Optimization of Faecal Sludge Management (FSM) and effectiveness of Refuse Derived Fuel (RDF) Generation

By

Aniqa Gulraiz

Sharjeel Shafqat Khawaja

Arsal Sher Khan

Supervisor

Dr. Sher Jamal Khan

Institute of Environmental Sciences and Engineering (IESE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST), Islamabad

June 2024

Optimization of Faecal Sludge Management (FSM) and effectiveness of Refuse Derived Fuel (RDF) Generation

A thesis submitted to the

National University of Sciences and Technology

in partial fulfillment of the requirements

for the degree of Bachelor of Engineering in

Environmental Engineering

By

Aniqa Gulraiz

Sharjeel Shafqat Khawaja

Arsal Sher Khan

Supervisor

Dr. Sher Jamal Khan

Institute of Environmental Sciences and Engineering (IESE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST), Islamabad

June 2024

Approval Sheet

It is certified that the contents and form of the thesis entitled "Optimization of Faecal Sludge Management (FSM) and effectiveness of Refuse Derived Fuel (RDF) Generation" submitted by Aniqa Gulraiz, Sharjeel Shafqat Khawaja, and Arsal Sher Khan have been found satisfactory for the requirement of the degree.

Sher Jamal

Dr. Sher Jamal Khan
Professor (Project
Supervisor) SCEE (IESE),
NUST

Nida Maqbool.

Engr. Nida Maqbool
Assistant Professor (Project
co-supervisor) SCEE (IESE),
NUST

Dr. Muhammad Ali Inam
Assistant Professor
HoD Environmental Engineering
SCEE (IESE), NUST
H-12 Islamabad

M Ali Inam
11/06/2024

Dr. Muhammad Ali Inam
Assistant Professor (Head of
Department) SCEE (IESE),
NUST

Prof. Dr. Imran Hashmi
Associate Dean
IESE (SCEE) NUST Islamabad

11/06/2024

Dr. Imran Hashmi
Professor (Associate Dean)
SCEE (IESE), NUST

Table of Contents

Acknowledgement

First and foremost, we are filled with gratitude for the opportunities, resources, and abilities Allah has provided us with to undertake this endeavor. With His blessing, we were successfully able to work on a project, under the supervision of Prof. Dr. Sher Jamal Khan, that would be of great service to society.

We would like to thank our project supervisor for his expert guidance, and unwavering support throughout the project. His valuable insights and feedback have been instrumental in shaping the course of this work. His expertise and knowledge in the field of environmental engineering have been truly exceptional and it shows in the way our project is practical and aims to serve humanity.

Additionally, we would like to thank our families and friends for their unwavering support and encouragement during this journey. Their belief in us has been a constant source of inspiration and motivation.

Lastly, we would like to express our gratitude to all the participants, respondents, and residents of Bahria Enclave who generously gave their time and cooperation, enabling us to gather the necessary data for this project.

We are deeply indebted to all of you for your contributions, guidance, and encouragement. Your support has been invaluable, and this project would not have been possible without you.

Abstract

This study presents in-depth research on optimizing Faecal Sludge Management (FSM) and evaluating the effectiveness of Refuse Derived Fuel (RDF) generation from collected sludge in urban areas of Islamabad, Pakistan. The research addresses the inefficiencies in the current collection and transportation of faecal sludge and explores its potential as a sustainable energy source through the production of hydrochar briquettes.

A comprehensive literature review highlights the advantages of Hydrothermal Carbonization (HTC) over traditional pyrolysis, noting the higher yield and energy content of hydrochar. The methodology involved collecting sludge samples from Bahria Enclave, followed by dewatering, drying, and processing through HTC at 250°C and 20 bar pressure for 2.5 hours. The resulting hydrochar was then combined with crop residues and binders to form briquettes, which were tested for calorific value, bulk density, emission levels, and mechanical properties.

The results indicated that hydrochar briquettes have a calorific value comparable to natural coal, with lower emissions of PM2.5 and PM10. Among the tested briquettes, those with rice husk exhibited optimal balance in terms of energy content, emission levels, and mechanical strength. The economic analysis demonstrated a cost-effective production process with a short return period on investment, suggesting significant potential for scaling up.

This study underscores the dual benefits of improved FSM and the valorization of faecal sludge into a viable alternative fuel, contributing to environmental sustainability and energy security. Future work should focus on pilot-scale implementation and long-term performance monitoring to refine the process and enhance its feasibility for broader application.

List of Figures

List of Table

List of Abbreviations

CMS - Content Management System
FSM - Faecal Sludge Management
FS - Faecal Sludge
FS+RH - Faecal Sludge with Rice Husk
FS+WS - Faecal Sludge with Wheat Straw
GCV - Gross Calorific Value
GIS - Geographic Information System
HTC - Hydrothermal Carbonization
IRI - Impact Resistance Index
MJ/kg - Megajoules per Kilogram
PM - Particulate Matter
PKR - Pakistani Rupee
PSLM – Pakistan Social and Living Standards Measurement
RDF - Refuse Derived Fuel
SDGs - Sustainable Development Goals
WASH - Water, Sanitation, and Hygiene
WHO - World Health Organization

Chapter 1 Introduction

1.1 Background

Effective Faecal Sludge Management (FSM) is crucial for maintaining public health and environmental sustainability, particularly in regions relying on on-site sanitation systems. In Pakistan, an estimated 114 million people depend on these systems (PSLM 2019-2020), which include pit latrines, septic tanks, and other facilities that do not involve a central sewer network. Proper FSM ensures that faecal sludge is safely collected, transported, treated, and disposed of, thereby mitigating the risks associated with open defecation and unsafe waste-handling practices.

The current state of sanitation in Pakistan presents significant challenges. Poor sanitation infrastructure and practices lead to severe public health issues, environmental degradation, and economic losses. According to WaterAid (2019), the indirect costs of inadequate sanitation in Pakistan far exceed the investments required to improve the WASH (Water, Sanitation, and Hygiene) infrastructure to meet national and international targets. These costs include healthcare expenses due to waterborne diseases, loss of productivity, and environmental clean-up costs.

1.1.1 Current Scenario and Challenges

Pakistan faces multiple challenges in managing faecal sludge effectively:

- **Inefficiencies in Collection and Transportation:** The process of collecting and transporting faecal sludge from urban areas is often inefficient. This inefficiency is due to a lack of optimization in the scheduling and routing of desludging activities, leading to increased operational costs and substandard service delivery.
- **Substandard Waste Management Practices:** Inadequate infrastructure and lack of proper waste management protocols result in the unsafe disposal of faecal sludge, contributing to environmental pollution and public health hazards.
- **Low Investment in Sanitation:** Despite the critical need for improved sanitation services, current spending on WASH is insufficient. This underinvestment hinders the development and implementation of comprehensive FSM systems.

1.1.2 Importance of Faecal Sludge Management

Implementing an effective FSM system is essential for several reasons:

- **Public Health:** Proper management of faecal sludge reduces the prevalence of waterborne diseases, such as cholera, diarrhea, and typhoid, which are often caused by the contamination of water sources with untreated human waste.
- **Environmental Protection:** Effective FSM prevents the indiscriminate dumping of faecal sludge into water bodies and open fields, thus protecting ecosystems and reducing pollution.
- **Economic Benefits:** Investing in FSM can yield significant economic returns. It can reduce healthcare costs, improve productivity by preventing illness, and create job opportunities in the sanitation sector.

1.1.3 Innovative Approaches in FSM

To address these challenges, innovative approaches are necessary. One such approach is the use of digital technology to optimize faecal sludge collection and transportation. Developing a user-friendly digital dashboard can streamline the scheduling and routing of desludging activities, making the process more efficient and transparent. Additionally, exploring the potential of faecal sludge as a resource for generating Refuse Derived Fuel (RDF) can provide an environmentally friendly and cost-effective alternative to traditional fuels.

1.1.4 Global Context

Globally, many countries are recognizing the importance of FSM in achieving sustainable development goals (SDGs). For instance, SDG 6 aims to ensure availability and sustainable management of water and sanitation for all, while SDG 7 focuses on affordable and clean energy. Efficient FSM systems contribute to both these goals by improving sanitation and exploring alternative energy sources from waste.

In summary, the need for a well-planned and executed FSM system in Pakistan is critical. This study aims to address the inefficiencies in the current system and explore the feasibility of using faecal sludge for RDF generation. By optimizing the collection and transportation processes and evaluating the potential of faecal sludge briquettes, this research contributes to the broader goals of sustainable waste management and environmental protection.

1.2 What is Faecal Sludge Management?

Faecal Sludge Management (FSM) refers to the systematic process of safely handling faecal sludge from onsite sanitation systems, such as septic tanks and pit latrines. The primary components of FSM include:

- **Capture and Containment:** Faecal sludge is initially collected in containment units like septic tanks or pit latrines, designed to hold excreta safely until it can be removed.
- **Collection and Transportation:** The collected faecal sludge is then removed and transported to treatment facilities using vacuum trucks or other specialized vehicles.
- **Treatment:** At the treatment facilities, the faecal sludge undergoes various processes to reduce its volume and harmful components. Treatment methods can include mechanical, biological, and chemical processes.
- **Reuse or Disposal:** The treated sludge is either safely disposed of or repurposed. Reuse options include converting it into biofuel, compost, or construction material.

Effective FSM is crucial for maintaining public health and environmental safety. In Pakistan, where a significant portion of the population relies on onsite sanitation systems, proper FSM practices are essential to prevent environmental pollution and protect water resources.

FSM encompasses a range of activities, from the initial capture of excreta to its final disposal or reuse. The goal is to manage faecal sludge in a way that minimizes health risks, environmental impact, and costs. Effective FSM involves a combination of appropriate technology, infrastructure, regulatory frameworks, and community engagement.

In many urban areas of Pakistan, FSM is still a significant challenge due to inadequate infrastructure, limited financial resources, and lack of awareness. Improving FSM practices can lead to better health outcomes, enhanced environmental protection, and more sustainable urban development.

Figure 1.1 Faecal Sludge Managment Diagram

1.3 Problem Statement

In urban areas of Pakistan, the current methods of collection and transportation of faecal sludge are highly inefficient and poorly managed, leading to significant environmental contamination and public health risks. The inefficiencies stem from several critical issues: uncoordinated collection schedules, inadequate infrastructure, and suboptimal transportation routes. These challenges not only elevate operational costs but also contribute to an increased environmental impact, including soil and water contamination and the spread of diseases.

The process of converting faecal sludge into Refuse Derived Fuel (RDF) remains underdeveloped, posing another layer of complexity to the waste management system. Despite the potential benefits of RDF, such as enhanced energy recovery and reduced environmental harm, the existing practices for its production are insufficiently optimized. This underdevelopment hinders the broader adoption of RDF as a viable alternative energy source, which is crucial for sustainable waste management and energy production.

Addressing these issues is imperative for establishing a more effective and sustainable waste management system in Pakistan. Enhancing the collection and transportation efficiency of faecal sludge can mitigate environmental contamination and public health risks. Moreover, optimizing the conversion process of faecal sludge to RDF can significantly contribute to energy recovery and environmental protection.

Therefore, we aim to evaluate the current inefficiencies in faecal sludge management in urban Pakistan, propose improvements in collection and transportation strategies, and develop a framework for optimizing the conversion of faecal sludge to RDF. By tackling these challenges, the research will contribute to improved urban sanitation, reduced environmental impact, and the promotion of alternative energy sources, ultimately supporting the development of a sustainable and resilient urban waste management system in Pakistan.

1.4 Objectives

1.4.1 Comparative life cycle assessment of hydrothermal carbonization and pyrolysis of sewage sludge.

The primary objectives of this research are Comparative life cycle assessment of hydrothermal carbonization and pyrolysis of sewage sludge. Journal of Cleaner Production centered around addressing the inefficiencies in faecal sludge management (FSM) in urban areas of Pakistan and exploring the feasibility of converting faecal sludge into a viable alternative fuel source. These objectives are divided into two main areas of focus:

Objective 1: Digital Dashboard for FSM Optimization

Develop and implement a user-friendly digital dashboard aimed at optimizing the collection and transportation of faecal sludge. This system will enhance the efficiency, transparency, and overall effectiveness of FSM operations.

Specific Goals:

- **Data Accumulation:** Create a comprehensive system for collecting and managing data on faecal sludge generation, collection schedules, and transportation routes. This data will be essential for making informed decisions on FSM operations.
- **Scheduling and Routing:** Utilize the dashboard to automate the scheduling of desludging activities and optimize transportation routes. This will reduce operational costs and improve service delivery by ensuring timely and efficient collection of faecal sludge.
- **User Interface:** Design the dashboard to be intuitive and accessible, ensuring that operators with varying levels of technical expertise can easily use it. The interface will provide clear visualizations of data and generate alerts for upcoming desludging tasks.
- **Pilot Implementation:** Conduct a pilot implementation of the dashboard in Bahria Enclave, Islamabad. This will involve testing the system’s functionality, gathering user feedback, and making necessary adjustments before wider deployment.

Objective 2: Feasibility and Impact Assessment of Faecal Sludge Briquettes

Assess the feasibility and environmental impact of using faecal sludge briquettes as an alternative to coal for energy production. This involves several key steps and goals:

Specific Goals:

- **Sample Collection and Characterization:** Collect faecal sludge samples from Bahria Enclave and conduct comprehensive testing to characterize the sludge's physical and chemical properties. This will include measuring parameters such as moisture content, calorific value, and the presence of harmful substances.
- **Hydrothermal Carbonization (HTC):** Process the collected faecal sludge using hydrothermal carbonization to produce hydrochar. This involves subjecting the sludge to high temperatures and pressures to convert it into a carbon-rich material suitable for briquette formation.
- **Briquette Formation and Testing:** Mold the hydrochar into briquettes using a hydraulic press and test the resulting products for energy content, emissions, and mechanical properties. This will involve evaluating the briquettes' calorific value, bulk density, compressive strength, and emissions of pollutants such as particulate matter (PM2.5 and PM10).
- **Environmental Impact Assessment:** Compare the emissions and environmental impact of faecal sludge briquettes with traditional fuels like coal. This will help determine the potential benefits of adopting faecal sludge briquettes as a cleaner and more sustainable energy source.
- **Cost-Benefit Analysis:** Perform detailed cost-benefit analysis to assess the economic viability of producing and using faecal sludge briquettes. This will include analyzing production costs, potential savings on fuel expenses, and the overall financial sustainability of the project.

1.4.2 Integrating Objectives for Comprehensive FSM

The integration of these two objectives aims to provide a holistic approach to improving FSM in Pakistan. By developing a digital dashboard to optimize faecal sludge collection and exploring the potential of faecal sludge briquettes, this research seeks to:

- Enhance the operational efficiency of FSM systems.

- Provide a sustainable and economically viable alternative to traditional fuels.
- Contribute to public health and environmental protection by reducing the risks associated with improper faecal sludge management.
- Broader Impact and Future Prospects

Achieving these objectives will have significant implications for urban sanitation management in Pakistan. The successful implementation of the digital dashboard can be scaled to other urban areas, potentially transforming FSM practices nationwide. Furthermore, demonstrating the feasibility of faecal sludge briquettes as an alternative fuel can open new avenues for waste-to-energy initiatives, contributing to sustainable development goals (SDGs) related to clean energy and sanitation.

1.5 Study Area

The study was conducted in Bahria Enclave, Islamabad, Pakistan. This locality provided a controlled environment for the pilot implementation of the FSM dashboard and the collection of faecal sludge samples necessary for the study.

Chapter 2 Literature Review

2.1 General Overview

Faecal Sludge Management (FSM) is a critical aspect of urban sanitation, especially in developing countries like Pakistan. Effective FSM ensures the safe collection, transportation, treatment, and disposal of faecal sludge, thereby preventing environmental contamination and promoting public health. Pakistan faces significant challenges in sanitation, with a large portion of the population relying on on-site sanitation systems such as septic tanks and pit latrines. According to the World Health Organization (WHO), poor sanitation costs Pakistan an estimated USD 5.7 billion annually, highlighting the urgent need for improved FSM practices (WHO, 2015).

In Pakistan, FSM is often neglected, with many urban areas lacking adequate infrastructure and resources for proper sludge management. This has resulted in widespread environmental pollution and health issues. Innovative solutions are required to address these challenges and improve FSM practices in the country.

2.2 Importance of FSM

The importance of FSM cannot be overstated. In Pakistan, around 79% of the population relies on on-site sanitation systems, necessitating effective FSM to handle the capture, containment, collection, transportation, treatment, and reuse or disposal of faecal sludge (WaterAid, 2019). Poor FSM practices lead to the contamination of water bodies, soil, and air, posing severe health risks to the population. Moreover, inadequate FSM contributes to economic losses, with healthcare costs and productivity losses due to sanitation-related diseases.

The Sustainable Development Goals (SDGs) emphasize the need for improved sanitation and hygiene, with Goal 6 specifically targeting access to adequate and equitable sanitation for all. Effective FSM is crucial for achieving this goal and ensuring the well-being of communities.

2.3 Challenges in FSM

FSM in Pakistan faces numerous challenges, including:

- **Inadequate Infrastructure**: Many urban areas lack the necessary infrastructure for efficient FSM, such as treatment plants and proper transportation systems.
- **Limited Awareness**: There is a lack of awareness and education among the population regarding the importance of FSM and proper sanitation practices.

- **Financial Constraints**: Insufficient funding and financial resources hinder the development and maintenance of FSM infrastructure.
- **Regulatory Gaps**: Weak regulatory frameworks and enforcement mechanisms result in poor compliance with sanitation standards.

Strande et al. (2014) highlight the necessity of a complete management scheme encompassing the containment, collection, transportation, treatment, and disposal of faecal sludge. Addressing these challenges requires a multi-faceted approach involving government agencies, private sector participation, and community engagement.

2.4 Technological Advances in FSM

Technological advancements have the potential to revolutionize FSM practices. Recent innovations focus on improving the efficiency of collection and treatment processes. Digital tools and GIS-based systems can enhance the monitoring and management of FSM operations.

Muspratt et al. (2014) and Martin et al. (2017) have demonstrated the potential of faecal sludge as a resource for generating solid fuel. These studies highlight the high calorific content and lower emissions of faecal sludge briquettes compared to traditional fuels like coal. Additionally, hydrothermal carbonization (HTC) has emerged as a promising technology for converting faecal sludge into hydrochar, which can be used as a solid fuel.

2.5 Refuse Derived Fuel (RDF) from Faecal Sludge

RDF refers to fuel produced from various types of waste, including faecal sludge. The process involves drying and carbonizing the sludge to create a high-energy, low-emission fuel source. In Pakistan, the potential for producing RDF from faecal sludge is significant, given the large quantities of sludge generated in urban areas.

The formation of briquettes from RDF involves several key steps:

- **Collection and Transportation:** Faecal sludge is collected from septic tanks and transported to a treatment facility.
- **Dewatering:** The sludge undergoes a dewatering process to reduce its moisture content. This can be achieved using sludge drying beds or mechanical dewatering equipment.
- **Hydrothermal Carbonization (HTC):** The dewatered sludge is subjected to HTC, a thermochemical process that converts organic materials into a carbon-rich hydrochar. This

process occurs under high pressure and moderate temperatures, typically between 180°C and 250°C.

- **Briquetting:** The hydrochar produced from HTC is mixed with a binder (such as starch or waste engine oil) and compressed into briquettes using a hydraulic press. The briquettes are then dried to achieve the desired moisture content and improve their mechanical properties.

Ramke et al. (2010) found that carbonized faecal sludge contains approximately 70-71% carbon by weight, making it a viable alternative to conventional fuels. Fakkaew et al. (2015, 2017) studied the effects of hydrolysis and carbonization on hydrochar production, finding that HTC yields hydrochar with energy contents comparable to natural coals (19-20 MJ/kg).

The resulting faecal sludge briquettes have several advantages

- **High Calorific Value:** The briquettes have a high energy content, making them an efficient fuel source.
- **Low Emissions:** Compared to traditional fuels like coal, faecal sludge briquettes produce lower emissions of harmful pollutants, such as particulate matter (PM2.5 and PM10) and greenhouse gases.
- **Cost-Effective:** The production of faecal sludge briquettes is economically viable, with lower production costs compared to conventional fuels.

These advantages make faecal sludge briquettes a promising solution for sustainable energy production and waste management in Pakistan.

2.6 Case Studies on Faecal Sludge Utilization

Several case studies have explored the utilization of faecal sludge in RDF production:

- **Hydrolysis and Carbonization**: Fakkaew et al. (2015, 2017) studied the effects of hydrolysis and carbonization on hydrochar production, finding that hydrothermal carbonization (HTC) yields hydrochar with energy contents comparable to natural coals (19-20 MJ/kg).
- **Low-Cost Dewatering and Carbonization**: Atwijukye et al. (2018) demonstrated that using binders in the carbonization process increases the calorific value and decreases the ash content of faecal sludge briquettes. In our study, we used starch and engine oil as

binders, as supported by the findings of Francis Obi et al. (2022), who also reported that starch is an effective binder for increasing the calorific value and reducing the ash content of biomass briquettes.

- **Filtering Media in Sludge Drying Beds**: Ssazipius et al. (2021) found that fine sawdust performs better than sand media in faecal sludge dewatering, suggesting its adoption in sludge drying beds for improved efficiency.

These case studies highlight the potential of faecal sludge as a valuable resource for RDF production and demonstrate practical applications of innovative FSM technologies.

2.7 Environmental and Economic Impact

The environmental and economic benefits of using faecal sludge briquettes are significant. The low emissions of PM2.5 and PM10, as highlighted by Martin et al. (2024), indicate that faecal sludge briquettes are a cleaner alternative to traditional fuels. Furthermore, the lower cost of production compared to coal can make RDF from faecal sludge an economically viable solution for energy production.

The cost-benefit analysis presented in this study reveals that the production of faecal sludge briquettes can lead to substantial cost savings and environmental benefits. By optimizing desludging and collection routes, significant reductions in fuel consumption and emissions can be achieved.

2.8 Optimization of FSM Processes

The optimization of FSM processes through digital tools, such as the CMS dashboard developed in this study, can significantly enhance the efficiency and transparency of faecal sludge collection and transportation. The dashboard will allow real-time monitoring and scheduling, reducing inefficiencies and ensuring timely desludging operations.

The integration of GIS-based routing systems further will optimize the process by minimizing travel time and fuel consumption. The pilot implementation in Bahria Enclave will demonstrate that optimizing desludging and collection routes can save approximately 50,000 PKR on fuel expenses alone, highlighting the potential for cost savings and improved operational efficiency.

2.9 Summary of Findings

The literature review underscores the potential of faecal sludge as a valuable resource for RDF production and the importance of optimizing FSM processes. The studies reviewed provide a solid foundation for the methodologies and objectives of this research, which aim to enhance FSM practices and explore sustainable energy alternatives. By leveraging technological advancements and innovative approaches, significant environmental and economic benefits can be achieved.

Chapter 3 Development and Implementation of the FSM Dashboard

3.1 Introduction

This chapter details the planning, development, and implementation of a digital dashboard designed to optimize the Faecal Sludge Management (FSM) process. The dashboard aims to enhance the efficiency and transparency of faecal sludge collection, transportation, and disposal within Bahria Enclave, Islamabad. By leveraging digital tools, this initiative seeks to address the inefficiencies in current FSM practices and provide a user-friendly solution for stakeholders.

3.2 Planning Phase

The planning phase focused on identifying the specific needs and requirements for the FSM dashboard, conceptualizing the design, and researching existing solutions.

3.2.1 Identification of Needs and Requirements

The FSM dashboard was designed to streamline the scheduling and monitoring of faecal sludge collection. The initial objectives included improving the timeliness of desludging operations, reducing operational inefficiencies, and enhancing transparency.

To achieve these objectives, the dashboard required several key functionalities:

- **Real-time monitoring** of desludging operations to track progress and identify bottlenecks.
- **Automated scheduling** based on historical data and predictive analysis to optimize desludging frequency.
- **Data visualization tools** to display performance metrics and facilitate decision-making.
- **User notifications and alerts** for upcoming desludging tasks to ensure timely operations.
- **GIS-based component for displaying optimal routes**, reducing travel time and fuel consumption for desludging trucks.

These functionalities were aimed at addressing the operational challenges faced by FSM services and providing a comprehensive solution to enhance efficiency and transparency.

3.2.2 Research on Existing Solutions

In Pakistan, existing FSM solutions are limited, and major operating companies typically run on a "desludging on demand" system. This reactive approach often leads to inefficiencies, such as delayed responses to desludging requests and suboptimal route planning for desludging trucks.

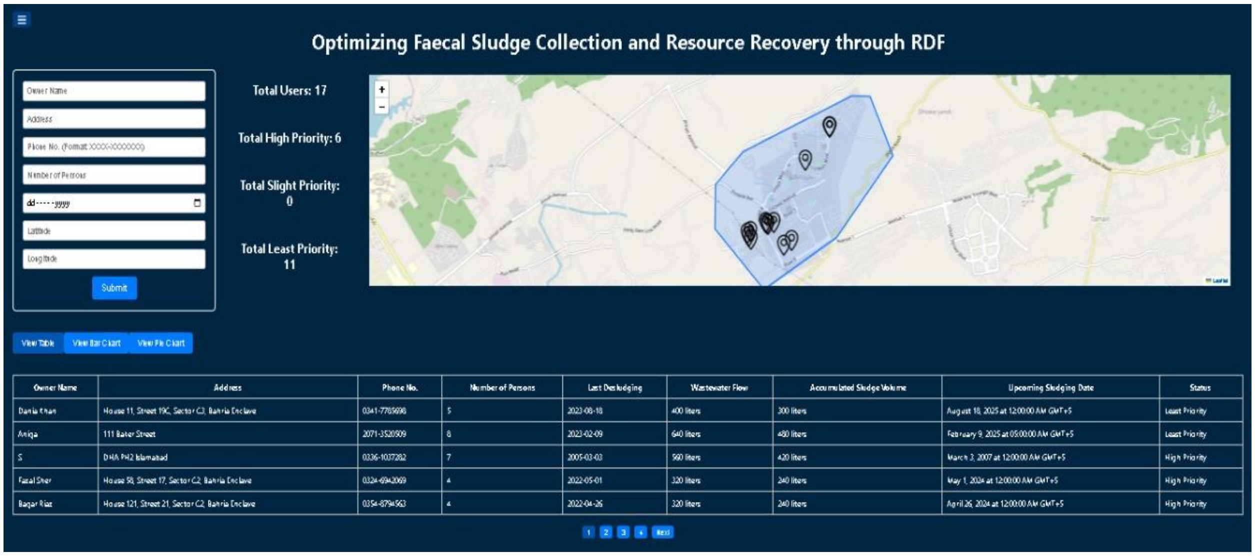
A review of available digital tools revealed several limitations:

- **Lack of user-friendliness:** Existing tools were often complex and difficult to use, especially for operators with limited technical expertise.
- **Inadequate data management:** Many tools lacked robust data management capabilities, making it difficult to track and analyze operational data effectively.
- **Poor integration:** Current tools did not integrate well with other systems, limiting their effectiveness in providing a comprehensive FSM solution.

These findings highlighted the need for a more user-friendly, data-driven, and integrated solution tailored to the specific needs of FSM operations in Pakistan.

3.2.3 Conceptualization

Based on the identified needs and research findings, the conceptualization phase involved developing a preliminary design for the FSM dashboard. The design focused on creating an intuitive interface accessible to all users, regardless of their technical expertise.



Optimizing Faecal Sludge Collection and Resource Recovery through RDF

Total Users: 17

Total High Priority: 6

Total Slight Priority: 0

Total Least Priority: 11

Owner Name	Address	Phone No.	Number of Persons	Last Desludging	Wastewater Flow	Accumulated Sludge Volume	Upcoming Sludging Date	Status
Dania Khan	House 11, Street 19C, Sector C3, Bahria Enclave	0341-7785698	5	2023-08-18	400 liters	300 liters	August 18, 2025 at 12:00:00 AM GMT+5	Least Priority
Aniqa	111 Baker Street	2071-3520909	8	2023-02-09	640 liters	480 liters	February 9, 2025 at 05:00:00 AM GMT+5	Least Priority
S	DHA PH2 Islamabad	0336-1037282	7	2005-03-03	560 liters	420 liters	March 3, 2007 at 12:00:00 AM GMT+5	High Priority
Faizal Sher	House 58, Street 17, Sector C2, Bahria Enclave	0324-6942069	4	2022-05-01	320 liters	240 liters	May 1, 2024 at 12:00:00 AM GMT+5	High Priority
Baqar Riaz	House 121, Street 21, Sector C2, Bahria Enclave	0354-8794563	4	2022-04-26	320 liters	240 liters	April 26, 2024 at 12:00:00 AM GMT+5	High Priority

Figure 3.1 Dashboard's Data Management Pages

Key features identified for inclusion were:

- **Real-time monitoring**: A central dashboard displaying the status of ongoing desludging operations, allowing operators to track progress and respond to issues promptly.

- **Automated scheduling:** A system that uses historical data and predictive analysis to generate optimized desludging schedules, ensuring timely operations and reducing the risk of overflow.
- **Data visualization:** Interactive charts and graphs displaying key performance metrics, such as desludging frequency, volume of sludge collected, and operational efficiency.
- **User notifications and alerts:** Automated alerts to notify users of upcoming desludging tasks, ensuring timely execution and reducing the likelihood of missed operations.
- **GIS-based routing:** A map-based interface displaying optimal routes for desludging trucks, minimizing travel time and fuel consumption while improving operational efficiency.

The design aimed to address the limitations of existing solutions and provide a comprehensive tool to enhance the efficiency and transparency of FSM operations.

3.3 Development Phase

The development phase involved selecting appropriate tools and technologies, designing the user interface, coding the backend, and establishing robust data management practices.

3.3.1 Selection of Development Tools and Technologies

The development included the use of JavaScript and React.js for front-end development due to their flexibility and strong community support. The backend was developed using Node.js and Express.js, while the database was managed using Google Firebase. Firebase was chosen for its real-time database capabilities and ease of integration with web applications.

3.3.2 User Interface (UI) Design

The UI design adhered to principles of simplicity and user-friendliness. Using Figma, first we created the design prototypes that were iteratively tested and refined based on user feedback. The goal was to ensure that the dashboard could be easily navigated by users with varying levels of technical expertise.


Optimizing Faecal Sludge Collection and Resource Recovery through RDF

Total Users: 0

Total High Priority: 0

Total Slight Priority: 0

Total Least Priority: 0

Figure 3.2 Dashboard User Interface

3.3.3 Backend Development

Backend development focused on creating a robust and scalable infrastructure to support the dashboard's functionalities. This included developing libraries for data processing, integrating with the frontend, and ensuring seamless data flow between components. The server was built using Express.js, with CORS and body-parser middleware to handle cross-origin requests and JSON data parsing.

Below is a snippet of the server setup:

```
const express = require("express");
const cors = require("cors");
const admin = require("firebase-admin");
const serviceAccount = require("./ascend-a7f20-firebase-adminsdk-ssu0t-38d4b9f671.json");

const app = express();
const port = process.env.PORT || 5000;

if (!admin.apps.length) {
  admin.initializeApp({
    credential: admin.credential.cert(serviceAccount),
  });
```

```
}

app.use(cors());
app.use(express.json());

const db = admin.firestore();
const firstCollection = db.collection("firstCollection");

app.get("/get-data", async (req, res) => {
  try {
    const snapshot = await firstCollection.get();
    const data = snapshot.docs.map((doc) => ({
      id: doc.id,
      ...doc.data(),
    }));

    res.json({ message: "fetched!", data: data });
  } catch (error) {
    res.status(500).json({ message: "Internal Server Error", success: false });
  }
});
app.post("/post-data", async (req, res) => {
  try {
    const body = req.body;
    await firstCollection.add(body);
    res.status(200).json({ message: "Posted!", success: true });
  } catch (error) {
    res.status(500).json({ message: "Internal Server Error", success: false });
  }
});

app.listen(port, () => {
  console.log(`Server running on port: ${port}`);
});
```

3.3.4 Data Management

Effective data management was crucial for the dashboard's success. We implemented secure methods for data collection, storage, and retrieval using **Google Firebase**. Emphasis was placed on data privacy and security to protect user information and maintain system integrity.

3.4 Implementation Phase

Bahria Enclave, Islamabad, was chosen as the pilot area due to its mandatory requirement for houses to include a septic tank in their construction, but lack of responsibility in maintaining or desludging them. The pilot implementation involved sector-by-sector digitization of data and lasted approximately one month. Major challenges included the poorly stored data, necessitating manual surveys at many houses to gather accurate information.

The steps involved in the pilot implementation were:

- **Sector-by-Sector Digitization:** Collecting and digitizing data from each sector to ensure comprehensive coverage.
- **System Setup and Configuration:** Setting up the dashboard, including backend integration and database configuration.
- **Initial Testing:** Conducting initial tests to identify and resolve any technical issues before full deployment.
- **Full Deployment:** Rolling out the dashboard across the entire pilot area and monitoring its performance.

3.4.1 Monitoring and Evaluation

The performance and success of the dashboard were monitored based on several criteria:

- **Data Accessibility:** Evaluating how easily users could access and manage data within the system.
- **Scheduling Efficiency:** Assessing the effectiveness of the automated scheduling feature in organizing upcoming desludging dates.
- **Route Optimization:** Analyzing the efficiency of the GIS-based routing system in minimizing travel time and fuel consumption.

Data was collected informally, based on user satisfaction and feedback. Key findings included:

- **Fuel Savings:** Optimizing desludging and collection routes resulted in significant cost savings, with Bahria Enclave management saving approximately 50,000 PKR on fuel expenses alone.
- **User Satisfaction:** Users reported high levels of satisfaction with the dashboard's functionalities and ease of use.

Chapter 4 Production of Refuse Derived Fuel (RDF) from Faecal Sludge

4.1 Introduction

4.1.1 Faecal Sludge as Potential resource for RDF

The utilization of faecal sludge as a potential resource for producing Refuse-Derived Fuel (RDF) offers significant environmental and economic advantages. This section focuses on the viability of converting faecal sludge into RDF, particularly focusing on briquettes, which have shown promise as a low-emission, high-calorific alternative to traditional fuels.

- **Emission Levels of Faecal Sludge Briquettes:** One of the primary benefits of using faecal sludge briquettes is their minimal emission levels. Studies have demonstrated that these briquettes emit lower levels of particulate matter (PM2.5 and PM10) compared to conventional fuels like charcoal or sawdust briquettes.

  According to Martin et al. (2024), the emission of harmful particulates is significantly reduced when faecal sludge is used as a raw material for briquette production. This reduction in emissions contributes to better air quality and lower health risks associated with air pollution, making faecal sludge briquettes an environmentally friendly option for fuel.

- **Carbon Content of Carbonized Faecal Sludge:** The carbon content is a critical factor in determining the fuel efficiency and energy output of RDF. Carbonized faecal sludge has been found to contain approximately 70–71% carbon by weight, as reported by Ramke et al. (2010).

  This high carbon content suggests that faecal sludge briquettes have substantial energy potential, comparable to other high-calorific fuels. The high carbon percentage indicates that faecal sludge, when properly processed and carbonized, can serve as an efficient and potent source of energy.

- **Calorific Value:** The calorific value of a fuel is a measure of the amount of energy released during combustion. Faecal sludge boasts a high calorific content of 17 MJ/kg solids, according to Muspratt et al. (2014).

  This energy density is comparable to, and in some cases surpasses, that of traditional biomass fuels. The high calorific value signifies that faecal sludge briquettes can provide a substantial amount of energy, making them a viable alternative to conventional fuels like coal and wood.

- **Economic Advantages:** Beyond the environmental benefits, faecal sludge briquettes offer significant economic advantages. The cost of producing briquettes from faecal sludge is expected to be substantially lower than the cost of coal.

  This price competitiveness is crucial for countries like Pakistan, where economic constraints often limit access to affordable energy sources. By providing a cheaper alternative to coal, faecal sludge briquettes can help reduce fuel costs for industries, contributing to economic sustainability and energy security.

4.1.2 Hydrothermal Carbonization Vs Pyrolysis

Hydrothermal carbonization (HTC) and pyrolysis are two significant thermochemical processes employed for converting biomass into valuable products such as solid fuels. Both methods have distinct characteristics, advantages, and applications, particularly when applied to the treatment of faecal sludge for resource recovery.

Hydrothermal carbonization operates at relatively low temperatures (180-250°C) and high pressures (2-10 MPa) in a water environment. This process is highly advantageous for wet biomass like faecal sludge, as it does not require pre-drying. HTC produces hydrochar, a carbon-rich solid fuel, along with liquid and gaseous by-products.

The lower energy requirements and ability to handle wet feedstock make HTC energy-efficient and cost-effective for processing high-moisture content materials (Danso-Boateng et al., 2021). Additionally, the process conditions in HTC can lead to a reduction in hazardous compounds, resulting in a cleaner solid fuel (Wang et al., 2018).

In contrast, pyrolysis involves the thermal decomposition of organic materials at higher temperatures (300-900°C) in the absence of oxygen. Pyrolysis is flexible and can be optimized to produce varying proportions of biochar, bio-oil, and syngas by adjusting the operating conditions. However, it typically requires dry feedstock, necessitating additional energy input for drying wet materials like faecal sludge (Wang & Zhang, 2021). Pyrolysis can break down more complex organic compounds due to its higher operating temperatures, producing a broader range of chemical products that can be utilized for various applications (Tripathi et al., 2016).

Comparatively, HTC's lower operating temperatures and pressures result in lower energy consumption compared to pyrolysis. The hydrochar produced by HTC is generally more stable and has a higher energy content than biochar from pyrolysis, making it a superior solid fuel (Funke & Ziegler, 2010). However, pyrolysis offers greater flexibility in product diversity, which can be beneficial for integrated waste management systems aiming to produce multiple useful by-products.

Environmental impacts also differ between the two processes. HTC has been shown to result in lower emissions of pollutants such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals in the final product compared to pyrolysis, making it a more environmentally friendly option for treating faecal sludge (Lu et al., 2022). On the other hand, the higher processing temperatures of pyrolysis can ensure the breakdown of more complex and potentially harmful organic compounds, albeit with a higher energy footprint.

4.1.3 Hydrothermal Carbonization Advantages

Hydrochar is a renewable energy source that offers multiple benefits including:

- **Reduction of greenhouse gas emissions** and compliance with regulations. It is an energy efficient technology that operates at lower temperatures and has shorter processing times, making it well-suited for large-scale industrial applications.
- One of the advantages of hydrochar is its ability to process a wide range of feedstocks, including wet and high-moisture materials. This flexibility in feedstock selection allows for the utilization of various waste streams, making hydrochar a versatile technology.
- In addition to its energy production capabilities, hydrochar also produces valuable co-products such as bio-oil and biogas. These co-products have potential **applications in fuel production, chemical synthesis, and heat generation**. The utilization of these co-products can provide additional revenue streams, enhancing the economic viability of hydrochar technology.
- By leveraging hydrochar as a renewable energy source, industries can contribute to the reduction of greenhouse gas emissions and meet regulatory requirements. The energy-efficient nature of hydrochar, along with its ability to process diverse feedstocks, makes it an attractive option for large-scale industrial applications. The generation of valuable co-products further enhances its economic and environmental benefits, creating a sustainable energy solution.

4.2 Methodology

A proper stepwise procedure was followed for the completion of the project. The importance of proper methodology for any project cannot be overstated. A well-defined and structured methodology provides a systematic approach to project execution, ensuring its success. The project was completed using the following steps.

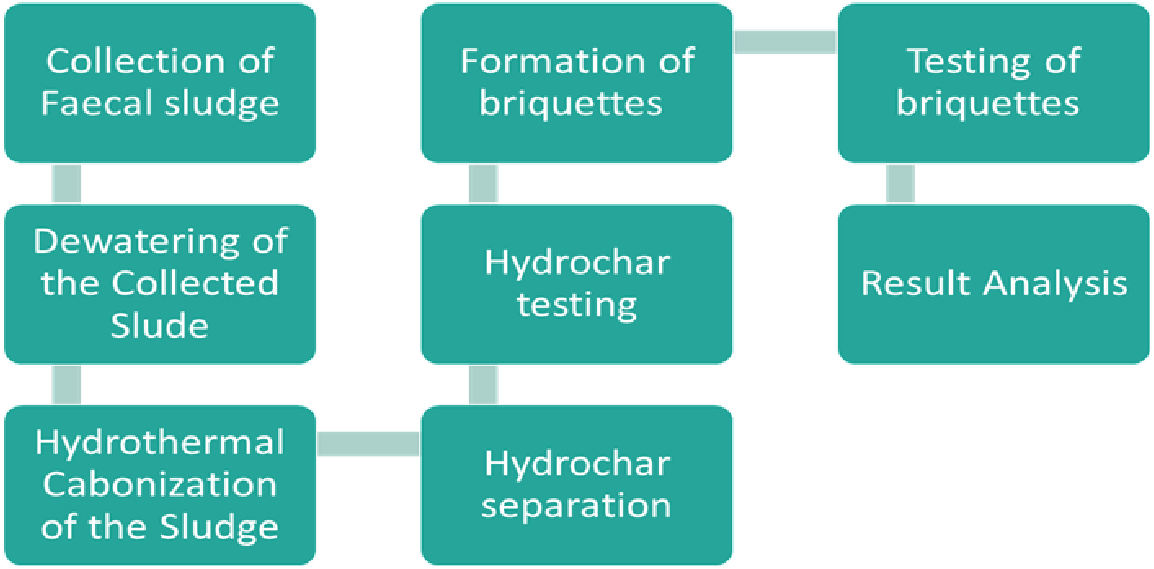


Figure 4.1Steps followed through the course of the Project

4.2.1 Apparatus Used

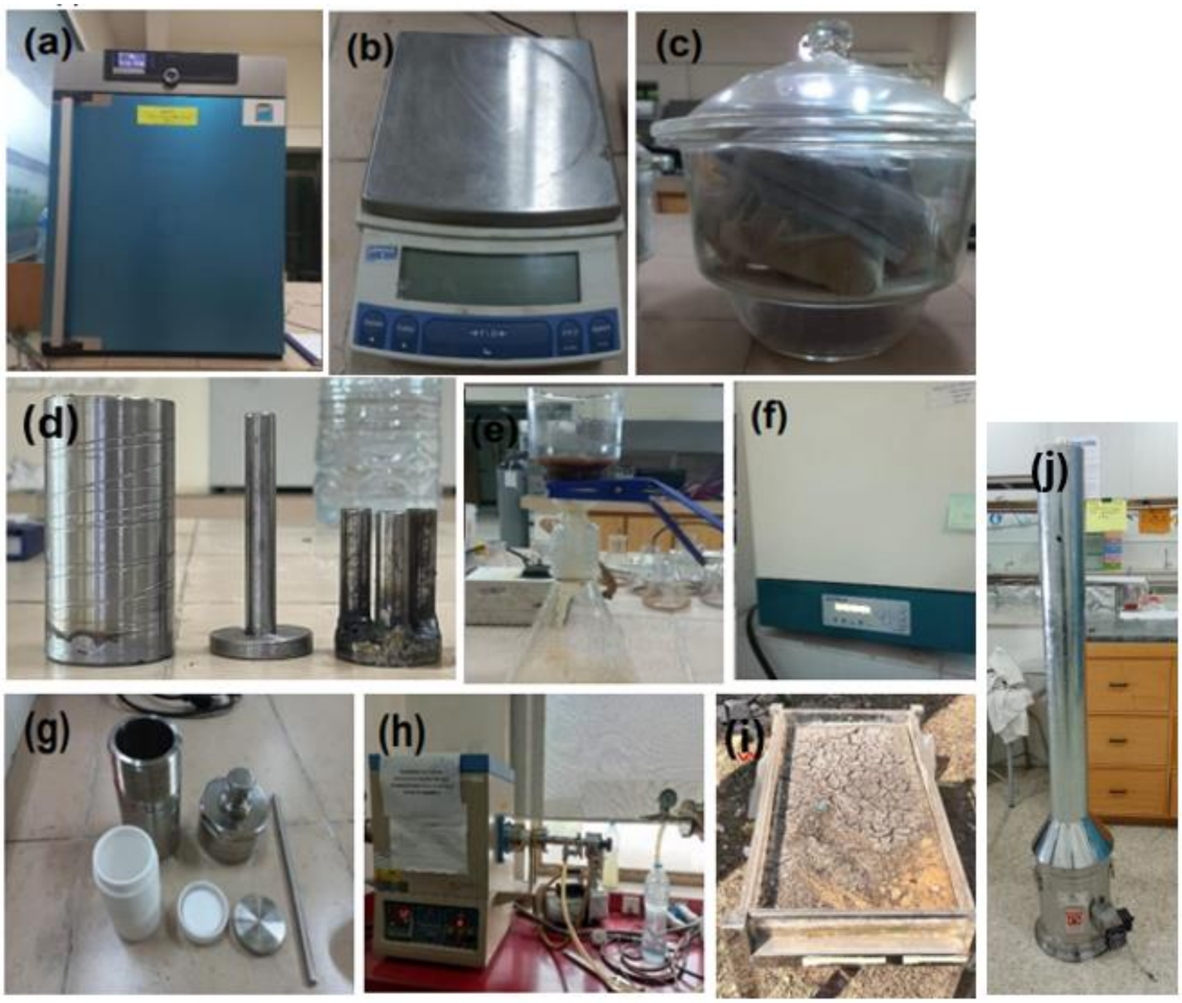


Figure 4.2 shows the apparatus used throughout the project

(a) Hot air oven (b) Measuring Balance (c) Desiccator (d) Briquette mould (e) Filtration Assembly (f) Muffle Furnace (g) Teflon Lined Stainless Steel Autoclave (h) Tube Furnace (i) Sludge drying bed (j) Combustion Chamber

4.2.2 Collection of Faecal sludge

In this study, faecal sludge was collected from septic tanks in Bahria Enclave, focusing on those with a retention time of 2-5 years. Samples were gathered from two houses, each contributing 20 liters, resulting in a total of 40 liters for analysis. The collection process involved accessing the septic tanks and using manual scooping to extract the samples. These were then placed into clean, sealed containers labeled with pertinent information such as house number, date, and time of collection.

The containers were transported to the laboratory under conditions that prevented contamination or degradation of the samples. Detailed records of the collection process, including the location, personnel involved, and observations, were meticulously maintained to ensure the integrity of the samples. This methodical approach aims to provide reliable data for analyzing the characteristics of the faecal sludge, such as chemical composition and potential for reuse or safe disposal, thereby contributing to improved waste management practices in the area.

4.2.3 Dewatering of Faecal sludge

In this study, a crucial step involved the dewatering of faecal sludge collected from septic tanks in Bahria Enclave. To facilitate this, a lab-scale sludge drying bed was constructed according to established design criteria by Sustainable Sanitation Alliance. The drying bed consisted of three layers: a top layer of sawdust, a middle layer of fine gravel, and a bottom layer of coarse gravel.

This layered structure was carefully planned to optimize the dewatering process, with an innovative modification replacing the traditional sand layer with sawdust. The dimensions of the bed are as follows:

Table 4.1 shows the dimensions of lab-scale sludge drying bed

Material	**Design Criteria (cm)**	**Actual dimensions (in)**
Fecal Sludge	< 30 (12”)	2
Wood Sawdust	< 30 (12”)	1.5
Fine Gravel	< 20 (8”)	2.4
Coarse Gravel	> 15 (6”)	7
Underdrain Diameter	> 8 (3”)	3
Height	N/A	30
Length	N/A	40
Width	N/A	20
Length to Width Ratio	N/A	2:1
Area (in^2)	N/A	880
Volume	Designed for 20L of Fecal Sludge	

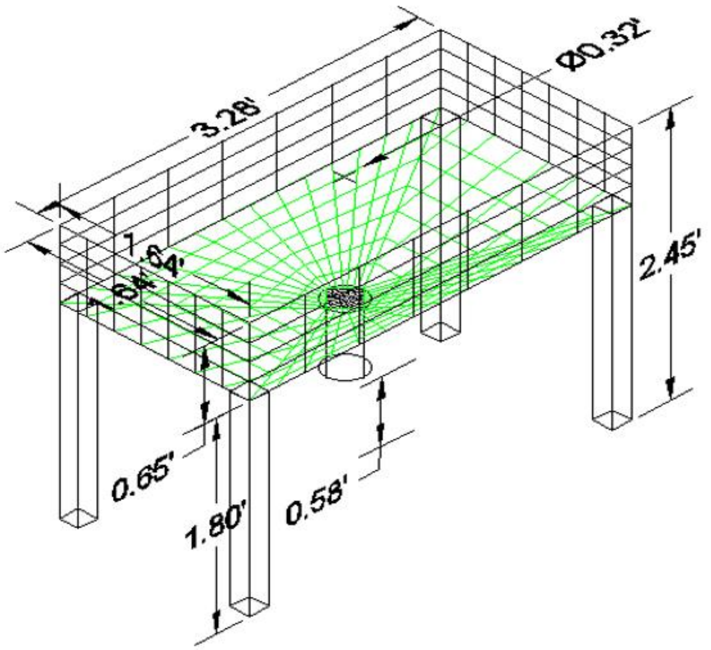


Figure 4.3 shows AutoCAD design of Sludge drying bed

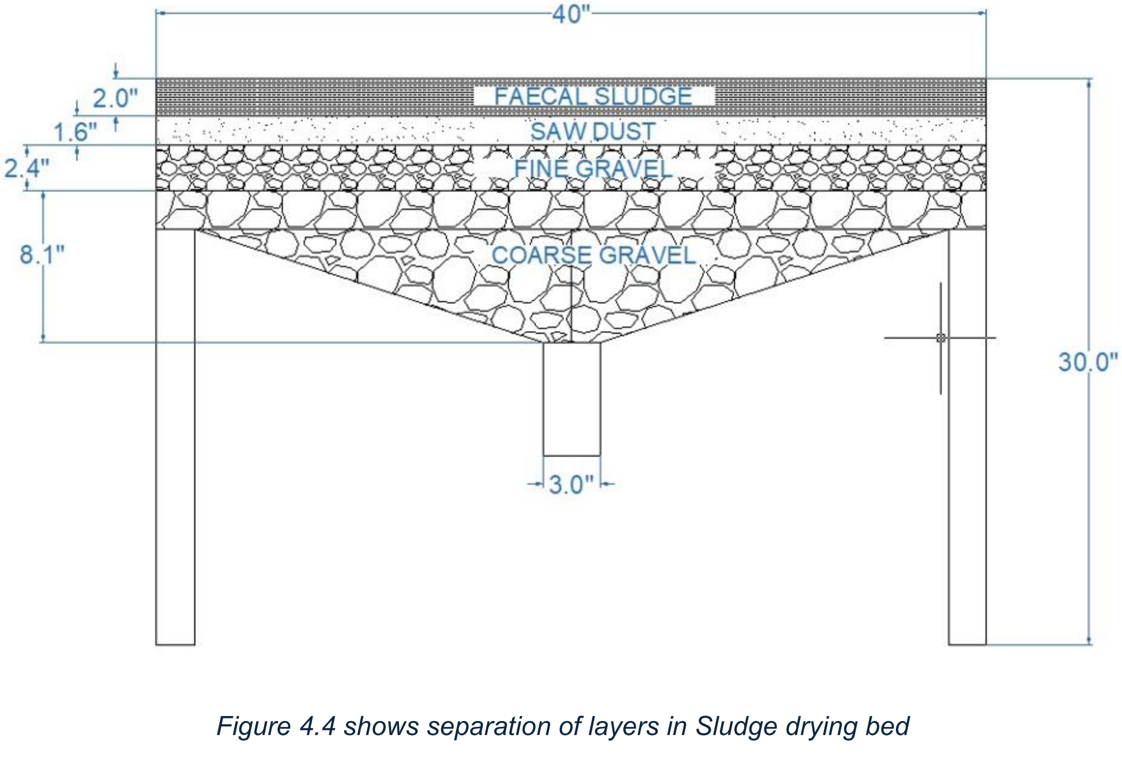


Figure 4.4 shows separation of layers in Sludge drying bed

Figure 4.5 shows the fabricated lab-scale sludge drying bed.

The collected faecal sludge was evenly distributed onto the surface of the lab-scale drying bed. Ensuring an even spread was critical to achieve consistent dewatering across the entire bed. The sawdust layer on top played a pivotal role in this process due to its high absorbent capacity. Sawdust, being more effective at moisture absorption than sand, expedited the drying process, resulting in a quicker reduction of the sludge's moisture content.

Daily monitoring of the sludge's moisture content was conducted to ensure it reached the desired range of 70-75%, which is essential for the effective production of hydrochar. Samples were taken from various points on the bed each day to measure their moisture levels. This consistent monitoring allowed for timely adjustments to the drying process, ensuring the sludge's moisture content remained within the optimal range.

The use of sawdust in the drying bed provided several significant benefits. It not only improved the dewatering efficiency but also increased the calorific value of the sludge. Higher calorific value is beneficial for subsequent processes, such as hydrochar production, which require sludge with greater energy content. Additionally, sawdust is a cost-effective and sustainable alternative to sand, often readily available as a byproduct of wood processing. This substitution not only enhanced the efficiency of the drying bed but also contributed to waste recycling efforts.

4.2.4 Hydrothermal Carbonization of the Dewatered Sludge

The hydrothermal carbonization (HTC) process represents a crucial step in converting dewatered faecal sludge into valuable carbonaceous products. This process is meticulously carried out following stringent procedures and conditions, as outlined below:

1. **Moisture Content Determination:** Before initiating the HTC process, the moisture content of the dewatered sludge sample is carefully determined. This step ensures that the moisture level falls within the optimal range of 70-75%. Accurate measurement of moisture content is vital as it directly influences the efficiency and quality of the subsequent HTC process.
2. **Preparation of Sludge Sample:** The dewatered sludge, confirmed to have the appropriate moisture content, is precisely weighed to ensure consistency and reproducibility of the HTC process. This step involves meticulous handling to avoid any loss or contamination of the sludge sample.
3. **Transfer to Teflon Cup:** The weighted sludge sample is then transferred into a Teflon cup designed specifically for use in the thermal autoclave. Teflon is chosen for its resistance to high temperatures and chemical inertness, ensuring the integrity of the container during the HTC process. The sludge sample is carefully placed into the cup to avoid spillage or uneven distribution.
4. **Thermal Autoclave Setup:** The Teflon cup containing the sludge sample is securely closed to prevent any leakage or escape of material during the HTC process. The thermal autoclave, now tightly sealed with the sludge sample inside, is placed in a muffle furnace preheated to the predetermined temperature of 250 degrees Celsius.
5. **HTC Process Execution:** The thermal autoclave remains in the muffle furnace for a predetermined duration of 2.5 hours. This duration allows for the optimal progression of HTC reactions, ensuring the complete conversion of organic matter present in the sludge into carbonaceous products.
6. **Controlled Heating Rate:** During the HTC process, a controlled heating rate of 5 degrees Celsius per minute is maintained. This gradual increase in temperature prevents sudden thermal shocks to the sludge sample, ensuring uniform heat distribution and efficient reaction kinetics. The controlled heating rate is crucial for maximizing the yield of carbonaceous products while minimizing the risk of undesirable side reactions.

On the completion of the process time, the muffle furnace is turned off. The autoclave was cooled down for further two hours before continuing with subsequent steps (Czerwińska et al., 2022)

4.2.5 Separation of Hydrochar

The products of the process are both solid hydrochar and liquid bio-oil. However, for this project we will only be dealing with the solid part and hence separation of the useful solid part is achieved through filtration.

Vacuum-assisted filtration is used for required separation. The resulting mixture of hydrothermal carbonization is poured into the filtration assembly with filter paper of size 20 µm. The residue on filter paper is hydrochar whereas the liquid is obtained as filtrate (Zhang et al., 2018).

4.2.6 Hydrochar Characterization Analysis

This step is important for the characterization of the obtained hydrochar, especially for the next step of our research i.e. energy generation. The following tests will help us find the suitability of hydrochar and potential problems that can occur during combustion.

1. **Gross Calorific Value:** The prepared hydrochar samples are taken to USP-CASE, NUST for Higher Heating value (HHV) or Gross Calorific value (GCV) analysis. The determination of calorific value takes place inside a bomb calorimeter.

   A mass of between 0.5 to 1.0 g of hydrochar inside a crucible with a pellet is introduced into the bomb that is filled with oxygen. The calorimeter filled with water is maintained at adiabatic conditions and is ignited electrically. The rise of water temperature can be used to determine the HHV (Friedl et al., 2005).

2. **Proximate Analysis:**

   Considering the sample obtained is dry basis we performed proximate analysis is used to find three important characteristic values of the hydrochar which are:

   a. <u>Volatile Combustible Matter:</u> The next step is to determine the volatile organic matter content of hydrochar. The ASTM methods E857 are used for this purpose. The hydrochar is weighed and placed in the muffle furnace inside a covered crucible at 950°C for 7 minutes. After seven minutes it is taken out and cooled down before reweighing it.

$$VM\,\% = \frac{v_i - v_f}{V1} \text{………………………………………………… eq 1}$$

v_i = initial mass of hydrochar before placing it in the furnace

v_f= final mass of hydrochar after taking it out of the furnace

However, the preliminary results obtained from the proximate analysis in the muffle furnace was not satisfactory. The process was repeated in a tube furnace which gave promising results (Cassel et al., 2012).

b. Ash Content:

Ash content determination is important to find as it reduces the HHV value of hydrochar. It also has a negative impact on combustion efficiency. Following the ASTM method, 31 E1755 the remaining contents in the crucible are again placed in the muffle furnace but this time without cover and at about 750°C.

There is no set time limit for this step to continue the process until the mass becomes constant or turns grayish white. Initially, it is placed for an hour, but the time can go as high as 4 hours. The sample is weighed at an interval of 30 minutes. After taking it out of the furnace it is placed in the desiccator to allow it to cool and then reweighed.

$$Ash\,\% = \frac{f_i - f_f}{v_f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq 2}$$

Where, f_i = initial mass of hydrochar before placing it in the furnace the second time

f_f= final mass of hydrochar after taking it out of the furnace

c. Fixed Carbon Content:

Fixed carbon content is another important parameter as high fixed carbon content means high HHV value (Heidari et al., 2019).

$$FC\,\% = 100\% - \%\,VM - \%\,Ash \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq 3}$$

3. Ultimate Analysis:

The prepared hydrochar samples are taken to Pakistan Institute of Nuclear Science & Technology (PINSTECH) for Ultimate analysis. It determines the amount of carbon, hydrogen, nitrogen, sulphur, and oxygen in a sample. The determination of calorific value takes place inside an Elemental Analyzer. A mass of between 0.5 to 1.0 g of briquette inside a crucible with a pellet is introduced into the analyzer. The Elemental Analyzer works on combustion principle. The combustion of the sample generates uniform compound gases of the elements C, H, N and S. These combustion products (e.g. CO2, H2O, NO2, etc.) are measured using gas chromatography.

C, H, N and S are determined simultaneously whereas O is analyzed by pyrolysis in the next step. The CHNS content of a sample is determined by weighing the sample and wrapping it in tin boats and for oxygen silver boats. High temperature combustion of the sample (1150°C for CHNS analysis) in an oxygen rich environment oxidizes the sample, this is followed by controlled reduction of the gases formed during combustion.

Through this process any carbon contained in the sample is converted to CO2, hydrogen to H20, nitrogen to N2 and sulphur to SO2.

4.2.7 Production of Briquettes

After separating the hydrochar from the HTC slurry, the next step involves converting it into cylindrical briquettes for effective utilization. This process begins with fabricating a mold with specific dimensions tailored to produce uniformly shaped briquettes. The briquetting process offers several advantages, including improved handling, storage, and combustion efficiency.

Table 4.2 shows the Dimensions of Briquette mold

Parameters	Dimension (inch)
Height	6
Diameter	3.2
Diameter of center rod	0.75

Figure 4.6 shows the fabricated Briquette mold

In this study, three variants of briquettes were produced:

Table 4.3 shows the composition briquettes

	FS hydrochar	Rice husk	Wheat Straw
FS	100%	0%	0%
FS+RH	70%	30%	0%
FS+WS	70%	0%	30%

Each variant also includes 5% by weight engine oil and 10% by weight starch, which act as binding agents to enhance the structural integrity and durability of the briquettes.

The FS hydrochar was mixed with the respective crop residues (rice husk or wheat straw) and binding agents (engine oil and starch). The proportions were carefully measured to ensure homogeneity in the mixtures. The mixture was transferred into the mould and then compressed using a hydraulic press. The hydraulic press ensures that the mixture is compacted to the desired density, which is crucial for the structural integrity and performance of the briquettes. Once formed, the briquettes were left to dry for two weeks under ambient conditions. This drying period allows for the evaporation of any residual moisture, ensuring that the briquettes attain optimal hardness and stability. Proper drying is essential to enhance the briquettes' combustibility and storage lifespan.

By incorporating crop residues and binding agents, the briquettes' strength and utility are significantly enhanced, making them a viable option for sustainable energy production. This approach not only improves the mechanical properties of the briquettes but also adds value to agricultural residues, contributing to a more sustainable waste management strategy.

4.2.8 Briquettes Characterization Analysis

Characterization of the produced briquettes is crucial for determining their suitability for energy generation and identifying potential problems during combustion. The following tests will provide comprehensive insights into the physical, chemical, and mechanical properties of the briquettes.

1. **Bulk Density:** Determining the bulk density helps in assessing the storage and handling characteristics of the briquettes. Higher bulk density indicates better energy storage and transportation efficiency. Briquettes with maximum bulk density have a slower burning rate and longer ignition time due to their denser structure, which requires more time for heat to penetrate and ignite the fuel.

   According to ASTM E873 - Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels, a known volume of briquettes is weighed using a digital balance. The volume of the briquettes is measured using a graduated cylinder or by calculating the volume based on the briquettes' dimensions. The bulk density is then calculated using the formula:

$$Bulk\ density = \frac{Mass\ of\ Briquette}{Volume\ of\ Briquette} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ eq\ 5$$

2. **Gross Calorific Value:** Same procedure followed as mentioned in Section 4.2.5 (part a).
3. **Proximate Analysis:** Same procedure followed as mentioned in Section 4.2.5 (part b).
4. **Ultimate Analysis:** Same procedure followed as mentioned in Section 4.2.5 (part c).
5. **Mechanical drop Test:** The mechanical drop test was adapted from the principles outlined in ASTM D440 - Standard Test Method of Drop Shatter Test for Coal. In this adapted procedure, briquettes were dropped from three different heights—2 feet, 4 feet, and 6 feet—onto a hard surface to assess their impact resistance and durability.

   For each height, the appearance of cracks and other visible structural damages were carefully observed and recorded. The test was repeated for multiple samples to ensure reliability. By comparing the extent of cracking and damage at each height, we evaluated the robustness of the briquettes, with those showing minimal damage at higher drop heights demonstrating superior durability.

6. **Mechanical Impact Resistance Test:** Briquette durability was determined using standardized briquette strength tests proposed by Taulbee et al. and Richards. This method provides a quantitative measure of the impact resistance of the briquettes, crucial for evaluating their performance under handling and transportation conditions.

   In this procedure, each briquette was dropped from a height of 2 feet onto a hard surface, and the number of drops required to shatter each briquette was recorded. This process was repeated for multiple samples to ensure reliability. The average number of drops required to shatter the briquettes and the average number of pieces into which they shattered were calculated. The Impact Resistance Index (IRI) was then determined using the formula:

   $$IRI = 100 \times \frac{average\ number\ of\ drops}{Average\ number\ of\ pieces} \text{ .... eq 6}$$

   A higher IRI indicates better impact resistance and durability, suggesting that the briquettes can withstand handling and transportation stresses more effectively. The acceptable limit for IRI is 50, and briquettes with an IRI above this threshold are considered durable enough for practical applications.

7. **Compressive Strength:** The mechanical compression test measures the strength and structural integrity of the briquettes, which is crucial for ensuring they can maintain their shape under pressure. Following ASTM D440 - Standard Test Method of Drop Shatter Test for Coal, a briquette is placed in a compression testing machine.

Compressive force is applied until the briquette breaks, and the maximum force applied is recorded. This process is repeated for multiple samples to calculate the average compressive strength.

8. **Flue gas Analysis:** Flue gas analysis helps assess the environmental impact of the briquettes by measuring the emissions produced during combustion. According to ASTM D6522 - Standard Test Method for Determination of Nitrogen Oxides, Carbon Monoxide, and Oxygen Concentrations in Emissions from Natural Gas-Fired Reciprocating Engines, Combustion Turbines, Boilers, and Process Heaters using Portable Analyzers, the briquette is burned in a controlled combustion chamber.

   A flue gas analyzer is used to measure the concentration of gases such as CO_2, CO, NO_x, and SO_2. The gas concentrations are recorded and analyzed to determine the emissions profile.

9. **PM Analysis:** Particulate matter (PM) analysis determines the amount and size distribution of particulates released during combustion, which is crucial for assessing air quality and health impacts. This analysis helps identify the potential environmental and health risks associated with using the briquettes as a fuel source.

   In this procedure, a combustion chamber equipped with a PM sensor, following guidelines from ASTM D6216 - Standard Practice for Opacity Monitor Manufacturers to Certify Conformance with Design and Performance Specifications, was used to measure particulate emissions during the burning of briquettes. A briquette sample is placed in the combustion chamber, where controlled conditions simulate typical combustion scenarios.

   Upon ignition, the PM sensor continuously monitors and records particulate emissions in real-time, specifically measuring PM2.5 and PM10. These measurements are critical as PM2.5 and PM10 represent fine and coarse particulate fractions that have significant health implications. The sensor records the values of particulate emissions, which are then extracted from its software for further analysis.

Chapter 5 Results and Discussions

5.1 FSM Dashboard

5.1.1 Overview of Pilot Implementation

The pilot implementation of the FSM dashboard in Bahria Enclave, Islamabad, aimed to optimize the collection, transportation, and management of faecal sludge. The primary objectives were to improve efficiency, reduce operational costs, and enhance transparency in the FSM process. The pilot phase, which lasted for one month, involved sector-by-sector digitization of data and faced challenges such as poorly stored data and the need for manual surveys to gather accurate information.

5.1.2 Scheduling Efficiency and Route Optimization

One of the key functionalities of the FSM dashboard was the automated scheduling of desludging activities based on historical data and predictive analysis. This feature significantly improved the scheduling efficiency, ensuring timely operations and reducing the risk of overflow. The GIS-based routing system further optimized the process by minimizing travel time and fuel consumption.

The performance metrics indicated that the optimized scheduling and routing resulted in significant cost savings. The management of Bahria Enclave saved approximately 50,000 PKR on fuel expenses alone due to the reduction in travel distance and more efficient route planning. The dashboard's role in enhancing transparency and accountability in FSM processes was also highlighted in the user feedback.

5.1.3 Challenges and Solutions

The implementation phase encountered several challenges, including technical glitches and resistance to change from some users. These issues were addressed through iterative testing, user training, and continuous support. The development team worked to resolve technical problems and incorporate feedback for continuous improvement.

Overall, the pilot implementation of the FSM dashboard yielded positive results, demonstrating its potential for broader application in other urban areas. The dashboard's functionalities significantly improved the efficiency and transparency of faecal sludge management processes.

5.2 Faecal Sludge Briquettes

5.2.1 Overview of Briquette Production

The study explored the feasibility and environmental impact of using faecal sludge briquettes as an alternative to coal for energy production. The production process involved several steps, including the collection and dewatering of faecal sludge, hydrothermal carbonization (HTC), and briquetting.

5.2.2 Collection and Dewatering of Faecal Sludge

Faecal sludge was collected from septic tanks in Bahria Enclave, focusing on those with a retention time of 2-5 years. The collected sludge was dewatered using a lab-scale sludge drying bed, which consisted of layers of sawdust, fine gravel, and coarse gravel. The use of sawdust, instead of sand, significantly improved the dewatering efficiency and increased the calorific value of the sludge.

5.2.3 Hydrothermal Carbonization (HTC)

The dewatered sludge was subjected to HTC, a thermochemical process that converts organic materials into carbon-rich hydrochar. The HTC process was carried out at 250°C for 2.5 hours, with a controlled heating rate of 5°C per minute. The resulting hydrochar was then separated from the liquid bio-oil using vacuum-assisted filtration.

The yield per process was approximately 82% in terms of mass, with 63 g of collected faecal sludge producing around 60.6 g of hydrochar. The mass balance is as follows:

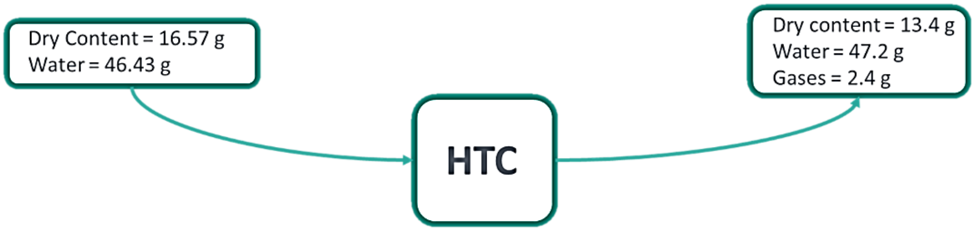


Figure 5.1 shows Mass balance of the HTC process

5.2.4 Briquetting

The hydrochar was mixed with binding agents (5% engine oil and 10% starch) and compressed into cylindrical briquettes using a hydraulic press. Three variants of briquettes were produced: 100% faecal sludge hydrochar (FS), 70% faecal sludge hydrochar with 30% rice husk (FS+RH), and 70% faecal sludge hydrochar with 30% wheat straw (FS+WS). The briquettes were dried for two weeks under ambient conditions to achieve optimal hardness and stability.

5.2.5 Characterization and Testing

The briquettes were subjected to various tests to determine their suitability for energy generation. The tests included bulk density, gross calorific value, proximate analysis, ultimate analysis, mechanical drop test, compressive strength, flue gas analysis, and particulate matter (PM) analysis.

1. **Bulk Density**

Table 5.1 shows Bulk Density of Briquettes.

Type	**Bulk density (g/cm3)**
FS	1.13
FS+RH	0.92
FS+WS	0.77
Lignite coal*	0.75

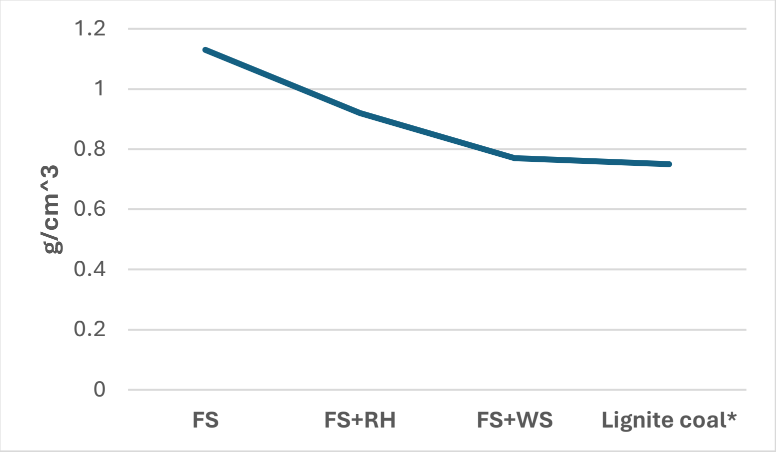


Figure 5.2 shows graphical representation of bulk densities of briquettes

The bulk density of 100% Faecal Sludge hydrochar (FS) is the highest at 1.13 g/cm³, indicating a denser and potentially more energy-efficient fuel. The FS+Rice Husk (0.92 g/cm³) and FS+Wheat Straw (0.77 g/cm³) variants have lower bulk densities, suggesting lighter briquettes. Interestingly, lignite coal has the lowest bulk density at 0.75 g/cm³. These results suggest that faecal sludge briquettes, particularly FS, could be more efficient and sustainable than lignite coal. Studies have shown that denser briquettes often have higher energy content, which contributes to their efficiency (Bhattacharya et al., 1993).

The inclusion of agricultural residues (rice husk and wheat straw) in FS+RH and FS+WS variants further enhances sustainability by recycling waste materials. Incorporating agricultural residues not only improves sustainability but also leverages waste materials effectively (Demirbas, 2004). The briquette with maximum bulk density (FS) has a slower burning rate and longer ignition time due to its denser structure, which requires more time for heat to penetrate and ignite the fuel. In contrast, FS+RH has an optimal bulk density and ignition time, balancing efficiency and practical usability. The relationship between bulk density and combustion characteristics, such as ignition time and burning rate, is well-documented, indicating that denser fuels typically exhibit longer ignition times (Lu et al., 2000).

2. Gross Calorific Value

Table 5.2 shows Gross Calorific Values of Briquettes.

Type	**Calorific value (MJ/kg)**
FS	28
FS+RH	26.7
FS+WS	23.4
Lignite coal*	21.28

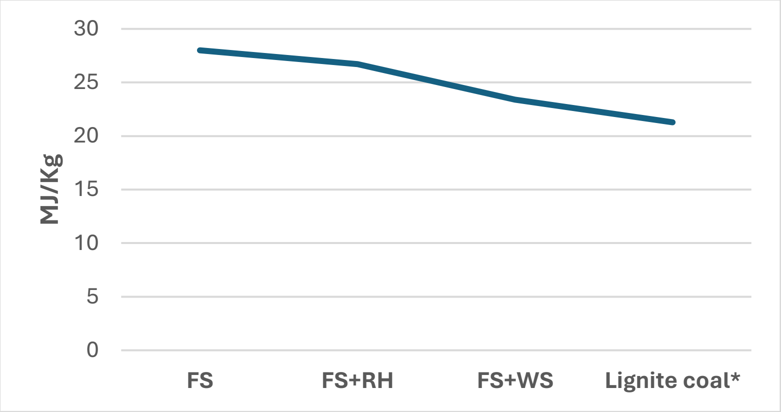


Figure 5.3 shows graphical representation of Gross Calorific value of briquettes

The Gross Calorific Values of various faecal sludge-based briquettes indicate their potential as sustainable fuel alternatives. The 100% Faecal Sludge hydrochar (FS) briquette has the highest calorific value at 28 MJ/kg, making it the most energy-rich among the tested samples. The FS+Rice Husk (FS+RH) and FS+Wheat Straw (FS+WS) variants have calorific values of 26.7 MJ/kg and 23.4 MJ/kg, respectively. Lignite coal has the lowest calorific value at 21.28 MJ/kg. These results suggest that faecal sludge-based briquettes, especially FS, are more energy-efficient compared to lignite coal. FS+RH also shows a relatively high energy content, making it a viable alternative while incorporating agricultural residues.

3. Proximate Analysis

Table 5.3 shows Proximate analysis of briquettes.

Type	**Moisture Content %**	**Volatile Matter %**	**Ash Content %**	**Fixed Carbon %**
FS	7.65	56.81	13.14	22.4
FS+RH	7.16	59.7	11.34	21.8
FS+WS	7.43	54.52	14.67	23.38
Lignite coal*	20.5	50.34	9.82	19.34

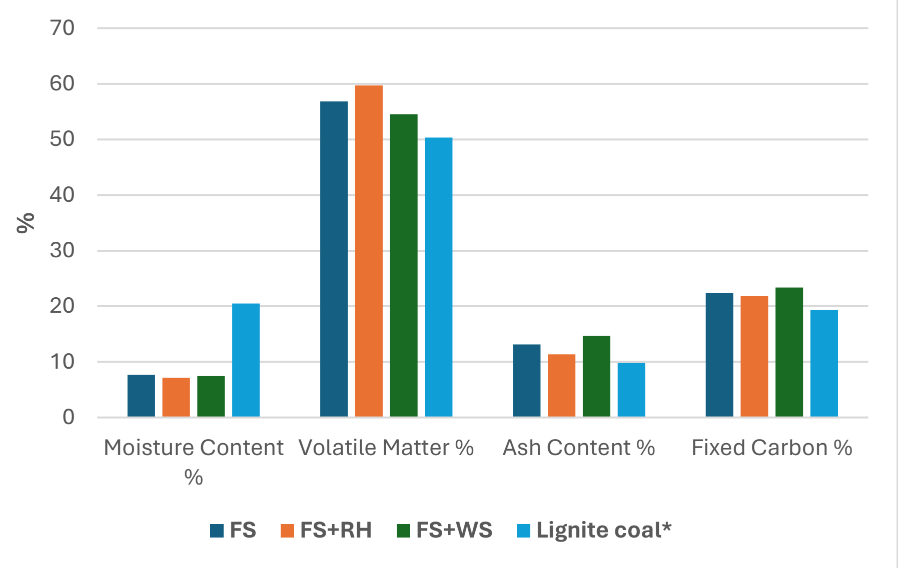


Figure 5.4 shows graphical representation of Proximate Analysis of briquettes

The proximate analysis of various faecal sludge-based briquettes compared to lignite coal reveals their potential as efficient and sustainable fuel alternatives. Faecal sludge (FS) briquettes show lower moisture content (7.65-7.43%) compared to lignite coal (20.5%), enhancing combustion efficiency and reducing energy loss (Bhattacharya et al., 1993). FS+Rice Husk (FS+RH) briquettes have the highest volatile matter at 59.7%, facilitating better ignition and easier combustion (Lu et al., 2000). FS+RH also has the lowest ash content at 11.34%, resulting in less residue and higher fuel efficiency (Demirbas, 2004). Additionally, FS+Wheat Straw (FS+WS) briquettes exhibit the highest fixed carbon content at 23.38%, contributing to a higher calorific value and prolonged combustion (Vassilev et al., 2010).

4. Ultimate Analysis

Table 5.4 shows Ultimate Analysis of Briquettes.

Type	**C%**	**H%**	**N%**	**S%**	**O%**
FS char	58.4	4.26	2.05	0.8	9.42
FS + RH	56.8	3.5	1.76	0.62	17.2
FS + WS	51.44	3.64	1.25	0.41	12.4
Lignite Coal*	47.4	5.7	0.63	2.05	37.4

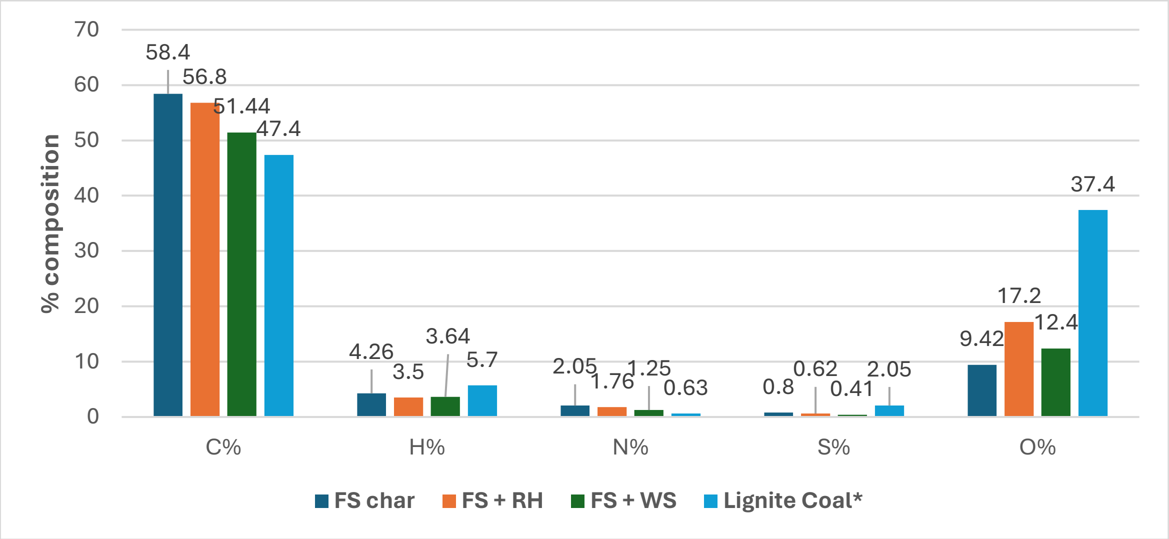


Figure 5.5 shows graphical representation of Ultimate Analysis of briquettes

The ultimate analysis of various faecal sludge-based briquettes compared to lignite coal reveals significant differences in their chemical composition, impacting their fuel performance. FS char has the highest carbon content (58.4%), indicating higher energy density compared to FS+RH (56.8%) and FS+WS (51.44%), with lignite coal having the lowest at 47.4%. High carbon content is associated with higher energy density and efficiency (Bhattacharya et al., 1993). Hydrogen content is highest in lignite coal (5.7%), which may enhance combustion efficiency, while FS char, FS+RH, and FS+WS have lower hydrogen contents.

Nitrogen content is highest in FS char (2.05%), which can lead to higher NOx emissions, a noted environmental concern (Demirbas, 2004). Sulfur content is significantly lower in faecal sludge briquettes, with FS+WS having the lowest (0.41%), reducing SOx emissions compared to lignite coal's 2.05% sulfur content, a benefit for air quality (Lu et al., 2000). The oxygen content is highest in lignite coal (37.4%), which correlates with lower calorific value and combustion efficiency; FS char's lower oxygen content (9.42%) suggests better combustion properties (Vassilev et al., 2010).

5. Mechanical Drop test

Table 5.5 shows results of Drop test of Briquettes

Type of Briquette	**2ft**	**4ft**	**6ft**
FS char	No cracks	No cracks	few small cracks
FS + RH	No cracks		
FS + WS	No cracks	No cracks	few cracks
Lignite Coal*	No cracks		

The mechanical drop test results of faecal sludge-based briquettes compared to lignite coal reveal their structural integrity under impact conditions. FS char, FS+RH, FS+WS, and lignite coal all show no cracks when dropped from 2ft and 4ft. At 6ft, FS char shows a few small cracks, FS+WS has a few cracks, while FS+RH and lignite coal remain intact. This suggests that FS+RH briquettes have comparable mechanical strength to lignite coal, making them suitable for handling and transportation. The inclusion of rice husk enhances the structural integrity of FS+RH briquettes, as supported by literature indicating that lignocellulosic materials improve mechanical strength (Bhattacharya et al., 1993; Grover & Mishra, 1996).

6. Impact Resistance test

Table 5.6 shows IRI of Briquettes

Type of Briquette	IRI (2ft)
FS char	61
FS + RH	74
FS + WS	56
Lignite coal*	81

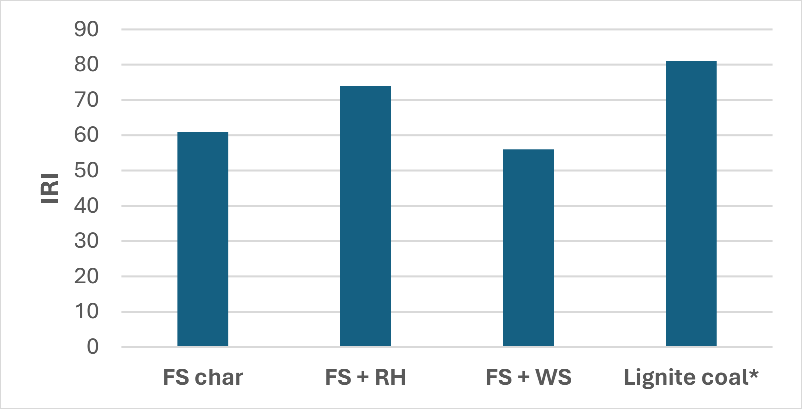


Figure 5.6 shows graphical representation of Impact resistance index

The Impact Resistance Index (IRI) test results indicate that lignite coal has the highest IRI at 81, demonstrating superior impact resistance, followed by FS+RH briquettes at 74, FS char at 61, and FS+WS at 56. This suggests that FS+RH briquettes, reinforced by rice husk, possess considerable mechanical strength, making them suitable for handling and transportation (Kaliyan & Morey, 2009). While lignite coal exhibits the best impact resistance, the inclusion of lignocellulosic materials like rice husk in FS+RH improves the structural integrity of these briquettes (Mani et al., 2006).

7. Mechanical Compression test

Table 5.7 shows Compressive Strength Value of Briquettes.

Type of Briquette	**Compressive Strength (N/mm2)**
FS char	1.53
FS + RH	2.35
FS + WS	0.78
Lignite Coal*	3.75

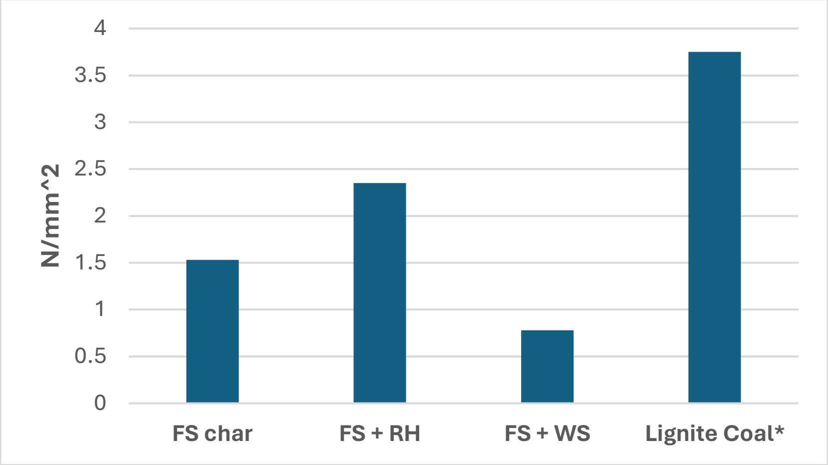


Figure 5.7 shows graphical representation of Compressive strength of briquettes

The mechanical compression test results show that lignite coal has the highest compressive strength at 3.75 N/mm², indicating superior structural integrity. Among the faecal sludge briquettes, FS+RH exhibits the highest compressive strength at 2.35 N/mm², followed by FS char at 1.53 N/mm², and FS+WS at 0.78 N/mm². These findings suggest that FS+RH briquettes, reinforced by rice husk, have considerable compressive strength, making them suitable for handling and storage (Okot et al., 2018). FS char also demonstrates good durability, though lower than FS+RH. The lower compressive strength of FS+WS indicates it may be less durable under mechanical stress.

8. Flue gas Analysis

Table 5.8 Shows Flue gas emissions of briquettes

Type of Briquette	CO (ppm)	NO (ppm)	NOx (ppm)	Sox (ppm)
FS char	17	2	2	0
FS + RH	14	1	1	0
FS + WS	20	1	1	0
Lignite Coal*	1004	14	14	11

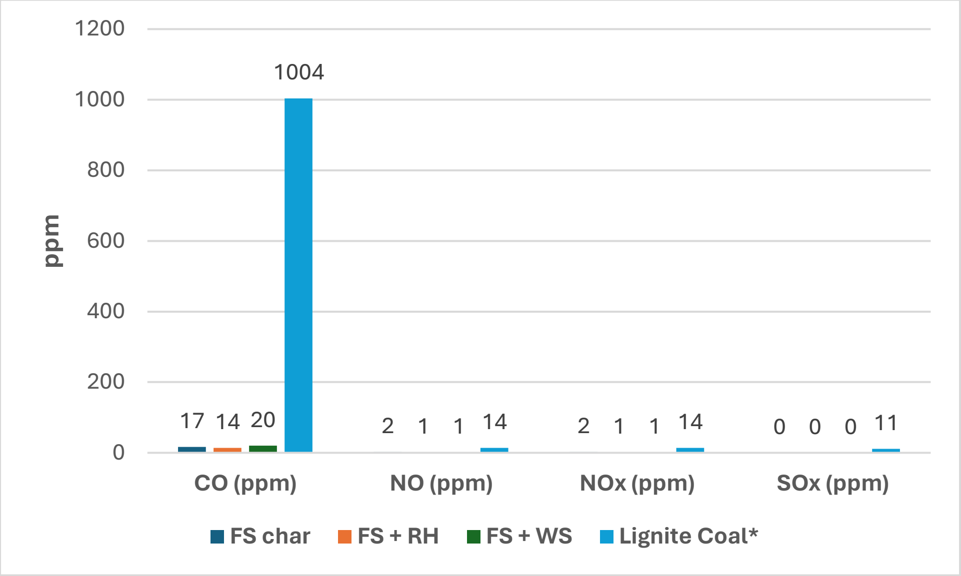


Figure 5.8 shows graphical representation of Flue gas emission

The flue gas analysis of various faecal sludge-based briquettes compared to lignite coal reveals significant differences in their emissions, highlighting their environmental impact. FS char, FS+RH, and FS+WS briquettes all produce CO emissions far below the National Environmental Quality Standards (NEQS) limit of 640 ppm, with values of 17 ppm, 14 ppm, and 20 ppm respectively. In stark contrast, lignite coal produces a CO emission of 1004 ppm, significantly above the NEQS limit. Similarly, NO and NOx emissions from all faecal sludge-based briquettes are minimal, ranging from 1-2 ppm, well below the NEQS limit of 900 ppm, whereas lignite coal emits 14 ppm for both NO and NOx. Importantly, all faecal sludge-based briquettes produce no SOx emissions, compared to lignite coal's 11 ppm, which, although within the NEQS limit of 500 ppm, still contributes to air pollution. The absence of SOx emissions underscores their environmental benefits, reducing the risk of acid rain formation and respiratory problems associated with sulfur oxides (Grover & Mishra, 1996).

These results suggest that faecal sludge-based briquettes are environmentally superior to lignite coal, emitting significantly lower levels of harmful gases. The low CO and NOx emissions from faecal sludge-based briquettes indicate a cleaner combustion process (Demirbas, 2004).

9. PM (2.5 & 10) Analysis

Table 5.9 shows PM emissions of briquettes

Type of Briquette	PM 2.5 (ug/m3)	PM 10 (ug/m3)
FS char	265	310
FS + RH	69	74
FS + WS	138	142
Lignite Coal*	730	754

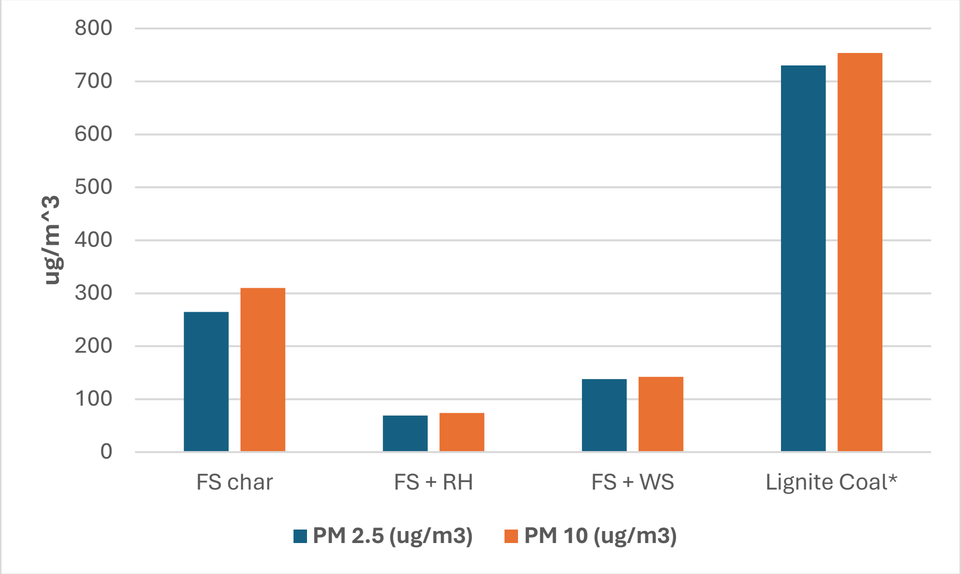


Figure 5.9 shows graphical representation of PM emissions

The PM (2.5 and 10) analysis of various faecal sludge-based briquettes compared to lignite coal highlights significant differences in particulate matter emissions, a critical factor for air quality and health. FS char, FS+RH, and FS+WS briquettes produce PM 2.5 emissions of 265 µg/m³, 69 µg/m³, and 138 µg/m³, respectively, while lignite coal emits a substantially higher 730 µg/m³. Similarly, for PM 10, FS char emits 310 µg/m³, FS+RH emits 74 µg/m³, FS+WS emits 142 µg/m³, and lignite coal emits 754 µg/m³. These results indicate that all faecal sludge-based briquettes emit lower levels of particulate matter compared to lignite coal, although they still exceed the World Bank's guideline limit of 50 mg/nm³ for power plants (World Bank, 1998).

FS+RH briquettes show the lowest PM emissions among the faecal sludge variants, making them the most environmentally friendly option. The reduced particulate matter emissions from FS+RH can be attributed to the presence of rice husk, which enhances combustion efficiency and reduces the formation of particulate pollutants (Kaliyan & Morey, 2009). FS char and FS+WS, while better than lignite coal, still have higher PM emissions but remain below the emissions of lignite coal, suggesting improved air quality when using these briquettes (Demirbas, 2004).

**Kanwal. S et al (2019).*

5.2.6 Environmental and Economic Impact

The results indicated that faecal sludge briquettes have several advantages over traditional fuels:

- **High Calorific Value**: The briquettes had a high energy content, making them an efficient fuel source.
- **Low Emissions**: Compared to traditional fuels like coal, faecal sludge briquettes produced lower emissions of harmful pollutants, such as particulate matter (PM2.5 and PM10) and greenhouse gases.
- **Cost-Effective**: The production of faecal sludge briquettes was economically viable, with lower production costs compared to conventional fuels.

The environmental impact assessment showed that the use of faecal sludge briquettes could significantly reduce emissions and improve air quality. The cost-benefit analysis revealed substantial cost savings in fuel expenses, making faecal sludge briquettes a sustainable and economically viable alternative to traditional fuels.

5.2.7 Cost Benefit Analysis

The cost-benefit analysis of producing faecal sludge briquettes demonstrates significant economic and environmental benefits. The analysis reveals that the production process is both viable and cost-effective.

Production Costs

The initial investment costs include the purchase and installation of briquetting machines and an HTC reactor. The breakdown is as follows:

- **Briquetting Machine (x2)**: 900,000 PKR
- **Reactor for HTC**: 550,000 PKR
- **Installation Costs**: 100,000 PKR

The total investment cost is **1,550,000** PKR.

Annual operational costs include maintenance and electricity:

- **Maintenance (Briquetting)**: 50,000 PKR
- **Maintenance (HTC Reactor)**: 50,000 PKR
- **Electricity (Briquetting)**: 743,600 PKR
- **Electricity (HTC Reactor)**: 365,040 PKR

The total yearly operational costs amount to **1,208,640** PKR.

Revenue and Savings

The revenue generated from selling the briquettes provides substantial returns:

- **Faecal Sludge Collected**: 1,044 kg/week
- **Briquettes Produced**: 877 kg/week
- **Selling Price per kg**: 100 PKR

The total annual revenue from briquette sales is 4,560,192 PKR. With annual costs of 1,208,640 PKR, the total profit per year is **2,441,552** PKR.

Investment Costs	**Amount (PKR)**
Briquetting Machine x2	900,000
Reactor For HTC	550,000
Installation Costs	100,000
Total Investment Cost	1,550,000

Yearly Costs	**Amount (PKR)**
Maintenance (Briquetting)	50,000
Maintenance (HTC Reactor)	50,000
Electric (Briquetting)	743,600
Electric (HTC Reactor)	365,040
Total Yearly Costs	1,208,640

Revenue	**Amount (PKR)**
Faecal Sludge Collected	1,044 kg/week
Briquettes Produced	877 kg/week
Selling Price per kg	100 PKR
Total Revenue Per Year	4,560,192

Return Period	
Total Profit Per Year	2,441,552
Return on Investment	0.63 years

Table 5.1 Cost Benefit Analysis of Briquetting and Return Period

Savings

The implementation of the FSM dashboard also contributed to cost savings:

- Total Savings on Fuel Expenses per Year: 50,960 PKR

	Current	**Proposed**
Total Average Desludging Per Day	1	1
Total Maximum Desludging Per Day	3	3
Total Distance Travelled Per Trip	30 km	30 km
Total Average Fuel Used Per Trip	3.3 liters	3.3 liters
Total Cost Per Trip	980 PKR	980 PKR
Total Cost Per Year	101,920 PKR	50,960 PKR
Total Savings Per Year	-	**50,960 PKR**

Table 5.2 Breakdown of Expenditures of Desludging of Septic Tank

Overall, the project not only demonstrated the environmental benefits of reducing harmful emissions but also proved to be economically viable with a short return on investment period of just 0.63 years. These savings and profits underscore the potential for broader adoption of faecal sludge briquettes as a sustainable energy source.

Chapter 6 Conclusion

6.1 Summary of the Project

This project aimed to address critical issues in Faecal Sludge Management (FSM) in urban areas of Pakistan, with a particular focus on Bahria Enclave, Islamabad. The dual objectives were to design and implement a digital dashboard to optimize the FSM process and to explore the feasibility of converting faecal sludge into Refuse Derived Fuel (RDF) briquettes as a sustainable energy alternative. The comprehensive approach included planning, development, implementation, and evaluation of both the digital solution and the physical product.

6.2 Key Findings

FSM Dashboard:

- Improved Efficiency and Cost Savings: The FSM dashboard, featuring automated scheduling and GIS-based route optimization, significantly improved the efficiency of desludging operations. The optimized scheduling and routing reduced operational costs, saving approximately 50,960 PKR annually on fuel expenses.
- Enhanced Transparency and User Satisfaction: The dashboard provided a user-friendly interface for real-time monitoring and data entry. Users reported high satisfaction levels, appreciating the transparency and accountability it brought to the FSM process.
- Effective Training and Support: Comprehensive training sessions and continuous support ensured that users could effectively utilize the dashboard, addressing initial resistance and technical challenges.

Faecal Sludge Briquettes:

- High Calorific Value: The briquettes produced from faecal sludge, with additives like rice husk and wheat straw, demonstrated high calorific values. Specifically, 100% faecal sludge briquettes had a calorific value of 28 MJ/kg, faecal sludge with rice husk had 26.7 MJ/kg, and faecal sludge with wheat straw had 23.4 MJ/kg, whereas lignite coal has a value of 21.28 MJ/Kg.
- Environmental Benefits: The briquettes produced lower emissions of harmful pollutants, such as PM2.5 and PM10, compared to traditional fuels like coal, contributing to improved air quality.

- Economic Viability: The production process for faecal sludge briquettes was found to be economically viable. The cost-benefit analysis revealed that the total yearly revenue from briquette sales could reach 4,560,192 PKR, with an annual profit of 2,441,552 PKR, and a return-on-investment period of just 0.63 years.

6.3 Challenges and Solutions

The project encountered several challenges:

- Data Collection and Management: Poorly stored data necessitated manual surveys, which were time-consuming and resource intensive. The dashboard addressed this by digitizing data and improving data management practices.
- Technical Glitches: Initial technical issues with the dashboard were resolved through iterative testing and feedback from users, ensuring a stable and reliable system.
- Resistance to Change: Users initially resisted adopting new technologies. Comprehensive training and continuous support helped mitigate this resistance and facilitated smoother adoption of the dashboard.

6.4 Significance of the Study

This project demonstrated the potential for innovative solutions in FSM to bring about significant improvements in efficiency, cost savings, and environmental benefits. The successful implementation of the FSM dashboard and the production of faecal sludge briquettes underscore the importance of integrating digital tools and sustainable practices in urban sanitation management. These solutions align with the Sustainable Development Goals (SDGs), particularly those related to clean energy and sanitation.

References:

1. Abanyie, S., et al. (2023). “Sources and Factors Influencing Groundwater Quality and Associated Health Implications: A Review.”
2. Adjama, I., Derkyi, N. S. A., Uba, F., Akolgo, G. A., & Opuko, R. (2022). “Anaerobic Co-Digestion of Human Feces with Rice Straw for Biogas Production: A Case Study in Sunyani”. Modelling and Simulation in Engineering, 2022.
3. Arachchige, U.S.P.R. (2021). “Briquettes Production as an Alternative Fuel.” Nature Environment and Pollution Technology, vol. 20, no. 4.
4. Atwijukye et al. (2018) Low cost faecal sludge dewatering and carbonisation for production of fuel briquettes.
5. Bhattacharya, S. C., Sarker, T., & Pham, H. L. (1993). Some physical and thermal characteristics of biomass briquettes. International Journal of Energy Research, 17(9), 983-994.
6. Borowski,G. et al (2013) Utilization of Fine Coal Waste as a Fuel Briquettes.
7. Chisha, K. (2023). “Marketing Potential and Factors Leading to the Acceptability of Faecal Sludge Briquettes in Low Income Areas of Lusaka: A Case of Kamanga Compound.”
8. Danso-Boateng, E., Holdich, R. G., Martin, S. J., & Shama, G. (2021). Hydrothermal carbonisation of sewage sludge: Effect of process conditions on product characteristics and methane production. Bioresource Technology, 319, 124230.
9. Demirbas, A. (2004). Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science, 30(2), 219-230.
10. Eawag/Sandec (Department of Water and Sanitation in Developing Countries), Faecal Sludge Management (FSM), Sandec Training Tool 1.0 – Module 5 (2008).
11. Francis Obi et al. (2022) A Review of Biomass Briquette Binders and Quality Parameters
12. Funke, A., & Ziegler, F. (2010). Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering. Biofuels, Bioproducts and Biorefining, 4(2), 160-177.
13. Grover, P. D., & Mishra, S. K. (1996). Biomass briquetting: Technology and practices. FAO Regional Wood Energy Development Programme in Asia.

14. Ismi K. A., et al. (2023). “Valorization of Durian Peel Waste and Sewage Sludge as Bio-Briquette.” IOP Conference Series, vol. 1239, no. 1, pp. 012018–012018.

15. Kabango, K., Thulu, F., Mlowa, T., Chisembe, C., & Kaonga, C. (2023). Effect of carbonisation on combustion characteristics of faecal sludge and sawdust blended briquettes. Environmental Sustainability.

16. Kaliyan, N., & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy, 33(3), 337-359.

17. Kanwal, S. et al (2019) Physicochemical characterization of Thar coal and torrefied corn cob.

18. Lu, G., Yan, Y., & Colechin, M. (2000). Monitoring of combustion emissions through digital imaging. Proceedings of the Combustion Institute, 28(1), 287-293.

19. Lu, X., Jordan, B., Berge, N. D., & Ma, X. (2022). Comparative life cycle assessment of hydrothermal carbonization and pyrolysis of sewage sludge. Journal of Cleaner Production, 362, 132450.

20. Maqbool, N., et al. (2022). “Situational Assessment for Fecal Sludge Management in Major Cities of Pakistan.” Environmental Science and Pollution Research.

21. Maqbool, N., Khan, S. J., Sam, S., & Strande, L. (2022). Not Measured, Not Managed: Faecal Sludge Management in Pakistan.

22. Mala, J., et al. (2022). “Manual Scavenging and the Right to Health in India – Social and Medicolegal Perspectives.” Medicine, Science and the Law, p. 002580242211260.

23. Mani, S., Tabil, L. G., & Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass and Bioenergy, 30(7), 648-654.

24. Martin, S., et al. (2024). Production of low emission briquettes from carbonized faecal sludge as an alternative source of cooking energy.

25. Muspratt, et al. (2014). Fuel potential of faecal sludge: Calorific value results from Uganda, Ghana and Senegal.

26. Okot, D. K., Bilsborrow, P. E., & Phan, A. N. (2018). Briquetting characteristics of bean straw-maize cob blend. Biomass and Bioenergy, 108, 19-27.

27. Pakistan Social and Living Standards Measurement Survey (2019-20).

28. Richards, S.R (1990) Physical testing of fuel briquettes (fuel processing technology)

29. Schullehner, J., Hansen, B., Thygesen, M., Pedersen, C., & Sigsgaard, T. (2018). “Nitrate in drinking water and colorectal cancer risk: a nationwide population-based cohort study.” International Journal of Cancer, 143(1), 73-79.

30. Ssazipius et al. (2021) Sawdust as a filtering media in sludge drying beds.

31. Strande, et al. (2014). Faecal Sludge Management: Systems Approach for Implementation and Operation.

32. Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews, 55, 467-481.

33. Tumuluru, J. S., Wright, C. T., Kenny, K. L., & Hess, J. R. (2011). A review on biomass densification technologies for energy application. Renewable and Sustainable Energy Reviews, 15(9), 392-413.

34. Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the chemical composition of biomass. Fuel, 89(5), 913-933.

35. Wang, J., & Zhang, X. (2021). Pyrolysis of biomass and plastic wastes for energy and resource recovery: A review. Science of The Total Environment, 764, 142840.

36. Wang, L., Chang, Y., & Li, A. (2018). Hydrothermal carbonization for energy-efficient processing of wet municipal solid waste in China: A review. Renewable and Sustainable Energy Reviews, 93, 676-688.

37. Wolf, J., Prüss-Ustün, A., Cumming, O., Bartram, J., Bonjour, S., Cairncross, S., et al. (2014). “Systematic review: assessing the impact of drinking water and sanitation on diarrhoeal disease in low- and middle-income settings: systematic review and meta regression.” Trop Med Int Health, 19, 928-942.

FYDP Report 2024.pdf

ORIGINALITY REPORT

10%	7%	5%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Higher Education Commission Pakistan Student Paper	1%
2	energsustainsoc.biomedcentral.com Internet Source	<1%
3	Submitted to University of Sunderland Student Paper	<1%
4	huggingface.co Internet Source	<1%
5	dep.wv.gov Internet Source	<1%
6	Chin-Seng Liew, Worapon Kiatkittipong, Jun-Wei Lim, Man-Kee Lam et al. "Stabilization of heavy metals loaded sewage sludge: Reviewing conventional to state-of-the-art thermal treatments in achieving energy sustainability", Chemosphere, 2021 Publication	<1%
7	www.ajol.info Internet Source	<1%

8	www.susana.org Internet Source	<1 %
9	niua.in Internet Source	<1 %
10	www.geeksforgeeks.org Internet Source	<1 %
11	www.tandfonline.com Internet Source	<1 %
12	gyan.iitg.ac.in Internet Source	<1 %
13	Submitted to East Union High School Student Paper	<1 %
14	knowledgecommons.lakeheadu.ca Internet Source	<1 %
15	m.moam.info Internet Source	<1 %
16	Ayomide, Oduwole Tosin. "Preparation of Tea Bag Containing Saraca Indica Bark Extract for the Treatment of Uterine Disorders in Female", Rajiv Gandhi University of Health Sciences (India), 2023 Publication	<1 %
17	saniup.org Internet Source	<1 %
	savoirs.usherbrooke.ca	

18	Internet Source	<1 %
19	dspace.knust.edu.gh Internet Source	<1 %
20	Giulia Ischia, Nicole D. Berge, Sunyoung Bae, Nader Marzban et al. "Advances in Research and Technology of Hydrothermal Carbonization: Achievements and Future Directions", Agronomy, 2024 Publication	<1 %
21	prr.hec.gov.pk Internet Source	<1 %
22	Submitted to Pimlico State High School Student Paper	<1 %
23	cyberleninka.org Internet Source	<1 %
24	Submitted to Galway-Mayo Institute of Technology Student Paper	<1 %
25	Ward, Barbara J., Tesfayohanes W. Yacob, and Lupita D. Montoya. "Evaluation of Solid Fuel Char Briquettes from Human Waste", Environmental Science & Technology Publication	<1 %
26	gutenberg.us Internet Source	<1 %

27	iwaponline.com Internet Source	<1%
28	unglobalcompact.org Internet Source	<1%
29	www.mdpi.com Internet Source	<1%
30	www.pca.state.mn.us Internet Source	<1%
31	www.snv.org Internet Source	<1%
32	Petro Mwamlima, Aloyce W. Mayo, Sara Gabrielsson, Richard Kimwaga. "Potential use of faecal sludge derived char briquettes as an alternative cooking energy source in Dar es Salaam, Tanzania", Hygiene and Environmental Health Advances, 2023 Publication	<1%
33	Submitted to University of Leeds Student Paper	<1%
34	admin.lidsen.com Internet Source	<1%
35	Submitted to University of Bolton Student Paper	<1%
36	digitalcollection.utem.edu.my Internet Source	<1%

37	Submitted to Intercollege Student Paper	<1 %
38	Submitted to Texas A&M University, College Station Student Paper	<1 %
39	www.scirp.org Internet Source	<1 %
40	Chun-Yang Yin, Mohanad El-Harbawi, Zhong-Tao Jiang. "Life Cycle Assessment of Production of Hydrochar via Hydrothermal Carbonization of Date Palm Fronds Biomass", Materials, 2023 Publication	<1 %
41	Submitted to Eastern Mediterranean University Student Paper	<1 %
42	Lidia Lombardi, Francesca Tuci, Maciej Śliz, Klaudia Czerwińska, Simone Fabrizi, Małgorzata Wilk. "Life cycle assessment of the hydrothermal carbonization process applied to the wet fraction mechanically separated from municipal mixed waste", Waste Management, 2023 Publication	<1 %
43	Submitted to London Design Engineering UTC Student Paper	<1 %

44	Submitted to Loughborough University Student Paper	<1 %
45	Submitted to Marquette University Student Paper	<1 %
46	docplayer.net Internet Source	<1 %
47	matheo.uliege.be Internet Source	<1 %
48	www.astm.org Internet Source	<1 %
49	Stefan Diener, Swaib Semiyaga, Charles B. Niwagaba, Ashley Murray Muspratt et al. "A value proposition: Resource recovery from faecal sludge—Can it be the driver for improved sanitation?", Resources, Conservation and Recycling, 2014 Publication	<1 %
50	jbes.cbiore.id Internet Source	<1 %
51	repozitorij.unizg.hr Internet Source	<1 %
52	www.freecodecamp.org Internet Source	<1 %
53	123docz.net Internet Source	<1 %

54	access.archive-ouverte.unige.ch Internet Source	<1 %
55	etd.aau.edu.et Internet Source	<1 %
56	ir.lib.hiroshima-u.ac.jp Internet Source	<1 %
57	mafiadoc.com Internet Source	<1 %
58	ulspace.ul.ac.za Internet Source	<1 %
59	www.unicef.org Internet Source	<1 %
60	Afolabi, Oluwasola O.D., and M. Sohail. "Microwaving human faecal sludge as a viable sanitation technology option for treatment and value recovery – A critical review", Journal of Environmental Management, 2016. Publication	<1 %
61	Aza Hani Shukri, Nashwan Shawkat Mizzouri, Alan Saifadeen, Diyar Saleem, Martin O'Malley. "Assessing and improving the sanitation services in Kabarto 2 IDP camp using the Smart sanitation approach", Ain Shams Engineering Journal, 2023 Publication	<1 %

62	Bei Zhang, Basanta Kumar Biswal, Jingjing Zhang, Rajasekhar Balasubramanian. "Hydrothermal Treatment of Biomass Feedstocks for Sustainable Production of Chemicals, Fuels, and Materials: Progress and Perspectives", Chemical Reviews, 2023 Publication	<1 %
63	Judy A Libra, Kyoung S Ro, Claudia Kammann, Axel Funke et al. "Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis", Biofuels, 2014 Publication	<1 %
64	academy.hsoub.com Internet Source	<1 %
65	ethesis.nitrkl.ac.in Internet Source	<1 %
66	link.springer.com Internet Source	<1 %
67	slideplayer.com Internet Source	<1 %
68	www.intechopen.com Internet Source	<1 %
69	Adarsh Kumar, Komal Saini, Thallada Bhaskar. "Hydochar and biochar: Production, physicochemical properties and techno-	<1 %

	economic analysis", Bioresource Technology, 2020 Publication	
70	Branislav Hredzak, Guoxiao Guo. "A method for improving the resolution of active and passive balancing schemes for disc drives", Engineering Optimization, 2006 Publication	<1%
71	Jumoke Oladejo, Kaiqi Shi, Xiang Luo, Gang Yang, Tao Wu. "A Review of Sludge-to-Energy Recovery Methods", Energies, 2018 Publication	<1%
72	Mehedi Hasan Mishuk, Janeefer Flower Janee, S.M. Tariqul Islam, Muhammed Alamgir. "Assessment of treatment efficiency by non-energy consuming aeration system for faecal sludge management in an emergency human settlement in Bangladesh", Groundwater for Sustainable Development, 2022 Publication	<1%
73	Moses Ahmed Daramy, Ryoka Kawada, Shinya Oba. "What Is the Threshold Carbonization Temperature for Sustainable Preservation of the Good Nitrogen Supply Ability of Chicken Manure?", Sustainability, 2020 Publication	<1%

74	Prasityousil, Jitthep, and Akarawit Muenjina. "Properties of Solid Fuel Briquettes Produced from Rejected Material of Municipal Waste Composting", Procedia Environmental Sciences, 2013. Publication	<1 %
75	Ramos, Ana Isabel Martins Casal. "Experimental Study of the Operating Conditions Impact on Fuel Blends Co-Gasification: Environmental and Socio-Economic Assessment", Universidade do Porto (Portugal), 2024 Publication	<1 %
76	dspace.nm-aist.ac.tz Internet Source	<1 %
77	dspace.unza.zm Internet Source	<1 %
78	ir.mu.ac.ke:8080 Internet Source	<1 %
79	wiredspace.wits.ac.za Internet Source	<1 %
80	Aziz, Hamidi Abdul, Nor Habsah Md Sabiani, Miskiah Fadzilah Ghazali, Abu Ahmed Mokammel Haque, and Yung-Tse Hung. "Chapter 1: BIOSOLIDS MANAGEMENT",	<1 %

	Handbook of Environment and Waste Management, 2014. Publication	
81	Paulo Martin Sanka, Olivier Germain, Leyla Khalifa, Hans Komakech, Hezron Magambo. "Production of low emission briquettes from carbonized faecal sludge as an alternative source of cooking energy", Energy, Sustainability and Society, 2024 Publication	<1 %
82	Yi Herng Chan, Serene Sow Mun Lock, Bridgid Lai Fui Chin, Mee Kee Wong et al. "Progress in thermochemical co-processing of biomass and sludge for sustainable energy, value-added products and circular economy", Bioresource Technology, 2023 Publication	<1 %
83	Okey Francis Obi. "Effect of briquetting temperature on the properties of biomass briquettes", African Journal of Science, Technology, Innovation and Development, 2015 Publication	<1 %
84	library.oapen.org Internet Source	<1 %

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		