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Research Article

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Eco-Friendly Approach: Affordable Bio-Crude Isolation from Faecal Sludge Liquefied Product

Mohammad Aman Ullah Sunny*

* Department of Civil Engineering, Port City International University, Chattogram, Bangladesh.
Department of Engineering Management, Lamar University, USA.
Corresponding Author Email: amanullah6628@gmail.com.

Abstract This study introduces an innovative and eco-friendly approach aimed at addressing the critical challenges associated with faecal sludge management, particularly in regions with limited resources. Traditional methods for isolating bio-crude from faecal sludge liquefied products often rely on solvent-based processes, which are not only costly but also environmentally detrimental. In response, our research focuses on the development of a solvent-free separation process, specifically tailored to efficiently extract bio-crude from faecal sludge. Through a comprehensive investigation involving physical and thermal techniques, we have successfully demonstrated the feasibility and effectiveness of our approach in laboratory-scale experiments. The results underscore the potential of this method to significantly reduce operational costs and environmental impact while simultaneously converting waste into a valuable renewable energy resource. By promoting sustainable sanitation practices and resource recovery technologies, this study contributes to advancing global efforts aimed at improving public health, environmental sustainability, and socio-economic well-being. The findings of this research have far-reaching implications for the implementation of sustainable faecal sludge management strategies, with the potential to benefit communities worldwide.

Keywords Eco-Friendly Approach, Bio-Crude Isolation, Faecal Sludge Liquefied Product, faecal sludge management, solvent-free separation process

Introduction

The management of faecal sludge presents an urgent and multifaceted challenge in both developed and developing regions worldwide. Faecal sludge, a complex mixture of excreta, water, and solid waste generated from onsite sanitation systems such as pit latrines, septic tanks, and cesspools, represents a significant public health and environmental concern. Inadequate management of faecal sludge can lead to the contamination of water sources, the spread of waterborne diseases, and adverse environmental impacts, exacerbating existing sanitation-related issues and posing significant risks to human health and well-being.

Across the globe, billions of people lack access to safely managed sanitation facilities, forcing them to rely on rudimentary and often unsanitary systems for waste disposal. In low-income and densely populated urban areas, informal settlements and slums are particularly vulnerable to inadequate sanitation infrastructure, exacerbating the challenges associated with faecal sludge management. In these settings, faecal sludge often accumulates in open pits, drains, or water bodies, posing serious health hazards and contributing to the transmission of diseases such as diarrhoea, cholera, and typhoid fever.

Moreover, the environmental consequences of faecal sludge mismanagement are profound, with untreated or improperly treated sludge contaminating soil, surface water, and groundwater resources. Nutrient-rich sludge can promote the growth of algae and other aquatic organisms, leading to eutrophication and the depletion of oxygen in water bodies, while pathogen-laden sludge can pose risks to both human and ecological health. In agricultural contexts, the application of untreated faecal sludge as fertilizer can introduce pathogens and contaminants into the food chain, jeopardizing food safety and public health.

Against this backdrop, the need for sustainable and innovative approaches to faecal sludge management has never been more pressing. Traditional methods of faecal sludge treatment, such as anaerobic digestion, composting, and land application, have proven effective to some extent but often suffer from various limitations, including high capital and operational costs, energy requirements, and land availability constraints. Additionally, these methods may not adequately address the challenges associated with faecal sludge transport, treatment, and disposal, particularly in resource-constrained settings where infrastructure and financial resources are limited [1-2].

In recent years, there has been growing interest in the potential of converting faecal sludge into valuable products, such as biogas, fertilizers, and biofuels, through processes known as resource recovery or waste valorization. By extracting energy and nutrients from faecal sludge, these approaches offer a sustainable and environmentally sound alternative to conventional treatment methods, simultaneously addressing sanitation, energy, and environmental challenges. Among the various products that can be derived from faecal sludge, bio-crude, a liquid fuel precursor obtained through the thermochemical conversion of organic matter, holds particular promise for its potential applications in renewable energy production and resource recovery.

Bio-crude, also known as bio-oil or pyrolysis oil, is produced through the thermal decomposition of organic materials, such as biomass or organic waste, in the absence of oxygen. During the pyrolysis process, complex organic molecules are broken down into simpler compounds, resulting in the formation of a dark brown or black liquid with properties similar to petroleum crude oil. Bio-crude contains a mixture of hydrocarbons, oxygen-containing compounds, and other organic constituents, making it a versatile feedstock for various downstream processes, including combustion, upgrading, and refining [11]. Das (2024) describes set up time reduction time as a part of Industrial Engineering tools in an electronics industry that is our further research which has significant role to conduct our research [14].

In summary, the management of faecal sludge presents a complex and multifaceted challenge with far-reaching implications for public health, environmental sustainability, and socio-economic development. By harnessing the potential of bio-crude production from faecal sludge, it is possible to transform a pressing sanitation problem into an opportunity for sustainable resource recovery and renewable energy production. Through interdisciplinary research and innovation, we can unlock the full potential of bio-crude production technologies and pave the way towards a more sustainable and inclusive future for all.

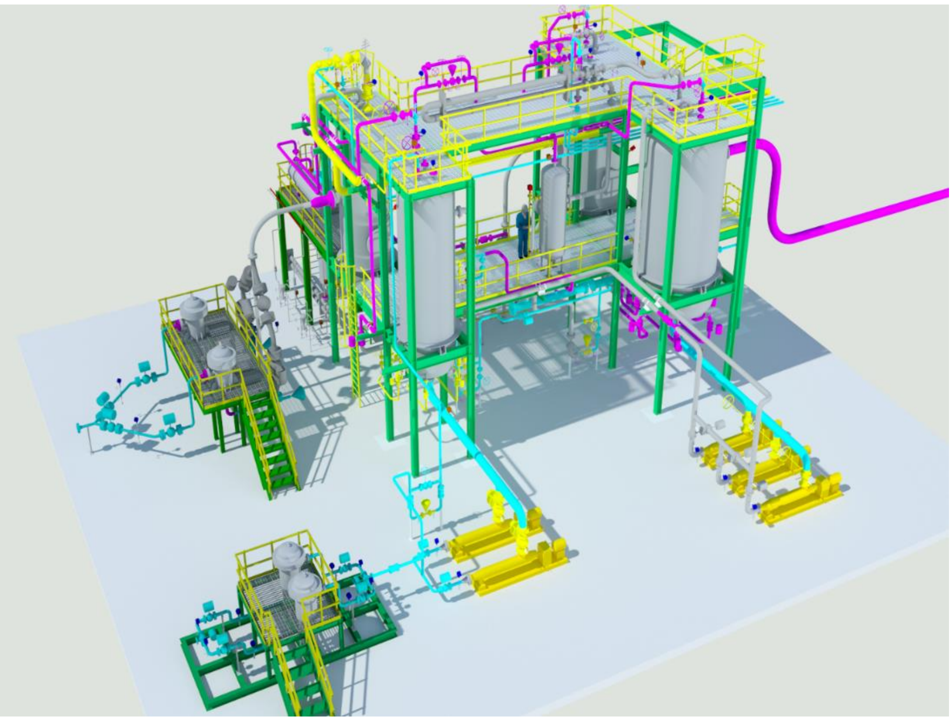

Figure 1: Hydrothermal Liquefaction Process

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. 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].

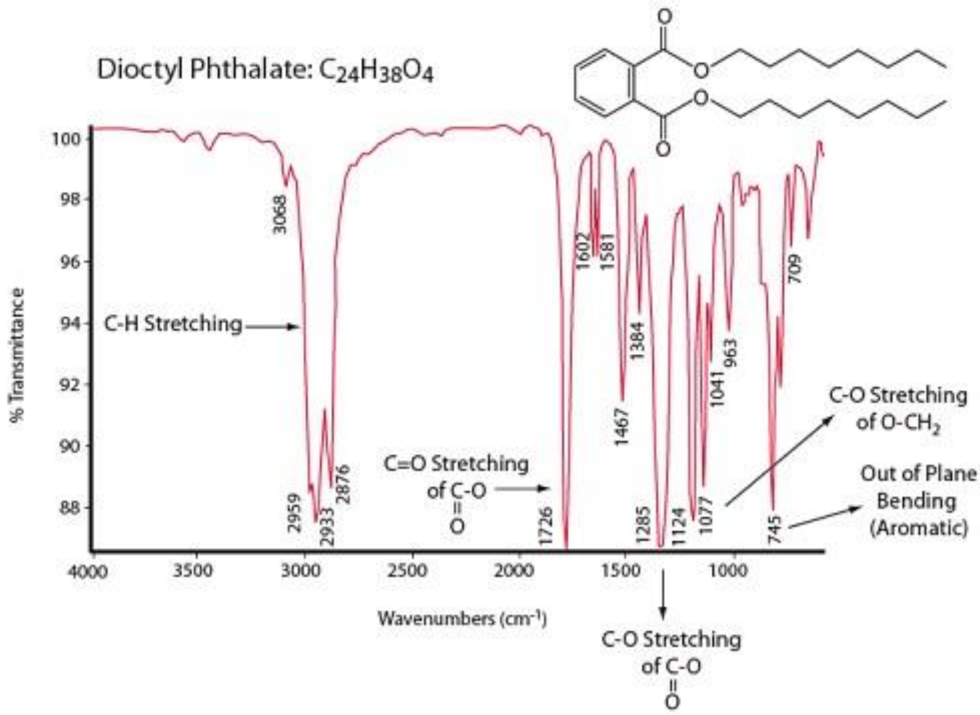

Figure 2: Typical FTIR graph [6]

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 [7]. 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

This study employs a comprehensive and multi-faceted methodology to investigate the feasibility, viability, and sustainability of bio-crude production from faecal sludge. The methodology encompasses several key components, including experimental design, data collection and analysis, techno-economic assessment, and environmental evaluation, each aimed at addressing specific research objectives and questions related to bio-crude production.

Experimental Design

The experimental phase of the study involves the development and implementation of laboratory-scale experiments to evaluate various aspects of bio-crude production from faecal sludge. The experimental design is structured to systematically investigate the effects of key parameters and variables on the pyrolysis process and bio-crude yield. This includes factors such as feedstock composition, moisture content, particle size, heating rate, reactor configuration, and operating temperature. The experimental design also incorporates control treatments and replication to ensure the reliability and repeatability of the results [8-9].

Data Collection and Analysis

Data collection is conducted throughout the experimental process to capture relevant information on faecal sludge characteristics, pyrolysis performance, and bio-crude properties. This includes the collection of faecal sludge samples from diverse sources, such as pit latrines, septic tanks, and sanitation facilities, followed by pre-treatment and characterization to determine key parameters such as moisture content, organic content, volatile solids, and chemical composition. During pyrolysis experiments, data is collected on process parameters such as temperature, heating rate, residence time, and gas composition, as well as product yields, including bio-crude, biochar, and syngas. Analytical techniques such as proximate analysis, ultimate analysis, gas chromatography, and mass spectrometry are employed to quantify and characterize the composition of bio-crude and other pyrolysis products.

Techno-Economic Assessment

A techno-economic assessment is conducted to evaluate the economic feasibility and viability of bio-crude production from faecal sludge. This involves the development of process models and cost estimation methodologies to determine capital and operating costs associated with bio-crude production technologies. Key cost components include equipment costs, labor costs, feedstock acquisition and pre-treatment costs, energy consumption, maintenance and depreciation expenses, and revenue from bio-crude sales or utilization. Sensitivity analysis is performed to assess the impact of uncertain factors and assumptions on the overall economics of bio-crude production. Economic indicators such as net present value (NPV), internal rate of return (IRR), payback period, and cost of production are calculated to assess the financial viability of bio-crude production technologies under different scenarios and market conditions.

Environmental Evaluation

An environmental evaluation is conducted to assess the environmental sustainability and impact of bio-crude production from faecal sludge. This includes life cycle assessment (LCA) methodologies to quantify the environmental burdens and benefits associated with bio-crude production, from raw material extraction and processing to end-of-life disposal or utilization. Key environmental indicators such as greenhouse gas emissions, energy consumption, water usage, air emissions, land use, and ecosystem impacts are assessed and compared across different bio-crude production pathways and scenarios. Sensitivity analysis is performed to identify critical environmental hotspots and trade-offs, as well as opportunities for environmental improvement through technology innovation, process optimization, and resource efficiency measures.

Integration and Synthesis

The findings from the experimental, techno-economic, and environmental assessments are integrated and synthesized to provide a comprehensive understanding of the opportunities and challenges associated with bio-crude production from faecal sludge. This includes the identification of key factors influencing bio-crude yield, quality, and economics, as well as the implications for sustainable sanitation, energy access, and environmental stewardship. Recommendations are provided for policy-makers, practitioners, and researchers on strategies to promote the adoption and scaling up of bio-crude production technologies, including regulatory incentives, financial mechanisms, capacity-building initiatives, and knowledge sharing platforms. The integrated analysis also highlights areas for further research, innovation, and collaboration to advance the field of bio-crude production from faecal sludge and contribute to the achievement of global sustainability goals.

Results and discussion:

FTIR Analysis of Product Separated at 6000 RPM

Bio-crude and Bio-char

FTIR analysis was conducted to determine the functional group, mode of vibration and strength of spectra of bio-crude and bio-char separated at a centrifugal speed of 6000 rpm for 5 minutes is presented in Figure 3. The result showed that ranges from 2800 cm^{-1} to 3000 cm^{-1} and 1350 cm^{-1} to 1460 cm^{-1} representing medium peaks of C-H stretching ($-CH_3$ and $-CH_3$ vibrations), which indicates the presence of long-chain aliphatic hydrocarbons (Li et al., 2018). There is absorbance peak at the range of 1020 cm^{-1} to 1100 cm^{-1}, which represents alcohol and phenol compound because of the presence of C-O stretch. There is also peak at 1590 cm^{-1} to 1800 cm^{-1} which indicates C=O vibration suggesting the presence of ketones, aldehydes, carboxylic acids and esters functional group [10].

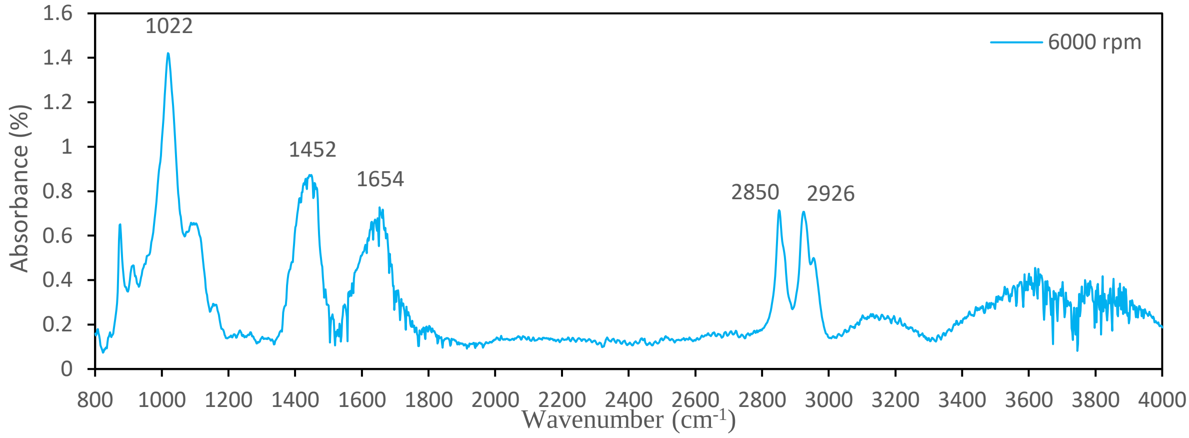

Figure 3: FTIR spectra of Bio-Crude and Bio-Char separated at 6000 rpm with correction for CO_2 contamination

Aqueous Phase

FTIR analysis was conducted of aqueous phase separated at 6000 rpm for 5 minutes as well to determine the functional group, mode of vibration and strength of spectra is presented in Figure 4. There is peak at 2850 cm^{-1} and 2922 cm^{-1} which indicates the presents of C-H stretching. Peak at 1654 cm^{-1} indicates the presence of C=O vibration for presence of ketones, aldehydes, carboxylic acids and esters functional group. Where, 1018 cm^{-1} absorption indicates the presence of alcohol and phenol compounds. There is also peak at 3628 cm^{-1} indicating the O-H stretching in water molecule.

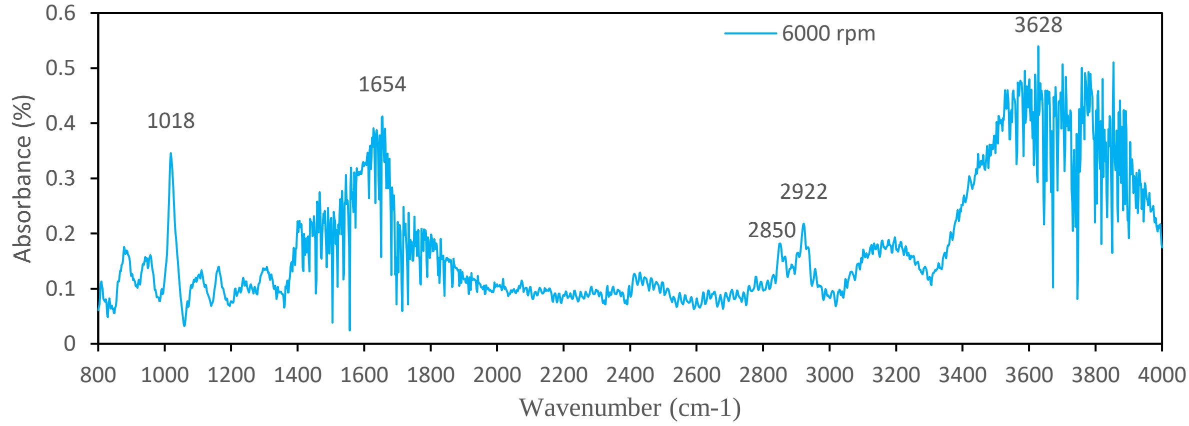

Figure 41: FTIR spectra of Aqueous Phase separated at 6000 rpm with correction for CO_2 contamination

As it is shown in FTIR spectra that at 6000 rpm there is bio-crude part to be specific C-O and C-H stretches are present then it can be said that at 6000 rpm bio-crude and bio-char are not fully separated from the aqueous phase. Thus, this result is not valid for further discussion.

Conclusion

Our findings indicate that bio-crude production from faecal sludge holds significant promise as a means of valorizing organic waste streams and generating renewable energy resources. Laboratory-scale experiments have demonstrated the technical feasibility of pyrolysis-based processes for converting faecal sludge into bio-crude, with yields comparable to those obtained from conventional biomass feedstocks. Furthermore, our techno-economic assessment suggests that bio-crude production from faecal sludge can be economically viable under certain conditions, particularly in regions where energy prices are high and waste disposal costs are significant. Sensitivity analysis has highlighted key factors influencing the economics of bio-crude production, including feedstock availability, process efficiency, and market dynamics.

Looking ahead, further research, innovation, and collaboration are needed to overcome remaining technical, economic, and institutional barriers to the widespread adoption and commercialization of bio-crude production technologies. This includes the development of scalable and cost-effective pyrolysis processes, the optimization of feedstock collection and pre-treatment methods, and the integration of bio-crude production into existing sanitation and energy systems. Policy support and regulatory incentives are also essential to create an enabling environment for investment and innovation in bio-crude production technologies, particularly in regions where sanitation and energy access are most limited. In conclusion, bio-crude production from faecal sludge represents a promising opportunity to address the intertwined challenges of sanitation, energy, and environmental sustainability. By harnessing the potential of bio-crude production technologies, we can create a more sustainable and resilient future for communities around the world, while advancing progress towards the achievement of global sustainability goals.

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