RESEARCH ARTICLE

Transforming Fecal Sludge into an Affordable Biofuel Alternative: A Sustainable Solution for Developing Countries

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Abstract: Developing countries are facing challenges due to rapid urbanization and insufficient sanitation facilities. However, valorizing treated fecal sludge as a fuel source presents an opportunity to recover energy and mitigate environmental impacts. This experimental study aimed to produce low-cost biofuel from dried fecal sludge and enhance its energy efficiency by incorporating locally available organic matters. Various organic materials like rice husk, cow dung, sawdust, and coal were carbonized and mixed with the sludge to enhance calorific value. Eight sludge and organic matter mixtures were formed into briquettes. The blend of 50% sludge and 50% coal yielded the highest calorific value of 14618 KJ/kg and a boiling time of 14 minutes. The second-highest result was for 50% sludge and 50% cow dung, with a calorific value of 14427 KJ/kg and a boiling time of 23 minutes. The study found that blending sludge with organic materials enhances energy output. Briquettes with 50% sludge and 50% coal cost 19.87 BDT/kg, while those with 50% sludge and 50% cow dung cost 14.37 BDT/kg, proving more economical. The latter blend emerged as the most efficient and cost-effective biofuel, offering a sustainable eco-friendly solution for Bangladesh's rural energy market.

Keywords: Biofuel, briquette, dried fecal sludge, resource recovery, fecal sludge management

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1 Introduction

Fecal sludge, the semi-solid remains of human waste after the process of primary treatment, poses significant challenges in sanitation management worldwide since it consists of a complex mixture of organic and inorganic matter, pathogens, and other contaminants, presenting health hazards and environmental risks if not properly managed (Krueger et al., 2020). Globally, there is a growing concern to address fecal sludge (FS) management issues and explore its potential as a valuable resource in fuel generation. The problem of fecal sludge (FS) management arises from inadequate sanitation systems, particularly in densely populated urban areas of developing countries like Bangladesh. More than half of Bangladesh's population lacks access to improved sanitation facilities (WHO/UNICEF/JMP, 2021), leading to uncontrolled dumping of fecal sludge into the environment that contaminates water bodies, causing waterborne diseases and ecosystem degradation. In addition to health and environmental concerns, the mismanagement of fecal sludge also represents a missed opportunity for resource recovery. Fecal sludge contains organic matter that can be converted into valuable products such as biogas for energy generation. However, without proper management systems in place, this potential resource goes untapped, perpetuating reliance on fossil fuels and exacerbating climate change.

In Bangladesh, FS has emerged as a prospective low-cost fuel source with significant implications. Traditionally, rural areas have relied on the utilization of bio-solid waste, such as manure, either in its dried form or as biogas, as a means of fuel. However, there exists a compelling opportunity to advance beyond these conventional practices or be replaced by an improved version of fuel generated from solidified fecal sludge. Nevertheless, the energy efficiency of dried FS only is suboptimal due to the low calorific value of the fuel content, though fecal sludge charcoals are often proven to serve high energy efficiency (Sagor et al., 2022; Ward et al., 2014).

Fecal sludge valorization offers a promising pathway for recovering energy and nutrients from waste, while simultaneously mitigating the financial burdens associated with treatment processes and alleviating the environmental and health impacts. Various methods for obtaining biofuel products from sewage raw materials are extensively being researched (Otieno et al., 2022; Sagor et al., 2022; Ward et al., 2014;

Xu et al., 2023; Yahav et al., 2023). Various studies have explored the utilization of different waste materials, such as fecal sludge, pineapple peels, food waste and sewage sludge, to produce biochar-briquettes (charred or non-charred) for cooking and heating purposes (Ariani et al., 2023; Kizito et al., 2022; Atwijukye et al., 2018; Sagor et al., 2022; Ward et al., 2014; Xu et al., 2023). Biochar, a type of charcoal-like substance, produced through the process of controlled pyrolysis of organic biomass in a low-oxygen environment, has been widely acknowledged as a more environmentally friendly fuel alternative when compared with conventional biomass fuels (Kim and Parker, 2008; Sagor et al., 2022;Ward et al., 2014). These bio-briquettes have been found to have favorable characteristics, including low moisture content, high calorific value, and good physical properties. However, the composition of the waste materials used in the briquettes affects their properties. Kizito et al.(2022) explored the production of briquettes made from dried fecal sludge mixed with fresh food waste, and found that the calorific value of the briquettes was highest when mixed with pineapple peels (Kizito et al., 2022). Pineapple peel was also mixed with FS in another study by Ariani et al. (2023) along with different types of adhesives, such as starch, rejected papaya, and cow dung, with starch showing better physical properties of the bio-briquettes (Ariani et al., 2023). The production of bio-briquettes from fecal sludge and other waste materials offers a low-cost and environmentally friendly solution for energy poverty and poor sanitation issues in developing countries (Atwijukye et al., 2018).

To address the limitation of calorific value, a pioneering experimental study was undertaken that aimed at augmenting the calorific value of solidified FS collected from the fecal sludge treatment plant situated in Rajbandh, Khulna, under the jurisdiction of the Khulna City Corporation, Bangladesh. This study holds immense significance since reuse of waste was encouraged in the Sustainable Development Goals. Moreover, there exists a substantial demand for a fuel option in local market of Bangladesh that not only offers high efficiency but also remains cost-effective.

The utilization of biochar briquettes, tailored to the requirements of local rural stoves in Bangladesh, facilitates ease of use and user-friendly adoption. Given the substantial annual production of human waste in the country, briquette production from fecal sludge presents an attractive, reliable, and sustainable fuel paradigm. Furthermore, this eco-friendly option not only offers reduced health hazards but also provides potential employment opportunities within rural communities.

This study was focused on achieving the objectives including assessing the potential of fecal sludge as a biofuel and then improving the energy content of dried fecal sludge by adding different types of organic matters such as sawdust, rice husks, cow dung, wood, and coal through dewatering and carbonization process and then manufacturing biochar briquettes from them and also finding out the most efficient and cost-effective blend among them. The implementation of this fecal sludge-based biofuel approach would yield multifaceted benefits. It would not only alleviate the waste burden faced by urban areas instead it would produce environmentally friendly fuel alternative that effectively meets the burgeoning energy demands of the country.

2 Material and methods

2.1 Sample collection

The fecal sludge samples were collected on March 2022 from the Fecal Sludge Treatment Plant (FSTP) (Figure 1) operated by the Khulna City Corporation (KCC) at Rajbandh, Khulna. This FSTP has a capacity of 180 cum/day and designed to treat waste of Khulna City with 1.5 million population. The high fecal sludge generation rate recorded in KCC is approximately 450 tons/day that facilitates as well as highlights the importance and relevance of this research in tackling the challenges related to managing fecal sludge in Bangladesh.

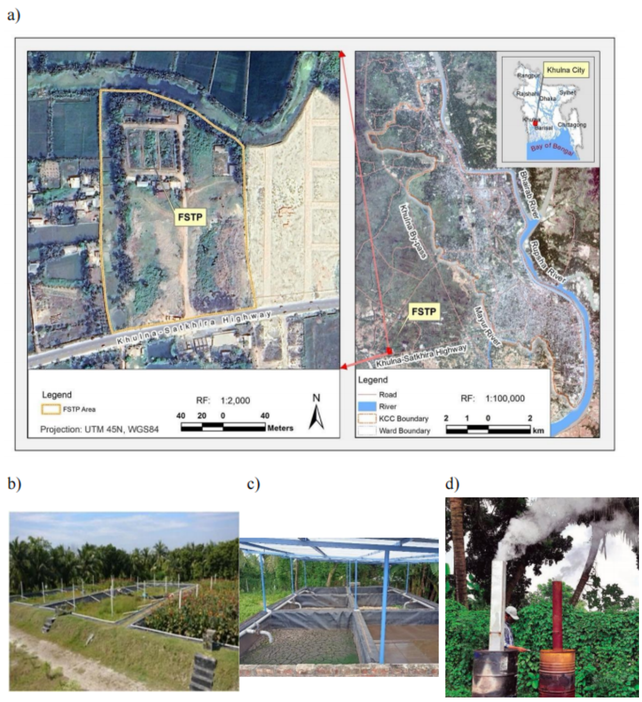

Figure 1. a) Site map of FSTP and its location with respect to Khulna City & b) Snapshot of the fecal sludge treatment plant, c) the sludge emptying and drying bed, d) Carbonization kiln Single drum (right), Double drums (left).

2.2 Sample processing and preparation

To ensure effective biochar formation, it is advantageous to solidify and dry the fecal sludge beforehand, as the typical total solid (TS) concentration in fecal sludge ranges from 8.9 to 58 g/L and needs to be increased to 90% by reducing the moisture content (Muspratt et al., 2014; Werther and Ogada, 1999). Drying beds are widely used for sludge dewatering (Muspratt et al., 2014; Seck et al., 2015; Tchobanoglus et al., 2003). The FSTP of KCC is equipped with a drying bed facility where the collected FS from the municipalities of Khulna was disposed of and underwent a drying process in open air for 14 and 21 days (Figure 1(c)). In this point, dried FS was collected from the drying bed as a sample for this study.

2.2.1 Fecal sludge and other organic matter drying and processing

The collected air-dried FS was then kept in a greenhouse until the moisture content lowered to less than 15% and then stored for further carbonization process. To increase the energy content of the FS based biofuel, it is necessary to decrease the moisture content. The addition of a bulking agent i.e. organic matter (OM) like sawdust, rice husks, or wood chips has been proven effective in lowering the moisture content of sludge. In Asia, this technique is commonly employed during the desludging process to facilitate the extraction of fecal sludge from pit latrines or septic tanks (Montangero and Strauss, 2004a).

However, identifying the optimal FS-OM combination remains a significant challenge. A study was aimed at manufacturing FS charcoal briquettes using rice starch as a binder, along with varying ratios of rice husk (RH) powder, corncob powder (CP), wheat powder (WP), and cow dung (CD). The RH, CP, and WP briquettes were made at 80:20, 75:25, and 70:30 ratios respectively, while the CD briquettes were prepared using ratios of 70:30, 50:50, and 30:70 for FS charcoal and CD and found the best blend (Sagor et al., 2022). Efficient energy content was generated after blending FS with charcoal dust in ratio of 1:1 (Montangero and Strauss, 2004b).

In this study, 4 OMs namely, saw dust, rice husk, cow dung and coal were selected as associate biomass and purchased from local markets. Subsequently, all the biomass was dried in the greenhouse to lower their moisture content. Once the desired moisture level was achieved, the FS and organic biomass underwent carbonization separately to manufacture biochar briquette.

2.2.2 Carbonization of the biomass

Carbonization or slow-pyrolysis process converts biomass into a highly carbonaceous, charcoal-like material. This charcoal is a stable form of carbon that remains after the volatile components of the biomass have been driven off. This high carbon content give rise to high burning capacity of the biochar (Krueger et al., 2020; Kim and Parker, 2008). However, different studies found different temperature efficient in pyrolyzing the biomass, for instances, pyrolysis at 300°C was able to produce fecal chars with higher calorific value i.e. 25.6 ± 0.08 MJ/kg that can easily compete with wood chars and bituminous coal, while pyrolyzing at 750°C made fecal chars with lower energy content of around 13.8 ± 0.48 MJ/kg (Ward et al., 2014). Though, 500°C as a minimum temperature was suggested by B. Krueger (2020). Desirable calorific value was also achieved at 400°C temperature during fecal charcoal production (Sagor et al., 2022).

In this study the carbonization process has taken place in locally customized drums, 1) single drum 2) double drums (Figure 1(d)), called as a carbonization kiln. The overall process flow diagram is showing in Figure 2. Various moisture contents were tested in the kiln to determine the optimal combination of moisture content, temperature requirements, and time duration. The optimal temperature found between 350 to 400°C. It was observed that higher moisture content resulted in longer carbonization times. The FS required approximately 2.5 hours to achieve 90% carbonization, while rice husk took around two hours to reach complete carbonization (100%). On the other hand, carbonizing sawdust was quiet challenging. In the single drum, only 20-30% carbonization was achieved due to the compact nature and high cohesiveness of sawdust. Carbonization attempts in the double drum were also unsuccessful, and no consistent trend in carbonization time was observed. However, the most favorable outcome was obtained when the moisture level was at 2.5%, and it took approximately three hours to achieve 40-45% carbonization. To overcome this difficulty, a mixture of sawdust and rice husk in a 2:1 ratio was used, resulting in complete carbonization (100%) within three hours in the double drum. Carbonizing dried cow dung was comparatively faster, taking approximately 40 to 50 minutes to complete the process.

2.2.3 Biochar briquette preparation

Following carbonization, the biomass was grinded into a powder form by using a milling machine. The powdered biomasses were then stored in large bags. In order to create the biofuel briquettes, the powdered materials were carefully weighed and mixed with other organic biomass in a half-cut drum according to specified ratios. To ensure the particles remained intact, molasses, also known as Chita Gur, was used as a binding material or adhesive. Typically, molasses was mixed with water at a ratio of 10:1.

A total of eight different mixtures of biofuel were prepared, each with varying ratios of ingredients. These mixtures included Coal 50%: Sludge 50%, Coal 40%: Sludge 60%, Coal 30%: Sludge 70%, Rice Husk 50%: Sludge 50%, Sawdust 50%: Sludge 50%, Cow Dung 50%: Sludge 50%, Rice Husk 40%: Sludge 60%, and Sludge 100%. The next step involved the briquetting process, which took place in an agglomerate or rotating drum. As the drum revolved and mixed with molasses, it formed the biofuel mixture into round-shaped briquettes. The rotation speed of the drum was maintained at around 17-19 RPM (see Figure 2). Following the briquetting process, the formed briquettes were air dried for a period of three days, during which the moisture content decreased to approximately 10-15%.

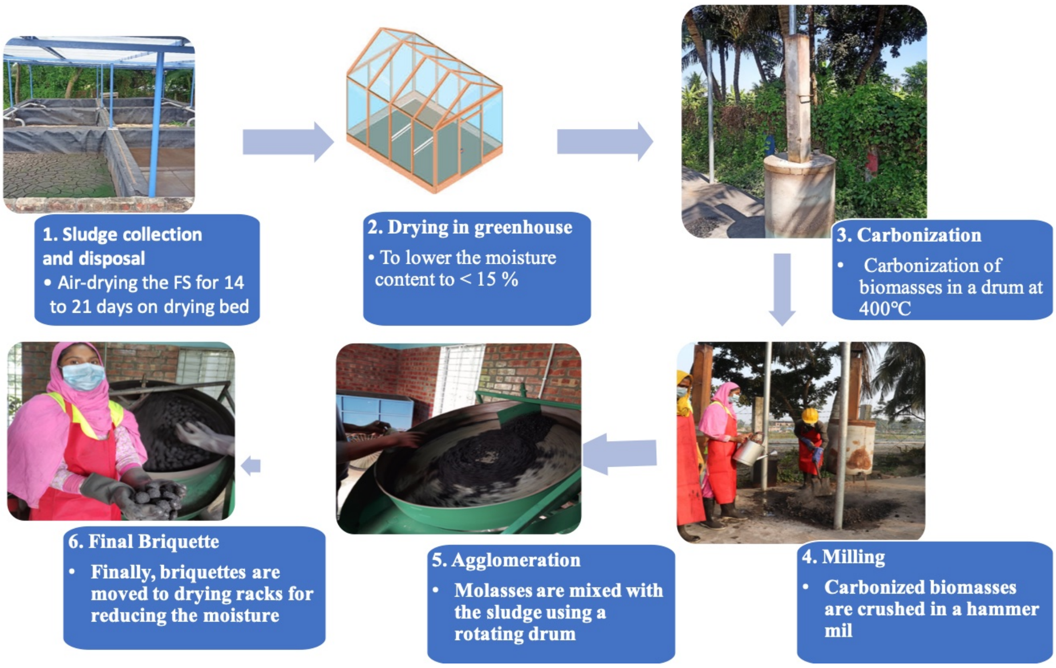

Figure 2. The process flow diagram of fecal sludge biochar briquette preparation.

2.3 Sample Analysis

2.3.1 Proximity analysis of the biochar briquettes

Proximate analysis of biofuel involves determining the content of moisture, volatile matter, fixed carbon, and ash which are crucial for understanding the fuel's composition and behavior during combustion. Also, calorific value serves as a crucial property for evaluating the efficiency of thermal processes, measuring how efficiently fuel is transformed into the desired energy services. In this study, the moisture content, volatile matter, fixed carbon, and ash content were measured using thermogravimetric analysis (TGA) (Donahue and Rais, 2009) and calorific value of the fuel was determined by a bomb calorimeter (ISO, 2017). 2 gm of sample from all the 8 different variants of briquettes were used for these analyses.

2.3.2 Analyzing the energy efficiency of biochar briquettes

The objective of this endeavor was to identify the ideal combination of briquette variant within the eight different blend that balanced cost-effectiveness and energy efficiency. To assess the energy efficiency of the biochar briquettes, they underwent a water boiling test using five different cookstoves. The Water Boiling Test (WBT), developed by Volunteers in Technical Assistance (VITA) in 1982, is an internationally recognized protocol that provides standardized guidelines for testing cookstoves Arora et al., 2014; VITA, 1985. In each cookstove, paper was utilized as the kindling material to ignite the briquettes and initiate the boiling process. Simultaneously, the calorific values of the briquettes were measured in a laboratory setting, that allowed a comprehensive analysis of the energy content and efficiency of each briquette variant.

3 Results and Discussion

3.1 Dewatering and carbonization

In this study, open air drying in drying bed dewatering process was applied. Drying beds are widely used for sludge dewatering (Muspratt et al., 2014; Seck et al., 2015; Tchobanoglus et al., 2003), particularly in low-income countries, due to their cost-effectiveness and operational simplicity. However, a significant drawback of this technology is the substantial land area requirement. For instance, studies have shown that achieving a 20% total solids (TS) concentration using drying beds necessitates approximately 0.08 m^2 of land per capita (Cofie et al., 2006; Tchobanoglus et al., 2003). The findings suggest that adequate drying can be achieved within a span of two weeks when utilizing open-air drying beds or, alternatively, in a shorter timeframe with the implementation of innovative approaches to drying beds (Muspratt et al., 2014; Seck et al., 2015), thus, in this study the air-dried FS was collected after 14 and 21 days.

After further drying in greenhouse, the FS and other OM were carbonized. However, this is not always as helpful as the simple burning of dry fecal sludge (Strande et al., 2014). This high-heating process alters fuel properties, produces ash content, and decreases the calorific value. Another by product is the emission of CO_2, CO, CH_4, H_2, C_2H_6, and C_2H_4 malodorous sulfur compounds (Yaman, 2004). Unless the combustion technology or end user necessitates the use of a carbonized product, non-carbonized fecal sludge fuel is preferable (Andriessen et al., 2019). Despite of this, car-

Table 1. The proximate analysis and calorific values of biochar briquettes

Sample Composition	Moisture (%)	Volatile Materials (%)	Ash (%)	Fixed Carbon (%)	Calorific Value (KJ/Kg)
Coal 50%: Sludge 50%	**12**	**10.4**	**66.1**	**11.5**	**14618**
Coal 40%: Sludge 60%	2.5	10.85	71	15.65	12682
Coal 30%: Sludge 70%	3.1	17.35	68.55	11	12983
Rice Husk 50%: Sludge 50%	4.45	11.2	78.55	5.8	11796
Sow dust 50%: Sludge 50%	5.25	7.3	77.25	10.2	12870
Cow Dung 50%: Sludge 50%	**7.35**	**16.4**	**66.1**	**10.15**	**14427**
Rice Husk 40%: Sludge 60%	5.85	17.7	69.05	7.4	11031
Sludge 100%	2.25	10.4	50.6	36.75	9766

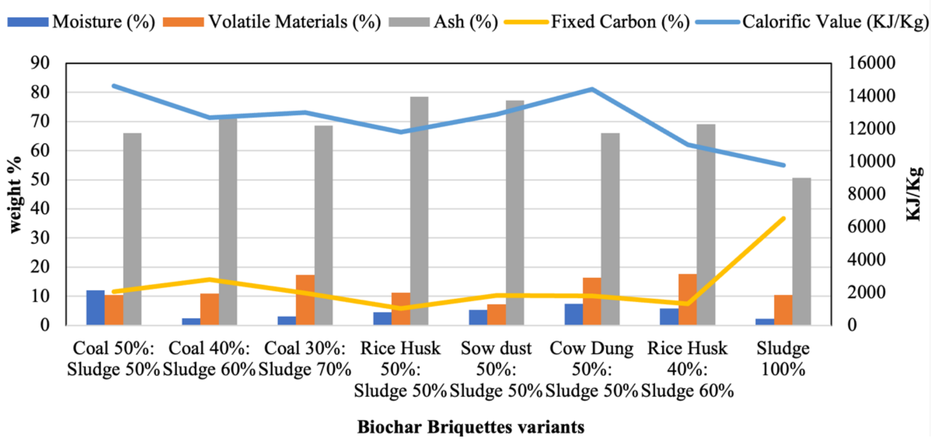

Figure 3. The proximate analysis and calorific values of biochar briquette variants.

bonization of human waste is essential to render it pathogen-free and safe for manual handling by humans.

3.2 Proximity analysis of the biochar briquettes

Table 1 and Figure 3 illustrate the proximate analysis of bio briquettes. It presented a significant variation in values of moisture, volatile materials, ash, fixed carbon, and calorific value, demonstrating the impact of using different compositions. The dried and carbonized 100% FS has the highest fixed carbon content, the solid residue remaining after the volatile matter has been driven off during heating, indicates a higher heating value and greater energy content, though the calorific value of it was the lowest i.e 9766 KJ/Kg. This can be because of the low volatile materials and high inorganic content of the septic tank sourced FS that obstruct the combustion performance and decrease the calorific value, which was also observed in the study by Krueger et. al (2020) and Kizito et al (2022). However, this can still be preferred for its lower ash content, 50.6%, found in this study as well as in other studies (Gold et al., 2017; Krueger et al., 2020) to avoid slagging, fouling, and corrosion in combustion equipment.

Again 100% FS has the lowest volatile materials which is increased by mixing with different OM, thus, leads to an increase in calorific values, and this result is supported by literature (Ward et al., 2014; Xu et al., 2023). At the same time, this mixing approach increases the moisture content and ash content and lower the fixed carbon content of FS. Overall, the calorific value increases with OM addition, hence adopted and recommended in many studies (Ariani et al., 2023; Kizito et al., 2022). Now to find out the best blend we need to find the most suitable OM. The composite with coal, cow dung, and rice husk have the higher volatile materials while coal and cow dung have lower ash content as well, which is not the case for rice husk. Again, coal and cow dung based briquettes have higher calorific value whereas that of lower for rice husk. Sow dust blend has relatively lower volatile materials and calorific value but higher ash content. Thus, from this discussion it can be said that either the coal based or the cow dung based FS briquette can be suggested from this study.

3.3 Water Boiling Test (WBT)

The biochar briquettes that took the less amount of time to bring the water into boiling point was considered the most efficient in this test. As depicted in Figure 4, the optimal outcome in the water boiling test was achieved with a blend of 50% coal and 50% sludge, requiring just 14 minutes to reach the boiling point. The high energy content of coal was surfaced in all three blends of it with FS. Another noteworthy

Table 2. Cost of biofuel preparation and marketing

Material	Price BDT/kg	Operational Cost BDT/kg	Marketing Cost BDT/kg	Total Cost BDT/kg
Sludge 100 %	0.0	10.87	3	13.87
Cow dung 50%: Sludge 50%	1.0	10.87	3	14.37
Saw Dust 50%: Sludge 50%	1.63	10.87	3	15.495
Rice Husk 40%: Sludge 60%	3.2	10.87	3	17.07
Coal 30%: Sludge 70%	3.6	10.87	3	17.47
Rice Husk 50%: Sludge 50%	4.0	10.87	3	17.87
Coal 40%: Sludge 60%	4.8	10.87	3	18.67
Coal 50%: Sludge 50%	6.0	10.87	3	19.87

result was obtained with a combination of 50% cow dung and 50% sludge, taking 23 minutes to reach the boiling point. While the biochar of FS took the highest boiling time i.e. 56 min which regarded it as the less efficient fuel source. This result is completely in align with the calorific value of each variant of briquettes. WBT performance of different FS based biofuel was also reported in other studies suggesting higher WBT performance for FS-Saw Dust briquette i.e. 6.2 min with calorific value of 20.79 MJ/kg (Kabango et al., 2023), burning rate of FS and pineapple peel blend with calorific value of 17.92 MJ/kg in a WBT was 4 g/min (Kizito et al., 2022)

3.4 Cost of biofuel preparation and marketing

The cost per kilogram of raw materials was determined by dividing the equivalent cost by the quantity handled per day. The total operating cost amounted to 10.87 tk. To produce 25 kilograms of briquettes, 1 kilogram of molasses was required, equating to a cost of 1.8 tk per kilogram of briquettes. While the sludge itself was free, additional expenses such as transportation and maintenance costs were factored into the overall cost. Among the raw materials, coal was the most expensive, valued at 12 tk per kilogram in the market. Rice husk and wood followed suit as the second most costly materials at 8 tk per kilogram. Cow manure proved to be the most cost-effective raw material, priced at just 1 tk per kilogram.

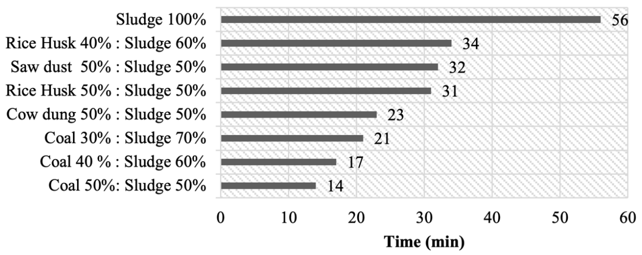

Figure 4. Result of water boiling test.

Producing a briquette solely from 100 percent sludge incurred a cost of 13.87 tk per kilogram. Although the cost was relatively low, the energy efficiency was significantly compromised. On the other hand, the combination of 50% sludge and 50% coal required an expenditure of 19.87 tk per kilogram, despite its commendable efficiency. The optimum blend consisted of 50% sludge and 50% cow manure, offering superior efficiency compared to coal and a relatively affordable briquette cost of only 14.37 tk per kilogram. Reducing marketing expenses could potentially result in lower briquette prices. Additionally, as the daily production of briquettes increases, the guaranteed expenses per unit will decrease, thereby lowering overall costs.

3.5 Finding the most efficient and cost-effective blend among the studied variants

Given the objective of developing an affordable biofuel from dried fecal sludge, it was essential to subject the fecal sludge to a drying process as an initial treatment which has been suggested in many studies (Ariani et al., 2023; Kizito et al., 2022; Sagor et al., 2022; Ward et al., 2014; Xu et al., 2023). However, dried fecal sludge alone proved ineffective as a biofuel, necessitating its combination with other treated organic materials. Locally available resources such as rice husk, cow dung, sawdust, and coal were utilized for this purpose. The resulting mixture underwent carbonization and was shaped into briquettes, whose effectiveness was assessed through a water boiling test.

The briquette consisting of 50% coal and 50% sludge demonstrated the highest efficiency in the water boiling test, reaching the boiling point in a mere 14 minutes. Following closely, the mixture of 50% cow dung and 50% sludge attained boiling in 23 minutes. Efficiency was further evaluated through proximity analysis and calorific value tests in laboratory, revealing that the 50% coal and 50% sludge briquette exhibited the maximum calorific content at 14618 KJ/kg. The second-highest value was observed for the Cow Dung 50%: Sludge 50% combination, with a calorific value of 14427 KJ/kg. Conversely, the 100% Sludge briquette yielded the lowest calorific value at 9766 KJ/kg. Evidently, the calorific value of sludge alone fell short of expectations.

Considering cost effectiveness, the briquettes composed of 50% coal and 50% sludge were found to be relatively expensive, with a production and packaging cost of 19.87 tk per kilogram. In contrast, the packaging cost for briquettes made from 50% sludge and 50% cow dung amounted to 14.37 tk per kilogram. Therefore, from the perspective of the Bangladeshi market, the most practical, cost-effective, and highly efficient biofuel option was the briquettes comprising of 50% sludge and 50% cow dung.

4 Conclusion

In rural areas of Bangladesh, there is a pressing need for an alternative fuel source that is efficient, ecologically friendly, safe, and sustainable, to replace the conventional use of biomass. This study seeks to advance our understanding of fecal sludge as a fuel, going beyond conventional calorimetry methods. Dried carbonized fecal sludge has showed potential fuel properties alone having low moisture content, low ash content, high fixed carbon content and moderate level of calorific value and can be manufactured by costing only 13.87 tk/Kg. Blending dried fecal sludge with organic matters can significantly enhance its volatile material content and calorific value, resulting in a substantial increase in heating value. The mixture of sludge with cow dung at a 50:50 ratio offers a combination of high efficiency and cost-effectiveness. The transformation of this sanitation challenge and waste management issue into a valuable energy resource justifies careful consideration and merits further scientific investigation for quantifiable application.

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Author Contributions

Rabeya Sultana: Conceptualization, Formal analysis, Investigation, Writing – original draft, Supervision. Md. Riad Hossain: Writing – review & editing. Anirban Saha and Fahim Rahman Rafi: Formal analysis, Investigation. Sk Shaker Ahmed: Methodology, Investigation, Supervision. Md. Esraz-Ul-Zannat: Visualization, Writing – review & editing

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

References

Andriessen, N., Ward, B.J., Strande, L., 2019. To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge. Journal of Water Sanitation and Hygiene for Development, 9(2): 210–224. https://doi.org/10.2166/washdev.2019.184

Ariani, I.K., Anifah, E.M., Sholikah, U., Banaget, C.K., Maharani, V.G.S., 2023. Production of bio-briquettes from pineapple peels and sewage sludge as an alternative renewable energy. IOP Conference Series: Earth and Environmental Science, 1201(1): 012014. https://doi.org/10.1088/1755-1315/1201/1/012014

Arora, P., Das, P., Jain, S., Kishore, V.V.N., 2014. A laboratory based comparative study of Indian biomass cookstove testing protocol and Water Boiling Test. Energy for Sustainable Development, 21(1): 81–88. https://doi.org/10.1016/J.ESD.2014.06.001

Atwijukye, O.R., Kulabako, C., Niwagaba, S., Sugden., 2018. Low cost faecal sludge dewatering and carbonisation for production of fuel briquettes. Transformation towards Sustainable and Resilient Wash Services.

B., Krueger., 2021. An investigation of pyrolysis for the treatment of faecal sludge from onsite sanitation systems.

Cofie, O.O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., Kone, D., 2006. Solid–liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture. Water Research, 40(1): 75–82. https://doi.org/10.1016/J.WATRES.2005.10.023

Donahue, C.J. and Rais, E.A., 2009. Proximate Analysis of Coal. Journal of Chemical Education, 86(2): 222. https://doi.org/10.1021/ed086p222

Gold, M., Ddiba, D.I.W., Seck, A., Sekigongo, P., Diene, A., Diaw, S., Niang, S., Niwagaba, C., Strande, L., 2017. Faecal sludge as a solid industrial fuel: a pilot-scale study. Journal of Water, Sanitation and Hygiene for Development, 7(2): 243–251. https://doi.org/10.2166/WASHDEV.2017.089

ISO, 18125., 2017. Solid Biofuels—Determination of Calorific Value.

Kabango, K., Thulu, F.G.D., Mlowa, T., Chisembe, C., Kaonga, C.C., 2023. Effect of carbonisation on combustion characteristics of faecal sludge and sawdust blended briquettes. Environmental Sustainability 2023, 6(3): 331–339. https://doi.org/10.1007/S42398-023-00269-6

Kim, Y. and Parker, W., 2008. A technical and economic evaluation of the pyrolysis of sewage sludge for the production of bio-oil. Bioresource Technology, 99(5): 1409–1416. https://doi.org/10.1016/J.BIORTECH.2007.01.056

Kizito, S., Jjagwe, J., Ssewaya, B., Nekesa, L., Tumutegyereize, P., Zziwa, A., Komakech, A.J., 2022. Biofuel characteristics of non-charred briquettes from dried fecal sludge blended with food market waste: Suggesting a waste-to-biofuel enterprise as a win–win strategy to solve energy and sanitation problems in slums settlements. Waste Management, 140: 173–182. https://doi.org/10.1016/j.wasman.2021.11.029

Krueger, B.C., Fowler, G.D., Templeton, M.R., Moya, B., 2020. Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. Water Research, 169: 115253. https://doi.org/10.1016/J.WATRES.2019.115253

Montangero, A. and Strauss, M., 2004a. Duebendorf: Swiss Federal Institute of Aquatic Science (EAWAG).

Montangero, A. and Strauss, M., 2004b. Faecal sludge treatment.

Muspratt, A.M., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M., Strande, L., 2014. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. Journal of Water, Sanitation and Hygiene for Development, 4(2): 223–230. https://doi.org/10.2166/WASHDEV.2013.055

Otieno, A.O., Home, P.G., Raude, J.M., Murunga, S. I., Gachanja, A., 2022. Heating and emission characteristics from combustion of charcoal and co-combustion of charcoal with faecal char-sawdust char briquettes in a ceramic cook stove. Heliyon, 8(8): e10272. https://doi.org/10.1016/J.HELIYON.2022.E10272

Sagor, S.M., Shafiquzzaman, M., Bari, Q.H., 2022. Evaluation of faecal sludge charcoal briquette produced from different binding materials. https://Doi.Org/10.1680/Jwarm.21.00047, 177(1): 13–22

Seck, A., Gold, M., Niang, S., Mbéguéré, M., Diop, C., Strande, L., 2015. Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. Journal of Water, Sanitation and Hygiene for Development, 5(1): 72–80. https://doi.org/10.2166/WASHDEV.2014.213

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal Sludge Management. IWA Publishing. https://doi.org/10.2166/9781780404738

Tchobanoglus, G., Burton, F., Stensel, H.D., 2003. Wastewater engineering: Treatment and reuse. American Water Works Association. Journal, 95(5).

VITA (Volunteers in Technical Assistance), 1985. Testing the Efficiency of Wood-Burning Cookstoves: Provisional International Standards, Volunteers in Technical Assistance.

Ward, B.J., Yacob, T.W., Montoya, L.D., 2014. Evaluation of solid fuel char briquettes from human waste. Environmental Science and Technology, 48(16): 9852–9858. https://doi.org/10.1021/es500197h

Werther, J. and Ogada, T., 1999. Sewage sludge combustion. Progress in Energy and Combustion Science, 25(1): 55–116. https://doi.org/10.1016/S0360-1285(98)00020-3

WHO/UNICEF/JMP, 2021. Progress on household drinking water, sanitation and hygiene from 2000-2020: five years into the SDGs. ISBN (WHO) 978-92-4-003084-8 (electronic version). https://washdata.org/sites/default/files/2021-07/jmp-2021-wash-households.pdf

Xu, P.P., Sun, K., Du, J., Xie, G., Xing, D., Liu, B.F., 2023. Biochar prepared from human feces (HFBC) as a promoter in biohydrogen production using simulated feces as substrate. Chemical Engineering Journal, 461: 142074. https://doi.org/10.1016/J.CEJ.2023.142074

Yahav Spitzer, R., Belete, Y.Z., Johnson, H.A., Kolusheva, S., Mau, V., Gross, A., 2023. Hydrothermal carbonization reaction severity as an indicator of human-excreta-derived hydrochar properties and it's combustion. Science of The Total Environment, 872: 162176. https://doi.org/10.1016/J.SCITOTENV.2023.162176

Yaman, S., 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Conversion and Management, 45(5): 651–671. https://doi.org/10.1016/S0196-8904(03)00177-8