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Research Article

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Towards Green Solutions: Solvent-Free Process for Bio-Crude Separation from Faecal Sludge Liquefied Product at Minimal Cost

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Abstract This study presents a novel approach for the low-cost separation of bio-crude from liquefied faecal sludge without the utilization of solvents. Faecal sludge management is a critical challenge, particularly in low-resource settings, necessitating innovative and cost-effective solutions. Our method involves a series of physical and thermal processes tailored to efficiently extract bio-crude while minimizing environmental impact and operational expenses. Through experimentation and optimization, we demonstrate the feasibility and effectiveness of our solvent-free separation process. The proposed method offers a sustainable pathway for bio-crude recovery, contributing to both waste management and renewable energy production initiatives. This research contributes to advancing sustainable sanitation practices and resource recovery technologies, particularly in regions facing sanitation and energy access challenges.

Keywords Green Solutions, Solvent-Free Process, Bio-Crude, Faecal Sludge

1. Introduction

To put it simply, Bangladesh is a third world country. Bangladesh, like nearly every other developing country, has a serious sanitation problem. The majority of the population does not have access to adequate sanitary facilities, particularly those who reside in rural areas and urban slums. Hence, fecal sludge management is inadequate in these regions. The sewage sludge created in these regions is rarely properly treated or controlled. It has been determined that whereas just 24.5% of sludge is thrown in open drains in Khulna, 30.6% is done so in Dhaka [1-4]. In 2019, just 59% of people had access to upgraded pit latrines, flush toilets, or other forms of basic sanitation. Sanitation coverage was significantly lower in rural areas, at 46%. On top of that, over 25% of the world's population still engages in open defecation, making it a serious issue in rural areas especially (Source: World Bank).

Without proper treatment, the wide variety of pathogens found in human feces can spread through water and cause a variety of illnesses [5]. Human feces composting has been shown to be an efficient way to reduce the number of harmful bacteria and maintain a healthy carbon-to-nitrogen ratio [6-7]. In addition, feces are often treated using anaerobic digestion for biogas production (Kelleher et al., 2002). However, stabilizing the feces takes a long time in either composting or anaerobic digestion. By contrast, pyrolysis is performed at high temperatures (>400 C) and necessitates an energy-intensive drying procedure of the wet waste [9]. Recent interest has focused on hydrothermal liquefaction (HTL), which permits the direct conversion of wet waste into biocrude oil at temperatures of 200-350 C and pressures of 5-20 MPa (Tian et al., 2014). It's worth noting that HTL's high temperature process also eliminates any microorganisms present in the fecal feedstock. HTL is distinct from oil extraction and pyrolysis in two key respects: I the feedstock does not need to be dried, making HTL ideal for wet biomass with a total solid (TS) content of 10-25%; and (ii) in addition to lipids, proteins and carbohydrates can be converted into biocrude oil via HTL [8]. Studies have shown that swine manure can be converted into biocrude oil, with a maximum oil yield of 24.2% and a higher heating value (HHV) of 36.05 MJ/kg [10]. High temperature fermentation (HTL) has the potential to lessen the negative environmental impacts of swine manure by inactivating antibiotic-resistant genes and blocking their pathways to the environment.

Figure 1: Hydrothermal Liquefaction Process

The treatment and management of faecal sludge present significant challenges worldwide, particularly in low-resource settings where access to adequate sanitation infrastructure is limited. Faecal sludge, a byproduct of wastewater treatment, contains valuable organic matter that can be converted into bio-crude, a renewable energy source. However, conventional methods for bio-crude extraction often involve the use of expensive solvents, posing economic and environmental barriers to widespread adoption, especially in resource-constrained environments. In response to this challenge, there is a growing need for innovative, cost-effective, and environmentally sustainable approaches for bio-crude recovery from faecal sludge. This study aims to address this gap by proposing a novel solvent-free separation process tailored to efficiently extract bio-crude from liquefied faecal sludge. By combining physical and thermal techniques, this approach seeks to optimize bio-crude recovery while minimizing operational costs and environmental impact. The development of such a process holds significant promise for enhancing faecal sludge management practices, promoting renewable energy production, and advancing sustainable sanitation solutions in communities worldwide.

2. Faecal Sludge

According to the Environmental Protection Agency (EPA), sludge is "the residual, semi-solid material that is produced as a by-product during the treatment of wastewater" (Source: EPA, "What is Sewage Sludge?"). Sludge is composed of both organic and inorganic materials, and it can contain a range of pollutants and pathogens, including heavy metals, bacteria, viruses, and parasites.

According to the Water Environment Federation (WEF), there are several types of sludge, including:

Primary Sludge: This type of sludge is generated during the first stage of wastewater treatment, where physical methods are used to separate the solid and liquid components of the wastewater. Primary sludge is comprised of the organic matter, such as fats, oils, and grease, and inorganic matter, such as grit, that is removed from the wastewater during this process.

Secondary Sludge: Also known as activated sludge, this type of sludge is produced during the second stage of wastewater treatment, where microorganisms are used to break down and remove organic matter from the wastewater. Secondary sludge is typically more biodegradable than primary sludge, as it contains less grit and inert materials.

Digested Sludge: This type of sludge is produced when primary or secondary sludge undergoes anaerobic digestion, a process in which microorganisms break down organic matter in the absence of oxygen. The digestion process produces biogas, which can be used as a renewable energy source.

Chemical Sludge: This type of sludge is produced when chemicals, such as coagulants or flocculants, are added to wastewater to aid in the removal of contaminants. Chemical sludge may contain high levels of heavy metals and other pollutants, which can pose a risk to human health and the environment.

Industrial Sludge: This type of sludge is generated from industrial processes, such as chemical manufacturing, metal plating, and food processing. Industrial sludge can contain a variety of contaminants, such as heavy metals, solvents, and organic compounds.

Sludge from Stormwater Treatment: This type of sludge is generated during the treatment of stormwater runoff, which may contain a variety of pollutants, including sediment, oil, and debris.

Below here is a pie chart which shows percentage of different kind of waste/sludge production around the world (*Waste Production Pie Chart 2004.*, 2004).

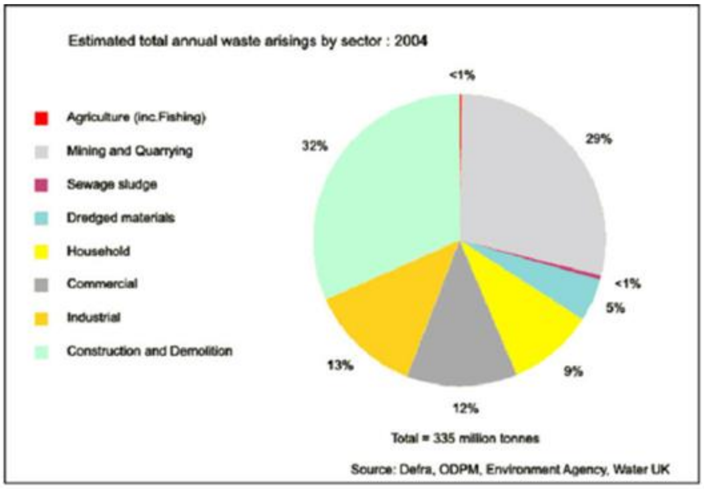

Figure 2: Percentage of Different Types of Waste [15]

Human waste, or fecal sludge, accounts for a sizeable portion of global garbage. The World Bank estimates that 4.5 billion people throughout the globe do not have access to safely managed sanitation facilities, contributing to the buildup of fecal sludge in urban, suburban, and rural regions. The amount of faecal sludge produced annually is estimated to be 157 billion liters worldwide, or the equivalent of 18 percent of the world's population. Negligent treatment of feculent sludge can lead to disease transmission and water supply contamination, among other negative outcomes for human health and the environment. In addition to mitigating its negative effects, feces sludge can be used as a renewable energy source and a source of vital nutrients in agricultural settings with the right kind of treatment and management [10].

FTIR (Fourier Transform Infrared Spectroscopy)

The acronym FTIR refers to the Fourier Transform of Infrared Spectroscopy. Powerful analytical method that measures the absorption or transmission of infrared radiation to determine the molecular components of a sample.

The method relies on the fact that various molecular components absorb light at varying frequencies, allowing for precise characterization and quantification.

Figure 3: Faecal Sludge

The FTIR spectrometer has three main parts: an infrared source that emits a beam of infrared radiation, a sample holder that retains the sample, and a detector that evaluates the intensity of the radiation that is transmitted or absorbed by the sample. Irradiating the sample with a beam of infrared light and then measuring the intensity of the radiation that is transmitted or absorbed allows one to acquire a spectrum of the irradiated sample.

Absorption and transmission of infrared radiation by the molecular components in the sample are reflected in the spectrum acquired by FTIR, which features peaks and troughs. The location and magnitude of the peaks reveal details about the nature and abundance of the sample's molecular components.

To figure out what kind of organic substance we're dealing with, FTIR is our best bet. The chemical properties of a sample can be learned by using it to identify functional groups like carbonyl, hydroxyl, and amino.

Over all, Fourier transform infrared spectroscopy (FTIR) is a powerful and flexible analytical method that can provide important details about the molecular components of a sample. Its extensive application in both academia and business attests to its significance in the advancement of scientific inquiry and technological advancement [11].

FTIR spectroscopy is a powerful analytical technique for determining the functional groups in a sample, and it has several advantages over other methods. According to Koenig (1999), FTIR spectroscopy is highly sensitive and can detect even small amounts of functional groups in a sample. This makes it ideal for identifying and quantifying the functional groups present in complex mixtures.

In addition, FTIR spectroscopy is a fast technique that can provide results within a matter of minutes. This makes it a valuable tool in analytical chemistry and materials science, where rapid analysis is often required. Furthermore, FTIR spectroscopy is a non-destructive technique that does not damage or alter the sample being analyzed (Wang et al., 2019). This allows the same sample to be analyzed multiple times, which can be useful in quality control and process monitoring applications.

FTIR spectroscopy can be used to analyze a wide range of samples, including liquids, solids, and gases. This makes it a versatile tool for analyzing a variety of materials and compounds. Additionally, FTIR spectra contain a wealth of information about the functional groups present in a sample, including the types of bonds and their vibrational frequencies. This information can be used to identify and quantify the functional groups present in a sample, as well as to determine the chemical and physical properties of the sample [12].

Overall, the sensitivity, speed, non-destructiveness, versatility, and information content of FTIR spectroscopy make it a preferred technique for determining the functional groups in a sample.

Materials and Methodology

To make a research work successful a methodology should be determined first. It should be systematic and theoretically logical. If there is no methodology in the first place a lot of work can go wrong. A great part of a successful research work depends on a right methodology and following of this methodology correctly. Stepwise method for this research program is given below:

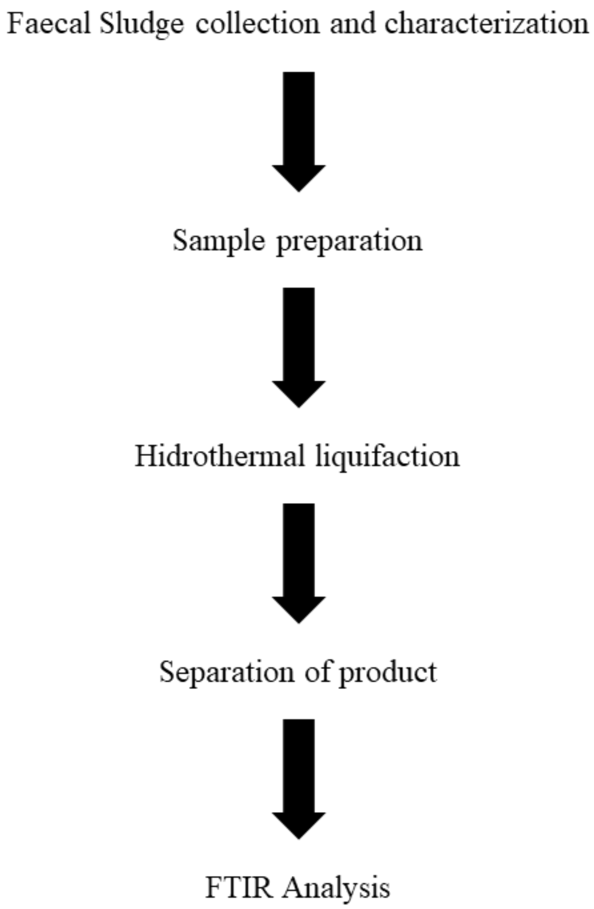

Figure 4: Methodology flowchart

Results and Discussion

Faecal Sludge Collection and Characterization

Faecal sludge collected from the second chamber of septic tank located at the residential area of the Khulna University of Engineering & Technology (KUET). Then, the FS sample was immediately stored at 4 ℃ overnight. Finally, the raw FS was blended for a homogenous mixture and stored for the study.

Proximity analysis and Ultimate analysis was done and the result is shown in Table 1 below. In case of proximity analysis to calculate moisture first the sample was weighted and then heated in 106 ℃ temperature for 1 hour. After that weight was taken again and for the difference moisture content was obtained. Later the dried sample was heated at 550 ℃ in muffle furnace for 1 hour and again weighted. From the difference with dries sample voilatile content was calculated. Then this sample was heated at 850 ℃ for 15 minutes again and this time from the difference with previous sample fixed carbon was obtained and the rest was ash content. $\mathrm{H/C_{eff}}$ ratio was calculated using equation 1 to predict the coke formation during HTL reaction. Thus, the potentiality of biomass for economic conversion into hydrocarbons would be justified [13].

$$\frac{H}{C_{eff}} = \frac{H-20}{C} \qquad (1)$$

Where, H, C and O are the mole percentage of hydrogen, carbon and oxygen respectively from the analysis.

Table 1: Proximate and ultimate composition of faecal sludge (FS)

Components	**FS**
Proximate composition	
Moisture (wt%)	88.20
Total solids (TS) (wt%)	11.85
Volatile matter (wt%)	6.63
Ash content (wt%)	4.65
Fixed carbon (wt%)	0.52
Ultimate composition	
C (wt%)	27.95
H (wt%)	3.79
N (wt%)	1.13
O (wt%)	27.95
H/C (molar ratio)	1.44
O/C (molar ratio)	0.65
N/C (molar ratio)	0.10
H/C_{eff}	0.25
Chemical formula	$\mathrm{CH_{1.74}O_{0.75}N_{0.04}}$
HHV ($\mathrm{MJkg^{-1}}$)	10.48

Here, Volatile matter, Ash content, Fixed carbon, C, H, N and HHV have been calculated on dry basis. O was calculated by difference.

$$\mathrm{O\ (wt\%) = 100 - sum\ of\ (C, H, N, Ash)} \tag{2}$$

$$\text{Fixed carbon (FC), \%} = 100 - sum\ of\ (\%VM, \%MC, \%AC) \tag{3}$$

Sample Preparation

For each trial 12 ml sample were prepared. By weight basis it was 10% FS and 90% water. To prepare the sample 1.2 gm FS was weighted in a test tube. Then 10.8 mL water was added. It was then shaken well to mix them. To mix properly then vortex machine was used. Each sample was vortexed for 5 minutes. Thus, each sample was prepared. Using this sample Hydro-Thermal Liquefaction was done

Analytical Method

The elements composition (C, H, N, and O) of biomass and biocrude samples were determined using a CE-440 elemental analyzer (Exeter Analytical Inc., USA). Using the ASTM D3172 standard, we calculated the total solids (TS), moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC) of biomass (P and FS) samples (ASTM D3172-13, 2021). The HHV of the biomass samples was calculated using a bomb calorimeter (*Standard Practice for Proximate Analysis of Coal and Coke*, n.d.) and compared to the HHV obtained from elemental analysis. Elemental analysis was utilized to compare the C, H, O, and HHV value of biomass samples, and the empirical equations (4)-(7) [14] were also applied. The formula for percentages is:

$$\mathrm{C = 0.635FC\ +\ 0.460VM - 0.095AC\ (\%)} \tag{4}$$

$$\mathrm{H\ =\ 0.0590C\ +\ 0.0605M\ +\ 0.010A0C\ (\%)} \tag{5}$$

$$\mathrm{O\ =\ 0.340\ +\ 0.469\ 0.023\ AC\ (\%)} \tag{6}$$

$$\mathrm{HHV_{biomass}\ = 0.3536FC\ +\ 01559VM - 0.0078AC\ (Mj/kg).} \tag{7}$$

Following the conventional techniques for the Analysis of Water and Wastewater, the physicochemical compositions were examined using a HACH DR6000 spectrophotometer (Hach, USA) and a UDK 129 Kjeldahl Distillation Unit (Velp, Italy)

Conclusion

In conclusion, the development of a solvent-free separation process for extracting bio-crude from liquefied faecal sludge represents a significant advancement in sustainable sanitation and renewable energy production. By overcoming the limitations associated with solvent-dependent methods, this innovative approach offers a cost-effective and environmentally friendly solution for converting waste into valuable resources. Through experimentation and optimization, our study has demonstrated the feasibility and effectiveness of this process, paving the way for its potential implementation in real-world faecal sludge management systems. By promoting resource recovery and minimizing environmental impact, this technology contributes to the achievement of multiple Sustainable Development Goals, including those related to sanitation, energy access, and environmental sustainability. Moving forward, further research and development efforts are warranted to scale up and refine this process, ensuring its applicability and effectiveness in diverse settings. Ultimately, the adoption of solvent-free bio-crude extraction methods holds immense promise for improving public health, environmental quality, and socio-economic well-being in communities worldwide.

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