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Potential of Fecal Sludge Briquette as Biofuel: A Review

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Abstract: Fecal sludge from fecal wastewater treatment may create problem to environment and human health as Its high production number and its hazardous content. The high volume of fecal sludge production not only reflects the scale of sanitation needs but also signifies a substantial opportunity for renewable energy generation by transforming the fecal sludge to briquettes. This article is a critical review to evaluate the potential of fecal sludge, especially about its characteristics as a raw material, the method to create the briquettes, the briquette composition and finally its performance regarding the fecal sludge composition. Interestingly, even though fecal sludge is hazardous as the high pathogen level such as bacteria, worm and its egg, they will die after drying and carbonizing process. Hence, it will be safe to utilize the fecal sludge briquettes for human need. Comparing the calorific value of fecal sludge briquettes and coal (fossil fuel which has high energy value), the fecal sludge's energy is about 3 times lower. This mean, if it is expected to achieve the fecal sludge briquettes' calory equivalent to the coal, the number of fecal sludge briquettes should be multiplied 3 times.

Keywords: Fecal sludge briquette; Biofuel; Renewable energy.

1. Introduction

Sanitation problems, particularly those related to wastewater from feces and its sludge management, remain unresolved issues, especially in developing countries [1-2]. In general, developing countries still rely on on-site fecal wastewater treatment, where, after a certain period, the waste is emptied and transported to a centralized fecal sludge treatment facility [2]. The treatment of fecal wastewater generates fecal sludge which, if not properly managed, can lead to new problems, both for the environment and for human health.

The environmental impacts, for example, include the contamination of groundwater and surface water due to the potential seepage of fecal sludge into the soil or water bodies [3-4]. Fecal sludge also has the potential to damage ecosystems. The heavy metal, organic matter and pathogens contained in the sludge can disrupt the balance of aquatic ecosystems, leading to the death of organisms living within them [5]. Moreover, fecal sludge that is left on the ground surface or disposed of through open dumping can cause air pollution. The methane gas it produces contributes to greenhouse gas emissions, which lead to ozone layer depletion and drive climate change [6].

The impact of poorly managed fecal sludge on human health includes the spread of diseases such as typhoid, worm infections, and diarrhea [7-8]. Fecal sludge can contain bacteria such as E. coli and Shigella in potentially uncountable numbers, and it may also carry intestinal worm eggs, including hookworm eggs. If left unmanaged, the spread of these pathogens can lead to outbreaks of disease.

One of solutions for managing fecal sludge is to convert it into a new source of energy in the form of briquettes [2]. By transforming fecal sludge into combustible briquettes, countries can reduce their reliance on traditional fossil fuels and biomass such as firewood and charcoal, which are major contributors to deforestation and indoor air pollution [9]. This article provides a review of the potential of fecal sludge as a new energy source. The review covers the methods used to produce fecal sludge briquettes, the composition of these briquettes, as well as their properties and performance.

If the converting the fecal sludge into briquette success, it may not only support improved sanitation practices but also aligns with sustainable development goals by promoting clean energy, responsible consumption, and climate action.

2. Fecal Sludge Production over countries

In most developing countries, fecal wastewater (commonly known as blackwater) is treated by on-site treatment. It treats the wastewater directly from the source. The water from toilet is directed to a chamber what is called septic tank. The wastewater is treated anaerobically. In a period of time, it has to be emptied and transported to a central treatment or fecal wastewater treatment. As the final process of the treatment, it generates fecal sludge that needs to manage well [2].

The production of fecal sludge may vary in every country. It depends on the number of people live in, sanitation infrastructure, water usage and its availability [10]. More people live in a country, more fecal sludge production generated. The extent and quality of sewerage networks as sanitation infrastructure, directly impact the volume of fecal sludge. Higher water usage (e.g., for flushing) dilutes sludge, affects its volume, and alters treatment needs.

Evaluation of fecal sludge production, can be seen in Table 1. As shown in Table 1., it indicates that the number of fecal sludge production is enormous in every country, highlighting the urgent need for effective fecal sludge management systems. As this waste accumulates in vast quantities (often untreated or improperly managed), it poses serious health and environmental risks.

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Table 1. Fecal Sludge Production Over Countries

No.	Country	The Fecal Sludge (FS)
1	Western Africa [11]	1000 m^3 FS/1 million people
2	Phenom Penh, Cambodia [12]	18,800 m^3/year
3	Ghana, Africa [13]	1 million m^3 in 2018
4	Bangladesh [14]	17 million metric tons/year
5	Jakarta, Indonesia [15]	2129 ton/day
6	Dar es Salam, Tanzania [16]	4512 m^3/day

The volume of fecal sludge produced in a country not only reflects the scale of sanitation needs but also signifies a substantial opportunity for renewable energy generation. Given that fecal sludge is rich in organic matter, it can be harnessed through various technologies to produce energy, contributing to sustainable development goals. Dried fecal sludge can be combusted directly or subjected to pyrolysis to produce biochar and energy [17]. The energy input required for these processes varies, with pyrolysis requiring approximately 297 kWh/ton of end products [18].

The potential energy generated from fecal sludge can be approached through multiplying the fecal sludge production by conversion rate to briquette and calorific value. Take a case of 20% of fecal sludge production in Jakarta (2129 ton/day or equal to 2.1 million kg/day) can be converted to briquettes and if each kilogram of fecal sludge briquette production may have calorific value about

12 MJ/kg then the potential energy of fecal sludge production convert to briquette is about 25.2 million MJ per day. Hence, it shows that the value of potential energy is in great number.

3. Fecal Sludge Characteristics as Raw Material for Fecal Sludge Briquettes

It is crucial to understanding the characteristics of fecal sludge before it will be used as the raw material for the briquettes. The summary of the fecal sludge characteristics is shown in Table 2. It compares the fecal sludge characteristics over some countries. As illustrated in Table 2., the carbonized fecal sludge as the raw material for briquette has varied calorific value [19]. The calorific value found based on the studies range from 1289.77 Cal/g to 4561.91 Cal/g. This means the carbonized fecal sludge has potential energy and qualified as raw material for briquettes [20-21].

Table 2. The Characteristics of Fecal Sludge from Previous Studies [19]

Location	MC	VM	AC	FC	CV	S
	%	%	%	%	Cal/g	%
Malang, Indonesia	37.7	22.8	31.82	7.61	3514.44	0.83
Boulder, USA	-	42.7 - 61.10	36.8 -51.2	0.4 - 6.20	2483.99 - 3487.15	-
Kumpala, Uganda	8.1	-	58.7	-	2603.42	0.7
Dakar, Sinegal	6.7	-	47	-	3200.54	-
Netherlands	-	58.50±5.00	41.30±8.90	11.80±6.60	3224.42 ± 358	-
Kumasi, Ghana	-	-	-	-	4561.96	-
Accra, Ghana	-	-	-	-	3620.91 – 3778.54	-
Uganda	7.10±1.40	28.85±0.33	55.35±1.34	8.70±1.20	1478.46±217	-
Brazil	14.11	-	-	-	3,179.04±45	-
Tamil Nadu, South India	-	26.50–47.70	39.00–69.30	3.20–11.40	1289.77 – 3200.54	-

Note: MC = Moisture Content, VM = Volatile Matter, AC = Ash Content, FC = Fixed Carbon, CV = Calorific Value, S = Sulfur

As the calorific value depends on other parameters, such as moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC), it is a challenge how to adjust these parameters to generate more energy for briquettes [18],[20],[22]. The moisture content directly related to the type of toilet, containment, or latrine used, the duration of storage, inflow, and infiltration to the environment, the desludging method, the local weather and climate, and the treatment mechanism—such as open or semi-open, porosity, and saturation level of filtering sand [19]. The higher the moisture content, the lower efficiency and need more adjustment (need initial drying) to make the fecal sludge compatible for briquettes' raw material [23].

Volatile matter is vaporized compounds when it is heated. The nature of the volatiles is it easily burnt and flamed, contributing to initial combustion. High value of volatile matter may cause high smoky combustion and low energy density [20]. The ideal for calory efficiency is the moderate value of volatile matter [19-20]. There are options as the strategies to develop moderate volatile matter of fecal sludge; (1) mixing the fecal sludge with other biomass materials [20], (2) pyrolyzing the fecal sludge and [24], (3) controlling the drying procedure [25].

Ash content exhibits the remaining inorganic residue after organic material burnt. The lower ash content, the higher energy and cleaner combustion. There are approaches to reduce the ash content: (1) integrated processing with biomass [26], (2) carbonizing fecal sludge with hydrothermal carbonization (HTC) [27], (3) Treating the sludge with chemical, such as adding the sodium additive under reducing conditions can boost phosphorus bioavailability and decrease heavy metal content, obliquely shaping the ash composition [28].

Fixed carbon content keeps heat in the solid fuel. The higher fixed carbon content, the higher calorific value. The adjustment to control the fixed carbon content can be done by controlling the ash content and volatile matter [20].

Another crucial parameter of fecal sludge as raw material for briquettes is related to its pathology condition. As fecal sludge has potential of pathogen such as worm egg, bacteria and virus. A study reveals that pathogen level of raw fecal sludge before drying and carbonizing was very high. The study's investigation results exhibit that the number of E-Colli, Shigella, and Salmonella was too numerous to count [20]. The study also found that Ascaris lumbricoides and Hookworms eggs were existed. Yet, after the process of drying under sunlight and carbonization under temperature exceeding 45^0C, the fecal sludge was free of those bacteria and both worm and its egg [20]. Hence, the condition makes fecal sludge more potential for biofuels in the form of briquettes.

4. Fecal Sludge Briquette Method

Converting fecal sludge into biofuel in the form of briquette possess a multi-step procedure. Initially the fecal sludge is collected and dewatered from on-site sanitation systems such as pit latrines or septic tanks. Dewatering is the process to reduce the moisture content of fecal sludge; it can be achieved by mechanical or natural drying methods. After adequate drying, the sludge undergoes carbonization (can be through pyrolysis in a controlled environment or open-air charring). Carbonization is the process of gaining a carbon rich char material. This process not only expand the energy content of the sludge but also kills pathogens, making the material safer to handle [18].

Once the sludge already carbonized, the resulting fecal biochar is mixed with a binder. The aim of the process is to enhance fecal briquette cohesion and durability. Generally, it uses cassava starch, molasses, or paper pulp to bind. The optimal binder to char ratio varies depending on the desired hardness and combustibility of the briquettes. After binding process, the mixture is shaped into briquettes using manual or mechanical press molds [20].

Eventually, the briquettes are subjected to drying, either through solar exposure or using a drying chamber, to reduce their moisture content before packaging and distribution. Quality control measures such as testing for calorific value, moisture content, ash content, and microbial safety are crucial to ensure the briquettes meet fuel standards and public health requirements. Practical application in East Africa, for example pilot project in Kampala, Uganda, shows the process's scalability and economic potential. More than 3 tons of briquettes have been successfully made and sold, demonstrating a viable model for reclaiming resources and generating sustainable fuel [17].

5. Fecal Sludge Composition

The base substance of fecal sludge briquettes is carbonized fecal sludge which is typically produced by drying and pyrolyzing fecal sludge from pit latrines, septic tanks or other sanitation systems. The aim of drying and pyrolyzing is not only enhance the energy content of the sludges but also sanitize the material by killing the pathogens. The carbonized fecal sludge is often high in ash content and poor in fixed carbon when used alone, which negatively influence combustion. Hence, it is seldom used in pure form and usually blended with higher-energy-density materials to improve performance [20][29]. To improve the energy content and structural integrity of fecal briquettes, carbonized fecal sludge is mixed with other biomass material such as sawdust, rice husks, charcoal dust, coconut husks, or agricultural residues. These additives help reduce ash content and increase calorific value. The selection of biomass as an additive lean on local availability and cost. Making the composition highly adaptable to different regional context [16], [23].

Binders are essential in fecal sludge briquette formulation, enhancing particle cohesion and mechanical durability. Frequently utilized binders consist of cassava starch, molasses, cow dung, and paper slurry. The selection and proportion of binder can greatly influence briquette properties such as density, burn time and resistance to breakage during transportation and storage. While organic binders are favored for environmental reasons, their cost and readiness can affect scalability. Previous study has shown that 5-15% binder by weight is generally sufficient for strong, combustible briquettes [29-30].

An optimal fecal sludge briquette formulation ensures a balance between thermal efficiency, mechanical strength, affordability, and public health considerations. Studies recommends that combining 30-40% carbonized fecal sludges with 50-60% biomass residues and 10% bunders results in briquettes that are both efficient and socially acceptable. Although a sufficient fecal sludges content is necessary to ensure sanitation benefits, excessive levels may lower energy yield and raise ash production [3],[17].

6. Fecal Sludge Briquette Characteristics and Performance

The fuel performance, environmental impact and user acceptability of fecal sludge briquettes rely on its properties/parameters. The main physical and chemical fecal briquette properties (calorific values, ash content, moisture content, volatile matter and mechanical strength) make the its 'viability as cooking fuel. The properties depend on the characteristics of the raw fecal sludge, the option of additives, the carbonization method and material used as binder [17],[20].

Calorific values (CV) is a main indicator of fuel quality which indicates how much energy is released by the briquettes during combustion. Calorific values of the briquettes commonly ranging from 14 MJ/kg to 20 MJ/Kg (3346.08 Cal/g to 4780.11 Cal/g), depending on the carbonized sludge proportion and biomass used as the additive. Briquettes with have higher ratios of additive biomass (for example charcoal dust) tend to have better energy content compared to those dominantly composed by fecal sludge. It might happen as it has lower inherent energy value due to its high ash and moisture content. It is very important to optimize the calorific value as it is essential to enable briquettes to serve as a substitute or complement to conventional fuels such as firewood or charcoal [3],[23]. The characteristics of fecal sludge briquette can be seen in Table 3.

Table 3. The characteristics of Fecal Sludge Briquettes Based on Composition of Biomass

Ref	Composition	MC	VM	AC	FC	CV	S	Density
		%	%	%	%	**Cal/g**	%	**(g/cm3)**
[19]	100 % Fecal Sludge	4.27	38.75	51.91	5.07	3,921.43	0.64	0.88±0.12
	75% Fecal Sludge: 25% Sawdust	3.26	51.34	32.97	12.42	4237.78	0.41	0.68±0.05
	50% Fecal Sludge: 50% Sawdust	7.09	48.68	17.61	26.62	4693.11	0.33	0.56±0.03
	25% Fecal Sludge: 75% Sawdust	7.57	68.97	12.02	11.44	5158.64	0.23	0.50±0.09
[31]	Charcoal dust, agricultural waste, clay, Cassava flour, faecal sludge - 50%	7.7	23.3	33.8	35.2	4373.805	-	-
	Charcoal dust Faecal sludge - 30%	7.5	19.1	26	47.3	5043.02	-	-

	Charcoal dust, clay Molasses, faecal sludge - 40%	7.4	18.3	26.5	47.8	4780.11	-	-
	100% Fecal Sludge	4.87	46.2	47.31	1.65	2,509.56	-	1.23
	100% Sawdust	5.52	27	26.2	41.6	4278.203	-	0.89
	100% Charcoal dust	7.37	26.3	28.02	40.3	5231.8356	-	0.74
	25% Fecal Sludge: 75% Sawdust	5.78	39.5	39	16.9	3704.589	-	0.86
[20]	50% Fecal Sludge: 50% Sawdust	6.8	43.9	43	6.4	3107.07	-	1.01
	25% Fecal Sludge: 75% Sawdust	5.9	46	45.5	2.7	3346.08	-	1
	25% Fecal Sludge: 75% Charcoal Dust	8.5	29.8	31.28	30.4	4302.1	-	0.78
	50% Fecal Sludge: 50% Charcoal Dust	7.29	33	33	27.1	4507.6482	-	0.97
	25% Fecal Sludge: 75% Charcoal Dust	6.11	36.9	40.7	16.8	4610.4207	-	0.98

Note: MC = Moisture Content, VM = Volatile Matter, AC = Ash Content, FC = Fixed Carbon, CV = Calorific Value, S = Sulfur

Ash content has big influence to the briquette's combustion efficiency and the handling of residues. Fecal sludge which comes from unlined pit latrines, commonly has high number of inorganic materials (such as sand and grit) causing its ash content may range between 15 – 35%. The high number of ash content may impede the combustion, lower thermal efficiency and necessitate more frequent stove cleaning. Hence, mixing fecal sludge with low ash biomass is a common practice to lower overall ash content and make the better combustion performances. Lower ash content briquettes are more desirable at end-user and more efficient for cooking application [16-17].

Other properties of the briquettes are volatile matter and fixed carbon. They contribute vital role in combustion efficiency. Commonly it ranges from 25-45% of volatile matter in fecal sludge briquettes and it affects how quickly ignition occurs and the intensity of the flame. High number in volatile content may lead faster ignition and may cause increased smoke and emissions. For fixed carbon, commonly is set between 20-30% to support long-lasting combustion. It is also important to note that moisture content is ideally kept below 15% as excessive moisture hampers ignition and results in more smoke. Thus, proper drying and storage are important to preserve the quality of the briquettes [29-30].

Coal and its variation generate the highest energy comparing to other solid fuel. The calorific value may exceed 7000 Cal/g (29.2 MJ/Kg). For example, Anthracite is a kind of the hard coal which produce the highest energy value. It is about 7504.78 Cal/g or 31.4 MJ/Kg [32]. Comparison of coal calorific value and fecal sludge briquettes' calorific value can be seen in Table 4. Table 4. Illustrates that coal's calorific value to fecal sludge briquettes' calorific value which may range 1.3 to 3 times of fecal sludge briquettes. This proven that fecal sludge briquettes is potential as solid biofuel. This also mean, if it is expected to achieve the fecal sludge briquettes' calory equivalent to the coal, the number of fecal sludge briquettes should be multiplied 3 times.

Besides combustion characteristics, fecal sludge briquettes 'mechanical strength is urgent for their effective transport, storage and handling. Briquettes are supposed to be dense and sturdy enough to withstand breakage. It is especially because in informal markets packaging and handling can be rough. The mechanical strength depends on the type and amount of binder used; particle size and the pressure applied during combustion. Common binder (cassava and molasses) improves cohesion of the particle and the compressive strength. Researches indicate that fecal sludge briquettes with bulk density around 600 and 900 kg/m3 and low rate of breakage tend to perform well under real world condition [18].

Table 4. Comparison of coal calorific value and fecal sludge briquettes' calorific value

Kind of Briquette	Calorific Value	Unit	Coal/Fecal Sludge Briquettes Calorific Value Comparison
Anthracite [32]	7504.78	Cal/g	3.0 - 1.4
Hard coal [32]	7002.87	Cal/g	2.8 - 1.3
Lignite [32]	6381.453	Cal/g	2.5 - 1.2
Coal briguettes [32]	7002.868	Cal/g	2.8 - 1.3
Fecal Sludge	2509.56 - 5231.8356	Cal/g	1 - 1

7. Potential Challenges for Future Researches

Future researches are still widely open for fecal sludge briquettes as biofuel. The focus for the next researches may deal with: (1) the kind of binder used in composition and its effect to the calorific value and other parameters, (2) the use of other biomass for complementary substances in fecal sludge briquettes and its impact to the energy produced, (3) the acceptance of market to utilize the fecal sludge briquettes, (4) the economy value of fecal sludge briquette especially in connection to circular economy, etc.

8. Conclusion

Fecal sludge briquettes is a substantial opportunity to a renewable energy production. Its implementation not only fix the issue of sanitation but also create cleaner and sustainable biofuel. Fecal sludge briquettes' calorific value depends on parameters such as moisture content, volatile matter, ash content and fixed carbon. It needs parameter adjustment to create more compatible composition which generate higher energy. The option can be mixing the composition to other biomass, pyrolysis or hydrothermal carbonization can be the alternative for carbonizing the fecal sludge, adding some chemical additive. Based on the previous study, the coal energy is about 1.3 to 3 times of fecal sludge briquettes. Hence, the fecal sludge is very potential for functioning as new solid energy.

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