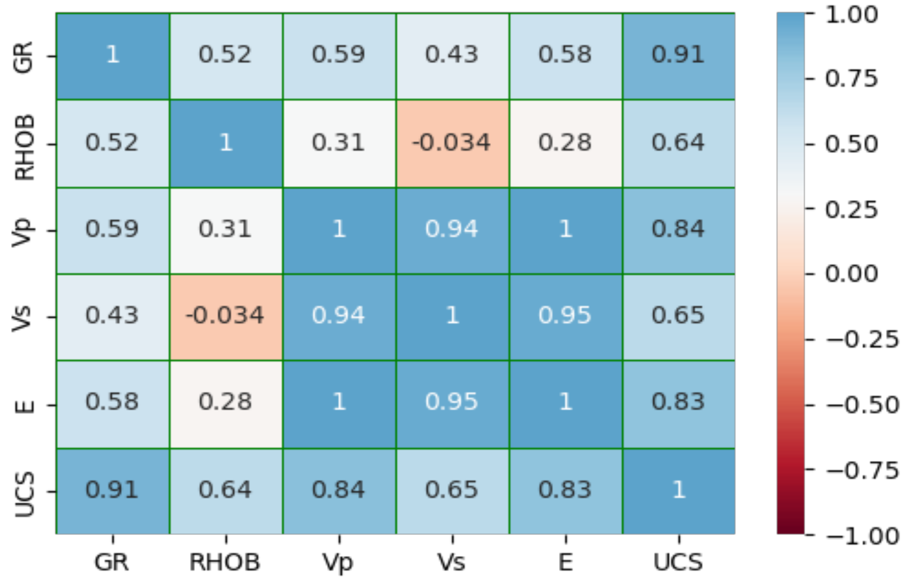


Figure 3: Heatmap of relationship between predictor and target variable of UCS.

3.2 Assessment of LSSVM-CSA based Predictive Model

In the predictive model development of UCS, the 'single variable elimination' strategy is applied to find the relative importance of predictor variable using statistical parameters for each training and testing data phases. In the study, the training dataset contains 65 % data while testing dataset covers 35 % data. To ensure the model's performance with data stratification, trial and error approach is conducted to avoid the overfitting of the training dataset. In the predictive models with an input of single variable, the gamma-ray and compressional wave velocity variables have more impacts with high precision and minimal error which shown in Figures 4 and 5 respectively on the UCS prediction than the other variables of shear wave velocity, modulus of elasticity and formation bulk density using LSSVM-CSA approach.

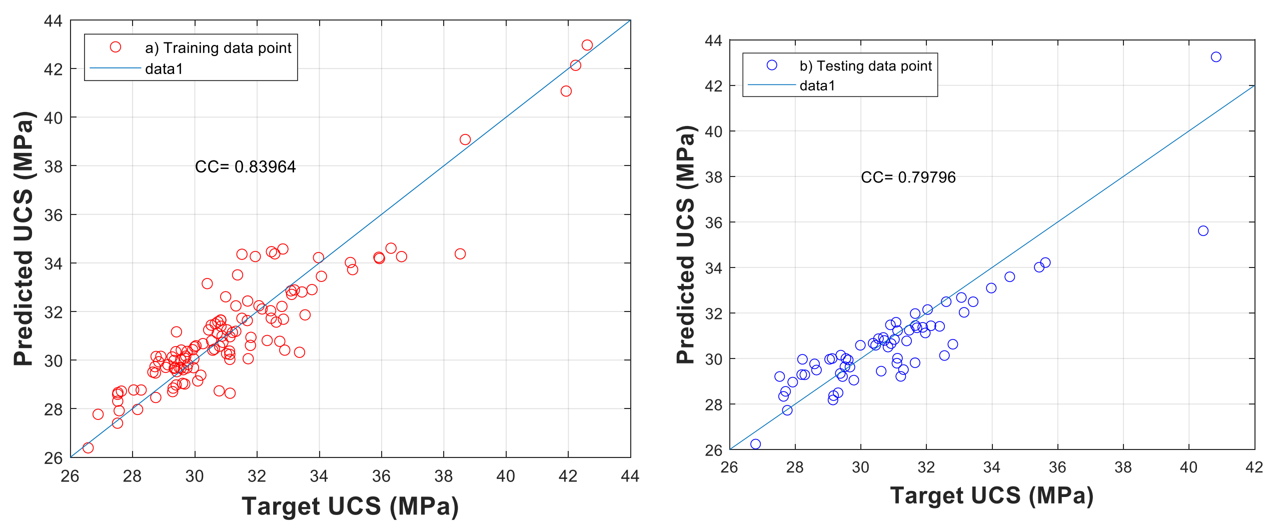


Figure 4: A representation between target and predicted results of UCS with GR for a) training and b) testing data sets.

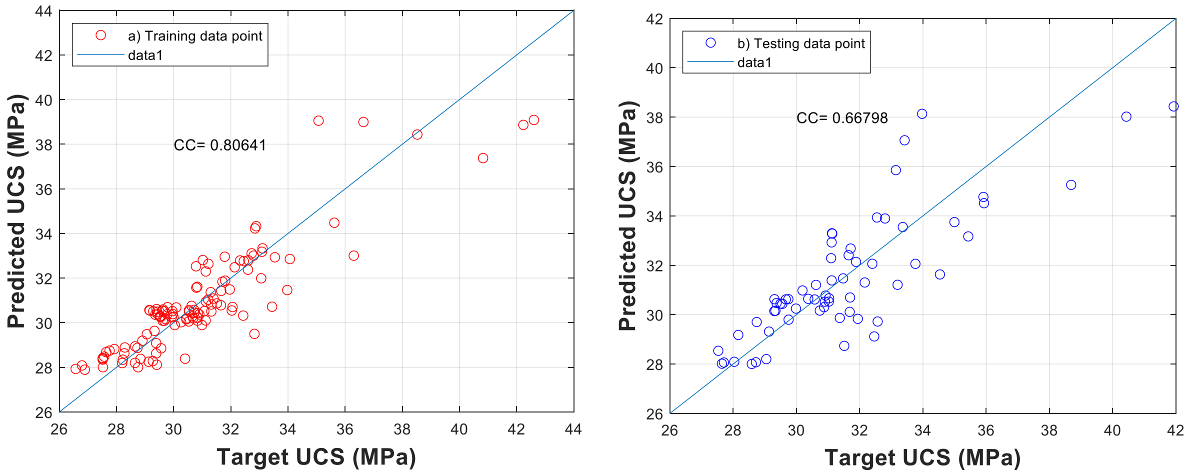


Figure 5: A representation between target and predicted results of UCS with Vp for a) training and b) testing data sets.

According to the simulation studies, the detailed performance of each model scheme such as models 1-5 with single input variable in the predictive model of UCS for LSSVM is shown in Table 2. The graphical representation of relative performance of the predictive models using LSSVM method is shown in Figures 6-7.

Table 2: Relative significance of the predictor variables to obtain UCS with LSSVM-CSA approach.

Model Scheme No.	Input variable	CC (%) Training (Testing)	AAPE (%) Training (Testing)	Hyper parameters: b; γ; σ^2
1	GR	83.96 (79.80)	2.72 (2.69)	-0.44; 1120; 2.07
2	Vp	80.64 (66.80)	2.75 3.10	0.62; 3.72; 1.66
3	E	79.03 (55.19)	2.62 (4.10)	0.63; 4.36; 0.17
4	RB	61.50 (61.96)	4.05 (4.58)	4.27; 480.54; 1.80
5	Vs	48.76 (19.86)	4.40 (4.23)	0.65; 3.23; 10.15

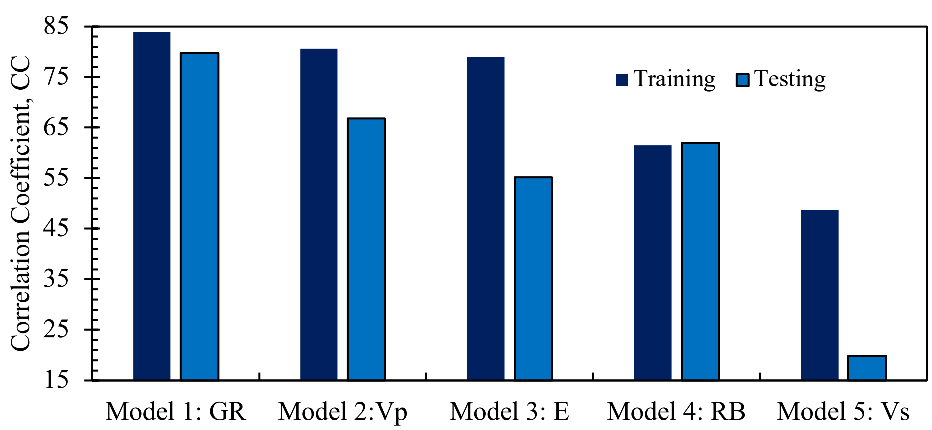


Figure 5: A comparison of CC performance for LSSVM-based model schemes using predictor variable.

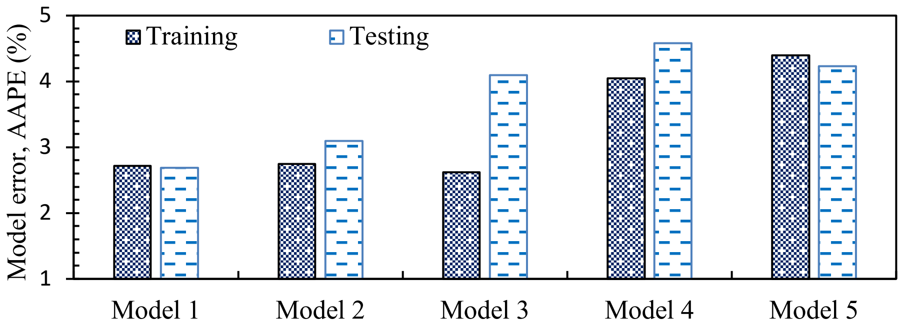


Figure 6: A comparison of AAPE performance for LSSVM-based model schemes using predictor variable.

Moreover, the effects of modulus of elasticity, formation bulk density and shear sonic travel waves have minimal impacts on the UCS prediction because of model schemes 3 through 5 performed with less CC and high error using LSSVM-CSA based predictive model in the study for clastic sedimentary rocks of the Bengal basin.

3.3 Effects of Geophysical Log Data for UCS Estimation

To investigate the effects of geophysical log data with rock strength of UCS, the regression-based polynomial curve fitting also studied and illustrated in Figures 7- 11 using real filed log data of a gas well, Bengal basin.

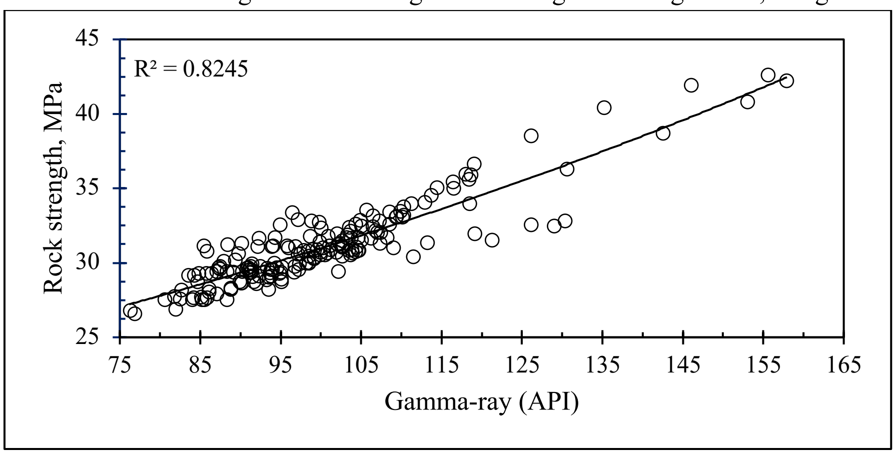


Figure 7: A relationship between gamma-ray and rock strength with CC of 81.44 %.

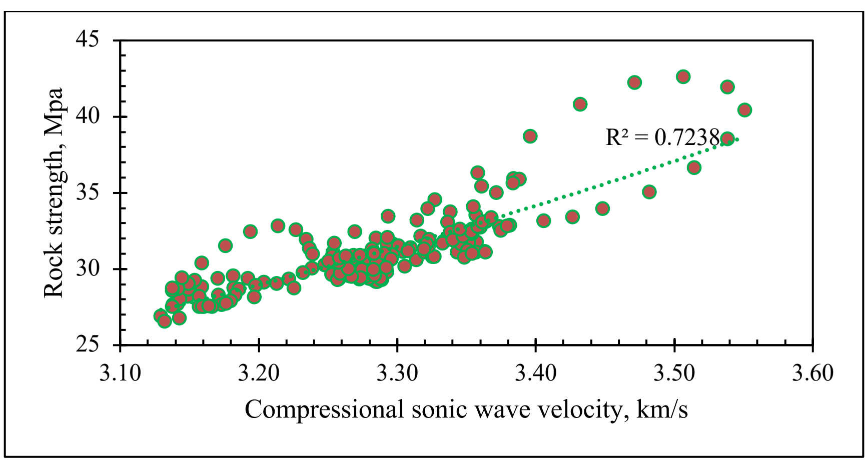


Figure 8: A relationship between compressional sonic velocity and rock strength with CC of 72.71 %.

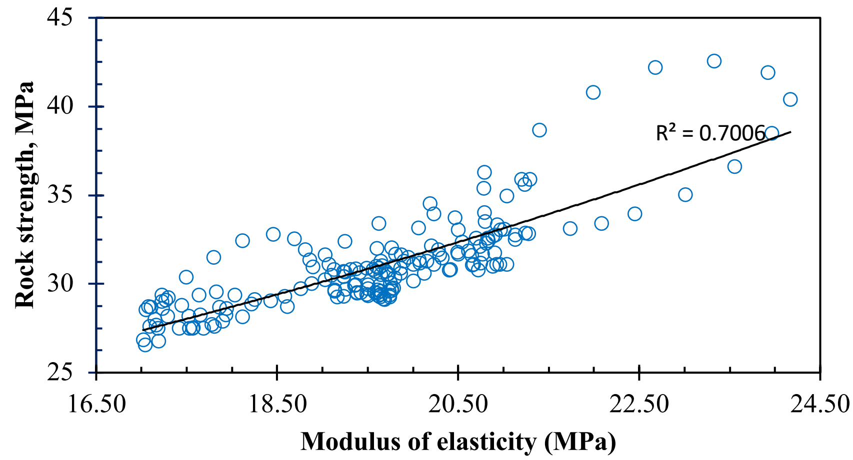


Figure 9: A relationship between modulus of elasticity and rock strength with CC of 70.49 %.

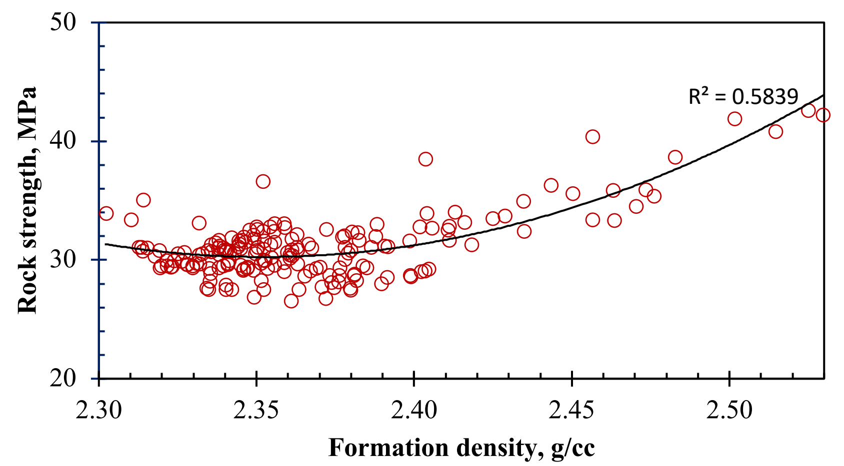


Figure 10: A relationship between formation bulk density and rock strength with CC of 58.39 %.

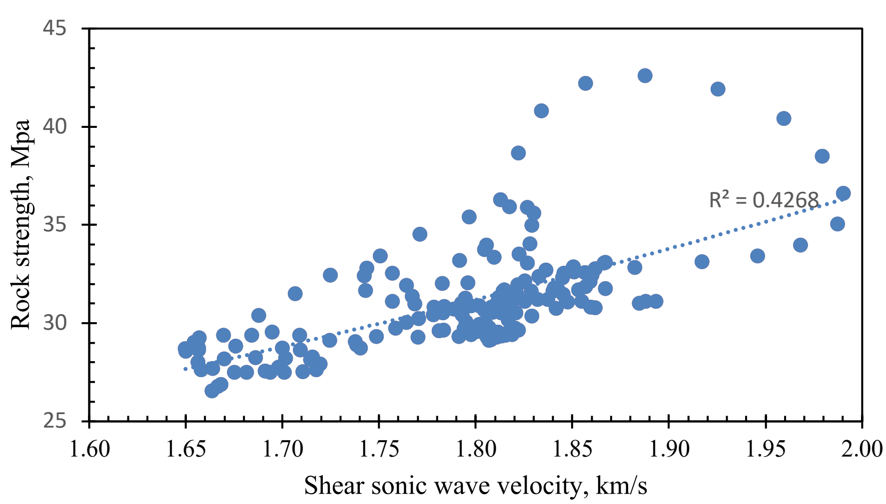


Figure 11: A relationship between shear sonic velocity and rock strength with CC of 45.33 %.

Based on the simulated results with LSSVM-CSA based predictive models and the exponential regression-based correlations, it is found that the gamma-ray radioactive property has major effects on formation UCS estimation while shear sonic velocity minor effects in the studied gas field of the Bengal formation. The geophysical log data of a gas well in the Bengal basin can be ranked, higher to lower order: GR> Vp >E >RB >Vs.

4. CONCLUSIONS

The machine learning techniques of least square support vector machine (LSSVM) is utilized to predict the dynamic rock strength of unconfined compressive strength (UCS) of clastic sedimentary rocks using geophysical log data such as gamma-ray, formation bulk density, modulus of elasticity, compressional and shear wave velocities. The key findings of this work are mentioned as follows:

- The connectionist models based on the LSSVM with CSA optimization strategy is capable of accurately estimating the dynamic rock strength parameter of UCS using geophysical log data.
- The formation gamma-ray property and compressional sonic velocity are two crucial parameters and have major impacts on dynamic rock strength estimation of clastic sedimentary formation.

For the scope of future study for the scholars, the studied similar methodological steps with deep learning and ensemble machine learning tools such as convolution neural network (CNN), long-short term memory (LSTM), and random forest (RF) can be applied for data-driven model developments and feature ranking in the discipline of petroleum and chemical engineering using big datasets.

ACKNOWLEDGEMENT

The authors would like to express gratitude to the peoples associated with the Petroleum Data Analytics Laboratory, Department of Petroleum and Mining Engineering (PME), Chittagong University of Engineering & Technology (CUET) to accomplish this study.

REFERENCES

1. Raaen, A. M., Hovem, K. A., Joranson, H., & Fjaer, E. (1996). FORMEL: A step forward in strength logging. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.
2. Miah, M. I. (2020). Predictive models and feature ranking in reservoir geomechanics: A critical review and research guidelines. Journal of Natural Gas Science and Engineering, 82, 103493. https://doi.org/10.1016/j.jngse.2020.103493.
3. Miah, M. I. (2021). Improved prediction of shear wave velocity for clastic sedimentary rocks using hybrid model with core data. Journal of Rock Mechanics and Geotechnical Engineering, 13(6), 1466-1477.
4. Miah, M. I., Ahmed, S., Zendehboudi, S., & Butt, S. (2020). Machine Learning Approach to Model Rock Strength: Prediction and Variable Selection with Aid of Log Data. Rock Mechanics and Rock Engineering, 1-25.
5. Aladejare, A. E., Alofe, E. D., Onifade, M., Lawal, A. I., Ozoji, T. M., & Zhang, Z. X. (2021). Empirical estimation of uniaxial compressive strength of rock: database of simple, multiple, and artificial intelligence-based regressions. Geotechnical and Geological Engineering, 39, 4427-4455.
6. Afolagboye, L. O., Ajayi, D. E., & Afolabi, I. O. (2023). Machine learning models for predicting unconfined compressive strength: A case study for Precambrian basement complex rocks from Ado-Ekiti, Southwestern Nigeria. Scientific African, 20, e01715.
7. Suykens, J. & Vandewalle, J. (1999). Neural Processing Letters 9, 293. https://doi.org/10.1023/A:1018628609742.
8. Suykens, J.A.K., Van Gestel, T., Brabanter, J., De Moor, B., & Vandewalle, J. (2002). Least Squares Support Vector Machines. World Scientific, Singapore.
9. Xavier-de-Souza, S., Suykens, J. A., Vandewalle, J., & Bollé, D. (2009). Coupled simulated annealing. IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), 40(2), 320-335.
10. Smola, A. J., & Schölkopf, B. (2004). A tutorial on support vector regression. Statistics and computing, 14, 199-222.

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Unlocking Health Benefits: A Comparative Analysis of CSEB and Traditional Burnt Bricks in Bangladesh's Sustainable Building Practices

Asma Siddika[1] and Md. Ruhul Amin[2]

To cite the article:

Asma Siddika[1] and Md. Ruhul Amin[2], "Unlocking Health Benefits: A Comparative Analysis of CSEB and Traditional Burnt Bricks in Bangladesh's Sustainable Building Practices", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 16-23

The Institute of Engineers, Bangladesh (IEB)

Chemical Engineering Division

Journal of Chemical Engineering, IEB
Vol. ChE 32, No. 1, April 2024

Unlocking Health Benefits: A Comparative Analysis of CSEB and Traditional Burnt Bricks in Bangladesh's Sustainable Building Practices

Asma Siddika[1] and Md. Ruhul Amin[2]

[1]Department of Architecture, Ahsanullah University of Science and Technology, Dhaka, Bangladesh. E-mail: asma.buet.07@gmail.com
[2]Bangladesh Atomic Energy Regulatory Authority,Dhaka, Bangladesh. E-mail: ruhul_rm@yahoo.com

Abstract:

The study conducted a comprehensive analysis comparing the health impacts of traditional burnt clay bricks to Compressed Stabilized Earth Blocks (CSEB) in Bangladesh. Utilizing SimaPro software and the ReCiPe method, researchers evaluated the human health implications of both building materials. Results revealed that CSEB production significantly reduces environmental burdens and costs compared to conventional bricks. The study underscores the potential of CSEB as a green building material, offering tangible benefits for both environmental sustainability and economic viability. By utilizing dredged river sand mixed with cement, CSEB not only minimizes greenhouse gas emissions but also mitigates the depletion of agricultural land. These findings highlight the importance of transitioning towards sustainable building materials like CSEB to alleviate the adverse health impacts associated with conventional construction practices.

KEYWORDS: Green building material, health impact, earth block(CSEB), Traditional burnt brick.

1. Introduction

The built environment includes different organic compounds that affect the quality of the indoor and outdoor environment and greatly impact human health. So, any development projects should be concerned about environmental, social, and health consequences. Health determinants are the direct or indirect causes of a disease, condition, or injury [1].

The impact of the built environment is related to building materials. The building industry is one of the biggest sources of energy use and greenhouse gas emissions. The most widely used construction material in Bangladesh is fire brick, also known as burned clay brick. Every year, a considerable amount of burnt clay brick is used for construction purposes, and a massive amount of agricultural land is lost due to the production of the firebrick. So, initiatives have been taken by the Bangladesh House Building Research Institute (HBRI) researcher to find alternative green building materials that use less energy and have less impact on the environment during their lifetime. They have produced CSEB (Compressed Stabilized Earth Block) from the dredged soil of the river mixed with proportionate cement. Research suggests CSEB could be an alternative green building material toward sustainable development by saving natural resources, using less energy, and minimizing production costs.

The present study wants to know the health impact of this alternative building material compared to the traditional burnt brick. A proper health impact assessment requires a wide range of impact assessments, including socio-demographic, environmental health, epidemiological, and health systems data[2]. Due to limitations on time and resources, the present research considers only some specific health determinants, such as health impact analysis of building material using SimaPro software modeling following the Life Cycle Assessment (LCA).

2. RESEARCH BACKGROUND

2.1 Building Materials and Health

Numerous building materials could include questionable chemicals that have both immediate and long-term health effects. Skin allergies, eye irritation, throat irritation, and sneezing are possible short-term effects. Long-term effects could include infertility, asthma, and cancer, among others. Endocrine disorders, obesity, and autism are among the health issues that the next generation can inherit. Many of the ingredients in building materials can be Persistent Bio Bioaccumulative toxins (PDTs) and Persistent Organic Pollutants (POPs), which can severely damage the environment and have lasting impacts on human health. Diminishing various aspects of construction materials, like embodied energy, energy usage, carbon dioxide emissions, and recyclable nature, can have a dual impact on human and environmental well-being.[3].

2.2 Green Building Material

In industrialized nations, Buildings significantly impact the environment, using about 40% of natural resources[4]. Green building (GB) has emerged as a new building philosophy in an effort to lessen the impact. It aims to improve indoor environmental quality, use more ecologically friendly materials, and implement resource-saving and waste-reduction techniques. [5].

Using green building materials and products represents a critical strategy in designing a green building. An environmentally friendly, healthful, recyclable, or high-performing material that minimizes its effects on the environment and human health over the course of its life cycle(LC) is referred to as a green building material (GBM) [6]. It is specially made from non-toxic, natural, and organic substances and can reduce indoor air contaminants as well as health impacts [7].

2.3 Alternative Green Building Material in Bangladesh

Bangladesh is one of the most densely populated countries in the world. Bangladesh produces 17.2 billion bricks for residential use each year[8]. A million bricks are produced using about 240 tons of coal [9]. About 23,300 tons of particulate matter, 1.8 million tons of carbon dioxide, 302,000 tons of carbon monoxide, and other chemicals released annually from brick kilns are extremely harmful to human health, and this harm only occurs in the Dhaka region[10].

Bangladesh is now working to implement sustainable development targets. The Bangladeshi Housing and Building Research Institute has launched a study project to address the issue. The study looks for alternative building materials using readily available local resources. The study uses soil from river dredging instead of agricultural topsoil to create blocks that are sold in Bangladesh. Housing and Building Research Institute has produced CSEB from the dredged soil of the river mixing with proportionate cement. Using alternative green building materials minimizes transportation costs associated with carbon dioxide emissions, lowers the cost of building materials, creates opportunities for employment and skill development, and preserves our agricultural land[11].

2.4. CSEB (Compressed Stabilized Earth Block)

Early in the 19th century, Europeans first attempted compressed earth blocks. François Cointereaux, the architect, utilized hand rammers to compact the damp soil into a tiny wooden mold that he held in place with his feet after precasting little blocks of beaten earth. In 1950, Cinvaram, the first steel manual press, was produced. This method is used in South Asia, Africa, and India. Over the past three decades, compressed earth blocks have gained widespread usage across the globe, not only in developing nations but also in developed nations such as the United States, the United Kingdom, and Canada[12].

2.4 Health Impact Assessment

Environmental impact assessment (EIA) is an integral part of the development, and EIA methodology has been refined to examine potential social and health impacts[13]. Environmental impact assessment (EIA) often addresses this concern by considering little input from the health sector[1]. Sustainable development promotes comprehensive impact assessment is required to integrate health and ecological risk measurement with meaningful community consultation[14].

Often, it is difficult to prescribe a specific research method for Health Impact Assessment (HIA) because of a lack of resources, time, and available data. Research suggests some inferences about health impact, and the research components can be divided into four assessments, i.e.

_socio- demographic,
_health determinants,
_health status and
_health systems. [1].

Health determinants are the direct or indirect causes of a disease, condition, or injury. A health determinants assessment aims to measure the factors that affect people's health, such as waste management, public infrastructure, pollution, housing, food and fuel security, and access to and quality of water and sanitation. The present research considers only some specific health determinants.

2.5 Life Cycle Assessment (LCA): Software and Human Health

The impacts of building materials on human health have been compassed the emission of harmful substances through their life cycle, including raw materials during construction, maintenance, and renovation[15]. The LCA method quantifies the potential impacts of the product system throughout its lifetime. This approach is the only appropriate method for comparing materials and human health impact from the construction industry since 1990[7, 16]. The advancement of LCA software helps to resolve the complexity of this method and the Pact of the materials and products, despite the fact that LCA is an expensive and complex methodology. There are different methods for life cycle impact assessment (LCIA), such as CML 2000, ReCiPe, and EPS 2000, to determine the impact on human health, which are considered only for outdoor sources of pollution, not indoor ones[7].

3 Materials and methods

The present research is followed by previously published research on CSEB in Bangladesh. Recently in Bangladesh, research on CSEB, experimented with different ratios (1:4, 1:5, and 1:6) of cement mix with dredged sand (Table 1). Their experiment shows that all cement-sand ratios give satisfactory results when comparing compressive strength and water absorption capacity, which is very low compared to clay brick[17]. Following this experiment, the present research uses the same cement-sand ratio (1:4, 1:5, and 1:6) to investigate the health impact using SimaPro software within the LCA method.

3.1 Materials

Premier Ordinary Portland Cement (OPC) CEM-I 42.5N and 52.5N Grade was the cement manufacturer used in all the mixes. The soil used in that study was brought from the Turag River. The city's Dhaka water supply system supplied fresh tap water, free from all forms of organic water. An earthen block preparation machine, Cinvaram, was used to produce CSEB (Figure 1).

Table 1:Mixing Proportion of cement, sand, and water (Hasan 2020).

Series	Cement-Sand ratio	Cement	Sand	water
1st series	1:4	20%	80%	12.5%
2nd series	1:5	16.66%	83.33%	12.5%
3rd series	1:6	15.28%	85.71%	12.5%

Figure 1: Compressed Stabilized Earth Block (CSEB) production [17].

3.2 Methods

The present research has been designed in two parts: a theoretical part based on a literature review of relevant theories and research on the health impact of building materials and software modeling. The methodology employed in these two parts is explained below, focusing on the three interrelated phases.

1st phase_Literature Survey: The research will start with a literature survey on published knowledge (e.g., research papers, books, standards, codes, and websites) to understand the impacts of building materials on human health.

2nd phase_Data collection: The research is collecting data from published research on CSEB to follow the mixing proportion of cement, sand, and water.

3rd phase_SimaPro software modeling: The research is prepared CSEB model (Table 2) in SimaPro software by following the same mixing proportion (Table 1) of CSEB conducted by Hasan et al. 2020. ReCiPe method is used to evaluate human health impacts based on the LCIA (Life Cycle Impact Assessment) methodology.

Table 2: Mixing proportion and weight of the different samples.

Sample	Ratio	Cement	Sand	Water
CSEB-1	1:4	1 kg	4kg	12.5%
CSEB-2	1:5	0.83 kg	4.17 kg	12.5%
CSEB-3	1:6	0.7 kg	4.3 kg	12.5%
Traditional brick	5 kg			

3.3 Assumption and Limitations

For this section of the methodology, the following are the main presumptions and limitations:

- An essential consideration when comparing products is the functional unit. In this research, the functional unit is set to be five kilograms of output.
- The ReCiPe method is considered the only outdoor source of pollution, not indoor ones.

3.4 Grounding of SimaPro Software

The outcomes of SimaPro for LCIA encompass two levels of impact categories: midpoint and endpoint level. The ultimate damage assessment results from converting midpoint indicators with different units into endpoint levels. The Area of Protection (AoP) includes the ecosystem, human health, and resources, and these are the three categories of damage assessment. Furthermore, there are three different indicators at the endpoint level:

- Damage assessment,
- Normalization, and
- Weighting

In the ReCiPe method, 'damage to human health' combines mortality and morbidity represented by endpoint level. The loss of species represented the AoP of the natural environment, and the increased set of future extractions represented the AoP of natural resources[18].

4 RESULT AND DISCUSSION

The research focuses on human health by comparing the LCIA (Life Cycle Impact Assessment) of CSEB (three samples) and traditional brick. The damage assessment indicator result from the endpoint level utilized in the ReCiPe method is shown in Figure 2. A scale of 100% is used to display them. The term "disability-adjusted life years," or "DALYs," refers to the measurement of harm to human health. The number of years lost and the number of years lived with disability are used to quantify damage to human health[18]. Figure 2 shows the impact of the decline in human health on the three sample CSEB types compared to traditional brick.

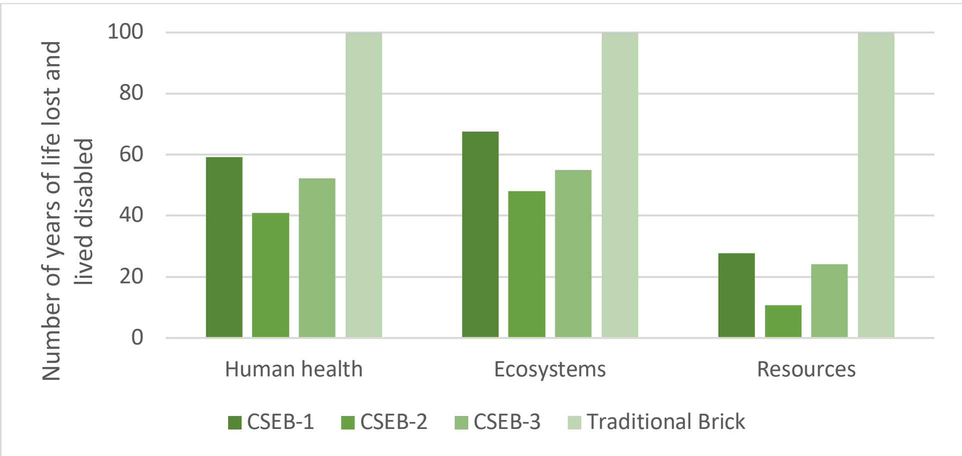


Figure 2: Damage Assessment Indicator at the Endpoint level.

Table 3 focuses on the impact categories on human health at the midpoint level. The values are shown in Figure 3, which indicate that the group with the most significant impact is human carcinogenic toxicity. Research also found a substantially reduced impact for three CSEB types compared to traditional brick.

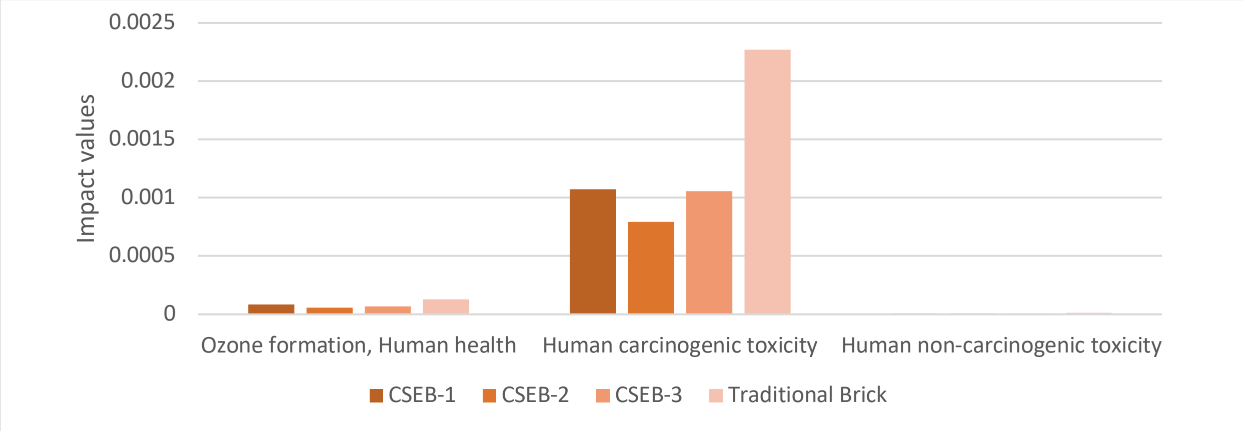


Figure 3: Normalization indicator at the Midpoint level.

Table 3: Damage Assessment Normalization indicator at Midpoint level.

Impact category	CSEB-1	CSEB-2	CSEB-3	Traditional Brick
Ozone formation, Human health	8.52E-05	5.7E-05	6.894E-05	0.000126229
Human carcinogenic toxicity	0.001075	0.000795	0.0010578	0.002268463
Human non-carcinogenic toxicity	8.98E-06	6.62E-06	8.426E-06	1.07837E-05

Further impact assessment indicators are normalization and weighting, which simplify the complex interpretation of the results at the midpoint level.

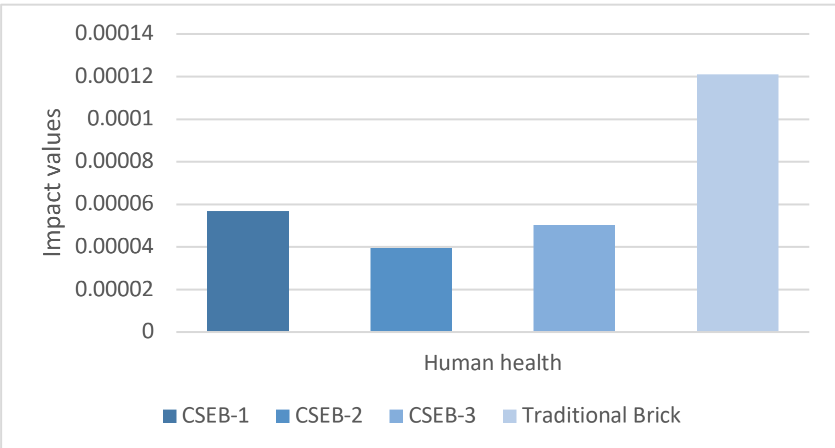


Figure 4: Normalization indicator at the Endpoint level.

Determining the extent to which an impact category adds to the overall issues related to human health and the environment is known as normalization. The incompatibility of units is also resolved by normalization. When comparing the effects of two products using the same unit, the normalization produces results that are easy to understand. When using emissions per year in the normalization process, a year is the precise unit of a normalized value[18].

The impact category on human health decreased significantly when the traditional brick was replaced with CSEB, from 0.0012 to 0.00004, according to normalization results (Figure 4).

Regarding midpoint approaches, which are heavily utilized for internal decision-making, weighting is the most robust and thought-provoking step in life cycle impact assessment. For weighting, mPt is the value. One mPt (mili point) is equivalent to 1/1000 Pt, and one point is equivalent to 1/1000 of Europe's average annual environmental impact. Complete weighting summarizes life cycle assessment (LCA) data into a single score that simplifies comparing the effects of two products on human health [18].

The weighting indicator, which establishes the research strategy's significant impact on the human health measure, is shown in Figure 5. The impacts on human health were reduced from 38 mPt to 16 mPt due to using CSEB-2.

Therefore, the SimaPro analysis shows that the total impact on human health declined by around half using CSEB rather than traditional brick.

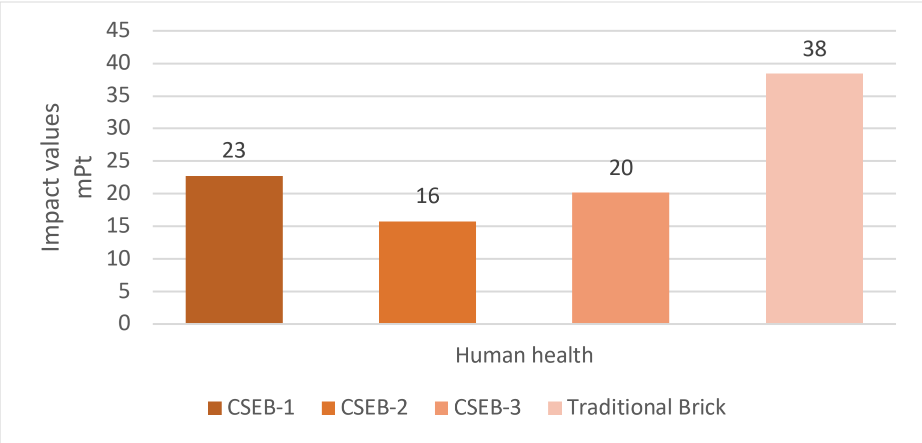


Figure 5: Weighting Indicator at the endpoint Level.

5. Conclusion

The present research analyzes three samples of the same building material's impact on human health. The result shows the effect of building materials on human health is unavoidable, but we can reduce the impact considerably. Previous research showed that CSEB has the potential to be a sustainable green building material in the context of Bangladesh. The present research focused on the health impact of CSEB compared to traditional brick, and the result shows the health impact of CSEB is substantially lower than brick. So it can be said that a green building material has the potential to minimize health impact.Furthermore, the result indicates that the raw material composition is also considered. The present research uses three different ratios of cement and sand for CSEB samples. The result shows in all three categories of damage assessment, CSEB-2 has the minimum health impact, followed by CSEB-3, CSEB-1, and traditional brick. Considering the different ratios of cement and sand (1:4, 1:5, 1:6), it has been shown the proportion of cement is maximum in CSEB-1 and minimum in CSEB-3, but CSEB-2 has the lowest health impact. So, it can be said a reasonable composition of raw materials of building materials can reduce human health impact. Considering the limitations of time and resources, the data is only software-based and follows only some specific damage assessment types. Further research is concerned with other impact assessment components such as socio-demographics, health determinants, health status, and health systems.

References

1. Lerer, L., *Health impact assessment.* HEALTH POLICY AND PLANNING; 14(2), 1999: p. 198–203

2. Briggs, D.J., *A framework for integrated environmental health impact assessment of systemic risks.* Environmental health, 2008. **7**: p. 1-17.

3. Promotion, B.o.H., D. Prevention, and C.o.D.I. Spaces, *Damp indoor spaces and health.* 2004.

4. Pulselli, R., et al., *Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability.* Energy and buildings, 2007. **39**(5): p. 620-628.

5. Wang, W., R. Zmeureanu, and H. Rivard, *Applying multi-objective genetic algorithms in green building design optimization.* Building and environment, 2005. **40**(11): p. 1512-1525.

6. Chang, Y.-H., et al., *A study on the color change benefits of sustainable green building materials.* Construction and Building Materials, 2015. **83**: p. 1-6.

7. Khoshnava, S.M., et al., *Rank of green building material criteria based on the three pillars of sustainability using the hybrid multi criteria decision making method.* Journal of cleaner production, 2018. **173**: p. 82-99.

8. Bank, W., *Introducing Energy-efficient Clean Technologies in the Brick Sector of Bangladesh.* Environment, Climate Change, and Water Resources Unit South Asia Region, 2011. Report No. 60155-BD.

9. Manandhar, U.M. and S.B. Dangol, *Study on evaluating energy conservation potential of brick production in SAARC countries.* Kathmandu, Nepal: Min Energy Initiatives, Nepal and SAARC Energy Center, Islamabad, 2013.

10. Skinder, B.M., et al., *Brick kiln emissions and its environmental impact: A.* 2014.

11. Sarker, M.A.H. and M. Ishtiak, *Alternative Building material in Bangladesh: A way towards sustainability.* Int. J. Res. Stud. Sci. Eng. Technol, 2018. **5**: p. 41-45.

12. Thakuri, L.S., *Life Cycle Cost Analysis of External Walls in Residential Building for Temperate Climate: A Comparative Study of AAC and CSEB block.* 2020, Pulchowk Campus.

13. McDonald, G.T. and L. Brown, *Going beyond environmental impact assessment: environmental input to planning and design.* Environmental Impact Assessment Review, 1995. **15**(6): p. 483-495.

14. Birley, M., M. Gomes, and A. Davy, *Health aspects of environmental assessment.* Environmental assessment sourcebook update, 1997. **18**.

15. Kiliç, E., et al., *Environmental optimization of chromium recovery from tannery sludge using a life cycle assessment approach.* Journal of hazardous materials, 2011. **192**(1): p. 393-401.

16. Fava, J.A., *Will the next 10 years be as productive in advancing life cycle approaches as the last 15 years?* The International Journal of Life Cycle Assessment, 2006. **11**(Suppl 1): p. 6-8.

17. Mohaiminul Hassan, S.R.C., *Performance of CSEB Block alternative to brick in the context of Bangladesh* IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 2020. **17**(4): p. 10-17.

18. Khoshnava, S.M., et al., *A cradle-to-gate based life cycle impact assessment comparing the KBFw EFB hybrid reinforced poly hydroxybutyrate biocomposite and common petroleum-based composites as building materials.* Environmental Impact Assessment Review, 2018. **70**: p. 11-21.

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Microplastic Impact: A Concise Overview of Pollution and Effects

Md Redowan Rashid[1] and Md Shakibur Rahaman Chowdhury[2]

To cite the article:

Md Redowan Rashid[1] and Md Shakibur Rahaman Chowdhury[2] "Microplastic Impact: A Concise Overview of Pollution and Effects", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 24-32.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Journal of Chemical Engineering, IEB
Vol. ChE 32, No. 1, April 2024

Microplastic Impact: A Concise Overview of Pollution and Effects

Md Redowan Rashid[1], Md Shakibur Rahaman Chowdhury[2]

[1]Department of Civil Engineering, Sonargaon University; redowan.iut@gmail.com
[2]Department of Chemical Engineering, Bangladesh University of Engineering and Technology; shakiburc@gmail.com

Abstract

Microplastic contamination, defined as plastic particles less than 5 mm in size, has become a major global environmental concern. This study synthesizes findings from carefully chosen studies undertaken in a variety of geographical areas and ecosystems, offering light on the multifaceted issues posed by microplastic pollution. These articles show the global prevalence of microplastics in both land and marine ecosystems. Seasonal fluctuations in microplastic abundance highlight the cyclical nature of this pollution, with larger amounts being reported during the summer months. Tourism, industrialization, and urbanization have all been highlighted as significant contributors to microplastic contamination, stressing the impact of man-made influences. Wastewater treatment plants (WWTPs) have been identified as hotspots for microplastic release into aquatic habitats, emphasizing the need for enhanced treatment procedures. Because microplastics can build up in the food chain, it underlines the possible health problems connected with microplastic pollution for both aquatic creatures and human consumers. Longitudinal studies, geographical variety, in-depth health and ecological impact evaluations, standardization, and effective mitigation methods should be prioritized in future studies. To address this worldwide issue, interdisciplinary collaboration among scientists, health professionals, politicians, and industrial stakeholders is required.

Keywords

Global environmental concern, Health and ecological impact evaluations, Geographical variety, Seasonal fluctuations, Industrialization.

1. Introduction

The issue of solid waste is a significant environmental and health concern on a global scale. This problem arises from various materials that originate from many sources, such as industrial, commercial, mining, agricultural, and community activities (Medina. 2010; Nkwachukwu et al., 2010). The phrase "solid waste" encompasses many abandoned materials, which may exist in solid, liquid, semi-solid, or enclosed gaseous states (Eddine & Salah, 2012). Municipal Solid waste (MSW) is a multifaceted and diverse matter encompassing several types of waste, including home, commercial, institutional, street sweeping, building, and sanitary (Sharholy et al., 2008; Cheru, 2011; Ding et al., 2021). The development of MSW is closely intertwined with the consumption and production cycles, resulting in the conversion of mass-produced and commercialized products into waste (Weitz et al., 1999; Magazzino & Falcone, 2022).
The widespread use of plastic materials in our daily lives has resulted in indisputable societal benefits ranging from improved health to increased convenience in our daily routines. Nonetheless, the massive increase in plastic manufacture and consumption has resulted in a hidden hazard to

our environment and human health: microplastic contamination. These small plastic particles, which are typically less than 5 mm in size, have invaded ecosystems all over the world, from the depths of our oceans to the air we breathe, leaving no corner of our planet unscathed (Zhai et al., 2023).

Plastics' extensive use and durability in modern civilization have resulted in unforeseen consequences, specifically the fragmentation of larger plastic goods into microplastics. As a result, these microscopic plastic particles enter ecosystems, contaminating air, water, soil, and even food. Microplastics are a formidable vector for pollutants due to their small size and capacity to adsorb hazardous substances, worsening their impact on both the environment and human health. Furthermore, the drinking water in developing nations is heavily contaminated with microplastics and other pollutants. Therefore, the usage of household water treatment technologies is essential to safeguard human health (Niloy & Chowdhury, 2017; Karim et al., 2018; Chowdhury et al., 2019).

A variety of scientific research is analyzed in this study, highlighting the severity of the microplastic dilemma. Each publication examines a distinct aspect of the microplastic problem, offering light on the varied challenges posed by these tiny contaminants. Figure 1 below illustrates how a chain mechanism allows our discarded plastic to end up on our dinner plates.

Figure 1: The Microplastic Chain: From Single use plastics to Ocean to Sea animals to Sea food to Our Stomach (Credit: francoillustration)

The studies that are being reviewed cover a wide range of geographic locations, including freshwater ecosystems in India (David et al., 2023), urban streets in Bangladesh (Rabin et al., 2023), marine environments in American Samoa (Polidoro et al., 2021), and wastewater treatment plants in Southeast Spain (Bayo et al., 2023). They highlight the worldwide breadth of microplastic pollution, indicating its pervasiveness and possible consequences.

The objectives, techniques, and major findings of this research compendium provide unique insights. Researchers have investigated the sources and paths of microplastics, as well as the ecological concerns they pose in many ecosystems and, most crucially, the consequences for human health. I hope to highlight the underlying trends, knowledge gaps, and important problems in the realm of microplastic pollution by merging various views.

1.1 Objectives

This study aims to examine microplastic pollution through a synthesis of recent research. This will provide a unified perspective on worldwide concerns, encompassing significant discoveries regarding the distribution, origins, seasonal fluctuations, ecological consequences, and risks to human health. In addition to highlighting trends and knowledge deficits, it advocates for a global response and emphasizes the interconnectedness of ecosystems. Contributing to the ongoing dialogue on how to resolve the escalating challenges posed by microplastic pollution, the study aims to increase awareness of the pervasiveness and effects of microplastics and advocate for additional research and effective mitigation strategies.

2. Background

Plastic pollution is becoming a major worldwide environmental issue that is negatively impacting wildlife, ecosystems, and human health. This review paper provides a thorough background on the widespread problem of microplastic pollution by drawing on a wide range of research. Because of their widespread usage and inappropriate disposal, plastics—which are defined by their non-biodegradable nature—are found in both terrestrial and marine habitats.

Microplastics, which are plastic particles smaller than 5 mm, have found their way into ecosystems worldwide, including rivers, lakes, oceans, and urban areas. Although marine microplastics have been the subject of much research (Luqman et al., 2021; Polidoro et al., 2021; Song et al., 2022; Zhang et al., 2022), little attention has been paid to the presence of microplastics in freshwater ecosystems (David et al., 2023) and indoor environments (Zhai et al., 2023).

Studies conducted in Bangladeshi beaches and Thailand (Kasamesiri et al., 2023) have highlighted the negative impacts of microplastic pollution on ecosystems and public health. The use of microplastics by marine animals, including fish and shellfish, has sparked worries about bioaccumulation and its repercussions for human consumers (Luqman et al., 2021).

Furthermore, research conducted in Spain has highlighted the intricate dynamics of microplastic release into the environment and illuminated the roles wastewater treatment plants play in contributing to microplastic contamination (Bayo et al., 2023). Physicochemical techniques can be utilized as both pre and post-treatment measures to address the issue (Rashid & Ashik, 2023). Studies from China demonstrate how dynamic this issue is by showing how seasonal fluctuations in microplastic buildup in various environments occur (Zhang et al., 2022).

Moreover, Song et al. (2022) noted that the COVID-19 pandemic offered a singular chance to examine the relationship between decreased human activity and microplastic contamination.

Research from Bangladesh sheds light on the effects of lockdown measures on microplastic levels in street dust and air quality, offering insights on the environmental effects of restrictions related to pandemics (Rabin et al., 2023).

Developing mitigation measures and policies is vital since plastic pollution is becoming worse, as is becoming increasingly widely agreed upon. The goal of this study is to provide an overview of the various issues presented by microplastic pollution by synthesizing the vast knowledge generated by published papers. The objective is to establish a basis for subsequent investigations, promote knowledgeable decision-making, and propel worldwide endeavors aimed at alleviating the ubiquitous and enduring problem of microplastic pollution.

3. Methodology

Together, the examined publications' techniques offer an approach to examining and mitigating microplastic pollution in a variety of habitats. Utilizing these approaches provides insightful information on the complex nature of microplastic research. Table 1 below provides the articles' methodologies for sample collecting and analysis.

Table 1: Overall sample collection and analysis methods

Sample Collection	Analysis	References
Collection of microplastic samples from in near-shore marine environments in American Samoa	Microscopy and spectroscopy techniques	(Polidoro et al., 2021)
Collection of disposable masks from various coastal locations in China during the COVID-19 pandemic	Stereomicroscope and FTIR spectroscopy	(Song et al., 2022)
Field sampling of microplastics in human Stools, Foods, and Drinking Water	Microscopy and FTIR	(Luqman et al., 2021)
Indoor dust sampling at various points within a university	Microscope analysis, LDIR, micro-FTIR, and Raman microscopy.	(Zhai et al., 2023)
Collection of samples from Phuket's coastal environment, including sediments and shellfish	Heavy metals and microplastics characterization	(Akkajit et al., 2021)
Sampling of indoor environments near wastewater treatment plants (WWTPs)	Microplastic abundance and characteristics analysis (size, shape, color, and polymer distribution)	(Bayo et al., 2023)
Collection of samples from Vellayani Lake	FTIR characterization	(David et al., 2023)
Investigation of plastic debris and air pollution during and after the COVID-19 lockdown	Air quality analysis, microplastic content analysis	(Rabin et al., 2023)
Seasonal sampling of plastic debris on Yugang Park Beach	Seasonal variation analysis, composition analysis	(Zhang et al., 2022)
Collection of surface water (0–30 cm) and bottom sediment from Ubolratana Reservoir	Microplastic extraction, characterization, risk assessment	(Kasamesiri et al., 2023)

In these investigations, sampling procedures are crucial. To measure the presence of microplastics, scientists have regularly gathered environmental samples from water, soil, and biota. The implementation of uniform procedures for gathering samples guarantees consistency amongst research projects. Furthermore, differentiating across other sample types—such as fish, street dust, marine sediments, and coastal sediments—allows for a more sophisticated understanding of the distribution of microplastics. The use of microscopic analysis becomes essential in the identification and characterization of microplastics. Scientists have visualized and categorized particles according to characteristics like size, shape, color, and polymer composition using optical stereo zoom microscopes and fluorescent microscopes. Fourier-transform infrared spectroscopy (FTIR) has been utilized to accurately identify and classify microplastic compositions, complementing these ocular approaches.

Numerous researchers have used risk assessment to evaluate the effects of microplastics on ecosystems and human health (Polidoro et al., 2021). Evaluating possible health concerns associated with exposure is made easier with the calculation of hazard quotient values based on the concentration of microplastics in sampled matrices. A crucial component of the approaches has been seasonal fluctuations and temporal dynamics (Zhang et al., 2022; Kasamesiri et al., 2023). Research done in a variety of seasons has shed important light on how human activity and the climate affect the spread of microplastics. Our understanding of the relationship between environmental factors and microplastic pollution has improved with the examination of shifts in the distribution of microplastic types during various phases of external influences, such as the COVID-19 lockdown (Song et al., 2022; Rabin et al., 2023).

The approaches have included the analysis of influent and effluent samples in the setting of wastewater treatment facilities (WWTPs) (Bayo et al., 2023). To gather samples from WWTPs and evaluate how well these facilities remove microplastics, researchers have conducted in-depth fieldwork. This methodology enables a thorough assessment of WWTPs' functions as microplastic sources and sinks.

4. Main Findings

The summary of the results from the studies that were evaluated highlights important information about microplastic pollution in different ecosystems and regions of the world. Together, these important findings influence how we perceive the complex phenomenon of microplastic pollution.

Seasonal Differences: Microplastic abundance is strongly influenced by seasonal dynamics. Research indicates that there can be significant seasonal variations in microplastic concentrations, with summertime often seeing higher levels due to increased human activity and weather-related factors (Zhang et al., 2022; Kasamesiri et al., 2023).

Abundance and Composition: Microplastics vary in abundance and composition depending on the ecology in which they are found. Microplastics are regularly found in water samples, marine sediments, and coastal sediments. Microplastics can take on a variety of shapes, the most common ones being fibers, fragments, films, and spheres. White, colorful, and transparent microplastics are frequently recognized as members of the population based on their color (Luqman et al., 2021; Song et al., 2022).

Size: Microplastics are tiny particles that are less than 1 mm in size, however bigger plastic pieces that are up to 2.5 cm in length are also included in the category of microplastics. The environment is full of larger plastic trash as well as microplastics. Their mobility, ability to be ingested by creatures, and possible admission into the food chain are all affected by their size diversity (Rabin et al., 2023; Zhai et al., 2023).

Sources: Together, the evaluated publications show many paths and sources of microplastic pollution. Stormwater runoff, wastewater effluents, industrial discharges, and plastic garbage are examples of common sources. According to David et al. (2023), microplastics can enter ecosystems through rivers, airborne deposits, and direct littering.

WWTPs as Sources and Sinks: According to Bayo et al. (2023), wastewater treatment plants (WWTPs) have become major sources of microplastic contamination. These establishments have the capacity to function as sinks, collecting microplastics from residential and commercial wastewater, and sources, discharging microplastics into the environment through effluents. Variations exist in the effectiveness of WWTPs in eliminating microplastics, highlighting the necessity for better treatment techniques.

Health and Ecological Risks: Taken together, the evaluated publications highlight the possible hazards to human health and the environment posed by microplastic pollution. Many kinds of species can consume microplastics, which can cause physical injury as well as the absorption of chemical toxins. When seafood is consumed, this intake may have a negative impact on marine life and, in turn, human health (Polidoro et al., 2021; Zhang et al., 2022).

5. Contribution to the Environmental and Occupational Health Field

We now have a much better understanding of microplastic contamination and its effects on the environment and occupational health because of the combined findings of these articles. When taken as a whole, these studies advance this discipline in numerous important ways:

Global Awareness: The evaluated publications have illuminated the widespread prevalence of microplastic pollution on a global scale. They emphasize the necessity of increased public, scientific, and policymaker understanding of the ubiquitous presence of microplastics in different ecosystems and the need for coordinated action.

COVID-19 and Microplastic Impact (Song et al., 2022): This research reveals that disposable masks are a significant contributor to the worldwide problem of microplastic contamination. It highlights the necessity for responsible waste management of pandemic-related trash and the significance of understanding the environmental impacts of public health initiatives.

Coastal Tourism Impact (Zhang et al., 2022): The findings show that tourism has a major impact in the accumulation of plastic litter on inaccessible coastal beaches. It highlights the significance of environmentally responsible tourist practices and helps us better comprehend the relationship between tourism and the health of our planet.

Microplastic Risk Assessment Models (Akkajit et al., 2021; Kasamesiri et al., 2023): There are several risk assessment models for microplastic pollution, and these papers introduce and examine several of them. They help policymakers and medical experts by assessing the threats posed by microplastics to the environment and human health.

6. Weaknesses of the Articles

These papers certainly have some shortcomings, even though they offer insightful information. Some studies restrict the applicability of their findings to wider contexts by concentrating on geographic areas or ecosystems. Some studies have relatively small sample sizes, which may have an impact on how representative the findings are. Different research approaches used in different studies might make direct comparisons difficult, which emphasizes the necessity for uniform procedures for sampling and analysis. There is a dearth of research that thoroughly examines the effects of microplastic contamination on the environment and human health, highlighting the need for more thorough studies in this area. Table 2 below lists the papers' specific limitations.

Table 2: Limitations of the selected articles

Limitations	References
Small-scale study with limited geographical scope. Lack of detailed ecological impact assessment.	(Akkajit et al., 2021)
Limited focus on specific marine environments. Variable sampling methods and data comparability issues.	(Polidoro et al., 2021)
Primarily focused on urban areas, limited representation of rural or remote regions. Challenges in quantifying the health impacts of airborne microplastics.	(Zhai et al., 2023)
Study conducted on a single beach. Exclusion of microplastics smaller than 1 mm.	(Luqman et al., 2021)
Limited to the assessment of microplastics from disposable masks; does not address other emerging plastic waste issues during the pandemic.	(Song et al., 2022)
Study conducted on specific beaches in China. Limited exploration of potential health risks. Excluded microplastics smaller than 1 mm	(Zhang et al., 2022)
Focused on WWTP discharge in Southeast Spain. Limited investigation of health impacts.	(Bayo et al., 2023)
Small sample size and restricted to a single freshwater lake. Insufficient exploration of ecological consequences.	(David et al., 2023)
Limited to Bangladesh during the COVID-19 lockdown. Focus on microplastics in street dust, excluding other sources.	(Rabin et al., 2023)
Primarily focused on the Ubolratana Reservoir in Thailand. Limited assessment of health impacts.	(Kasamesiri et al., 2023)

7. Future Work Needed

Future studies should concentrate on the following topics to further the study of environmental and occupational health in the context of microplastic pollution:

Longitudinal Studies: Long-term research projects that take many years or decades to complete can offer a more thorough grasp of the long-term effects of microplastic pollution and temporal trends.

Geographical Diversity: To evaluate worldwide trends in microplastic pollution, research must be extended to a greater range of geographic regions and ecosystems.

Evaluation of the Health and Ecological Impact: Detailed analyses are required to determine how microplastic contamination affects the environment and human health. The processes through which eating contaminated seafood harms organisms and any possible health effects on humans should be investigated in research.

Standardization: More reliable comparisons between research would be made possible by the development of standardized procedures for microplastic sampling, analysis, and reporting.

Mitigation Strategies: Research in the future should concentrate on creating and assessing efficient mitigation techniques, such as better waste management, environmentally friendly plastic substitutes, and legislative changes.

Collaboration: Promoting interdisciplinary collaboration among environmental scientists, health specialists, policymakers, and industrial stakeholders can provide a strategy for tackling microplastic pollution.

8. Recommendations

To effectively reduce microplastic pollution, a multifaceted strategy is required. First, waste management systems should be improved to reduce plastic leakage by enhancing waste collection and recycling and promoting responsible disposal methods. Second, it is crucial to reduce single-use plastics through the implementation of policies and the promotion of eco-friendly alternatives. To prevent microplastics from entering aquatic ecosystems, it is crucial to upgrade wastewater treatment facilities with advanced filtration technologies. To assure data comparability between studies, standardized measurement protocols must be developed. To comprehensively resolve this issue, scientists, health professionals, policymakers, and industry stakeholders must collaborate across disciplines. The public should be educated and encouraged to engage in responsible consumption and disposal practices via public awareness campaigns. Essential steps include supporting research into environmentally favorable materials and packaging solutions, conducting long-term monitoring, evaluating ecological and health impacts, and promoting international cooperation through global agreements. Enforcing policies, such as product restrictions and concentration limits, and promoting circular economy practices will help reduce microplastic pollution, preserve ecosystems, and protect human health.

9. Conclusion

In conclusion, the synthesis of these diverse studies on microplastic pollution exposes the global prevalence of this environmental challenge across a variety of ecosystems and regions. Seasonal fluctuations in the abundance of microplastics highlight the dynamic nature of this issue, with summer months exhibiting higher levels of contamination. The studies highlight the significant contributions of tourism, industrialization, and urbanization to microplastic contamination, while wastewater treatment plants emerge as prominent microplastic sources and drains. In addition, the potential threats to ecosystems and human health posed by the food chain are highlighted. Future efforts should focus on interdisciplinary collaboration, standardized measurement methods, and mitigation strategies, as well as increasing public awareness and international cooperation, to address this pressing issue comprehensively. These collective actions are necessary to combat microplastic pollution and protect the environment and human health.

References

Akkajit, P., Khongsang, A., & Thongnonghin, B. (2023). Microplastics accumulation and human health risk assessment of heavy metals in Marcia opima and Lingula anatina, Phuket. Marine Pollution Bulletin, 186, 114404.

Bayo, J., López-Castellanos, J., Olmos, S., & Rojo, D. (2023). A holistic approach on the impact of microplastic discharge from WWTPs to the neighboring environment in Southeast Spain. Water Research, 120516.

Chowdhury, O. S., Rashid, R., & Karim, M. R. (2019, January). E. Coli Removal Efficiency and Physical-Chemical Parameter Analysis of Mineral Pot Filters in Bangladesh. In In2nd International Conference on Water and Environmental Engineering (iCWEE-2019), Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, 2019, pp 1-8, ISBN: 978-0-6482681-1-6.

David, T. I., Sheela, M. S., Krishnakumar, S., Siyad, A. M., Abimanyu, A., Vikasini, V. K., ... & Dineshbabu, S. (2023). Distribution and characterization of microplastics and ecological risks in Vellayani Lake, Kerala, India. Total Environment Research Themes, 7, 100065.

Karim, M.R., Khan, M.A.I., Chowdhury, O.S. and Niloy, R.R. (2018) Assessment of Various Methods to Remove Pathogen from Raw Water to Meet Who Standard for Domestic Consumption. 7th Brunei International Conference on Engineering and Technology 2018 (BICET 2018), Ban-dar Seri Begawan, 12-14 November 2018, 1-4.

Kasamesiri, P., Panchan, R., & Thaimuangphol, W. (2023). Spatial–Temporal Distribution and Ecological Risk Assessment of Microplastic Pollution of Inland Fishing Ground in the Ubolratana Reservoir, Thailand. Water, 15(2), 330.

Luqman, A., Nugrahapraja, H., Wahyuono, R. A., Islami, I., Haekal, M. H., Fardiansyah, Y., ... & Wibowo, A. T. (2021). Microplastic contamination in human stools, foods, and drinking water associated with indonesian coastal population. Environments, 8(12), 138.

Niloy, M.R.R. and Chowdhury, O.S. (2017) Effectiveness of Household Water Treatment Technologies Based on WHO Guidelines. Master's Thesis, Islamic University of Technology (IUT), Gazipur.

Polidoro, B., Lewis, T., & Clement, C. (2022). A screening-level human health risk assessment for microplastics and organic contaminants in near-shore marine environments in American Samoa. Heliyon, 8(3).

Rabin, M. H., Wang, Q., Enyoh, C. E., Kai, X., & Sheuty, T. F. (2023). Distribution, Potential Sources, and Health Risk of Microplastics (MPs) in Street Dust during and after COVID-19 Lockdown in Bangladesh. Environments, 10(7), 130.

Rashid, M. R., & Ashik, M. (2023, June). Evaluation of Physicochemical Treatment Technologies for Landfill Leachate Induced Dissolved Organic Nitrogen (DON). In AEESP Research and Education Conference, Northeastern University, June 20-23, 2023.

Song, G., Cao, H., Liu, L., & Jin, M. (2022). Analysis of Marine Microplastic Pollution of Disposable Masks under COVID-19 Epidemic—A DPSIR Framework. International Journal of Environmental Research and Public Health, 19(23), 16299.

Zhai, X., Zheng, H., Xu, Y., Zhao, R., Wang, W., & Guo, H. (2023). Characterization and quantification of microplastics in indoor environments. Heliyon, 9(5).

Zhang, P., Wei, S., Zhang, J., Zhong, H., Wang, S., & Jian, Q. (2022). Seasonal distribution, composition, and inventory of plastic debris on the Yugang Park Beach in Zhanjiang Bay, South China Sea. International Journal of Environmental Research and Public Health, 19(8), 4886.

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Extraction of Medicinal Compounds from *Cynodon Dactylon* Using 1-Ethyl-3-Methylimidazolium Lactate

Pradip Chandra Mandal[a*], Onwesha Sarker[b]

To cite the article:

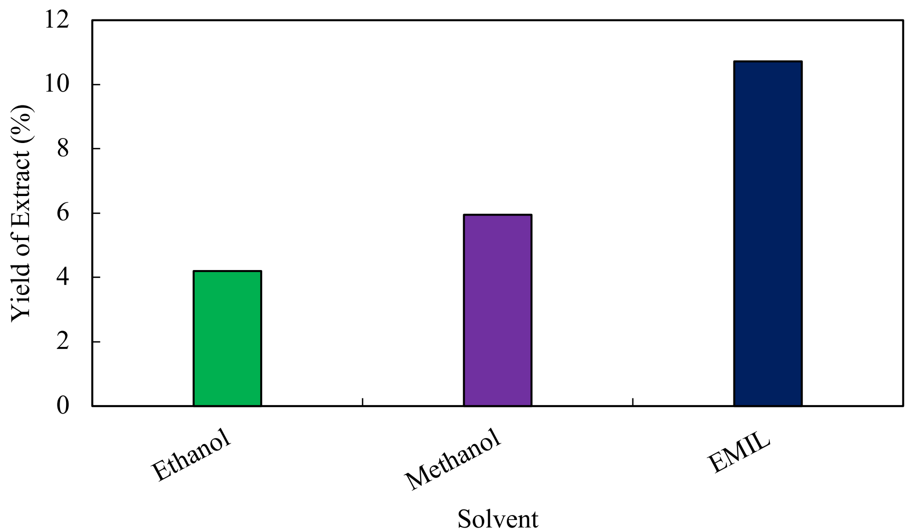
Pradip Chandra Mandal[a*], Onwesha Sarker[b], "Extraction Of Medicinal Compounds From *Cynodon Dactylon* Using 1-Ethyl-3-Methylimidazolium Lactate", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 33-41.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Extraction of Medicinal Compounds From *Cynodon Dactylon* Using 1-Ethyl-3-Methylimidazolium Lactate

Pradip Chandra Mandal[a*], Onwesha Sarker[b]
[a] *Planning Department, Titas Gas Transmission and Distribution Co. Ltd., 105, Kazi Nazrul Islam Avenue, Kawran Bazar, Dhaka-1215*
[b] *Department of English, City University, Khagan, Ashulia, Birulia, Savar, Dhaka*
*Corresponding author: pradipbd2002@yahoo.com

Graphical abstract



Abstract

Cynodon dactylon (CD) has been rich in metabolites and keep several biological activities. The objective of this paper is to extract medicinal compounds from CD by using green solvent, 1-ethyl-3-methylimidazolium lactate (EMIL) ionic liquid (IL) for the first time. In addition, the obtained results were compared with the extraction using organic solvent such as methanol and ethanol. The extractions using organic solvents, methanol and ethanol, were conducted in a Soxhlet Apparatus at temperatures of 65-80°C and IL based extraction was carried out in a round bottle flask at a temperature of 65°C and IL concentrations of 0.004-0.012 g/mL. The extract amount was analysed using volumetric method and the qualitative analysis was done using Gas Chromatography and Mass Spectrometry (GC-MS). The results show that maximum 10.72% extract was extracted at a temperature of of 65°C and an IL concentration 0.012 g/mL that was approximately 80.17% higher than methanolic extraction (5.95%) and 155.24% higher than ethanolic extraction (4.20%). In addition, a significant quantity of medicinal compounds such as oleic acid and fatty acid derivatives (9-Octadecenoic acid (Z)-, methyl ester) were successfully extracted which have antioxidant, antitumor, antifungal and anticancer activity. Therefore, EMIL was active to extract medicinal compounds from CD.

Keywords: *Cynodon Dactylon*, Bermuda grass, 1-ethyl-3-methylimidazolium lactate, Soxhlet Apparatus, Medicinal compound, Biological activity

1.0 INTRODUCTION

Over thousand years plants have been utilized traditionally to treat many diseases before their potential in medicine were being realized by researchers. For decades researchers have done numerous works to explore the medicinal potential from plants which help to boost the pharmaceutical development. Medicinal plants play a very important role in pharmaceuticals industry to develop alternative drugs to overcome the pitfalls possessed by the synthetic drugs. Chemical compounds in plants mediate their effects on the human body by binding to receptor molecules present in the body. Such processes are identical to those already well understood for conventional drugs and as such herbal medicine do not differ greatly from conventional drugs in terms of how they work. This enables herbal medicines to be in principle just as effective as conventional medicines but also gives them the same potential to cause harmful side effects. Among the 120 active compounds recently isolated from the higher plants and broadly used in modern medicine today, 80% of them show a positive correlation between their modern therapeutic use and the traditional use of the plants from which they are obtained. More than two thirds of the world's plant species, at least 35,000 of which are estimated to have medicinal value that come from the developing countries. At least 7,000 medicinal compounds in the modern pharmacopoeia are obtained from plants. Different parts such as leaf, root, stem, fruit, seed and park are used to obtain several phytochemical constituents. In addition, medicinal plants are rich in biologically active compounds and play an important role in drug discovery. The plant extracts are also being used for treatment of cancer [1]. Several anticancer agents from plants include taxol, vinblastine, vincristine, the camptothecin derivatives, topotecan and irinotecan, and etoposide derived from epipodo phyllotoxin are in clinical use all over the world. Numerous cancer research studies have been conducted using traditional medicinal plants in an effort to discover new therapeutic agents that lack the toxic side effects associated with current chemotherapeutic agents.

The weed, *Cynodon dactylon* (CD), is commonly known as Bermuda grass, Bahama grass, devil's grass or couch grass. This weed has been found to possess various potential medicinal properties, like, antidiabetic, antioxidant, and so on [2]. Duke (1983) [3] revealed that the species of CD is originated from East Africa. Now-a-days, it is found all over the world. It is especially abundant in moderate and subtropical regions. This grass is widely used in golf courses and lawns as turf grass [4]. In Bangladesh, it is not only available at public areas such as roadsides but also present in the crop-fields as a weed. It is reported in open literature that this weed is widely used as folk medications, especially in Indian culture, for curing different ailments like, cough, cramps, diarrhoea, epilepsy, headache, haemorrhage, hypertension, hysteria, insanity and snakebite [3]. The researchers have detected many compounds in CD extract that are summarized in **Table 1**.

Table 1 Chemical compounds detected in CD extract [2-11]

Solvent and parts of plant used	Detected Chemicals
Used solvent: Aqueous, Phosphate buffered saline, ethanolic, methanolic, phenolic fraction, aqueous and alcoholic, hydroalcoholic, chloroform-methanolic, ethylacetate fraction, acquous and non-polysaccharide fraction, butanolic	β-sitosterol, β-carotene, palmitic acid, triterpenoids, arundoin, friedelin, selenium, alkaloids- ergonovine and ergonovinine, Ferulic, syringic, p- coumaric, vanilic, p-hydroxybenzoic and o-hyroxyphenyl acetic acids, cyanogenic hyperoside, cyanogenic glucoside- triglochinin, furfural, furfural alcohol, phenyl acetaldehyde, acetic acid, phytol, β-ionone; mono and oligosaccharides, lignin; hydrocarbons (tritriacontane) esters, eicosanoic and docosanoic acids, free alcohol, free aldehydes (hexadecanal)

Solvent and parts of plant used	Detected Chemicals
Used parts: Whole plant, leaves, roots, rhizome, arial parts	and free acids (hexadecanoic acid) (surface cuticular wax); flavone – apigenin, luteolin, flavone glycosides – orientin (8-C-β-D-glycosyl luteolin), vitexin (8-C-β-D-glycosyl apigenin), iso –orientin (6-C-β-D-glycosyl luteolin) and iso-vitexin (6-C- β-D-glycosyl apigenin).

Shabi et al. in 2010 [6] have investigated a comparison study of the chemical constituents between phenolic fraction and hydro alcoholic extract of CD by GC-MS. Approximately 22 compounds are found in CD, but the yield of phenolic fraction is only 0.6%. Among the 20 characterized compounds in CD, the most abundant components are Hydroquinone (69.49%), Levoglucosenone (2.72), Furfural (6.0%) etc. In the year 2011, Jananie et al. [7] have disclosed that leaves extract of CD contain Glycerin (38.49%), 9,12-octadecadienoyl acid chloride,(Z,Z)-(15.61%), Hexadecanoic acid, ,ethyl ester (9.50%), Ethyl α-d-glucopyranoside (8.42%), Linoleic acid,ethyl ester (5.32%), and Phytol (4.89%). The presence of these components are justified the use of CD to treat many aliments in folk and herbal medicine. Kaleeswaran et al. (2010) [8] has also found n-tricosane, which are reported to show antimicrobial characteristics [9], in the ethanol extract of the leave of this species. Abdullah et al. in 2012 [10] have operated a pioneering study to investigate the phytochemical constituents of the whole plant in seven different solvents, acetone, chloroform, diethyl ether, ethanol, ethyl acetate, methanol, and n-pentane. Their results confirmed that the plant contains many bioactive compounds such as alkaloids, cardiac glycosides, terpenoids and steroids, saponins, phenolic compounds, flavonoids, tannins, carbohydrates and proteins. Ashokkumar et al. in 2013 [2] have also discovered that CD extract shows antibacterial and wound healing characteristics. Solanki and Nagori in 2013 [11] have detected β-sitosterol in herbal semisolid formulation of CD using the whole plant of CD. Jegajeevanram et al. in 2014 [12] have investigated the phytochemical composition of CD leaves by GC-MS analysis for the presence of insecticidal compounds. They have concluded that the active compounds in the plant could be developed into consistently effective pesticides with additional research into triterpenoid chemistry and entomology. Therefore, the researchers have found alkaloids, flavonoids, steroids, triterpenoids, tannins, phenols, glycosides and so on from various part of the plant such as rhizomes, leaves, root, stem and also the whole plant using variety of solvents such as acetone, methanol, ethanol, water and etc. **Table 2** illustrates the medicinal values of the extract of CD.

Table 2 Medicinal values of the most common constituents found in CD [2]

Constituents	Medicinal Value(s)
Alkaloids	Cough medicine, antiarrhythmic, antihypertensive, antitumor
Flavonoids	Anti-viral, anti-cancer, anti-inflammatory, anti-allergic, antioxidant
Steroids	Inflammation treatment
Triterpenoids	Cancer treatment, antioxidants, antibacterial, analgesic
Tannins	Antioxidant, antimicrobial
Phenols	Anticancer, anaesthetic/analgesic
Glycosides	Analgesic, anti-rheumatic, anticancer, anti-inflammatory

It is concluded from the above literature review that CD extract contains a lot of medicinal compounds as well as bioactive compounds. But the previous studies were done using harmful organic solvents. Current study focuses on green solvent. Capello et al. in 2007 [13] defined the main objective of green solvents as to minimize the effect of using solvents in the chemical processing towards the environment.

Current world dislikes organic solvents. Water (H_2O), an inorganic compound, is recognized as a green solvent as it is safe and environmentally benign solvent [14]. But this solvent cannot give maximum yield in all extraction processes. Hence, the researchers have studied on other alternatives like Ionic Liquids (ILs), an organic salt having low volatility and flammability. ILs are also used as green solvent in some extraction processes. In 2000, Earle and Seddon [15] have disclosed that ILs can be used not only as designer solvents, but also as a reaction medium in different type of reactions. It is reported in open literature that some ILs can produce toxic or hazardous by-products [16]. Therefore, the selection of proper IL is vital for environmental and safety point of view. Open literature revealed that 1-ethyl-3-methylimidazolium lactate (EMIL) is an environmentally benign IL.

The objective of this paper was to extract medicinal compounds from CD by using EMIL IL and the obtained results were compared with the solvent extraction such as methanol and ethanol.

2.0 METHODOLOGY

2.1 Sample Collection and Preparation

The whole body of CD was collected discretely from different places of Singair, Manikganj in rainy season. The collected plants were cleaned properly with water to remove soils, dirt and unwanted parts of the plants. The specimens were then dried overnight in an oven at a temperature of 60°C. The dried plants were pulverized using an electrical grinder to form powder to increase the surface area for extraction. The particles of CD in a diameter of 250 μm or less were separated through sieve analysis and were used as samples for extraction. The samples were kept in a refrigerator to use it during experiments.

2.2 Extraction Procedure

2.2.1 Ethanolic or methanolic extract

Exactly 250 mL of ethanol or methanol was taken in a 300 mL round bottle flask. Then, approximately 5 g of CD sample was placed in a pre-measured thimble and the thimble was loaded in the Soxhlet apparatus. The extraction was performed for 8 hours at a temperature of 80°C (for ethanol) or 65°C (for methanol). The extract was then collected in sample bottle and the samples were stored in refrigerator until further use. The thimble was removed from the apparatus and was dried in an oven. Finally, the exacted amount was calculated by measuring the dried thimble. The experiments were done three times with 95% confidence and the average values are reported.

2.2.2 IL-based extract

Exactly 250 mL of methanol was placed in a 300 mL round bottle flask. Then exactly 1 - 3 g of EMIL was added into the round bottle flask to make its concentration 0.004 – 0.012 g/mL. Approximately 5 g of CD sample was placed in a pre-measured thimble and the open-end of the thimble was closed with cotton. The thimble was then placed into the round bottle flask. A condenser was kept at the top of the round bottle flask to prevent vaporization of volatile compounds. The round bottle flask was then heated at a constant temperature of 65°C and a time of 8 hr. The thimble was removed from the round bottle flask, was cleaned with methanol and was dried in an oven. Finally, the extracted amount was quantified by measuring the dried thimble.

2.3 Extract Analysis

The amount of extract was analysed using gravimetric methods. The percentage of extract was then calculated using the following formula:

$$Yield\ of\ extraction\ (\%) = \frac{A-B}{A} \times 100\ \% \qquad (1)$$

where A = Loaded amount of CD in g in the extractor and B = Amount of CD in g after extraction

GC-MS analysis was carried out to identify the compound present in the extracted samples. The GC-MS analysis was conducted on Agilent Technologies 7890A Gas Chromatograph with 5975C Mass Spectrometer using 30 m length, 0.25 mm diameter and 0.25 μm DB-23 column. Exactly 1µl extract was injected into the GC-MS using micro syringe at split less mode at temperature of 200^{o}C. The column oven temperature was hold at 45°C for 1 minute, then increased at a rate of 5°C/ min to reach 280°C and then hold for 15 min. Helium gas was used as a carrier gas at a flow rate of 1.4 mL/min. Total GC running time was 48 min.

3.0 RESULTS AND DISCUSSION

To investigate the solvent effect, three different solvent such as ethanol of boiling point 78.37^{o}C, methanol of boiling point 64.70^{o}C, EMIL at different concentrations in methanol were used. The ethanolic and the methanolic extraction were carried out in a Soxhlet Apparatus at temperatures of 80^{o}C and 65^{o}C respectively and IL based extraction was carried out in a round bottle flask at a temperature of 65^{o}C. **Figure 1** reveals that EMIL at a concentration of 0.012 g/mL extracted maximum 10.72% extract whereas the respective ethanolic and methanolic extract yields were 4.20% and 5.95% only. Therefore, EMIL at a concentration of 0.012 g/mL extracted approximately 80.17% higher than methanolic extraction and 155.24% higher than ethanolic extraction. Abdullah et al. [10] have conducted experiments using CD collected from Universiti Malaysia Sabah's area and revealed that ethanolic extraction produced the highest yield (7.07%) followed by methanolic extract (5.42%). Therefore, the whole body of CD obtained from Singair, Manikgang areas gives almost the same amount of methanolic extract as CD of Universiti Malaysia Sabah's area.

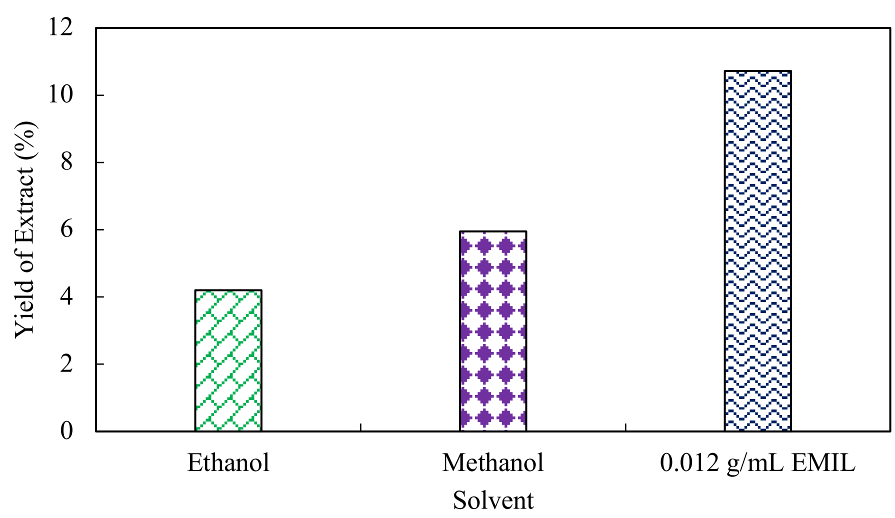


Figure 1 Extract yields obtained by using different solvents

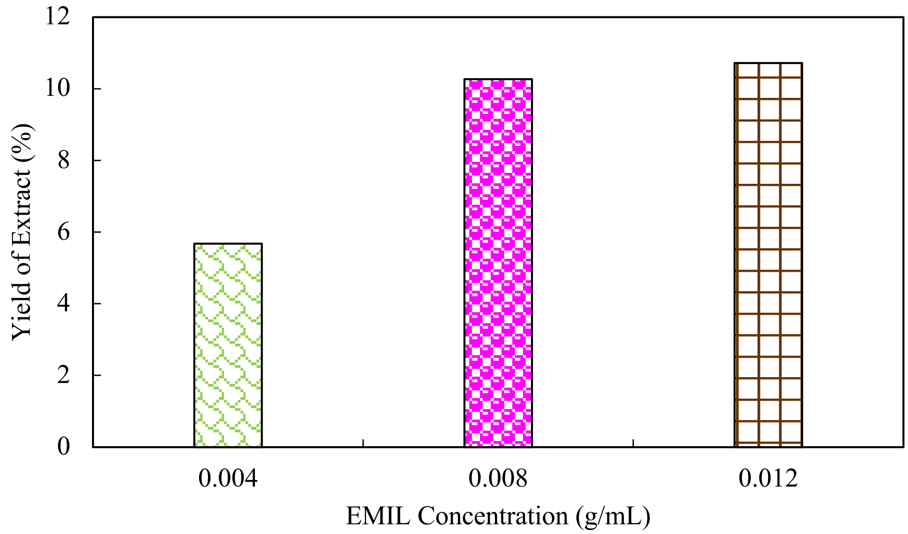


Figure 2 Extract yields at different concentration of EMIL in methanol

Figure 2 demonstrates that extract yields were increasing with the increase of concentration of EMIL in methanol. The yield of extract was only 5.68% at a concentration of 0.004 g/mL and this value was increased to 10.72% at a concentration of 0.012 g/mL. An escalation of yields was observed from EMIL concentration of 0.004 g/mL to 0.008 g/mL EMIL while there was only a small rise as it was further increased to 0.012 g/mL. This result indicates that the optimum extraction was very close to 10.72%. Wang et al. have disclosed that the density (1.1548-1.1140 $g.cm^{-3}$) and surface tension (53.37-48.63 $mN.m^{-1}$) of EMIL increased with the increase of temperatures of 10-60^{o}C. In addition, alike the alcohol EMIL is a hydrophilic IL. Mandal et al. in 2015 [17] revealed that IL molecules themselves could form cage structure through specific chemical bonds. In this cage, the extract molecules would be captured through forming liquid clathrate. These characteristics of IL increased its solubility power to extract more compounds than methanol.

The GC-MS analysis detected many phytochemical compounds in the extract of CD. The extracted phytochemical compounds and their corresponding biological activities are depicted in **Table 3**. It is seen that antitumor and anticancer active compound oleic acid found in both ethanolic and EMIL (0.012 g/mL) based extract. In addition, Antifungal, antioxidant, anticancer active compound 9-Octadecenoic acid (Z)-, methyl ester was found only in EMIL (0.012 g/mL) based extract. Furthermore, Octadecanoic acid can be used as Cancer preventive insectifuge that was found in both ethanolic and EMIL (0.004 g/mL) based extract. Therefore, EMIL based extraction can extract more medicinal compounds that ethanolic and methanolic extraction.

An organosilicon compound dimethoxydimethylsilane was observed in all the extract. Kregiel and Niedzielska in 2014 [18] disclosed that this compound can greatly improve the antiadhesive and antibacterial properties of a chemically altered polyethylene. In addition, organoborate compound boric acid, trimethyl ester, commonly known as trimethyl borate, was also extracted in all extract except ethanolic extract. This compound is used to synthesize barbigerone analogues that have high anti-proliferative behaviour [19].

Table 3 Major phytochemical component detected by GC-MS equipment

Component Extracted	Peak Area (%)				Biological activity	References
	Pure ethanol	Pure methanol	EMIL concentration in methanol (g/mL)			
			0.004	0.012		
Silane, dimethoxydimethyl-	2.80	19.34	16.34	1.52	Not reported in open literature	
Boric acid, trimethyl ester		16.15	13.75	2.09	No activity reported	[20]
Oleic Acid	1.50			1.02	Antitumor, anticancer	[21, 22]
1,2-Benzenedicarboxylic acid, dicyclohexyl ester	1.30				Not reported in open literature	
1,3,12-Nonadecatriene		1.41			Not reported in open literature	
1,9-Tetradecadiene				1.10	No activity reported	[23]
2-Methyl-2-docosene			1.14		Not reported in open literature	
Octadecanoic acid	2.12		2.23		Cancer preventive insectifuge	[22]
6-Octadecenoic acid, (Z)-	1.58		1.20		Not reported in open literature	
9-Octadecenoic acid, (E)-	1.37				Not reported in open literature	
9-Octadecenoic acid (Z)-, methyl ester				2.12	Antifungal, antioxidant, anticancer	[22]
Propanenitrile, 3-[2-(4-pyridyl)-1-indolyl)-	1.28				Not reported in open literature	
cis-11-Hexadecenal	1.14				Not reported in open literature	
E-9-Hexadecenal		2.87			Not reported in open literature	
Cyclopropaneoctanal, 2-octyl-	3.40				Not reported in open literature	
Octadecanal, 2-bromo-			2.52		Not reported in open literature	
Methyl 3-hydroxyoctadec-9-enoate			3.09		Not reported in open literature	
Z,Z-6,24-Tritriacontadien-2-one			4.42		Not reported in open literature	
Cyclohexadecane, 1,2-diethyl-			1.21		Not reported in open literature	
9,12-Octadecadien-1-ol, (Z,Z)-				14.46	No activity reported	[24]
Z,E-3,13-Octadecadien-1-ol	3.81				Not reported in open literature	
2-Methyl-Z,Z-3,13-octadecadienol				2.34	Not reported in open literature	

4.0 CONCLUSION

The medicinal plant, CD, obtained from Singair, Manikganj, Bangladesh contains antioxidant, antitumor, anticancer and antifungal active compounds. EMIL extract at a concentration of 0.012 g/mL yields respective 80.17% and 155.24% higher extract of ethanolic and methanolic extraction. Moreover, extract yield was increased with increasing the concentration of EMIL in methanol from 5.68% to 10.72%. In addition, EMIL can extract more medicinal compounds such as oleic acid, 9-octadecenoic acid (Z)-, methyl ester compare to ethanolic and methanolic extract. Other extracted compounds such as dimethoxydimethylsilane and trimethyl borate have their respective application in chemical industries. Extensive study related to extract optimization and kinetics will be required to discover the potentiality of commercial production.

References

[1] Albert-Baskar A., Ignacimuthu S. 2010. Chemo preventive effect of Cynodon dactylon (L.) Pers. extract against DMH-induced colon carcinogenesis in experimental animals. Exp. Toxicol. Pathol. 62(4): 423-431. DOI: 10.1016/j.etp.2009.06.003.

[2] Ashokkumar, K., Selvaraj, K., and Muthukrishnan, S. D. 2013. Cynodon dactylon (L) Pers.: An updated review of its phytochemistry and pharmacology, J. Medicinal Plants Research 7(48): 3477-3483. DOI: 10.5897/JMPR2013.5316x

[3] Duke J.A. 1983. Handbook of Energy Crops. Unpublished, retrieved from Purdue University, West Lafayette, India on 9 March 2016.
https://www.hort.purdue.edu/newcrop/duke_energy/Cynodon_dactylon.html

[4] Gobilik, J., Jerome, V., David, D. 2013. Preliminary selection of some ecotypes of Cynodon dactylon (L.) Pers. in Sabah, Malaysia, for turfgrass use. J. Trop. Biol. Conserv. 10(1): 51-66.

[5] Fetrow, C.W. and Avita, J.R. 2000. The Complete Guide to Herbal Medicine. Simon & Schuster Inc., New York, NY, USA.

[6] Shabi, M. M., Gayathri, K., Venkatalakshmi, R., Sasikala, C. 2010. Chemical constituents of hydro alcoholic extract and phenolic fraction of Cynodon dactylon, Int. J. ChemTech Res. 2(1): 149-154.

[7] Jananie, R. K., Priya, V., and Vijayalakshmi, K. 2011. Determination of bioactive components of Cynodon dactylon by GC-MS analysis, New York Science Journal 4(4): 16-20. Retrieved on 9 March 2016. http://www.sciencepub.net/newyork/ny0404/03_4901ny0404_16_20.pdf

[8] Kaleeswaran, B., Ilavenil, S., & Ravikumar, S. 2010. Screening of Phytochemical Properties and Antibacterial Activity of Cynodon dactylon L. International Journal of Current Research 3: 83-88.

[9] Samadi, N., Manayi, A., Vazirian, M., Samadi, M., Zeinalzadeh, Z., Saghari, Z., Abadian, N., Mozaffarian, V.O., Khanavi, M. 2012. Chemical composition and antimicrobial activity of the essential oil of Anthemis altissima L. var. altissima. Nat. Prod. Res. 26(20):1931-1934.

[10] Abdullah S., Gobilik J., and Chong, K. P. 2012. Preliminary phytochemical study and antimicrobial activity from various extract of Cynodon dactylon (l.) pers. (bermuda) against selected pathogens, Int. J. Pharm. Sci. 4(5): 227-230.

[11] Solanki R. and Nagori B. P. 2013. RP-HPLC method development and validation for estimation of β-sitosterol in herbal formulation of cynodon dactylon (linn.) pers., Internationale Pharmaceutica Sciencia 3(3): 55-59.

[12] Jegajeevanram P., Alhaji N. M. I. and Kumaravel S. 2014. Identification of pesticide compounds of Cynodon dactylon by GC-MS analysis. Int. J. Pharm. Bto. Sci. 5(2): 604-608.

[13] Capello, C., Fischer, U., & Hungerbühler, K. 2007. What is a green solvent? A comprehensive framework for the environmental assessment of solvents. Green Chemistry, 9: 927-934. DOI:10.1039/B617536H

[14] Prat, D. , Pardigon, O., Flemming, H.-W., Sylvie, L., Ducandas, V., Isnard, P., Guntrum,E., Senac, T., Ruisseau, S., Cruciani, P. and Hosek, P. 2013. Sanofi's Solvent Selection Guide: A Step Toward More Sustainable Processes. Org. Process Res. Dev. 17 (12): 1517–1525. DOI: 10.1021/op4002565

[15] Earle, M. & Seddon, K. 2009. Ionic liquids. Green solvents for the future. Pure and Applied Chemistry 72(7): 1391-1398. DOI:10.1351/pac200072071391

[16] Swatloski, R.P., Holbrey, J.D., and Rogers, R.D. 2003. Ionic liquids are not always green: hydrolysis of 1-butyl-3-methylimidazolium hexafluorophosphate. Green Chem. 5: 361-363. DOI: 10.1039/B304400A.

[17] Mandal, P. C., Abdalla M.A., and Moniruzzaman, M. 2015. Acidity Reduction of Naphthenic Acid Using Imidazolium Chloride Based Ionic Liquids. International Journal of Applied Engineering Research, 10(89): 69-74.

[18] Kregiel, D. and Niedzielska, K. 2014. Effect of Plasma Processing and Organosilane Modifications of Polyethylene on Aeromonas hydrophila Biofilm Formation. BioMed Research International 2014: 1-8. http://dx.doi.org/10.1155/2014/232514.

[19] Wang, G., Wang, F., Cao, D., Liu, Y., Zhang, R., Ye, H., Li, X., He, L., Yang, Z., Ma, L., Peng, A., Xiang, M., Wei, Y., Chen, L. 2014. Synthesis, structure-activity relationships and biological evaluation of barbigerone analogues as anti-proliferative and anti-angiogenesis agents. Bioorg. Med. Chem. Lett. 24(14):3158-63. DOI: 10.1016/j.bmcl.2014.04.121.

[20] Kaushik, P., Lal, S., Rana, A.C. and Kaushik, D. 2014. GC-MS Analysis of Bioactive Constituents of Pinus roxburghiiSarg. (Pinaceae) from Northern India. Research Journal of Phytochemistry, 8: 42-46. DOI: 10.3923/rjphyto.2014.42.46.

[21] Fontana, A., Spolaore, B., Polverino de Laureto, P., 2013. The biological activities of protein/oleic acid complexes reside in the fatty acid. Biochimica et Biophysica Acta (BBA)- Proteins and Preteomics 1834 (6): 1125-1143. DOI:10.1016/J.BBAPAP.2013.02.041

[22] Sharma, P., Vijayvergia, R. 2015. In Vitro α-Amylase Inhibitory Activity and GC- MS Analysis of Petrea volubilis. International Journal of Science and Research (IJSR) 4 (4): 190-194.

[23] Ananthi, P., Ranjitha Kumari, B. D. 2013. GC – MS Determination of Bioactive Components of Rorippa indica L. Int..J..ChemTech Res. 5(4), 2027-2033.

[24] Sujatha, Karthika, Sivakamasundari, Mariajancyrani and Chandramohan, 2014. GC-MS analysis of phytocomponents and total antioxidant activity of hexane extract of Sinapis Alba, IJPCBS 4(1): 112-117. http://www.ijpcbs.com/files/16-420.pdf.

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Technical Investigation on Baily Road Green Cozy Cotez Restaurant Fire: Incident Analysis and Lessons Learned

Easir A Khan

To cite the article:

Easir A Khan, "Technical Investigation on Baily Road Green Cozy Cotez Restaurant Fire: Incident Analysis and Lessons Learned", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 42-54.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Technical Investigation on Baily Road Green Cozy Cotez Restaurant Fire: Incident Analysis and Lessons Learned

Easir A. Khan

Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, Email: eakhan@che.buet.ac.bd

Abstract:

The Green Cozy Cotez Restaurant fire serves as a unique case study highlighting the catastrophic consequences of fire incidents on commercial establishments in Dhaka City. This abstract presents a thorough investigation into the circumstances surrounding the fire, focusing on incident analysis, fire spread mechanisms, causes of fatalities and deriving essential lessons for fire safety management. Through careful examination of the fire's origins, fire timeline, progression, structural vulnerabilities and emergency response, the study aims to uncover underlying causes contributing to the severity of the blaze and its impacts. The key findings reveal deficiencies in fire prevention measures, building safety standards, regulatory compliance, employee trainings, emergency evacuation and preparedness procedures. Additionally, the study analyzes the deficiencies and actionable recommendations for enhancing fire safety practices in commercial or industrial buildings. The recommended measures include the adoption of national building codes, installation of fire detection and alarm systems, fire protection systems, fire safety plans, emergency escape routes and implementation of comprehensive emergency response plans. By synthesizing empirical evidence with practical experiences, this investigation offers valuable insights and a roadmap for building owners, engineers, architects, interior designers, regulatory authorities, policymakers, business owners, and emergency responders to strengthen fire safety measures and mitigate future risks. Through continuous learning and awareness, communities can enhance their capacity to prevent fire incident in commercial buildings, ensuring the safety and well-being of all stakeholders.

Keyword: Fire Safety, Emergency Evacuation, LPG Hazards, Lessons Learned and Bangladesh

1. Introduction

On February 29, 2024, a devastating fire broke out in a seven-story building Green Cozy Cotez in Baily Road, Dhaka that killed 46 people. Dhaka City, the vibrant capital of Bangladesh, is characterized by its busy streets, dense population, and rapid urbanization. With its over-crowded areas, informal settlements, and inadequate infrastructure, the city faces significant challenges in mitigating fire hazards and ensuring public safety. Fire and explosion incidents are very frequent in the city areas in residential buildings, marketplaces, commercial establishment, factory buildings and chemical warehouses[1–9]. Several factors contribute to the increased risk of fires in Dhaka City. Firstly, the city's rapid population growth has led to overcrowding in residential areas and workplaces, increasing the probability of accidents. Moreover, the proliferation of informal settlements with temporary housing and narrow alleyways worsens the risk, hindering access for firefighting equipment and emergency responders, especially in old Dhaka. Number of deadly fire and explosion accidents occurred in past decades in residential, commercial, and industrial buildings in old Dhaka. In 2019, a fire and explosion incident occurred in a chemical warehouse, 1st floor of wahid mansion in old Dhaka where huge amount of flammable chemicals was stored. Consequently, a fire massive fire engulfed the nearby roads as the chemicals spread all over after the explosion. 71 People were killed in the accident who stacked there due to the heavy traffic in the narrow road[1]. The devastating fire sparked by a LPG release and explosion had gutted the Prime Pet and Plastic Industry factory that killed 22 people. Workers who stayed inside the factory were unable to evacuate and burnt to death. According to a survivor fire broke out close to where eight cylinders of inflammable gas were stored.

The lax enforcement of building codes and safety regulations allows for substandard construction practices, improper interior design, faulty electrical wiring, and improper storage of flammable materials, further amplifying the fire risk[6]. The consequences of fire incidents in Dhaka City are very severe and far-reaching[10]. The socio-economic impact is particularly severe for workers, small businesses, building residents who lack insurance coverage and financial resources to recover from such disasters. The release of toxic fumes generated form fire pose long-term health risks for residents and populations who are exposed. There are various challenges in both preventing fire and responding to fire incidents. Weak institutional capacity, limited resources, and inadequate training for firefighters impede effective emergency response efforts. Additionally, the lack of public awareness about fire safety practices, fire safety education and evacuation procedures leave residents vulnerable in the event of a fire. Moreover, corruption and bureaucratic hurdles hinder the strong enforcement of building codes and safety regulations, perpetuating the cycle of risk and recurrence of deadly accidents.

In major fire accidents, the investigation committee formed by the regulatory bodies came with the immediate causes of the events[1]. The root or underlying causes of the incidents were often ignored and had not been surfaced. Unfortunately, the similar events or accidents are recurring. This study conducted a careful technical investigation of deadly incident of Green Cozy Cotez restaurant fire to identify the underlying causes and find out the deficiencies in fire prevention measures, building safety standards, regulatory compliance, regulatory enforcement, employee trainings, emergency evacuation and preparedness procedures. This study also shares the investigation findings and lesson learned from the fire incident and identifies the key stakeholders' roles and responsibility in effective management of building fire safety and provide recommendations for preventing the recurrence of similar accidents.

2. Incident Description

Green Cozy Cotez was an attractive place for food lover at Baily Road located in Dhaka City. The building has number of reputed restaurants in its each floor; chumuk coffee shop and mezbany khan at ground floor, Khacchi vai restaurant at 1st floor, ready-made garments showroom at 2nd floor, khanas and fuku restaurants at 3rd floor, Pizza inn at 4th floor, Zesty and Street Oven at 5th floor, Hakka Dhaka at 6th floor and Ambroshia restaurant at the rooftop.

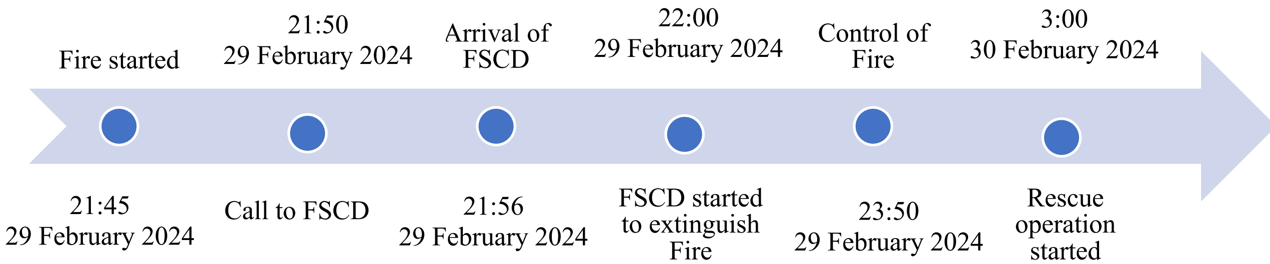


Figure 01: Incident timeline of Green Cozy Cotez Restaurant Fire (Thursday at 21:45, 29 February 2024)

On 29 February 2024, fire initially started at the ground floor at around 9:45 pm local time (BST) and quickly spread all over the building. The incident timeline is shown in Figure 01. Fire service personnel reached to the scene quickly and started to extinguish fire. However, fire spread very quickly to the whole building before the fire service personnel came. Fire initiated at the chumuk coffee shop located close to the main entrance as shown in Figure 02 building layout. The building has two lifts and one staircase which completely blocked by smoke and heat immediately after fire started. The people at upper floor were trapped in the fire and unable to evacuate and consequently 46 of them died because of direct burn injury, oxygen deficiency and/or smoke inhalation.

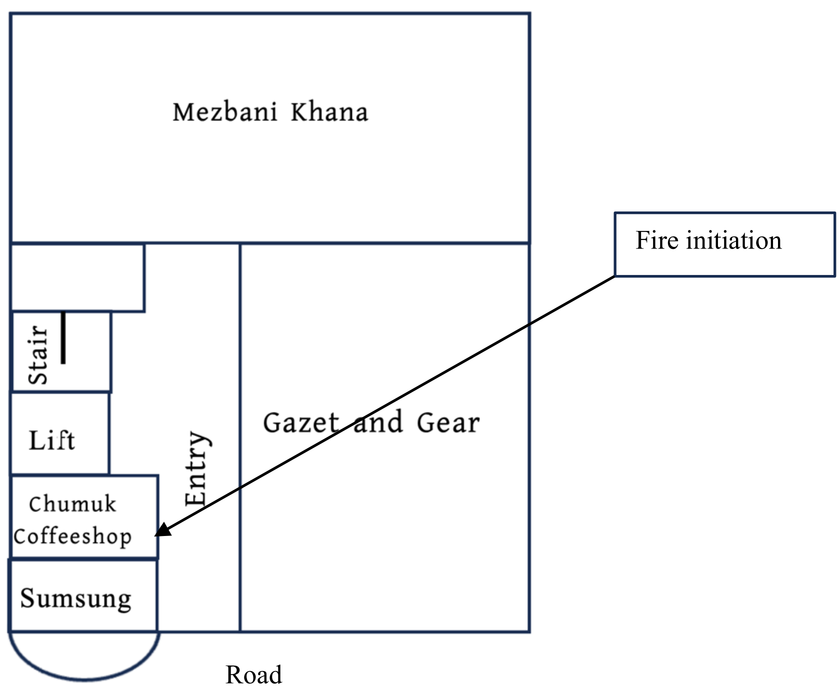


Figure 02: Ground floor layout of Green Cozy Cotez Restaurant

There was no fire alarm system that could be activated to sound in case of an emergency or fire. People were unaware of the fire and its possible risk. Some quickly realized the danger, took the staircase, and get shelter at the rooftop. Within fifteen minutes of the fire starting, firefighters arrived on the scene. The location of the fire source, initial fire scene and smoke spread can be seen in Figure 03 where people were trying to extinguish. People who died were mostly from smoke inhalation and lack of oxygen due to the fire. Out of 46 deaths, only three were due to burn. Approximately seventy-five people were rescued by firefighters from the rooftop. In the early stages of the fire, people used ladders to escape by breaking the first floor's window glass. However, as the fire suddenly became more intense, many could not escape through the windows.

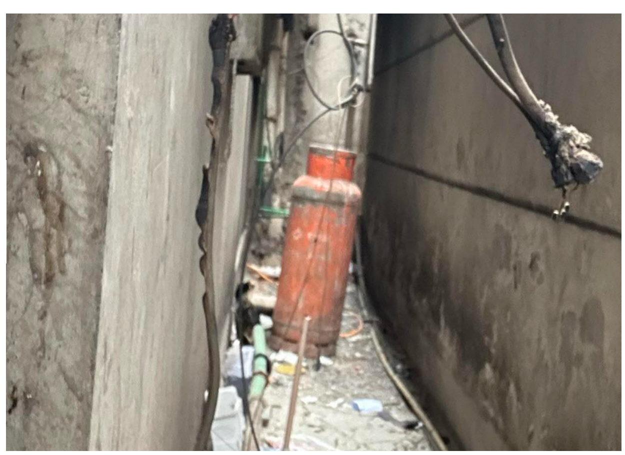
Figure 03: Location of fire source, initial smoke, and fire scene

3. Technical Analysis of the Fire Incident

3.1. Causal Analysis of fire initiation and fire spread:

According to early stage vedio analysis and eyewitness and fire service personnel interviews, the fire started on the ground floor of the Chumuk Coffee Shop, close to the main door. The precise reasons behind the fire's start remain a mystery. A number of factors, including electrical short circuits, electric heaters, gas leaks, and electrical equipment, can contribute to the start of a fire. LPG gas cylinder was used for cooking at Chumuk Coffee Shop.

Figure 04: LPG Gas cylinder used in Chumuk Coffeeshop



There was no cylinder inside the coffee shop. As seen in Figure 04, an LPG cylinder was discovered behind the coffee shop and linked with a hosepipe through the wall. This type connection is inherently hazardous. This line will get damaged and leaky in the event of a fire, which will make the fire worse. As a result, if there is a constant flow of gas because of a leak or pipeline failure, the fire will spread very quickly.

Analysis of the video footage shows that smoke was first observed spreading at the ground floor's main entrance. Afterwards, because of the open area and oxygen availability at the front side of the building, the fire and smoke spread quickly there. The direction of the combustion flame is determined by the availability of oxygen. Even the fire didn't spread in Mezbani Khana which is located at ground floor and backside of the building (see Figure 01). In addition to the main entrance, the staircase near the Chumuk Coffee Shop is another point of entry for fire in the building's interior. Smoke and fire swiftly filled the staircase and used it as a chimney to spread. As a result, those who had stayed on the upper level were trapped and were unable to escape using the only stairway that was available. Before the fire fighter arrived at the scene, the fire had reached the flashover stage. Fire spread from ground floor to top floor within 2 minutes as shown in Figure 05 (Left- fire scene at the ground floor before the fire fighter came, Right-fire scene just after two minutes).

Figure 05: Fire spread within two minutes from ground floor to top floor.

3.2. Causal Analysis of fire intensity and smoke spread:

The fire soon reached the flashover stage and quickly spread from the bottom to the top. The building's front side was primarily affected by the fire, with glass partitions breaking apart. Currently, the two most important questions are: (i) What was in the coffee shop that caused such a catastrophic fire? and (ii) How did the fire spread so quickly? Usually, presence of highly flammable may create such kinds of catastrophic fire scenario. The presence of an LPG cylinder connection, a highly flammable material, a continuous flow of LPG gas into the fire might have devastating consequences due to the high burning rate and significant energy released when burning. Therefore, this tragic fire may be consequence of continuous release of LPG gas due to pipeline failure or presence of gas cylinders in proximity of fire areas. LPG gas cylinder was stored haphazardly inside the building even at the only available staircase as shown in Figure 06.

Figure 06: LPG cylinders stored at the staircase (Left) and gas line connection using flexible plastic pipeline (Right)

The staircase became filled with smoke and fire. In the staircase, there were over 10 42 kg LPG cylinders. The pressure increased because of the heating of these cylinders. When an LPG cylinder encounters heat and flames and its temperature increases to 70 °C, its pressure also increases to 25 atm. Because of the extreme pressure, the cylinder's relief valve activates for preventing an explosion and releases gasses that fuels the flames. Additionally, cylinders were kept outside the building and connected using flexible plastic tubes (see Figure 06). These pipelines can damage in contact with the flames, can continue to supply fuel which would feed and exacerbate the fire.

Figure 07: Damaged staircase due to excessive heat (L) and damage doors due to fire (R)

The intense heat produced by the fire, which was caused by cylinders kept inside the stairs, severely destroyed the staircase. As seen in Figure 07, the fire also readily burned through the doors on each story, creating a space where smoke and flames could spread. Due to the irregular fuel load on some floors, the fire didn't go very far, but smoke filled the building's enclosure and nearly every floor.

3.3. Causal Analysis of Injuries and large casualties:

The majority of the victims in this fire catastrophe were caused by the poisonous smoke that the fire produced. In the early stages, the only possible escape route was obstructed by smoke and flames. There is no safe way out of the building in an emergency. People couldn't use the staircase to get out, not even on the first floor. Some people used ladders to escape after breaking through the front window glass frames. But the fire also produced too much radiant heat, which made it difficult to leave the area with a ladder and trapped inside. The room was filled with smoke even though there was no fire. The same thing was seen on every floor of the structure. As a result of the environment's low oxygen content and smoke inhalation, people passed out. Oxygen is consumed by fire, lowering the enclosure's oxygen content.

Toxic gas is produced by incomplete combustion of the building materials, which include plastic, wood, foam, and interior design elements. Reduced levels of fire oxygen in an enclosure slow down the rate at which the combustible materials burn and result in incomplete combustion. Hence, dangerous volatile organic compounds (VOCs), dust particles, and hazardous gases (such as cyanide and carbon monoxide) are all present in the smoke produced by the fire. Many became quickly unconscious due to the expoure of toxic gases and oxygen shortage, and consequently passed away from cardiac arrest and respiratory failure. In case of oxygen exposure below 10%, people became unconscious very quickly. Table-1 shows the effects of oxygen deficient environment for human exposure.

Table-1: Effects of Oxygen-Deficient Exposure

Oxygen concentration	Effects of Oxygen-Deficient Exposure
21%	Normal as outside air
19%	Some adverse physiological effects occur, but they may not be noticeable.
15-19%	Impaired thinking and attention. Increased pulse and breathing rate. Reduced coordination. Decreased ability to work strenuously. Reduced physical and intellectual performance without awareness.
12-15%	Poor judgment. Faulty coordination. Abnormal fatigue upon exertion. Emotional upset.
10-12%	Very poor judgment and coordination. Impaired respiration that may cause permanent heart damage. Possibility of fainting within a few minutes without warning. Nausea and vomiting.
6-10%	Nausea and unconsciousness.
Less than 6%	Inability to move. Fainting almost immediate. Loss of consciousness. Convulsions. Cessation of breathing followed by cardiac arrest.

4. Underline causes of the incident.

The green cozy cotez building's ground floor is where the fire originated. The National Building Code classifies this building as a high occupancy commercial building. Because of how it was used, the building was riskier or more vulnerable. Furthermore, the building's numerous levels of fire safety flaws contributed to the accident's catastrophic outcome. These shortcomings or primary causes of this fatal event are addressed in the sections that follow;

4.1. Fire Protection System and Regulatory Enforcement:

Green Cozy Cotez is a business building with a high occupancy rate. The fact that there were several restaurants housed in the same building increased the danger and risk. The building's fire safety system is extremely inadequate. In compliance with the National Building Code, its lacking internal fire suppression system. There was no regulatory enforcement at all. Numerous agencies responsible for enforcing regulations (such as the Fire Service and Civil Defense, the Explosive Department, the City Corporation, Rajuk, etc.) have certified and granted licenses to this business organization despite failing to address safety deficiencies and violation of code and standard.

The building lacked adequate fire extinguishers. The impacts of this tragedy could have been significantly decreased if the building had an emergency exit and people had been alerted at early stage of fire. The fire and possible risk of the event were unknown to those on the upper floor. The building features a single, unprotected stairway that lacks fire doors. Furthermore, LPG gas cylinders were kept at the staircase.

4.2. Building Construction and Interior Design:

The authority, RAJUK gave its approval for Green Cozy Cotez to be built as a mixed-use commercial building, with residential space on levels 6 and 7 and business space on levels 1 through 5. Nevertheless, the building was used for business purposes, with an industrial/commercial kitchen occupying most of the floor and a rooftop expansion. The fundamental fire safety concept and requirement has been deliberately ignored by the building's architect, construction company, structural engineer, interior designer, commercial institution, and regulatory or enforcement authorities. The building differed from its original plan even though it had safety flaws when it was designed.

The building featured a narrow entrance, with small and large businesses on either side. The Chumuk coffee shop was located at the entryway, narrowing it further despite not having regulatory agency approval. Interior designers severely disrupted or harmed passive fire safety issues (i.e. fire separations, horizontal and vertical fire separation, introduction of combustible/plastic materials, compartmentalization) as a result of the restaurants' floor-by-floor beautifying. The interior designer installed a thin glass wall to take over the extended and communal areas, demolishing the inside wall in the process. The primary method of fire spread between floors was the breaking of external glass barriers. The building's first and fourth floors, where the vertical fire separation is less than two feet, had extensive fire damage as shown in

Figure 08. This is also supported by the fact that fire didn't spread at the 2nd floor as there exist vertical fire separation by solid walls. Therefore, with correct design, the consequences could have been reduced if the fire and smoke had been contained at the ground floor.

Figure 08: Damaged building and exterior glass wall

4.3. Gas Cylinder storage, Installation, and User Awareness:

LPG gas cylinders were used in Green Cozy Cotez's commercial kitchen. Because LPG is a highly flammable and dangerous gas, there is a significant risk of fire and explosion. When installing, using, and storing LPG gas cylinders, the building's business owner neglected to consider the possible risk. LPG cylinders were haphazardly stacked at the building's stairwell. During installation, substandard pipelines and connections were employed. As seen in Figure 06, long, flexible plastic pipes rather than metal ones had been employed to link the commercial kitchen to the bank of cylinders kept outside the building. In the event of a fire, these flexible plastic pipes damage and helped to feed the fire with a steady flow of extremely combustible gas. The severity of the fire and its rapid spread suggest the possibility that the continuous supply and presence of LPG gas had a role in this tragic tragedy.

4.4. Fire Safety Plan and Emergency Evacuation:

The business owner of Green Cozy Cotez failed to address the fundamental safety requirements of the building, employee training on fire safety, fire safety awareness, safe passage during emergencies, and fire emergency responses. Workers received no training on what to do in the event of a fire, where to seek shelter, or how to evacuate. Some workers lost their life after jumped off from the building. The first floor witnessed many casualties as people were suffocating in a locked air-conditioned room after getting trapped within. If they took shelter in the kitchen store area of first floor, which was open to the air and devoid of smoke and fire, their lives might have been saved. Many lives could have been saved if there had been an appropriate fire safety and evacuation plan.

5. Findings and Lessons learned.

The fire at the Green Cozy Cotez restaurant was a tragic and fatal incident. There are always lessons to be learned from accidents. An extensive investigation has been conducted into this event in order to identify the root causes, flaws in the fire safety systems, noncompliance, and lessons learned. The key findings and takeaways from the incidents covered in this part are listed below.

a) Building should be constructed as per occupancy and following national building code. In case of mixed occupancy building, emphasis should be given in designing and implement active and passive fire protection systems.
b) There must have fire safety plan, fire alarm and safe passage or emergency evacuation route/exits. There must have active firefighting systems and fire extinguisher as per the risk and national building codes.
c) Fire separation and compartmentalization must not be destroyed during interior design and external beautification. Fire hazard, fire risk and safe passage during emergency has to be addressed in stage of building modifications.
d) Official and employees must have training on basic fire safety and response plan in case of any fire emergency.
e) LPG gas cylinder should be handled carefully and stored in open and ventilated area. It should not store in a closed space, in emergency exits or staircase and, in an area, where fire risk is high. Substandard connection and pipelines should not be used for gas line installations to avoid risk of gas leakage and potential accident. Metal standard pipeline should be used instead of flexible plastic pipe for gas line connections.
f) Regulatory agencies must implement the codes and standards for approval or giving license to the business owners. Accidents can be avoided through the effective implementation of compliances and appropriate fire safety system.

6. Recommendations

The opinions and suggestions for enhancing Bangladesh's fire emergency management and safety procedures are discussed in this section. In order to manage fire safety effectively, nations must delve deeper into the issue and adopt a comprehensive strategy for enhancing practices and procedures in a number of areas where they have identified significant shortcomings. To achieve effective management connected to fire safety, one needs investigate several areas, such as stakeholder participation, fire safety standards, guidelines and regulations, regulatory enforcement, fire prevention strategy, fire safety education, and safety culture. Everyone has an obligation to ensure fire safety. The needs and areas for improvement from the stakeholders' perspectives are explained in this section.

i. Building owners:
   - Expert and reputed companies or personnel must be engaged in architectural design and building construction.
   - The design, supervision and monitoring of construction work must be performed by professionals registered in Electronic Construction Permitting System- ECPS.
   - Building architectural and structural design, design approval and fire safety plan must be ensured as per national building code occupancy category.

ii. Architect and Construction Company:
   - Potential fire risk must be addressed during architectural design and building construction in accordance with occupancy and national building codes.
   - Passive fire protection and means of egress must be ensured during architectural and structure design of the building.
   - Supervision and monitoring of construction work must be conducted by professionals registered in Electronic Construction Permitting System- ECPS.

iii. Business owners and Users:
   - In case of change in occupancy and design of the buildings, necessary approval and fire safety requirement must be ensured.
   - For any internal and external beautification of the building, fire safety issues must be addressed carefully so that means of egress, horizontal and vertical separation has not been affected.

iv. LPG distribution Company:
   - LPG distribution company must provide technical service to ensure safe storage, pipeline connection and installation, reticulation system installation through their own technical teams.
   - LPG distribution company must implement national and internationals standard to manage risk in handling, storage and distribution of this highly flammable gases.
   - LPG distribution company must conduct thorough investigation of each accident and address the safety issues to prevent recurrence of any future events.

v. Regulatory agencies:
   - Regulatory agency must check the design carefully as per occupancy and national building code to provide approval of construction.
   - Regulatory agency must ensure monitoring and supervision of construction work as per national building code and approved design.
   - Regulatory must ensure fire safety plan and appropriate fire protection system as per occupancy to provide license to building owners. In case any changes in the occupancy of an establishment, regulatory agency must be informed and provide approval based on the implementation and requirement of appropriate fire protection system to manage fire risk.

vi. Relevant ministries and law enforcement agencies:
   - Establish Bangladesh Building Regulatory Authority (BBRA) to coordinate, monitoring and implement of compliance of national building codes.
   - Develop standard and appropriate guidelines for safe use, storage, reticulation systems, connections and fittings and safe installation guidelines.
   - Establish a national accident investigation board to conduct thorough investigation, identify root causes of the accident, share lesson learned and prepare recommendations for each stakeholder to prevent future accidents.

7. Conclusion

The baily road Green Cozy Cotez restaurant fire is a shocking and preventable accidents. With appropriate protection system, fire safety plan, fire alarm and emergency exit, the accident could have been avoided. The fire risk in Dhaka City requires a multi-faceted approach encompassing policy reforms, community engagement, and infrastructure improvements. Firstly, stringent enforcement of building codes and safety regulations is essential to prevent substandard construction and ensure compliance with fire safety standards. Investing in modern firefighting equipment, training programs for emergency responders, fire safety awareness and establishing fire stations in strategic locations can enhance the city's emergency response capabilities. Moreover, public awareness campaigns, school curriculum integration, and community-based initiatives can educate residents about fire prevention measures, evacuation protocols, and the importance of maintaining fire-safe environments.

The fire risk in Dhaka City presents a formidable challenge that requires concerted efforts from government authorities, urban planners, building owners, businesses entities, and community stakeholders. By addressing the underlying causes, strengthening emergency response mechanisms, and fostering a culture of fire safety awareness, Dhaka can mitigate the devastating impact of fires and enhance resilience against future incidents. Through collaborative action and sustained commitment, Dhaka City can emerge as a safer and more resilient urban center for its residents.

References

[1] Easir A. Khan, E. Haque, S. Sakib, M.K. Sarneabat, Chemical Management and Safety: Growing Concerns of Chemical Accidents in Bangladesh, Journal of Chemical Engineering, IEB 31 (2023) 1–12.

[2] Easir A. Khan, Dap-1 Ammonia Tank Explosion: Safety and Security Concerns in Chemical Process Plant in Bangladesh, International Journal of Petrochemical Science & Engineering 1 (2016). https://doi.org/10.15406/ipcse.2016.01.00003.

[3] U. Mondal, N. Salsabil, Easir A. Khan, Safety Performance Assessment of Hazardous Chemical Facilities in Bangladesh Using Indexing Approach, Chemical Engineering Research Bulletin (2021) 60–68. https://doi.org/10.3329/cerb.v22i1.54301.

[4] M.T. Siraj, B. Debnath, S.B. Payel, A.B.M.M. Bari, A.R.M.T. Islam, Analysis of the fire risks and mitigation approaches in the apparel manufacturing industry: Implications toward operational safety and sustainability, Heliyon 9 (2023) e20312. https://doi.org/10.1016/J.HELIYON.2023.E20312.

[5] M.M. Rahman, S.J. Khan, K.N. Tanni, Holistic individual preparedness in an urban fire-prone area: The case of Dhaka City, Bangladesh, International Journal of Disaster Risk Reduction 81 (2022) 103274. https://doi.org/10.1016/J.IJDRR.2022.103274.

[6] S. Islam, A. Sahin, Impacts of Illegal Urbanization on Fire Crash Hazards: A Case Study of Dhaka, Bangladesh, (2023). https://doi.org/10.35248/2375-4397.23.11.381.

[7] F.S. Sakib, R. Ahmed, Easir A. Khan, Study of Fire Growth Behavior in a Residential Apartment using Fire Dynamic Simulator, Chemical Engineering Research Bulletin (2021) 99–105. https://doi.org/10.3329/cerb.v22i1.54307.

[8] Easir A. Khan, M.A. Ahmed, H. Khan, S.C. Majumder, Fire Emergency Evacuation Simulation of a shopping mall using Fire Dynamic Simulator (FDS), 2017.

[9] Easir A. Khan, What can be done to Prevent Accidental Toxic Release, Fire & Explosion in Chemical Process Industry?, (2016).

[10] N. Ahmed Roni, S. Sultana, M.M.J. Ibne Iqbal, Investigation on Fire Protection System of Highrise Buildings in the Context of Bir Uttam Aminul Haque Avenue in Dhaka, Bangladesh, Engineering 14 (2022) 301–319. https://doi.org/10.4236/ENG.2022.148024.

Journal of Chemical Engineering

Vol. ChE 32, No. 1, April 2024

Article

Design and development of affordable cookstoves for the low-income households in developing countries like Bangladesh.

Md. Mominur Rahman*, Hridoy Roy, Sujala Tajneen Sultana, Sultana Razia Syeda

To cite the article:

Md. Mominur Rahman*, Hridoy Roy, Sujala Tajneen Sultana, Sultana Razia Syeda , "Design and development of affordable cookstoves for the low-income households in developing countries like Bangladesh", Journal of Chemical Engineering, IEB, ChE 32 (1), pp. 55-83.

The Institute of Engineers, Bangladesh (IEB)
Chemical Engineering Division

Design and development of affordable cookstoves for the low-income households in developing countries like Bangladesh

Md. Mominur Rahman*, Hridoy Roy, Sujala Tajneen Sultana, Sultana Razia Syeda

Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh. Email: mrrahman@che.buet.ac.bd

Abstract:
In this research work, biomass based low-cost energy efficient and low polluting household mud-built cookstoves were designed and developed targeting the rural population of Bangladesh who otherwise cannot afford to carry the overload of health cost due to indoor air pollution and purchasing excessive biomass fuel required for their existing traditional cookstove. Four mud-built stoves e.g., i) single pot circular grate (MS-1), ii) double pot circular grate (MS-2), iii) double pot elliptical grate (MS-3) and iv) triple pot circular grate (MS-4) was designed with double chimney to fit the average household cooking need in context of rural Bangladesh. The models were designed with the preheating facility of primary combustion air to facilitate better combustion. To compare the thermal and emission performance of the developed mud stoves (MSs), two concrete built single chimney improved cookstove (ICS) models e.g., single pot concrete stove (CS-1) and double pot concrete stove (CS-2) were procured from a leading NGO (Grameen Shakti). The purchased stoves were single chimney concrete stoves (CSs) and claimed to be the most popular variants among the general households in Bangladesh. Standard water boiling test (WBT) and controlled cooking test (CCT) were performed to evaluate the overall performances of the stoves. The thermal performances of MS-2, MS-3, MS-4 were better compared to CS models. The elliptical grate mud stove (MS-3) was better than circular grate mud stove (MS-2). In terms of CO_2, CO and CH_4 emission, MS models were less emissive compared to CS models except MS-1 that emits more CH_4 compared to CS-2. The NO emission was found to be lower for all MS models. Therefore, the developed MS models were thermally efficient, low polluting and low cost, which can be a better alternative to CS for the rural population of Bangladesh.

Keywords: Cookstoves; thermal efficiency; low emission; low cost; rural communit

Highlights:

1. Thermally efficient and cost-effective mud-based stoves (MSs) were fabricated and compared with available ICSs (CSs).
2. The overall thermal efficiency (at high power) of double pot elliptical grate stove (MS-3) was ~120% higher than the procured ICSs.
3. The highest turn down ratio (TDR) of 2.40±0.1 was obtained for MS-3 model.
4. The MS models showed lower emissions (CO_2, CO, NO and CH_4) compared to the procured CS models.
5. The construction cost of CSs models were ~2 times greater the fabricated MSs models.

Abbreviations

MS-1	Single pot mud stove (circular grate) [Designed]
MS-2	Double pot mud stove (circular grate) [Designed]
MS-3	Double pot mud stove (elliptical grate) [Designed]
MS-4	Triple pot mud stove (circular grate) [Designed]
CS-1	Single pot concrete stove [Procured]
CS-2	Double pot concrete stove [Procured]
MSs	Mud stoves
CSs	Concrete stoves
ICSs	Improved cookstoves
GHG	Greenhouse gas
PIC	Products of incomplete combustion
IAP	Indoor air pollution

1. Introduction

Bangladesh is the 8th most populous country in the world with an estimated population of 164.7 million and a population density 1265 persons per square km. About 20.5 % of the entire population lives below the national poverty line. In 2021, approximately 61 % of the population in Bangladesh were residing in rural areas. The increasing population contributes to the accelerating electricity and fuel demand in Bangladesh. The scarcity of natural gas and declining reserve have become a major obstacle for Bangladesh in the path achieving 100 % electricity coverage goal, which has now turned into a situation of searching for efficient fuel for household cooking (Saha et al., 2021). The urban users in Bangladesh use natural gas (NG) as their primary cooking fuel as they have access to the pipe NG supplied by gas distribution companies (Islam et al., 2022). In peri-urban and rural areas, people do not have access to the national gas grid; hence, they must use the imported or domestic liquefied petroleum gas (LPG) cylinders. The high cost of LPG has confined its use in a negligible portion of peri-urban and rural users.

Therefore, in Bangladesh the rural households mainly depend on biomass fuels for their primary sources of energy supply (Miah et al., 2010). Most of the rural population relies primarily on biomass fuels for cooking, which includes jute stick/wood/bamboo, cow dung, straw/leaf, and husk/bran (Huda et al., 2014). Lack of technological awareness and affordability gaps has led to low penetration of modern technologies like LPG and electric stoves, in both rural and peri-urban areas. Thus, most of the rural population of Bangladesh use traditional stoves for the cooking. A traditional stove in Bangladesh is generally a mud-built cylinder dug out in the earth with three raised points on which cooking utensil rests (Hossain, 2003). The common biomasses used for cooking purpose are firewood, leaves, tree twigs, agricultural crop e.g., rice straw, rice husk, jute sticks, sugarcane bagasse, sawdust, cow dung etc. (Mamun et al., 2009). The energy efficiencies of these traditional stoves vary between 5 and 15 %. The poor thermal efficiency of the traditional stove is due to large distance between the fuel bed and utensils (30 to 60 cm), low draught that causes stagnant fluid film over the bottom surface of the utensils, inaccessibility and improper distribution of combustion air at the bottom of the stoves (Khan et al., 1995). Therefore, with a poor thermal efficiency traditional cookstove has several disadvantages with respect to deforestation, biomass collection time, indoor air pollution and health impact, and climate change. Though large quantity of carbon dioxide (CO_2), regarded as one of the potential greenhouse gases (GHG), are emitted from these stoves, the emission from the use of biomass is considered as GHG neutral if the biomass fuel cycle relies on renewable harvesting (Smith et al., 2000a).

Design deficiency of the traditional cookstoves leads to incomplete and inefficient combustion which produces significant quantities of ‘products of incomplete combustion’ (PIC) importantly respirable particulates that have more global warming potential (GWP) than CO_2 (Panwar et al., 2009). Incomplete combustion of biomass in traditional cookstoves also releases carbon monoxide (CO), nitrous oxide (N_2O), methane (CH_4), polycyclic aromatic hydrocarbons (PAHs), particles composed of elementary or black carbon, and other organic compounds (Bhattacharya et al., 2000). Venkataraman et al. (2010) reported emission factors for traditional cookstoves using different biomasses which are shown in Table 1 (Venkataraman et al., 2010).

Table 1. Traditional stove emissions (g/kg fuel) from laboratory tests using the water-boiling test to determine emissions of biomass fuel types in Indian traditional cookstoves (Venkataraman et al., 2010)

Fuel type	Pollutant emission factor (g/kg)							
	Short-lived pollutant					Long-lived pollutant		
	CO	NMVOC	PM	BC	OM	CO_2	CH_4	N_2O
Wood	69±15	7.0±3.0	3.2±2.0	0.60±0.15	2.8±2.5	1358±43	5.0±4.0	0.09±0.09
Agricultural residue	65.6	8.5	6.3±2.5	0.60±0.23	4.6±3.3	1302	7.6	0.050
Dung	39.9	24.2	3.0±1.9	0.12	2.5	1046	4.5	0.30

In rural Bangladesh, women are the main cook in household cooking process and most of the households use traditional cookstoves for preparing their daily meals. Traditional stoves usually lack chimneys, which release the combustion products directly into the unventilated small kitchen causing indoor air pollution (IAP) that poses a serious health impact on the women (Rahman, 2007). Moreover, several pollutants in the biomass smoke are climate active (Bensch et al., 2021). The most important are nitrous oxide and methane, both well-understood greenhouse gases with much higher global warming potentials (GWPs) per tonne than CO_2 (Goldemberg et al., 2018). The CO_2 from burning of wood that is not harvested renewably (leading to deforestation) does contribute to global warming. Whether warming or cooling, the particles from biomass combustion contribute to regional air pollution (Chen et al., 2017). Biomass cookstoves are also contributors to ozone levels; one estimate put their contribution of ozone precursors as one-sixth globally and perhaps one-quarter in South Asia and their contribution to carbon monoxide emissions as one-third globally (Unger et al., 2006).

To address the poor efficiency and pollution issues, improved cookstoves (ICS) have been introduced. In general, the cookstoves with chimneys and closed combustion chambers are usually considered ICS. An improved stove can be designed to improve energy efficiency, remove smoke from the indoor living space, or lessen the drudgery of cooking duties (Urmee,Gyamfi, 2014).

The Institute of Fuel Research and Development (IFRD) of Bangladesh Council of Scientific and Industrial Research (BCSIR) started work in 1978 to develop ICSs in context of Bangladesh. IFRD developed several ICSs which include fixed and portable type, metal and clay, single and multiple pot, with chimney and without chimney, with grate and without grate, etc. (Rahman et al., 2006). Two NGOs, GIZ and Grameen Shakti, are the leading sellers of ICSs developed by IFRD, BCSIR in the local market. Different studies were conducted to find the performances of these ICSs in Bangladesh.

Arif et al., (2011) conducted household kitchen performance tests on different ICSs, e.g., i) portable single pot with grate and without grate, iii) double pot with chimney and with grate, and iii) double pot with chimney and without chimney and iv) traditional single pot portable cookstove in rural Bangladesh to compare thermal and fuel saving efficiency, cooking time and pollution level (Arif et al., 2011). The group reported higher fuel consumption, lower thermal efficiency, longer cooking time and less pollution for double pot ICS with chimney compared to traditional cookstove whereas, lower fuel consumption, higher thermal efficiency, shorter cooking time and alike pollution level for portable single pot ICS without chimney compared to the traditional cookstove. Since then, there were no such studies on the performance and overall feasibility of these ICSs to the rural community. Every year new cookstove models have been introduced with sophisticated design and technology, however the rural community can hardly manage or afford these stoves for their household cooking.

Therefore, with the goals in mind for conserving biomass fuel, reducing smoke emissions in the cooking are, reducing global warming potential, reducing deforestation, limiting the drudgery of women and children for biomass collection and reducing cooking time, this research work was endeavored to design and develop mud-built ICSs that may serve several million poor households in villages and semi-urban areas in Bangladesh. To compare the thermal and emission characteristics of designed mud-built cookstoves of this study, two highly disseminated and popular ICS versions marketed by a popular NGO (Grameen Shakti) have been sourced and used. From the socio-economic and environmental aspects, a strong emphasis was given in design phase of the ICSs in this project, as most of the people of the villages and semi-urban areas in Bangladesh use agricultural residue fired cookstoves. Materials of construction were selected accordingly to provide people easy access to those materials to build their own cookstoves. Moreover, emphasis was also given to reduce IAP and health impact, to reduce global warming potential from the emission, and to reduce fuel requirement for cooking of the designed ICSs.

2. Design and Experimental Methodology

Four mud-built cookstoves were designed and fabricated to evaluate and compare the thermal and emission performances with the mostly disseminated ICSs in Bangladesh. The mud-built ICSs were designed and installed in the Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh. The designed stoves were: 1) single-pot mud stove (circular grate), 2) double-pot mud stove (circular grate), 3) double-pot mud stove (elliptical grate), and 4) triple-pot mud stove (circular grate). These models are denoted as MS-1, MS-2, MS-3, and MS-4 respectively. Two types of ICSs were purchased from Grameen Shakti (a leading NGO involved in disseminating ICSs in Bangladesh), to compare the performances with the designed stoves. The ICSs of Grameen

Shakti were: 1) single-pot concrete stove (circular grate) and 2) double-pot concrete stove (circular grate). These models were denoted as CS-1 and CS-2 respectively.

2.1. Construction features of the stoves

Considering the cooking needs, shapes of cooking pots and types of biomass fuels, the four experimental cookstoves were designed. The stoves were constructed with locally available materials (mud, metallic grate, 'O' ring, and concrete chimney). All the MSs models have two chimneys to distribute the flames evenly under the utensils during cooking. The schematics of MSs models are shown in Figures 1 (A, B, C, D).

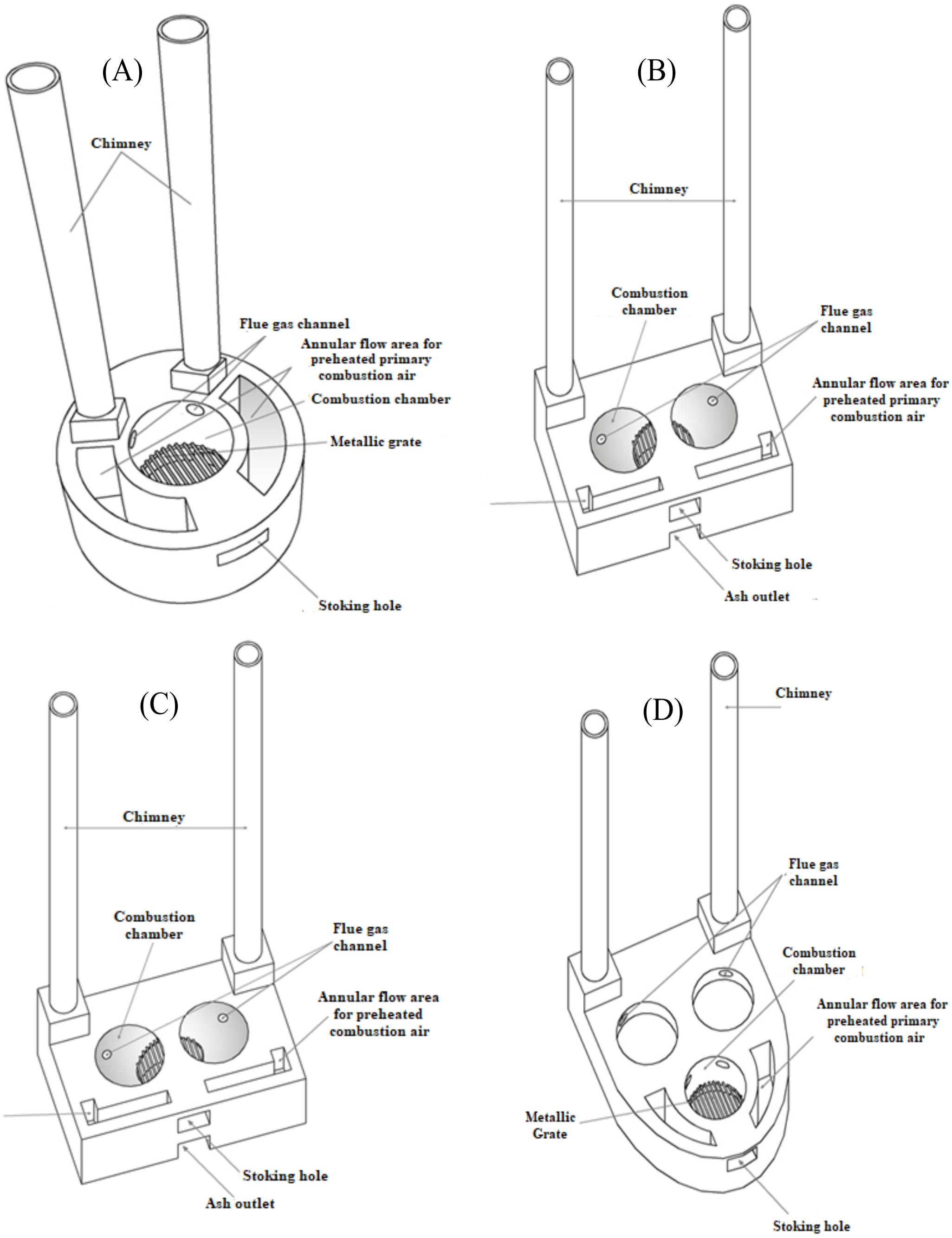


Figure 1: The schematic diagrams of (A) MS-1, (B) MS-2, (C) MS-3 and (D) MS-4 (all of the models contains ash outlet)

All the MSs models contain features that would help effective burning of the fuel, good heat transfers to cooking pot and diminution of indoor air pollution. Some common design rules were followed while sizing different dimensions of the stoves. The sizing and deciding parameters for combustion are chamber height (H) and wall thickness, pot mouth, metallic grate, stack or chimney, inlet air hole diameter, stack hole, ash-pit and ash hole etc.

The combustion chamber height (H) and wall thickness are important parameters for designing a cookstove. Combustion chamber height (H) was calculated using the formula, $H = A + P + L$. Where, A is the primary combustion air hole height in cm, P is the least height from air hole to pot bottom which is 0.4 times pot diameter for cylindrical pots, which can be extended for spherical pots and L is the distance between the pot bottom and the pot mouth in cm. Considering all these, the height of chamber of each stove was taken to be 20 cm from ground (floor) surface. For mud built cookstove, wall thickness should be in the range of 5.08-7.62 cm. In this case 5.08 cm wall thickness was chosen as design value (Baldwin, 1987).

The pot mouth of a cookstove is a hole where the utensil sits on. Pot mouth diameter for the was taken as 25.4 cm as this size of pots are usually used in general household in Bangladesh. A metallic 'O' ring of same diameter of pot mouth was placed on each of the pot mouths to prevent erosion of mud.

A metallic grate was used inside the combustion chamber of each type of stoves which was placed just above the primary combustion air inlet holes. The grate acts as fuel bed and allows better mixing of combustion air and fuel. Rectangular slits were incorporated in the grate instead of circular holes for better mixing of primary combustion air with fuel. This type of grate is also very useful for wood, leaves and agricultural residues as cooking fuels.

Stack or chimney acts as an integral part of an improved biomass cookstove providing clean indoor environment. Each of the stove models has two chimneys. It is a standard rule to take chimney height same as roof top height (~210-310 cm) for not being exposed to smoke. Considering this along with the provision of draft ranging from 10-15 Pa, the chimney height was taken as 215 cm. It is beneficial for combustion to have a flue gas velocity of 2-3 ms^{-1} within the chimney. Considering this, the internal diameter (ID) of the chimney was calculated to be 5.08 cm. For field application, ID of each stack was taken as 7.62 cm. A 2.08 cm provision was provided for deposition of soot particles to avoid excessive pressure drop after long-run operation (Shaha, 2018).

For designing efficient cookstove, it is a good practice to maintain constant cross-sectional area for combustion air inlet and combustion gas exit. That is why, along with the diameter of the chimney inlet, six primary air holes of 5.08 cm diameter were placed at the bottom of the combustion chamber wall.

A stoke hole or secondary combustion air inlet was placed in each of the stove models above the gate or fire bed to provide stoke (fuel) in the combustion chamber and secondary combustion air to the diffusion flame zone for better combustion. This hole dimension was so chosen to keep the hole size minimum and to adopt with reasonable size of stokes.

A second wall of 5.08 cm thick was provided outside the combustion chamber wall maintaining an annular space for each of the stove models to minimize heat loss to environment through convection, to minimize burn risk during cooking. The annular area of the double wall was also designed for preheating the primary combustion air to maximize waste heat utilization. In all stove models, a 15.28 cm-deep ash pit was provided underground at the bottom of combustion chamber with a view to lessen the cookstove mass and excessive heat loss. Ash hole was provided to collect ash and it was connected to ash pit through underground channel. Ash hole remains closed during cooking. All the MSs models with proper dimensions have been supplied in Supplementary Figure S1-4. The isometric view with dimensions of procured CS-1 and CS-2 are given in Supplementary Figure S5-6. The working mechanism of the designed MSs is supplied and visualized in video files.

Figure 2: Mud-stove fabrication and curing processes

2.2. Mud built stove construction procedure

First of all, all the initial structures were made with moulded sticky mud. Then structures were allowed to dry for 1-2 days in natural environment under the shade. After that a desired shape was given to the structures with knife and hands. Again, the structures were allowed to dry completely by keeping them under the shade for another 5-7 days. During this drying process structures were rubbed with mud and water to fill up the cracks. It is customary to rub the structure with moulded sticky mud twice a week. After several weeks of occasional firing and filling up the cracks with mud, no more new cracks were found and the stoves became strong like fired bricks. Different fabrication steps and curing are shown in Figure 2.

2.3. Cookstoves performance evaluation by WBT and CCT

All the cookstoves were fixed type and placed inside the kitchen. Standard Water Boiling Test (WBT) was followed to evaluate the performances of the MSs and CSs (ISO/IWA, 2014). WBT was carried out for cold and hot start in high power phase and simmering in low power phase. The cold start in high power phase began with the stove at ambient temperature and used a pre-weighed bundle of fuel to boil a measured quantity of water in aluminum pot. The hot start in high power phase followed immediately after the cold start in high power phase while the stove was hot. Simmering in low power phase started immediately after hot start in high power phase on the retained water in the pot and continued for 45 minutes and the temperature of the water in the primary pot was maintained average 3 ^{o}C below the local boiling point of water. Real time in-stack measurements of emission from all the cookstoves were also done during different phases of the entire WBT.

For WBT of different cookstoves, aluminum hemispherical-bottom pots were used. Each of the pots was identical with respect to their dead weight, capacity and dimensions. Each pot had a dead weight of 350 g and a thickness of 1.1 mm with a hemispherical bottom. Each of the pots was 116 mm high and the opening mouth diameter was 245 mm. The highest diameter of the pot was at the middle which was 290 mm.

For MS-1, MS-2, MS-3, and MS-4, WBT required one, two and three pots respectively for single test run. For each test run, initially each pot was charged with exactly 4,150 mL water. The cooking fuel used for WBT was locally available rice straw with measured moisture content: 6% (wet basis), higher heating value (HHV) on dry basis: 14.40 MJ/kg and a calculated lower heating value (LHV) on dry basis: 13.08 MJ/kg. HHV was determined in the laboratory using bomb calorimeter. Rice straw was collected from a single source of a local market. For multi-pot cookstoves, WBT was terminated with the boiling in the primary pot. No lid was used to cover the pot, so that evaporated water freely escapes from the pot. Fuel required heating up the known quantity of water to its local boiling point and the amount of evaporated water up to boiling point was recorded for each test run on all types of cookstoves. The stoking for entire WBT was carried by a several years experienced woman since stoking rate is highly person dependent. Photographs of WBT on different ICSs are shown in Supplementary Figure S7. From WBT, time to boiling, burning rate, specific fuel consumption, specific energy consumption, firepower, cooking power, turndown ratio, and overall stove thermal efficiency were determined. Combustion efficiency was determined as percentage of airborne fuel carbon released as CO_2. Thereafter, heat transfer efficiency and ESI were calculated.

Time to boil (Δt_c) is the time to boil water in the primary pot and it is simply a clock difference and expressed as Eqn. (1),

$$\Delta t = t_f - t_i \qquad (1)$$

Where, t_f is the final clock time (min) and t_i is the initial clock time (min).

Temperature corrected time to boil (Δt^T) adjusts the time to boil to a standard 75 °C temperature change (from 25 °C to 100 °C) to compensate different initial temperature and local boiling point which was calculated using Eqn. 2 (ISO/IWA, 2014),

$$\Delta t^T = (t_f - t_i) \times 75/(T_f - T_i) \; (2)$$

Where, T_f is local boiling temperature of water (°C) and T_i is initial temperature of water (°C)

Overall stove thermal efficiency (η) is a ratio of the work done by heating and evaporating water to the energy released by burning equivalent amount of dry fuel and expressed as Eqn. (3) (Ko,Lin, 2003),

$$\eta = \frac{[4.186 \times \sum_{j=1}^{3}\left(P_{ji} - P_j\right) \times (T_{jf} - T_{ji})] + 2260 \times (W_v)}{f_{d \times LHV}} \qquad (3)$$

Where, 4.186 J/g°C is specific heat of water, P_j is weight of empty pot (g), P_{ji} is weight of pot with water before test (g), T_{ji} is water temperature before test (°C), T_{jf} is water temperature after test (°C), f_d is equivalent dry fuel consumed (g), W_v is amount of water vaporized (g), LHV is lower heating value or net heating value of the dry fuel (kJ/kg).

Burning rate (r_b) was calculated from the recorded initial and final weight of the fuel and time taken for completing WBT. It was calculated by dividing the equivalent dry fuel consumed during test run by the time required for the test, which is expressed as Eqn. (4),

$$r_b = \frac{f_d}{(t_f) - (t_i)} \qquad (4)$$

Where, r_b is burning rate (g dry fuel/min), f_d is equivalent dry fuel consumed (g).

Specific fuel consumption (SC) was measured as the amount of equivalent dry wood required producing one g of boiling water (g fuel/g water) and is expressed as Eqn. (5),

$$SC = \frac{f_d}{\sum_{j=1}^{3}\left[(Pj_f - Pj) \times \left(\frac{Tj_f - Tj_i}{T_b - Tj_i}\right)\right]} \qquad (5)$$

Where, P_j is weight of empty pot (g), P_{jf} is weight of pot with water after test (g), T_{ji} is water temperature at the beginning of the test (°C), T_{jf} is water temperature after test (°C) and T_b is local boiling point of water (°C).

Temperature corrected specific fuel consumption (SC^T) corrects the specific fuel consumption to account for differences in initial water temperatures. This correction accounts for a standard temperature change of 75°C (from 25 to 100°C), and calculated as Eqn. (6),

$$SC^T = \left[(SC) \times \left(\frac{75}{T_f - T_i}\right)\right] \qquad (6)$$

Temperature corrected specific energy consumption (SE^T) was determined by multiplying SC^T with the net calorific value of the fuel and the unit is kJ/liter

Firepower (FP) is the equivalent dry fuel energy consumed by the stove per unit time and the unit of the firepower is watt. This parameter is useful for high and low power phase since turndown ratio of a cookstove can be found from high and low power phase firepower and expressed as Eqn. (7),

$$F_P = \frac{(f_d) \times (LHV)}{(60) \times (\Delta t)} \qquad (7)$$

Where, f_d is equivalent dry fuel consumed (g), LHV is lower heating value (J/g), Δt is duration of test run (min).

The cooking power (F_{CP}) is the average rate of energy released from fuel combustion that is transferred to the pot over the duration of the test and the unit of the useful/cooking power is watt. Cooking power was calculated for the cold start and hot start, but not for the simmer, because cooking power cannot be accurately measured during the simmer phase of the WBT, as discussed in the article. Cooking power is expressed as Eqn. (8),

$$F_{CP} = F_p \times (\eta) \qquad (8)$$

Turndown ratio (TDR) shows the operability of a stove with low power input and is the ratio of hot start firepower in high power phase to simmering firepower in low power phase.

Environmental stove index (ESI) is composed of two parameters e.g., $\frac{1}{(1-NCE)}$ is a direct indicator of how much products of incomplete combustion (PIC) is released and η indicates the effective amount of fuel used. ESI is expressed in Eqn. (9),

$$ESI = \ln(\frac{\eta}{(1 - NCE)} \qquad (9)$$

Here, NCE (Nominal combustion efficiency) is defined as the percentage of airborne fuel carbon released as CO_2 and evaluated by [1/(K+1)] and K is defined as [(FC/CO_2) – 1] (Kirch et al., 2018).

Where, Fuel carbon (FC) = (fuel consumed × carbon fraction) – (ash produced × carbon fraction), CO_2 indicated the carbon as carbon-di-oxide in flue gas η is overall stove thermal efficiency and is expressed as Eqn. (10),

$$\eta = NCE \times NHE \qquad (10)$$

Here, NHE (Nominal heat transfer efficiencies) is defined as the percentage of heat released by combustion that is absorbed by the water in the pot. This was not measured directly in our experiments and was determined using Equation, since both NCE and η are available from the tests.

In Bangladesh cooked rice is a traditional food and almost every general household cooks rice twice a day. Therefore, controlled cooking tests (CCT) were performed on every cookstove by cooking parboiled rice (Gebreegziabher et al., 2018). A several years experienced household female cook was hired to cook the parboiled rice. The same pots used in WBT were also used in CCT. A 40 kg bag of parboiled '*miniket*' rice was purchased from local market to maintain the homogeneity in rice quality. To conduct CCT on single pot cookstove, 750 gm parboiled *miniket* rice and 3,900 gm water were taken into a single pot. For double and triple pot cookstoves, two and three pots of equal dimensions were used respectively each of which contained 750 gm *miniket* rice and 3900 gm water. Stoking rate and termination time for cooking rice were solely determined by the cook based on her experience. Each cookstove was tested thrice for cooking identical amount of parboiled rice with water. Pot lid was used for each CCT run to maximize heat utilization. During CCT on each cookstove, amount of fuel consumed and time required were estimated. Some mentionable photography of CCT are shown in Supplementary Figure S8.

For WBT and CCT, in-stack flue gas compositions for CO, NO, and stack temperature and draft were measured using a portable combustion analyzer (PCA-3, Bacharach Inc., USA). Besides, flue gas samples were collected from the chimney in Tedlar bags at an interval of two minutes during CCT and WBT for each type of cookstove. The samples were then analyzed for CO_2, and CH_4 using gas chromatography (FID-GC-17A, Shimadzu, Japan). Background ambient concentrations of all above mentioned parameters were also measured to find out the net emission compositions of flue gas from combustion. Flue gas and ambient air compositions were measured on wet basis. An electronic weight balance (LP5001A, Gromy Industry Co. Ltd., China) was used in WBT and CCT for weight measurements. Stack temperature, flame zone temperature, fuel bed temperature, combustion air temperature was also measured using thermocouple (Allosun EM502C, China) with electronic reader during entire WBT for cold and hot start in high power phase, simmering in low power phase and CCT.

3. Results and discussions

3.1. Thermal Performance of stoves in WBT

The primary combustion air temperature for all stove models is presented in Figure 3 (A).

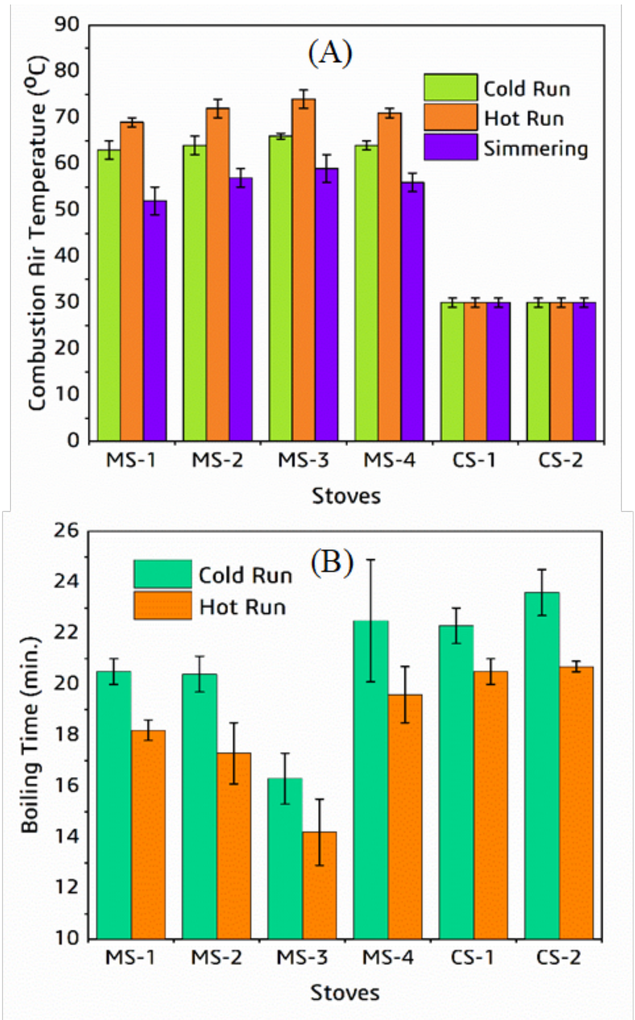


Figure 3: (A) Primary combustion air temperature (°C) of different stove models in high power (cold and hot run) and low power simmering phase, (B) temperature corrected boiling time (min.) for different stove models in high power phase (cold and hot run)

Figure 3 (A) refers that, the provision for preheating combustion air for MS-1, MS-2, MS-3 and MS-4 renders higher temperature of primary combustion air compared to CS-1 and CS-2. From Table 2, the combustion air temperatures of MSs varied from 63 to 74 ^oC for high power phase (cold and hot run) and 52 to 59 ^oC for low power simmering phase. Whereas, combustion air temperatures of CSs were found to be the ambient temperature (30 ^oC) for both high and low power phases.

Table 2: Combustion air temperature, fuel bed temperature, flame zone temperature, stack flue gas temperature, draft inside WBT of all the stoves

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
		Mean ± S.D.					
Combustion air temperature (^oC)	Cold Run	63±2	64±2	66±0.6	64±1	30±1	30±1
	Hot Run	69±1	72±2	74±2	71±1	30±1	30±1
	Simmering	52±3	57±2	59±3	56±2	30±1	30±1
Fuel bed temperature (^oC)	Cold Run	605±5	616±1	632±3	611±9	570±8	583±12
	Hot Run	623±3	645±5	660±10	647±6	588±8	601±4
	Simmering	584±3	605±4	611±5	590±8	549±5	560±8
Flame zone temperature (^oC)	Cold Run	712±3	713±3	722±3	710±5	673±15	667±6
	Hot Run	722±8	762±10	760±5	723±8	683±6	678±8
	Simmering	685±9	698±8	696±7	687±10	648±7	644±5
Stack flue gas temperature (^oC)	Cold Run	298±29	320±36	306±31	313±28	342±44	356±47
	Hot Run	307±27	341±40	340±40	315±33	348±51	338±45
	Simmering	240±30	291±32	287±30	281±29	307±25	310±27
Draft inside chimney (-Pa)	Cold Run	*7.4±1.14	*7.5±1.15	*7.5±1.12	*7.4±1.11	7.9±1.197	7.5±1.133
	Hot Run	*7.4±1.16	*7.5±1.14	*7.4 ±1.13	*7.5±1.11	7.8±1.11	7.6±1.13
	Simmering	*6.5±1.15	*6.7±1.14	*6.7±1.11	*6.61.11	6.9±1.18	6.8±1.12

This preheating phenomenon made a clear distinction between MSs and CSs with respect to thermal behavior, i.e., fuel bed temperature, and flame zone temperature. Detailed of the temperature and draft profiles during WBT of all the stoves is summarized in Table 2.

Table 2 summarizes the fuel bed temperature of MSs varied from 605 to 660 ^oC in high power phase and 584 to 611^oC in low power phase, whereas the temperature varied from 570 to 601 ^oC in high power phase and 549 to 560^oC in low power phase for CS ICSs. Flame zone temperature of MSs varied from 710 to 762 ^oC in high power phase and 685 to 698^oC in low power phase, whereas it varied from 667 to 683 ^oC in high power phase and 644 to 648^oC in low power phase for CSs ICSs. Stack flue gas temperatures of MSs stoves were lower than those procured CSs in both high and low power phases and ranges from 298 to 341 °C in high power phase and 240 to 291°C in low power phase for MSs, whereas these temperatures varied from 338 to 356 °C in high power phase and 307 to 310 °C in low power phase of CSs ICSs. These temperatures show a clear indication of better combustion and effective heat utilization in MSs compared to CSs ICSs. All of the designed MSs have double chimney to compensate excess pressure drop due to annular flow of pre-heated combustion air. Draft in each chimney of designed MSs varied from – 6.5 to – 7.5 pa for entire WBT test, whereas for single chimney of CSs, draft varied from – 6.8 to – 7.9 pa.

The WBT performance parameters (boiling time, burning rate, specific fuel and energy consumption, firepower, cooking power, turn-down ratio, and overall thermal efficiency) of all stoves are summarize in Table 3.

Table 3. WBT performance parameters (boiling time, burning rate, specific fuel and energy consumption, firepower, cooking power, turn-down ratio, and overall thermal efficiency) of stoves

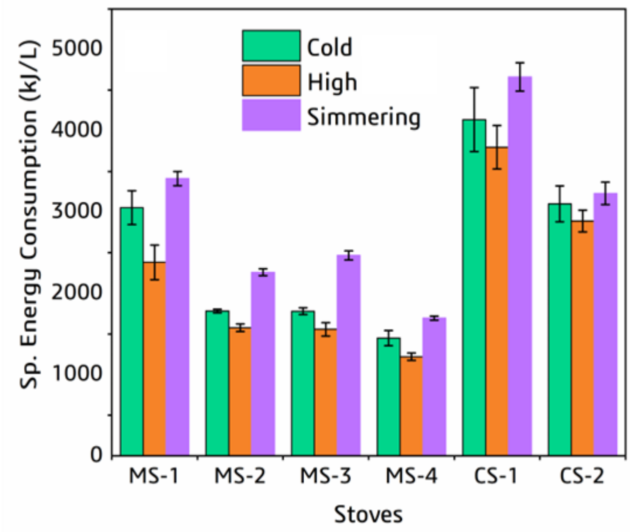
Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
		Mean±S.D.					
Boiling time (corrected) (min)	Cold Start	20.5±0.5	20.4±0.7	16.3±1.0	22.5±2.4	22.3±0.7	23.6±0.9
	Hot Start	18.2±0.4	17.3±1.2	14.2±1.3	19.6±1.1	20.5±0.5	20.7±0.2
	Simmering	na	na	na	na	na	na
Burning rate (gm/min)	Cold Start	44.4±1.7	53.8±1.8	67.0±2.9	46.0±2.4	56.5±3.4	59.4±2.3
	Hot Start	39.4±2.4	56.4±2.7	67.7±3.7	42.6±1.4	57.1±3.0	64.8±1.4
	Simmering	19.3±0.1	25.4±0.2	27.9±0.7	22.8±0.6	27.5±0.6	30.6±1.2
Sp. Fuel consumption (corrected) (gm/liter)	Cold Start	233.5±15.8	136.2±1.6	136.0±3.2	110.8±7.1	316.4±30.0	237.1±16.8
	Hot Start	182±16.2	120.5±3.7	119.0±6.4	93.2±3.5	290.4±20.5	220.9±10.1
	Simmering	260.9±6.6	172.7±3.3	188.6±4.2	129.6±2.0	356.4±13.3	246.9±10.5
Sp. Energy consumption (corrected) (kj/liter)	Cold Start	3054±207	1781.9±21	1779.2±42.2	1449.2±92.4	4137.9±392.8	3100.7±219.4
	Hot Start	2380.6±212.2	1576.4±48	1556.4±83.6	1219.2±45.1	3798.7±267.9	2889.2±132.5
	Simmering	3412.6±86.8	2258.7±42.7	2466.5±55.5	1695.1±25.9	4661.2±174.3	3229.6±137.6
Firepower (watt)	Cold Start	9,684±362.4	11,721±390.1	14,599±627.8	10,018±521.1	12,327±750.9	12,954±506.7
	Hot Start	8,590±520.4	12,300±593.6	14,755±813.4	9,290±305.4	12,446±656.1	14,121±296.8
	Simmering	4,195±29.4	5,527±68.8	6,094±172.8	4,930±112	5,924±225	6,702±253.1

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
		Mean±S.D.					
Turn down ratio	Simmering	2.31±0.1	2.12±0.1	2.40±0.1	2.03±0.1	2.08±0.1	1.93±0.1
Cooking power (watt)	Cold Start	1,549±57.9	2,696±89.7	3,504±150.7	2,705±140.7	1,233±75	1,684±65.9
	Hot Start	1,718±104	3,075±148.4	3,836±211.4	2,880±94.7	1,245±65.6	1,836±38.5
	Simmering	na	na	na	na	na	na
Overall thermal efficiency (%)	Cold Start	16±0	23±0	24±1	27±1	10±0	13±1
	Hot Start	20±1	25±1	26±1	31±1	10±1	13±1
	Simmering	na	na	na	na	na	na

na: means not applicable for the said purpose

The boiling time for different stove models in high power (cold and hot run) phase is presented in Figure 3 (B). From the cold and hot run, temperature corrected average boiling time was calculated and among the stove models, the average boiling time (temperature corrected) was found to be the lowest for MS-3 which was 15.25 min. and the 2nd lowest boiling time was 18.85 min. for MS-2. For MS-1 and MS-4, the average boiling time were 19.35 min. and 21.05 min. respectively. The CSs showed higher boiling time compared to MSs. The average boiling time was 21.4 min. and 22.15 min. for CS-1 and CS-2, respectively. Thus, the designed MSs were more efficient in rapid boiling compared to CSs.

From Table 3, the highest fuel burning rate during high power phase was obtained for MS-3, however the burning rate of this cookstove in low power phase was lower than CS-2. However, the lowest boiling time of MS-3 (Figure 3(B)) reveals better heat utilization pattern. The burning rate of the rest three MSs was lower than those CSs for both high and low power phases.



s

Figure 4: The specific energy consumption (kJ/L) for different stove models in high power (cold and hot run) and low power (simmering) phases

The specific energy consumption (kJ/L) for different stove models in high power (cold and hot run) and low power (simmering) phases is presented in Figure 4.

Specific energy consumptions (temperature corrected) of MSs were lower than CSs in both high and low power phases except MS-1 that consumed higher specific fuel and energy during simmering in low power phase compared to CS-2 but in comparison to single mouth CS-1, single mouth MS-1 consumed lower specific fuel and energy in in all phases of WBT (Figure 4). Specific fuel and energy consumptions were found to be the lowest for MS-4 during all power phases, whereas the highest specific fuel and energy consumptions were found for CS-1 in all power phases.

In performance evaluation cookstoves, firepower is an important parameter, which is the output power of a stove and indicates how much energy a cookstove can produce per time. Average firepower of the stoves varied from 8,590 to 14,755 watt in high power phase and 4,195 to 6,702 watts in low power phase. The lowest firepower was found for MS-1 in all power phases, whereas MS-3 was found to be the highest energy generator per time during high power phase. During simmering in low power phase, CS-2 showed the highest firepower (Table 3.). On the other hand, cooking power is the fraction of the firepower that is eventually transferred to the cooking pot for boiling water. The ratio of cooking power to firepower indicates the fraction of firepower actually used for cooking. The larger the fraction, the larger will be the effective cooking power. Figure 5 (A) presents the cooking power (watt) of the stove models in high power phase. The highest and lowest cooking power were obtained for MS-3 (3,836 watt) and CS-1 (1,245 watt), respectively. The ratios of cooking power to firepower in high power phase were 0.18, 0.24, 0.25, 0.29, 0.10, 0.13 for MS-1, MS-2, MS-3, MS-4, CS-1 and CS-2 respectively.

Turndown ratios of all the stoves were satisfactory and varied from 1.93 to 2.4 (Figure 5 (B)). The higher the TDR value, the better is the switching between power levels. All the MSs models showed a turndown ratio (TDR) above 2 referring MSs were capable to simmer water with a 50% reduced burning rate compared to hot start in high power phase. Turndown ratio of CS-2 was below 2, whereas for CS-1 turndown ratio was above 2 (Table 3). The highest TDR was obtained for MS-3 model.

All MSs models showed higher thermal efficiency compared to CSs models. Overall high power thermal efficiencies of MS-1, MS-2, MS-3, MS-4, CS-1 and CS-2 were 18%, 24%, 25%, 29%, and 10%, 13% respectively. About 41.66%, 84.61%, 115.38% and 123.07% increment were obtained for MS-1, MS-2, MS-3 and MS-4 respectively compared to the highly disseminated ICS CS-2.

Nada Chulha, an improved double pot mud stove with chimney of India, very similar to the procured CSs showed almost similar performance using rice straw as fuel. *Nada Chulha* showed overall thermal performances of 10%, 10.9%, 13.5%, 19.7% and 23.5% using cow dung, rice straw, mustard residue, root fuel and wood (Acacia) as fuel respectively in WBT. *Sugam Chulha, India* is a version of *Nada Chulha*, *India* that used ceramic lining inside the fire boxes, flue gas passing line and inside chimney, showed much better overall thermal efficiency using rice straw as fuel. This *Sugam chulha, India* showed overall thermal efficiencies of 12.8%, 18.5%, and 29% using cow dung, mustard residue, and wood (Acacia) as fuel respectively in WBT (Smith et al., 2000b). In comparison with the *Indial Nada Chulha*, the designed MSs performed better, contrarily performance of CSs models is very similar to *Nada Chulha* using rice straw as fuel.

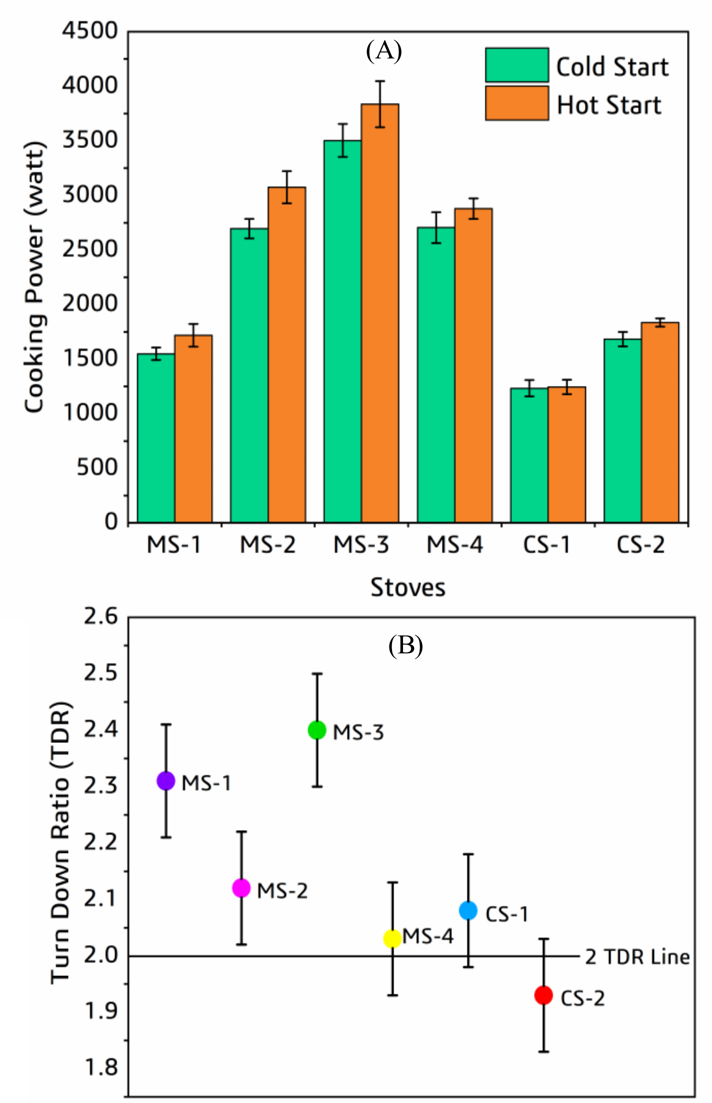


Figure 5: Cooking power in cold and hot start (A) and Turn down Ratio (TDR) (B) for stove models

The benchmark fuel and energy requirements to boil 5 L water and then simmer it for 45 min. for all stove models were calculated and shown in Table 4.

It was found that the lowest and the highest fuel or energy consuming cookstoves were MS-3 and CS-1 respectively. The fuel and energy consumptions per 5 L water for MSs varied from 1,158 to 2,343 g and 15,147 to 30,650 kJ respectively. The energy consumption standard to boil 5 L water and then simmer it for 45 min. for all types of biomass-based ICSs with chimney set by Aprovecho Research Center for Shell Foundation should be below 1500 g for wood or below 30,000 kJ for using alternative biomass fuel (Still,MacCarty, 2006). On this basis energy consumptions of MS-2, MS-3 and MS-4 were below the standard value of 30,000 kJ. Energy consumption of MS-1 was slightly higher than the standard value. Energy consumptions of the procured cookstoves CS-1 and CS-2 were much higher than the standard energy consumption value set by Shell Foundation (Table 4) (STOVE).

Table 4. Benchmark fuel and energy consumption values of stoves for entire WBT (5-liter water)

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
	Mean					
Dry Fuel (rice straw) consumed benchmark value (gm/5 liter)	2,343	1,505	1,580	1,158	3,299	2,379
Energy consumed benchmark value (kj/5 liter)	30,650	19,689	20,671	15,147	43,147	31,123
*Aprovecho-Shell Foundation benchmark fuel/energy consumption for wood burning chimney stove to boil 5-liter water and then simmer it for 45 minutes	Less than 1.5 kg wood/5-liter water or less than 30,000 kJ/5 liter water					

In literature, it was shown experimentally for several biomass cookstoves using different biomass fuel that overall thermal efficiency (η) of a biomass cookstove increases by moving up the energy ladder from dung cake to crop residue to wood (Smith et al., 2000b). Increasing thermal efficiency for a single cookstove with the biomass energy ladder (dung cake to crop residue to wood) means higher amount of effective energy utilization which in turn means less energy input. Therefore, there is every possibility for all the MSs in this study to perform better with the biomass energy ladder (dung cake to crop residue to wood) and hence an opportunity to become true ICSs (Venkataraman et al., 2010).

3.2. Emission performances of stoves in WBT

In-stack measurements of flue gas compositions on wet basis was performed for CO_2, CO, NO and CH_4. Composition of the relevant gaseous components (vol %), and combustion efficiencies during cold and hot start in high power phase and simmering in low power phase are shown in Table 5.

For entire WBT of MS and CS models, CO_2 concentrations varied from 6.52 to 6.88 vol%, and 6.29 to 6.57 vol% respectively. CO concentrations of MS and CS models varied from 0.325 to 0.381 vol% and 0.317 to 0.364 vol% respectively. NO concentrations of MS and CS models varied from 0.0047 to 0.0072 vol% and 0.0027 to 0.007 vol% respectively. Basically, NO forms at high temperature. Since the combustion temperatures of all MS models were higher than CS models, NO concentrations in flue gases were usually higher for MS models than for CS models. CH_4 concentrations of MS and CS models varied from 0.061 to 0.091 vol% and 0.063 to 0.073 vol% respectively. Combustion efficiencies of all MS models were found higher than CS models almost in all phases of WBT (Table 5). This may be attributed to the preheating process of primary combustion air in all MS models (Phusrimuang,Wongwuttanasatian, 2016). Combustion efficiencies of all MS and CS models for entire WBT varied from 80 to 85% and 77 to 81% respectively. However, combustion efficiencies of all stoves in low power phase were lower than in high power phase. Since the fuel burning rate was lower in low power phase compared to high power phase, combustion temperature was lower in low power phase. Therefore, combustion efficiencies of all stoves in low power phase fell down compared to high power phase.

Table 5. Emission characteristic and combustion efficiency of stoves for WBT (cold and hot start-high power phase; simmering-low power phase). Compositions are given in wet basis.

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate)	MS-6 Circular Grate
		Mean.'± S.D.					
CO_2 (vol%)	Cold Run	6.60±1.86	6.61±2.11	6.81±1.81	6.67±1.39	6.55±1.19	6.53±1.48
	Hot Run	6.74±1.06	6.84±1.09	6.88±1.24	6.66±1.62	6.46±1.03	6.57±1.63
	Simmering	6.53	6.52	6.69	6.61	6.29	6.37
CO (vol%)	Cold Run	0.335±.059	0.337±0.073	0.325±0.104	0.316±0.059	0.322±0.055	0.317±0.058
	Hot Run	0.364±0.10	0.376±0.107	0.349±0.0916	0.357±0.0915	0.352±0.088	0.349±0.091
	Simmering	0.369	0.381	0.371	0.367	0.359	0.364
NO (vol%)	Cold Run	0.0055±0.001	0.0056±0.00133	0.006±0.0012	0.005±0.00098	0.0027±0.0005	0.0062±0.0009
	Hot Run	0.007±0.0005	0.007±0.00096	0.0072±0.00076	0.0067±0.00066	0.007±0.0006	0.0064±0.0006
	Simmering	0.0051	0.0053	0.0056	0.0047	0.0051	0.0048
CH_4 (vol%)	Cold Run	0.085±0.002	0.091±0.006	0.061±0.004	0.074±0.003	0.068±0.003	0.065±0.002
	Hot Run	0.071±0.002	0.075±0.002	0.084±0.015	0.075±0.003	0.069±0.002	0.073±0.001
	Simmering	0.067	0.071	0.063	0.065	0.064	0.063
Combustion Efficiency (%)	Cold Run	81±4.90	81±4.15	84±3.64	82±5.50	80±2.53	80±3.28
	Hot Run	84±1.76	84±2.25	85±2.07	83±2.83	80±2.61	81±2.67
	Simmering	80±1.95	80±2.15	82±2.5	81±2.45	77±2.15	78±2.37

It is customary to report the emission status as the concentration ratio of a pollutant with respect to CO_2. As the ratio is dimensionless, it is very easy to compare the emission performance among the stoves. The emission ratios of all stoves in high and low power phase of WBT are shown in Supplementary Files Table S1.

Supplementary Table S2 shows the average emission ratios of all stoves for entire WBT. CO ratios of MS and CS models in high and low power phases of WBT varied from 0.047 to 0.055 and 0.049 to 0.057 respectively, whereas the average emission ratios for entire WBT varied from 0.051 to 0.055 for MS models and 0.053 to 0.054 for CS models. CO emission ratio of *Indian Nada Chulha* using rice straw as fuel varied from 0.0921 to 0.288 during the high and low power phases of WBT and the average CO emission ratio for entire WBT was found to be 0.1657 which is almost three folds higher than the emission ratios of all stove models of MS and CS (Smith et al., 2000b). NO ratios of MS and CS models in different power phases of

WBT varied from 0.00071 to 0.00104 and 0.00041 to 0.00108 respectively. The average NO emission ratios for entire WBT varied from 0.00082 to 0.00092 for MS models and 0.00077 to 0.00090 for CS models. CH_4 ratios of MS and CS models in high and low power phases of WBT varied from 0.0089 to 0.0138 and 0.0099 to 0.0111 respectively, whereas the average emission ratios for entire WBT varied from 0.0102 to 0.0119 for MS models and 0.0103 to 0.0104 for CS models. CH_4 emission ratio of *Indian Nada Chulha* using rice straw as fuel varied from 0.00916 to 0.0151 during the high and low power phases of WBT and the average CH_4 emission ratio for entire WBT was found to be 0.0118. CH_4 emission ratios are almost similar among MS models, CS models and *Indian Nada Chulha* (Smith et al., 2000b).

Emission factors by fuel mass on pollutant mass basis of all the stoves during different power phases of WBT are shown in Supplementary Table S3 and average emission factors by fuel mass on pollutant basis of all stoves for entire WBT are shown in Table 6.

Table 6. Average emission factors by fuel mass on a pollutant mass basis (gm/kg D.F.) of all stoves for entire WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
CO_2(gm/kg D.F.)	979	980	1003	983	948	956
CO(gm/kg D.F.)	33.49	34.11	32.72	32.63	32.27	32.16
NO(gm/kg D.F.)	0.590	0.597	0.630	0.550	0.497	0.583
CH_4(gm/kg D.F.)	4.07	4.22	3.72	3.55	3.59	3.59

CO_2 average emission factor (g/kg) for MS models varied from 979 to 1,003 and for CS models varied from 948 to 956. The upper limit of CO_2 average emission factor for CS models is lesser than the lower limit of CO_2 average emission factor for MS models. Whereas, Smith et al (2000) reported an average CO_2 emission factor for *Indian Nada Chulha* of 983 g/kg using rice straw as fuel (Smith et al., 2000b). CO average emission factor (g/kg) for MS models varied from 32.63 to 34.11 and for CS models varied from 32.16 to 32.27. In comparison with the average CO emission factor of the Indian Nada Chulha (101 g/kg), all the models of MS and CS emit less CO per kg of fuel (rice straw). NO average emission factor (g/kg) for MS models varied from 0.550 to 0.630 and for CS models varied from 0.497 to 0.583. CH_4 average emission factor (g/kg) for MS models varied from 3.55 to 4.22 and for CS models it was 3.59. Average emission factor of CH_4 *for Indian Nada Chulha* was reported as 4.24 g/kg using rice straw as fuel, which is very similar to MS models.

Average emission factors of pollutant mass by fuel energy content basis (g/MJ) of all the stoves for entire WBT are shown in Table 7 and Figure 6.

Table 7. Average emission factors of pollutant mass by fuel energy content basis (gm/MJ) of all stoves for entire WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
CO_2 (gm/MJ)	74.85	74.92	76.68	75.15	72.48	73.10
CO (gm/MJ)	2.56	2.61	2.50	2.50	2.47	2.46
NO (gm/MJ)	0.045	0.046	0.048	0.042	0.038	0.044
CH_4 (gm/MJ)	0.311	0.323	0.284	0.271	0.274	0.274

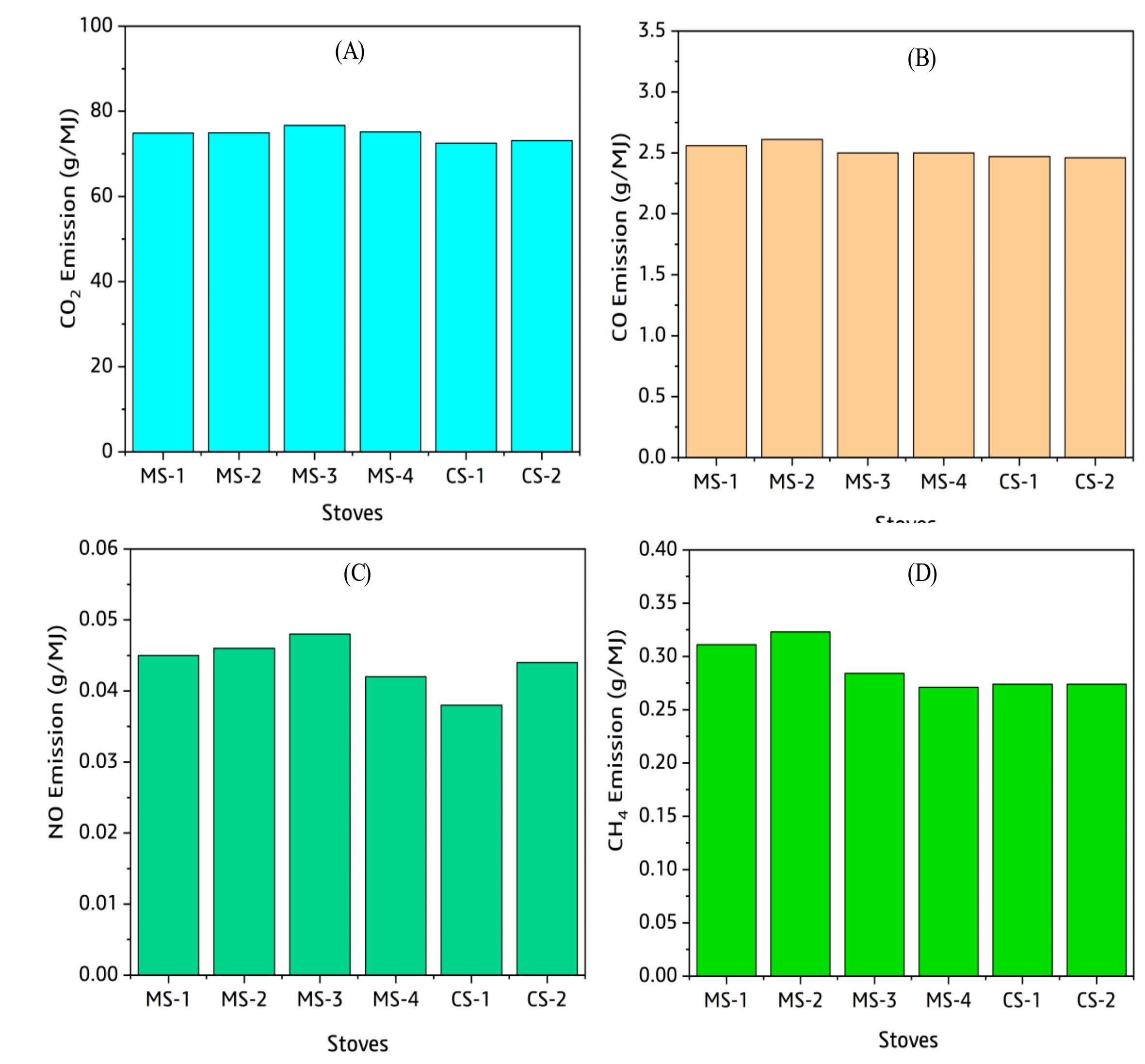


Figure 6: Average emission factors of (A) CO_2, (B) CO, (C) NO, (D) CH_4 mass by fuel energy content basis (g/MJ) of all the stoves for entire WBT

The CO_2 average emission factor (g/MJ) for MS models varied from 74.85 to 76.868, whereas this factor varied from 72.48 to 73.10 for CS models. CO average emission factor for MS models varied from 2.50 to 2.61 g/MJ, which was higher than CO emission factor for CS models that varied from 2.46 to 2.47 g/MJ. NO average emission factor for MS models varied from 0.042 to 0.048 g/MJ which was higher than NO emission factor for CS models that varied from 0.038 to 0.044 g/MJ. This was because of high combustion temperature in all MS models than in CS models. CH_4 emission factor (g/MJ) for all MS models were higher than CS models except for MS-4. CH_4 average emission factor for MS models varied from 0.271 to 0.323 g/MJ, whereas this emission factor for CS models was 0.274 g/MJ. Smith et al (2000) reported average emission factors of CO_2, CO and CH_4 to be 75.44, 7.751 and 0.3254 g/MJ respectively for *Indian Nada Chulha* using rice straw as fuel (Smith et al., 2000b).

Aggregated benchmark values of different polluting parameters (g/5-liter water) for boiling 5-liter water and then simmering it for 45 minutes during entire WBT are shown in Table S4. Total CO_2 emission values for entire WBT for 5-liter water of all MS models are lower than CS models except MS-1. Total CO_2 emission of MS-1 is somewhat higher than the CS-2. But in comparison with CS-1, MS-1 emits much lower content of CO_2 through the entire WBT for boiling 5-liter water and then simmering it for 45 minutes. The lowest CO_2 emission can be attributed to MS-4 whereas the second lowest CO_2 emitter is MS-2. MS-3 is the third lowest CO_2 emitter cookstove for entire WBT.

The ranking of all the stoves in terms of CO emission for entire WBT (to boil 5-liter water and then to simmer it for 45 minutes) is similar to that in terms of CO_2 emission. NO emission values were found to be lower for all MS models compared to CS models for entire WBT. The lowest NO emission can be attributed to MS-4. In terms of CH_4 emission for entire WBT, all the MS models emit less CH_4 compared to CS models except MS-1 that emits more CH_4 compared to CS-2 for entire WBT. Based on CH_4 emission, MS-4 can be ranked as the lowest emitter, the second lowest emitter is the MS-3 and the third lowest emitter is the MS-2. Among all the stoves, MS-4 emitted the lowest amount of each pollutant for entire WBT. The second and third lowest contributors to emission were MS-2 and MS-3 respectively.

3.3. Thermal Performance of stoves in CCT

During controlled cooking test (CCT) of all the cookstoves, combustion air temperature, fuel bed temperature, stack flue gas temperature and the draft inside the chimney were measure which are shown in Table 8.

The values found are almost identical to those found during WBT. Combustion temperature, fuel bed temperature, flame zone temperature is higher for MS models compared CS models. Although in some cases the average temperatures of some MS models were higher than CS-2, temperature difference between stack and flame zone was much higher in MS models compared to all CS models. Draft inside chimney of all MS models shows higher value compared to CS models which means better relative turbulence in MS models.

Table 8. Temperature and draft profile of all stoves during CCT

Parameters	Stove Type					
	MS-1	MS-2	MS-3	MS-4	CS-1	CS-2
	Circular Grate	Circular Grate	Elliptical Grate	Circular Grate	Circular Grate	Circular Grate
	Mean ± S.D.					
Combustion air temperature (°C)	71±5	68±3	70±5	72±6	30±1	30±1
Fuel bed temperature(°C)	633±8	628±8	638±8	645±6	602±4	606.±4
Flame zone temperature(°C)	731±10	726±6	726±8	724±9	690±13	683±10
Stack flue gas temperature(°C)	297±33	332±38	327±29	331±34	336±58	330±53
Draft inside chimney (-Pa)	*7.3±1.16	*7.5±1.12	*7.3.±1.11	*7.4±1.11	7.2±1.32	7.1±1.11

*All MS models have two chimneys. The draft reported here is the average draft per chimney.

Cooking menu of a traditional food (cooking of parboiled rice), average cooking time, average fuel requirement per cooking episode in CCT for each type of the stove model are shown in Supplementary Table S5. Normalized fuel and energy requirement per kg parboiled rice cooking following the same cooking menu for each type of the stove model, and therefore fuel and energy saving and cooking time saving taking the CS-1 and CS-2 as the reference stove separately are shown in Table 9.

Table 9. Fuel and energy consumption per parboiled rice cooking and fuel/energy saving and cooking time saving of the stoves considering CS-1 and CS-2 as the comparison base separately.

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
	Mean					
Fuel consumption (gm/kg parboiled rice cooking)	1504	1159.33	877.33	1044.44	1867.47	1378.67
Energy consumption (kj/kg parboiled rice cooking)	19,672.32	15,164	11,475.48	13,661.27	24,426.50	18,033
Fuel/energy saving	20%	38%	53%	44%	Base	26%
Time saving	8%	44%	60%	53%	Base	38%
Fuel/energy saving	(−) 9%	16%	36%	24%	(−) 35%	Base
Time saving	(−) 47%	10%	37%	24%	(−) 60%	Base

Figure 7 presents the energy consumed and boiling time for all the stoves. It was found that MS-3 (elliptical grate) consumed the lowest fuel and energy per kg parboiled rice cooking.

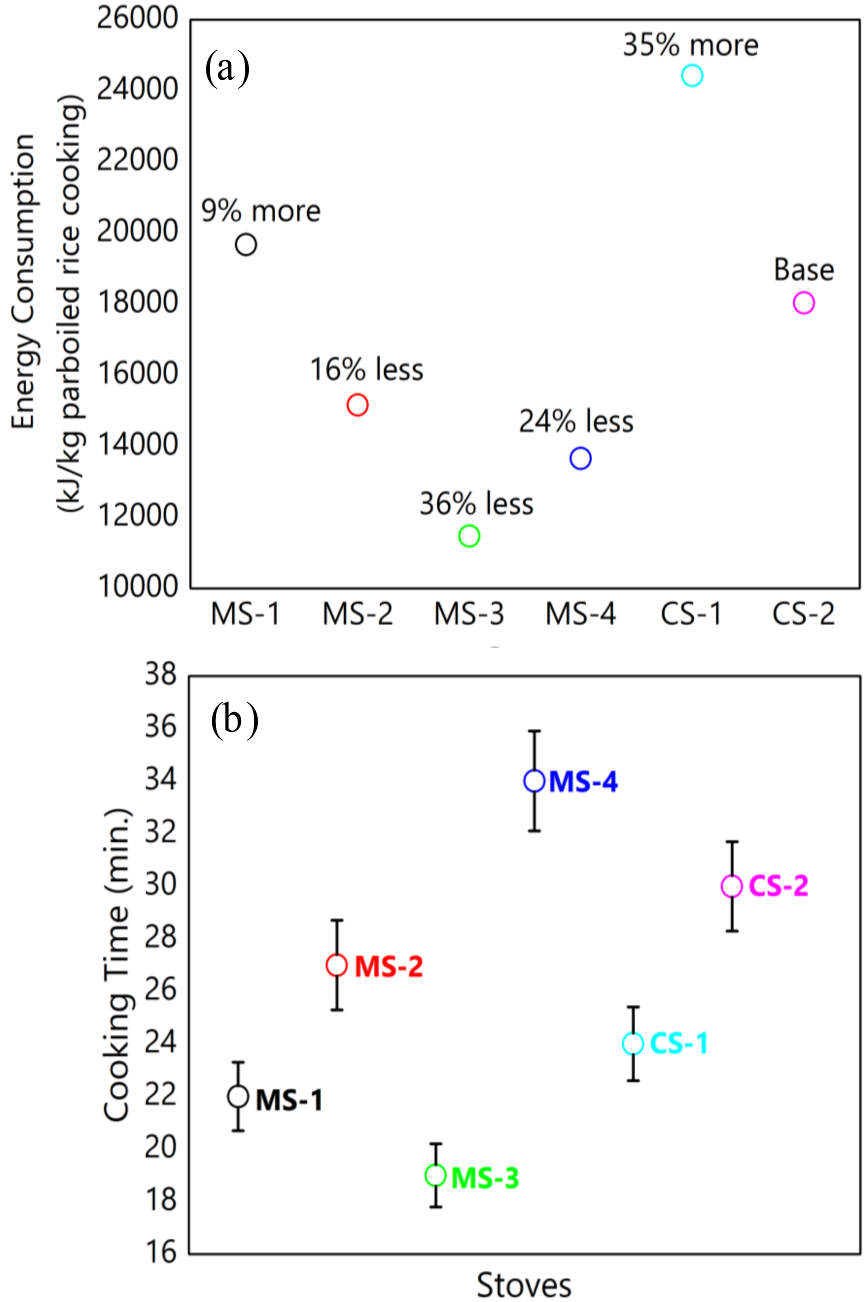


Figure 7: Energy consumption (kJ/kg) and cooking time (min) for all the stoves

As per Table 9, the rank order of the stoves (from the lowest to highest) based on the fuel and energy consumption for cooking 1 kg parboiled rice following the cooking menu is, MS-3 (the lowest fuel and energy consumer) < MS-4 < MS-2 < CS-2 < MS-1 < CS-1. Taking CS-1 as the base, MS-3, MS-4, MS-2, MS-1 and CS-2 save fuel/energy consumption by 53%, 44%, 38%, 19.50% and 26% respectively and save cooking time by 60%, 53%, 44%, 8% and 38% respectively. Even if the MS-3 and MS-2 (double pots) are compared with the CS-2 as a base, MS-3 (elliptical grate) and MS-2 (circular grate) mud stoves can save fuel/energy consumption by 36.4% and 16% respectively and save cooking time by 36.67% and 10% respectively. Whereas, MS-4e can save about 24.24% of fuel/energy compared to CS-2 (Table 9).

3.4. Emission performances of stoves in CCT

Pollutant concentrations (wet basis) of CO_2, CO, NO and CH_4 in flue gases and combustion efficiencies of all stoves during CCT are shown in Table 10.

Table 10. Emission characteristic and combustion efficiencies of different stoves during CCT (parboiled rice cooking)

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
	Mean±S.D.					
CO_2 (vol %)	6.63±1.20	6.76±1.35	6.61±1.77	6.61±1.38	6.44±1.03	6.49±1.73
CO (vol %)	0.286±.047	0.332±0.071	0.335±0.043	0.210±0.152	0.318±0.061	0.302±0.0478
NO (vol %)	0.006±0.00095	0.006±0.0016	0.0054±0.001	0.005±0.001	0.0055±0.001	0.005±0.0001
CH_4 (vol %)	0.073±0.001	0.081±0.002	0.069±0.002	0.070±0.002	0.071±0.002	0.069±0.001
Combustion efficiency	83±2.20	83±3.51	83±2.69	82±1.90	79±1.78	80±3.28

Average emission ratios of CO, NO and CH_4 in flue gases of all stoves during CCT with respect to CO_2 are shown in Table S6. It was noticed that the average emission ratios of CO of all the stoves during CCT were less compared to average emission ratios of CO of all stoves during WBT. Average CO ratios of MS models and CS models in CCT varied from 0.032 to 0.051 and 0.047 to 0.049 respectively (Table S6). Average NO ratios of MS models and CS models in CCT varied from 0.00076 to 0.00090 and 0.00077 to 0.00085 respectively. Whereas, average CH_4 ratios of MS models and CS models in CCT varied from 0.0104 to 0.0119 and 0.0106 to 0.0110 respectively.

Benchmark emission values of CO_2, CO, NO and CH_4 of all stoves for cooking one kg of parboiled rice using rice straw as fuel following the cooking menu are shown in Supplementary Table S7. In context of emission values of all the four gases (CO_2, CO, NO and CH_4) during cooking one kg parboiled rice, MS-3 (elliptical grate) was found to be the lowest emitter. The 2nd, 3rd and 4th lowest emitter were the MS-4, MS-2 and CS-2 respectively. CS-1 was found to be the highest emitter in context of all the four pollutants. Therefore, these stoves can be ranked in context of emission performance during CCT as follows: MS-3 elliptical grate (the lowest emitter) < MS-4 < MS-2, circular grate < CS-2 < MS-1 < CS-1 (the highest emitter).

Benchmark emission reduction by different stoves under consideration for cooking parboiled rice following the cooking menu given using rice straw as cooking fuel during CCT taking CS-1 concrete stove as reference stove are shown in Table S8. The highest pollution reduction was found in MS-3 (elliptical grate). The 2nd, 3rd , 4th and 5th highest emission reduction were found in MS-4, MS-2 (circular grate) and CS-2 and MS-1 respectively. Though the 5th highest emission reduction was found in MS-1 with respect to multiport cookstoves, it is better than Grameen Shakti-single pot concrete stove in context of emission reduction option.

CO_2, CO, NO and CH_4 emission reductions of MS models during CCT (considering CS-1 as reference stove) varied from 15 to 51%, 26-69%, 11 to 56% and 15 to 54% respectively whereas, these emission reductions were found to be 25%, 30%, 33% and 28% in CS-2. Though the emission reductions of CS-2 stove are close to those of MS-2, the latter is better in context of pollution reduction option.

3.5. Overall performances and insights of the stoves

The overall performance (overall thermal efficiency, combustion efficiency and heat transfer efficiency) and environmental stove index (ESI)) of all stoves (for entire WBT) using rice straw as fuel are shown in Table 11 and Figure 8.

Table 11. Benchmark efficiency values and environmental stove index of all cookstoves for WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
Overall thermal efficiency (%)	18	24	25	29	10	13
Combustion efficiency (%)	82	82	84	82	79	80
Heat transfer efficiency (%)	22	29	30	35	13	16
Environmental stove index (ESI)	0	0.29	0.44	0.48	-0.73	-0.43

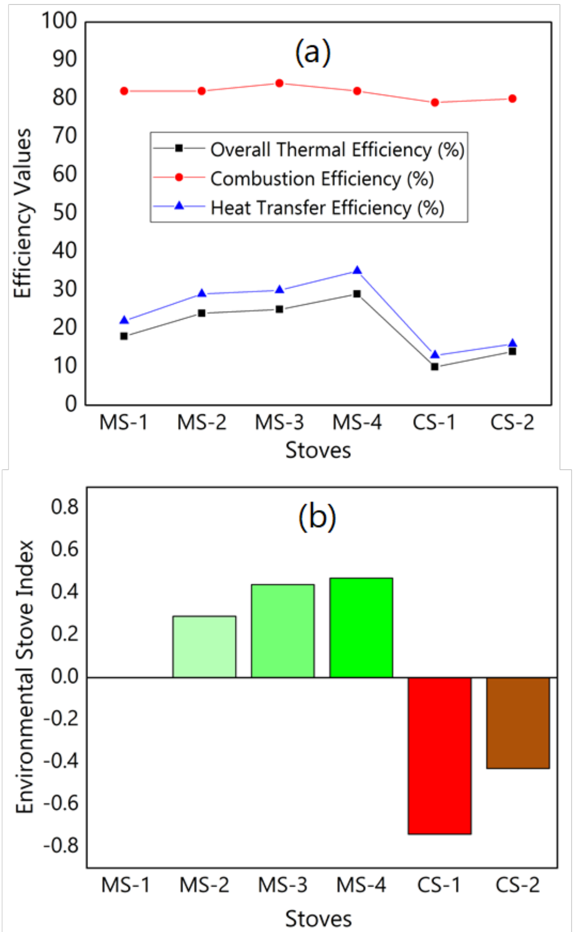


Figure 8: (a) Overall thermal efficiency, combustion efficiency, and heat transfer efficiency and (b) environmental stove index (ESI) of all stoves

All the parameters for MS models show higher values compared to CS models. Overall thermal efficiency, combustion efficiency, heat transfer efficiency and ESI of MS-1 and CS-1 stove were 18%, 82%, 22%, 0 and 10%, 79%, 13%, -0.73 respectively. If the MS-2 and MS-3 are compared with the CS-2, it can easily be seen that overall thermal efficiencies and heat transfer efficiencies of MSs are almost double than CS. Combustion efficiencies of MS-2/3 are also higher than CS-2. ESI of MS-2/3 is also much better than CS-2. The highest overall thermal efficiency and heat transfer efficiency were found for MS-4. Most of the performance parameters of MS models make them worthy to be ranked over the CS models.

Superiority of the MS models over CS models can be attributed to some unique design considerations of MS models. Preheating provision for combustion air, high fuel bed and flame zone temperatures, flame distribution pattern on pot bottom, reasonable draft in double chimney to create turbulence inside combustion chamber, comparatively short distance between fuel bed and pot mouth to facilitate radiative heat transfer, comparatively low stack temperatures and even distributions of combustion air channels under the fuel grate make all the MS models worthy to show their superiority over the CS models.

Some of the technical considerations have enhanced the thermal efficiency of the MSs stoves. There are some basic design principles for an effective biomass cookstove. The improved cooking systems (ICSs) possess low energy loss to surrounding environment, good combustion and heat transfer characteristics (Rathore et al., 2022). Insulation around the fire with light materials can resist heat from escaping to the surrounding (Okino et al., 2021). Wood ash was mixed with mud as insulating material in this study to fabricate all MSs as it is low-cost waste material (Urban et al., 2002).

Chimney increases the convectional heat transfer to the cooking pot. In convective heat transfer, surface boundary layer accounts to the primary resistance for heat flow by very slowly moving gas immediately adjacent to a wall (Xie et al., 2021). Within this region, heat transfer is primarily governed by conduction with low conductive gases. To improve the thermal efficiency of a stove, the thermal resistance of this boundary layer must be reduced by increasing the flow velocity of the hot gas over the surface of the pot (Karunanithy,Shafer, 2016). In the present study, it was followed for all the MSs models by increasing turbulence (Bryden et al., 2005). Increasing the radiative heat transfer from fire bed to cooking pot is another option to improve heat transfer efficiency of the cookstove. For the effective heating of cooking pot by radiation hear transfer directly from fuel bed, the average fuel bed temperature could be increased (without increasing the fuel consumption) by maintaining proper air to fuel ratio (Lucky,Hossain, 2001). Alternatively, radiative heat transfer can be increased by lowering the distance of cooking pot and fire bed or the view factor can be increased by increasing the size of the pot relative to the fire bed. In this work, all the stoves were designed to maintain the above criteria.

In this work, a unique phenomenon, preheating of combustion air, which raises the temperature of combustion chamber and provides relatively clean burning, was incorporated. All the cookstoves were designed with double wall to prevent burn, which is one of the most important safety factor of an improved stove. To mix the preheated combustion air with the fuel on fire bed for better combustion, total estimated combustion air was distributed evenly through several circular ducts under the fire bed (metal grate). Each of the stoves was fixed type and the base of the stove and floor surface were separated with insulating material (ordinary fired brick) to prevent excessive heat flow to floor materials. To lessen the excess heat load of the stove body, the height of all stoves was maintained a minimum providing the ash pit underground. Ash pit and ash hole on the floor surface were connected through an underground channel.

To validate the economic feasibility, a facile cost analysis for the construction of stove models is summarized in Table 12.

Table 12: The comparative costing for the stove models

Stove Model	Estimated Unit price (USD)
MS-1	5.30
MS-2	5.30
MS-3	5.30
MS-4	5.30
CS-1	8.20
CS-2	11.6

The designed MSs made with mud did not cost money except for metal O ring, grate, and chimney. The technique for the construction of these MSs was comprehensively described in this manuscript and easy to follow. On the other hand, the CSs models require stone aggregates, sand, cement, and mould for the construction. The rural people may find it difficult to build these CSs at home. The construction cost of CS-1 is 54 % higher than MSs, whereas CS-2 has 118% higher cost than MSs.

4.0. Conclusions

This work deals with the construction and feasibility (operational and economic) analysis of easily fabricated MSs over procured ICSs CSs. The study found that the MS models were better designed stoves in context of combustion efficiency, heat transfer efficiency, overall thermal efficiency, and emission reduction. If one compares the performances of single pot stove between MS and CS models, theMS-1 will be ascertained as the better option with respect to lesser amount of fuel requirement, lesser time requirement to cook, and lesser amount of pollutant emission. If one compares the performances of double pot stove between MS and CS models, no doubt that MS will get ride on the CS stove in context of reduced cooking time, reduced fuel consumption, and reduced emission. However, MS-3 (elliptical grate) is the best engineered stove among the double pot stoves designed, every nook of stove performances. MS-4 (triple-pot) stove can also be considered as one of the best models among the multi pot stove variant in context of reduced fuel consumption, cooking time and pollutant emission. Therefore, all the MS models superseded the performances of CS models within their respective group. This performance superiority of MS models can be attributed some basic concepts in engineering design of the stoves, i.e., preheating combustion air, better mixing of incoming combustion air with fuel and volatiles inside combustion chamber through evenly distributed multi channels under the fuel bed, increasing radiative heat transfer by shortening the distance between grate and pot mouth, and increasing convective heat transfer through maintaining high draft in chimney. Moreover, the designed MSs were much low cost compared to the CSs, which makes the MSs as excellent cookstoves for the rural community of any developing countries.

Acknowledgment
The author acknowledges the overall support from Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh.

Data Availability Statement
The detailed data will be available on reasonable request from the corresponding author.

Conflict of interest
The authors declare no conflict of interest.

References

Arif, T., Ashraf, A., Miller, G., Mobarak, A. M., Akter, N., Ali, A., Sarkar, M., Hildemann, L., Dey, N. C. & Rahman, M., 2011. Promotion of improved cookstove in rural Bangladesh.

Baldwin, S. F., 1987. Biomass stoves: engineering design, development, and dissemination, Volunteers in Technical Assistance Arlington, VA.

Bensch, G., Jeuland, M. & Peters, J., 2021. Efficient biomass cooking in Africa for climate change mitigation and development. One Earth, 4**,** 879-890.

Bhattacharya, S., Salam, P. A. & Sharma, M., 2000. Emissions from biomass energy use in some selected Asian countries. Energy, 25**,** 169-188.

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R. & Goyer, K., 2005. Design principals for wood burning cook stoves, Aprovecho Research Center.

Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M. S., Wang, S., Hao, J., Zhang, H. & He, C., 2017. A review of biomass burning: Emissions and impacts on air quality, health and climate in China. Science of the Total Environment, 579**,** 1000-1034.

Gebreegziabher, Z., Beyene, A. D., Bluffstone, R., Martinsson, P., Mekonnen, A. & Toman, M. A., 2018. Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia. Resource and Energy Economics, 52**,** 173-185.

Goldemberg, J., Martinez-Gomez, J., Sagar, A. & Smith, K. R., 2018. Household air pollution, health, and climate change: cleaning the air. Environmental Research Letters, 13**,** 030201.

Hossain, M. G., 2003. Improved cookstove and biogas programmes in Bangladesh. Energy for Sustainable Development, 7**,** 97-100.

Huda, A., Mekhilef, S. & Ahsan, A., 2014. Biomass energy in Bangladesh: Current status and prospects. Renewable and Sustainable Energy Reviews, 30**,** 504-517.

Islam, A., Roy, H. & Rahman, M. M., 2022. Energy efficiency study of household natural gas burner using pot-bottom shield and modified pot arrangement. Energy Reports, 8**,** 12871-12885.

Iso/Iwa, 2014. The Water Boiling Test, Version 4.2.3. Cookstove Emissions and Efficiency in a Controlled Laboratory Setting.

Karunanithy, C. & Shafer, K., 2016. Heat transfer characteristics and cooking efficiency of different sauce pans on various cooktops. Applied Thermal Engineering, 93**,** 1202-1215.

Khan, A., Eusuf, M., Prasad, K., Moerman, E., Cox, M., Visser, A. & Drisser, J., 1995. The development of improved cooking stove adapted to the conditions in Bangladesh. final report of collaborative research project between IFRD, BCSIR, Bangladesh, and Eindhoven University of Technology, Eindhoven, the Netherlands.

Kirch, T., Birzer, C. H., Medwell, P. R. & Holden, L., 2018. The role of primary and secondary air on wood combustion in cookstoves. International Journal of Sustainable Energy, 37**,** 268-277.

Ko, Y.-C. & Lin, T.-H., 2003. Emissions and efficiency of a domestic gas stove burning natural gases with various compositions. Energy Conversion and Management, 44**,** 3001-3014.

Lucky, R. A. & Hossain, I., 2001. Efficiency study of Bangladeshi cookstoves with an emphasis on gas cookstoves. Energy, 26**,** 221-237.

Mamun, M., Kabir, M., Alam, M. & Islam, M., 2009. Utilization pattern of biomass for rural energy supply in Bangladesh. Int. J. Sustain. Crop Prod, 4, 62-71.

Miah, M. D., Kabir, R. R. M. S., Koike, M., Akther, S. & Shin, M. Y., 2010. Rural household energy consumption pattern in the disregarded villages of Bangladesh. Energy Policy, 38, 997-1003.

Okino, J., Komakech, A. J., Wanyama, J., Ssegane, H., Olomo, E. & Omara, T., 2021. Performance Characteristics of a Cooking Stove Improved with Sawdust as an Insulation Material. Journal of Renewable Energy, 2021, 9969806.

Panwar, N. L., Kurchania, A. K. & Rathore, N. S., 2009. Mitigation of greenhouse gases by adoption of improved biomass cookstoves. Mitigation and Adaptation Strategies for Global Change, 14, 569-578.

Phusrimuang, J. & Wongwuttanasatian, T., 2016. Improvements on thermal efficiency of a biomass stove for a steaming process in Thailand. Applied Thermal Engineering, 98, 196-202.

Rahman, H., 2007. Policy gaps in household energy and indoor air pollution in Bangladesh. Practical Action Bangladesh.

Rahman, M., Akter, N. & Sarkar, M. Q., 2006. Assessment of Existing Improved Cook Stove in Bangladesh. Mizanur Rahman, BRAC Centre, 75.

Rathore, N. S., Singh, C. K., Rathore, N. & Panwar, N. L., 2022. Thermal performance and heat storage behaviour of three pots improved cookstove. Energy Nexus, 6, 100074.

Saha, A., Razzak, M. A. & Khan, M. R., 2021. Electric Cooking Diary in Bangladesh: Energy Requirement, Cost of Cooking Fuel, Prospects, and Challenges. Energies, 14, 6910.

Shaha, A. K., 2018. Combustion engineering and fuel technology, Oxford & IBH.

Smith, K. R., Uma, R., Kishore, V., Zhang, J., Joshi, V. & Khalil, M., 2000a. Greenhouse implications of household stoves: an analysis for India. Annual Review of Energy and the Environment, 25, 741-763.

Smith, K. R., Uma, R., Kishore, V. V. N., Zhang, J., Joshi, V. & Khalil, M. a. K., 2000b. Greenhouse Implications of Household Stoves: An Analysis for India. Annual Review of Energy and the Environment, 25, 741-763.

Still, D. & Maccarty, N., 2006. The effect of ventilation on carbon monoxide and particulate levels in a test kitchen. Boiling point, 52, 24-26.

Stove, M.-P. B. C., Sujala T. Sultana*, Fatema Parvez and MM Rahman.

Unger, N., Shindell, D. T., Koch, D. M., Amann, M., Cofala, J. & Streets, D. G., 2006. Influences of man-made emissions and climate changes on tropospheric ozone, methane, and sulfate at 2030 from a broad range of possible futures. Journal of Geophysical Research: Atmospheres, 111.

Urban, G. L., Bryden, K. M. & Ashlock, D. A., 2002. Engineering optimization of an improved plancha stove. Energy for Sustainable Development, 6, 9-19.

Urmee, T. & Gyamfi, S., 2014. A review of improved Cookstove technologies and programs. Renewable and Sustainable Energy Reviews, 33, 625-635.

Venkataraman, C., Sagar, A. D., Habib, G., Lam, N. & Smith, K. R., 2010. The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. Energy for sustainable development, 14, 63-72.

Xie, K., Cui, Y., Wang, J. & Qiu, X., 2021. Theoretical and numerical investigation of heat transfer characteristics of an integrated cookstove under different atmospheric pressures based on theoretical models of solid flame and impingement heat transfer. International Communications in Heat and Mass Transfer, 127, 105524.