ASSESSMENT OF CHARACTERISTICS OF FECAL SLUDGE FROM DIFFERENT SOURCES AND ITS EFFECT ON DRIED SLUDGE

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FEBRUARY 2023

Assessment of Characteristics of Fecal Sludge from Different Sources and its Effect on Dried Sludge

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In partial fulfilment of the requirements for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING (ENVIRONMENTAL)

Department of Civil Engineering
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

February 2023

The thesis titled "Assessment of Characteristics of Fecal Sludge from Different Sources and its Effect on Dried Sludge" submitted by Md Sirajul Islam roll no.: 1017042101 P, Session: October, 2017 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Environmental) on February 11, 2023.

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Dedicated to

My Loving Family

ACKNOWLEDGEMENT

At first the author acknowledges the blessings and mercy of the Almighty for enabling him to successfully complete this thesis.

The author expresses his sincerest gratitude to his thesis supervisor Dr. Muhammad Ashraf Ali, Professor, Department of Civil Engineering, BUET, for his continuous guidance, support, encouragement and timely follow up at every step of this research work starting from the development of the research proposal till writing this thesis.

The author expresses sincere thanks and appreciation to the respected members of the Board of Examiners, Dr. Abu Siddique, Professor and Head, Department of Civil Engineering, BUET, Dr. Tanvir Ahmed, Professor, Department of Civil Engineering, BUET, and Dr. Abdullah Al-Muyeed, Chief Operating Officer, CWIS-FSM Support Cell, Department of Public Health Engineering (DPHE), for their valuable advice and comments.

The author sincerely thanks the officials of Sakhipur Fecal Sludge Treatment Plant (FSTP) for their valuable support and assistance in providing necessary information about the Sakhipur FSM scenario. The author also acknowledges the support provided by ITN-BUET for carrying out sampling from Sakhipur FSTP.

The members of the Environmental Engineering Laboratory at BUET deserve the author's sincere gratitude and appreciation for their unflagging support and cooperation throughout the course of this research.

The author concludes by expressing sincere appreciation to his parents for their continual support, encouragement, and affection. Last but not the least, the author thanks his wife, Zarin Tasnim, for her support during the author’s entire postgraduate journey. Since 2017, she has been there every step of the way and it would not have been possible without her thoughtful insights and motivation that kept him going.

ABSTRACT

The purpose of this study was to evaluate the characteristics of raw fecal sludge emptied from different types of onsite sanitation facilities, and to assess its effect on the operation of FSTPs. Raw FS samples emptied from different types of containments were collected from Dhaka and Sakhipur (Tangail), and were analyzed for a wide range of parameters, including pH, EC, TS, TDS, TSS, COD, NH_4^+, NO_3^- and PO_4^{3-}. The raw FS samples were classified into four broad categories: (a) Sakhipur Public Septic Tanks; (b) Sakhipur household pits; (c) Dhaka household septic tanks; and (d) Dhaka public septic tank.

The mean pH values of the raw fecal sludge samples were in the neutral range, varying from 6.84 to 7.46. The EC values of the FS samples ranged from 2.68 mS/cm to 4.27 mS/cm, with no clear correlation with TDS values, possibly due to the presence of non-ionized dissolved solids in FS. The TSS concentration of FS samples from household pits in Sakhipur were also found to be significantly higher, possibly due to the leaching of water from pits. The mean COD and TSS values were 2,405 mg/l and 4,220 mg/l, respectively. The ammonium (mean 244 mg/l) and phosphate (mean 170 mg/l) concentrations indicate that FS could be an excellent source of nutrient for use in agriculture. No clear trend was observed between the source of FS and their characteristics. However, the COD values of FS samples collected from public septic tanks and pits were found to be significantly higher than those collected from containments in Dhaka. Compared to the reported raw FS characteristics from African regions (where dry toilets and use of toilet papers are common), the raw FS samples collected in this study are much more dilute. Because of lower TSS contents of raw FS, the estimated solids loading rates for the unplanted drying beds in Sakhipur FSTP have been found to be significantly lower than those typically used in the design of unplanted drying beds. It appears that introduction of settling-thickening tanks, as a pre-treatment unit, could significantly improve treatment efficiency and reduce the land requirements for FSTPs employing drying beds.

Dried FS samples produced in unplanted drying beds were collected from Sakhipur and Faridpur FSTP, and were analyzed for moisture content, nutrient and heavy metal contents. It was found that significant moisture content reduction could be achieved through the storage of dried fecal sludge. The ammonium nitrogen content (mean 215 mg/kg) and phosphate content (117 mg/kg) suggest that resource recovery from dried FS would be beneficial. Heavy metal (Pb, Cd, Cr, Cu, Ni, Zn) contents of the dried FS samples were significantly lower than the

corresponding Bangladesh standards for sludge. The mean calorific values of dried FS samples varied over a relatively narrow range of 8.7 to 13.4 MJ/kg. The dried FS samples from public septic tanks appears to have a slightly higher calorific values than those from household septic tanks and pits. Calorific values of dried FS calculated from elemental composition using the modified Dulong formula appear to provide results closer to the experimental values. The relatively lower calorific values of dried FS appear to be a constraint for energy recovery through combustion. Considering the properties of FS, co-composting, which is widely used in Bangladesh and worldwide, is an excellent option for the recovery of resources from FS.

Since the characteristics of FS varies significantly due to a range of factors, including type of containment, environmental conditions (e.g., infiltration capacity of soil), usage (e.g., use/volume of flush water) and empting methods, more extensive studies should be carried out to assess the characteristics of raw FS and its implication on the design/ operation of FSTPs and quality of end products (e.g., compost or solid fuel).

TABLE OF CONTENTS

ACKNOWLEDGEMENT........ v
ABSTRACT........ vi
TABLE OF CONTENTS........ viii
LIST OF FIGURES........ x
LIST OF TABLES........ xi
LIST OF ABBREVIATIONS........ xii
CHAPTER 1 INTRODUCTION........ 1
1.1 Background........ 1
1.2 Scope of the Research Work........ 2
1.3 Outline of Methodology........ 3
1.4 Organization of the Thesis........ 4
CHAPTER 2 LITERATURE REVIEW........ 5
2.1 Introduction........ 5
2.2 Characteristics of Fecal Sludge........ 6
2.2.1 Factors Affecting Characteristics of Fecal Sludge........ 7
2.2.2 Available Data on Characteristics of FS in Bangladesh........ 9
2.3 Treatment and Processing of Dried Sludge........ 10
2.3.1 Potential Use of Treated Sludge........ 11
2.3.2 Fuel Potential of Fecal Sludge........ 12
2.4 Overview FSM in Bangladesh........ 14
2.4.1 FSM Framework in Bangladesh........ 15
2.4.2 Overview of FSM services in Bangladesh........ 16
2.4.2.1 Overview of FSM in Sakhipur Paurashava........ 17
2.4.2.2 Overview of FSM in Faridpur Paurashava........ 19
2.5 Summary........ 21
CHAPTER 3 METHODOLOGY........ 23
3.1 Introduction........ 23
3.2 Description of the Sampling Locations and Sampling Procedures........ 24
3.2.1 Sakhipur Municipality........ 24
3.2.2 Dhaka City........ 27
3.2.3 Faridpur Municipality........ 29
3.3 Analysis of Raw and Dried FS Samples........ 31
3.3.1 Analysis of Raw FS Samples........ 31
3.3.2 Analysis of Dried FS Samples........ 31

3.4 Estimation of Solids Loading Rate for Sakhipur FSTP 34
CHAPTER 4 RESULTS AND DISCUSSION..36
4.1 Introduction 36
4.2 Characteristics of Raw Fecal Sludge from Different Sources.......................36
4.2.1 pH..40
4.2.2 Electrical Conductivity (EC) and Dissolved Solids (TDS)....................41
4.2.3 Total Solids (TS) and Total Suspended Solids (TSS)............................45
4.2.4 Chemical Oxygen Demand (COD)...46
4.2.5 Nutrients (Ammonia, Nitrate, Phosphate) 47
4.3 Solids Loading Rate of Unplanted Drying Bed 52
4.4 Dried Sludge from Sakhipur and Faridpur FSTPs 53
4.5 Heavy Metal Content of Dried FS..55
4.6 Relationship between Characteristics of Raw and Dried Sample 57
4.7 Calorific Value of Dried Fecal Sludge...57
4.7.1 Ultimate Analysis of Faridpur Dried Sample 58
4.8 Possible End Use of Fecal Sludge..59
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 63
5.1 General 63
5.2 Conclusions 63
5.3 Recommendations for Future Study...65
REFERENCE..66
APPENDIX..73

LIST OF FIGURES

Figure 2.1:	The elements of the entire FSM service chain	14
Figure 2.2:	FSM Framework for Bangladesh	16
Figure 2.3:	Vacutug is used in Sakhipur for collection and transportation of FS	18
Figure 2.4:	Schematic diagram of Faridpur FSTP (Source: Practical Action Bangladesh)	21
Figure 3.1:	Unplanted drying beds at Sakhipur FSTP	25
Figure 3.2:	Raw sample collection at Sakhipur prior to discharge into the unplanted drying bed	26
Figure 3.3:	Bomb Calorimeter used to determine calorific value of dried FS samples	33
Figure 3.5:	Ball-Mill grinder machine and fine pulverized samples for CHNS/O test	33
Figure 4.1:	Box plot of pH of four different sources of raw fecal sludge	40
Figure 4.2:	Box plot of EC of four different sources of raw fecal sludge	42
Figure 4.3:	Box plot of TDS of four different sources of raw fecal sludge	43
Figure 4.4:	Relationship between TDS and EC value for all sample	44
Figure 4.5:	Box plot of TS of three different sources of raw fecal sludge	45
Figure 4.6:	Box plot of COD of four different sources of raw fecal sludge	47
Figure 4.7:	Box plot of NH_4^+-N of four different sources of raw fecal sludge	48
Figure 4.8:	Box plot of NO_3^--N of four different sources of raw fecal sludge	49
Figure 4.9:	Box plot of PO_4^{3-} of four different sources of raw fecal sludge	51
Figure 4.10:	Comparison of Theoretical and Experimental Calorific value of Faridpur samples	59

LIST OF TABLES

Table 2.1:	Physicochemical characteristics of pit sludge (Rahman, 2018)	9
Table 2.2:	FS characteristics from Rohingya camps in Cox's Bazar (UMP, 2019)	10
Table 3.1:	Details of the raw FS samples collected from Sakhipur FSTP	27
Table 3.2:	Details of the dried FS samples collected from Sakhipur FSTP	27
Table 3.3 (a):	Details of the raw FS samples collected from "household septic tanks" in Dhaka city	28
Table 3.3 (b):	Details of the raw FS samples collected from "public septic tanks" in Dhaka city	29
Table 3.4:	Details of the dried FS samples collected from Faridpur FSTP	31
Table 3.5:	Mathematical models for theoretical calorific values	34
Table 4.1:	Characteristics of raw fecal sludge of four different sources	39
Table 4.2:	Characteristics of dried fecal sludge collected from Sakhipur and Faridpur	54
Table 4.3:	Heavy metal concentrations of dried FS samples and comparison with Bangladesh Standard for sludge substance	56
Table 4.4:	Calorific Value (experimental) of Dried FS Samples from Sakhipur and Faridpur	57
Table 4.5:	CNHS Values of dried FS samples from Faridpur FSTP	58
Table 4.6:	C:N ratio of Faridpur dried fecal sludge sample	61
Table 4.7:	Typical moisture content and C:N ratios of selected bulking agents (Tayler 2018)	61

LIST OF ABBREVIATIONS

BASA	Bangladesh Association for Social Advancement
BCSIR	Bangladesh Council of Scientific and Industrial Research
BOD	Biochemical Oxygen Demand
BUET	Bangladesh University of Engineering and Technology
COD	Chemical Oxygen Demand
CWIS	City Wide Inclusive Sanitation
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DGIS	Directorate General for International Cooperation
DPHE	Department of Public Health Engineering
DWASA	Dhaka Water Supply and Sewerage Authority
EC	Electrical Conductivity
ECR	Environmental Conservation Rule
EPA	Environmental Protection Agency
FS	Fecal Sludge
FSM	Fecal Sludge Management
FSTP	Fecal Sludge Treatment Plant
GCC	Gulshan Clean & Care
GPS	Global Positioning System
GW	Ground Water
HHV	Higher Heating Value
IRF	Institutional and Regulatory Framework
INARS	Institute of National Analytical Research and Service
ITN	International Training Network
MT	Metric Ton
MSSC	Multi Stakeholder Steering Committee
NGO	Non-Governmental organization
OM	Organic Matter
OSS	Onsite Sanitation
ppm	Parts per Million
PPP	Public Private Partnership
SSWM	Sustainable Sanitation and Water Management

TDS	Total Dissolved Solid
TSS	Total Solid
TSS	Total Suspended Solid
UPM	Umwelt Projekt Management
USEPA	United States Environmental Protection Agency
WAB	Water Aid Bangladesh
WTP	Water Treatment Plant

Chapter 1
INTRODUCTION

1.1 Background

Bangladesh has achieved noteworthy accomplishment in lowering open defecation from as high as 34% in 1990 to less than 1% recently (UNICEF 2017). Open defecation has been completely eradicated due to onsite sanitation facilities, mostly pour-flush latrines and septic tank systems. Fecal sludge (FS) from these facilities is being dumped into storm drainage systems, low-lying areas, and water bodies, which is seriously harming the environment and endangering public health.

To meet SDG Target 6.2, which calls for "safely managed sanitation" for all by 2030, proper management of FS is a requirement. According to a study, poor financial services management in Bangladesh causes annual economic losses of over USD 2.4 billion, or 6.3% of the country's GDP (World Bank, 2012). Recently, FSM services have been started in at least 30 Paurashavas in Bangladesh (DPHE-BMWSSP 2022) in accordance with the institutional and regulatory framework for fecal sludge management (IRF-FSM), where vacuum tankers are being used for containment emptying and treatment systems using various drying beds and co-composting are being used. For designing a treatment system for FS, it is important to understand the characteristics of FS. Numerous variables, including usage (e.g., household or community), type of sanitation facility/containment (e.g., pit or septic tank), and desludging method (e.g., manual versus vacuum tanker) affect the characteristics of raw FS. Studies from the African region have shown that the TSS and COD of fecal sludge collected from household septic tanks could be 5 to over 10 times greater than those from public toilets (Kalulua et al., 2015). However, there is limited data on characteristics of fecal sludge in Bangladesh. Rahman (2018) described the physicochemical (mainly nutritional content) and microbiological properties of dried fecal sludge and raw pit sludge that were both obtained from rural Bangladesh. But there is virtually no data on variation of fecal sludge characteristics from different types of facilities, which is vital in the design of treatment systems, including drying beds.

The fecal sludge treatment plants (FSTPs) that have been established in different cities and Paurashavas in Bangladesh utilize drying beds (both planted and unplanted) for solid-liquid separation. At most FSTPs employing unplanted drying beds, a fixed drying cycle (in the range of two weeks is typically used for solid-liquid separation, irrespective of the characteristics of fecal sludge. There is limited data on characteristics of local fecal sludge (FS). A significant part of the reported data on characteristics of FS is from African countries, where dry toilets are most commonly used. Characteristics of FS from such toilets are likely to be different from those in our country where significant water is used for flushing and cleaning. Characteristics of FS, particularly solids content, is an important parameter in the design of drying beds. Solids content of raw FS depends on a number of factors and are likely to vary widely depending on the type of containment, usage, and desludging methods employed. There is virtually no data/information on the effects of raw FS on the characteristics of dried fecal sludge (produced in unplanted drying beds). Also, very limited data is available on the characteristics of dried FS, in particular the energy/calorific value of FS and heavy metal contents of fecal sludge, which are very important for assessing further processing or resource recovery options from the dried sludge.

1.2 Scope of the Research Work

The overall objectives of this study are to evaluate characteristics of fecal sludge from different types of onsite sanitation facilities, and to assess the effect of raw fecal sludge characteristics on the quality of dried sludge produced in unplanted drying beds (with same drying cycle). The specific objectives include:

1) Characterization of raw fecal sludge (FS) collected from different types of sanitation facilities (i.e., household pour flush toilets, household septic tank, septic tank of communal/public toilets).
2) Estimation of solids loading rates (in kg TS/m^2/year) in the unplanted drying beds of the fecal sludge treatment plant (FSTP) at Sakhipur Paurashava for different types of FS, in order to assess whether loading rates need to be adjusted for different types of fecal sludge.
3) Characterization of dried fecal sludge (including heavy metal contents) produced in the drying beds of the FSTP at Sakhipur and Faridpur Paurashava.
4) Estimation of calorific value of dried fecal sludge (using a Bomb Calorimeter and from elemental analysis), and assessment of energy recovery options from dried fecal sludge.

1.3 Outline of Methodology

In this study, characteristics of raw fecal sludge (FS) have been assessed through analysis of fecal sludge collected from vacuum tankers employed in Sakhipur Paurashava and in Dhaka. The FS samples were collected directly from vacuum tankers used for emptying fecal sludge, and for each sample the source (i.e., type and location of containment) of FS were recorded. A total of six (6) FS samples were collected in Sakhipur; four (4) from septic tanks and two (2) from pour-flush toilet pits. A total of 18 FS samples were collected from Dhaka; among these nine (9) were from septic tanks and nine (9) from public toilets. The raw FS samples were tested for a range of parameters including pH, EC, COD, TS, TDS, TSS, NH_4^+, NO_3^- and PO_4^{3-} , following standard procedures. The effect of raw FS characteristics on quality of dried fecal sludge (in terms of moisture content) was evaluated at Sakhipur Paurashava, where unplanted drying beds are used for solid-liquid separation, using the same drying cycle for all types of sludge. The raw FS samples at Sakhipur were collected just before their entry into the drying beds.

The solids content of the FS and the loading cycle employed were used to determine solids loading rates (in kg TS/m^2/year). The estimated loading rates were compared with recommended loading rates, in order to assess whether loading rates need to be adjusted for different types of fecal sludge. At the end of the drying cycle, the dried fecal sludge samples were collected from the drying beds, and were analyzed for a range of parameters including moisture content, nutrient, heavy metal, and organic content. The effect of raw FS characteristics on quality of dried sludge was assessed based these data.

In addition to Sakhipur FSTP, dried fecal sludge samples were also collected from the FSTP of Faridpur Paurashava, where unplanted drying beds are used for solid-liquid separation. These dried FS samples, five (5) from Sakhipur FSPT and eight (8) from Faridpur FSTP, were also analyzed for a range of parameters. Calorific values of dried FS samples were determined using a Bomb Calorimeter (Isoperibol Calorimeter Model C 3000, IKA, Germany), and potential energy recovery options of dried fecal sludge have been assessed. Additionally, the calorific values of the dried FS samples were calculated from the mathematical models to compare the results obtained from the Bomb calorific meter. The elemental composition of the dried FS samples was determined using a CNHS Elemental Analyzer at the Institute of National Analytical Research and Service (INARS) at the Bangladesh Council of Scientific and

Industrial Research (BCSIR), Bangladesh. All other tests will be performed at the Environmental Engineering Laboratory of the Department of Civil Engineering, BUET.

1.4 Organization of the Thesis

The thesis consists of five chapters. Chapter 1 presents the background study and the objectives of this research, along with an outline of the methodology followed in this study. Chapter 2 gives an overview of the fecal sludge and its management, and describes formwork of FSM, current FSM scenario in Bangladesh. It also presents an overview of available information on characteristics of raw and dried fecal sludge, and different processing options for dried fecal sludge.

Chapter 3 presents the methodology followed in this study. It describes the sampling locations and the methodologies adopted for sampling of fecal sludge and testing different parameters including pH, EC, COD, TS, TDS, TSS, NH_4^+ and NO_3^-, and PO_4^{3-} for raw samples collected from septic tank and pit latrine. It also describes the test procedure of characterization of dried sludge collected from unplanted drying beds from different sources.

Chapter 4 presents the detailed characteristic of fecal sludge collected from different sources in Sakhipur and Dhaka. It also presents an assessment of FS loading on drying beds and the effects of FS characteristics on quality (particularly moisture content) of treated sludge for the Sakhipur FSTP. This Chapter also presents the calorific value of dried fecal sludge collected from two FSTPs, and presents and discussion on the calorific value and possible resource recovery options from fecal sludge.

Chapter 5 presents the major conclusions of the research work. This chapter also presents recommendations for future studies.

Chapter 2
LITERATURE REVIEW

2.1 Introduction

Public health and environment of a community depends to large extent on a safely managed sanitation system. Safely managed sanitation systems involve use of improved sanitation facilities, where excreta are collected and treated in-situ or transported to a treatment plant for treatment and disposal. Fecal sludge (FS) is human excreta along with flush water, cleansing materials and menstrual hygiene products. Onsite sanitation system is the predominant sanitation system in most developing countries, including Bangladesh. Onsite sanitation will continue to be the dominant sanitation system in Bangladesh in the near future. A complete onsite sanitation system includes a sanitation facility (consisting of a toilet and containment for temporary storage of fecal sludge) and a fecal sludge management (FSM) system that involves emptying/collection of FS from containments, transportation of emptied FS to a fecal sludge treatment plant (FSTP), and finally treatment and processing/disposal of treated sludge. During the last decade, FSM services have been initiated in a number of cities and Paurashavas in Bangladesh, were FSTPs have been built for the treatment of FS. The treatment process typically involves solid-liquid separation of FS in drying beds (both planted and unplanted). This is followed by treatment of the liquid stream and processing of the dried sludge (produced in the drying beds). The characteristics of raw FS vary over a wide range, and depends on a number of factors, including type of containment, toilet usage, storage duration in containment, and collection method. The characteristics of raw FS in turn affects the performance of drying beds used for solid-liquid separation of FS, and may affect the characteristics of dried fecal sludge. However, there is limited data on the characteristics of raw in Bangladesh. There is also limited data on the characteristics of dried FS (produced in drying beds), including moisture content and calorific value, which are vital for determining its processing/energy recovery options.

The objectives of this study were to assess the characteristics of raw and dried fecal sludge, assess possible effects of raw FS characteristics on the characteristics of dried FS, and estimation of calorific value of dried sludge for assessment of energy recovery options. This Chapter presents an overview of the characteristics of FS including factors affecting its characteristics. It also presents an overview of the treatment and processing options of treated/dried sludge, including its fuel potential. This Chapter also presents an overview of FSM services in Bangladesh.

2.2 Characteristics of Fecal Sludge

Physiochemical properties are essential for the proper operation of fecal sludge and septage management systems, as well as for the proper collection and disposal of fecal sludge. Inadequate information on the physiochemical characteristics of fecal sludge leads to improper storage design and inefficient fecal sludge disposal, both of which contribute to environmental degradation. Individuals' food, health, age, water intake, and income level all have an impact on the physiochemical properties of FS (Rose et al., 2015). The design for fecal sludge management and treatment must include a full characterization of the FS to be treated on site as well as the impact on any existing sewage treatment plant.

A comparison of the physicochemical and microbiological properties of public toilet pit sludge, septage, and sewage finds that all of the qualities are several times greater in public toilet pit sludge than in septage and sewage, according to Gudda et al. (2017)'s investigation. For septage and pit sludges, the following parameters are typically measured: pH, moisture content, BOD, COD, NH_3, NH_4^+-N, NO_3^--N, K^+, TS, TDS, TSS, and heavy metals. During the rainy season, the moisture content of pit sludge and septic tanks increases with the rising depth of the sludge. Heavy metal concentrations were found to be higher in septic tanks or pit latrines than in sewage (Heinss et al., 1998).

FS properties vary greatly depending on the type of onsite containment where the FS is stored prior to disposal. Again, the pit filling rate is determined by food habits, liquid intake, social and religious norms, age, and health problems. As a result, FS features and hole filling rates depend on population. However, there has been very few researches in Bangladesh on the loading rate and characterization of pit sludge and septic tanks.

2.2.1 Factors Affecting Characteristics of Fecal Sludge

Due to the variety of onsite sanitation technologies in use, such as pit latrines, household septic tanks, public septic tanks, and dry toilets, it is difficult to determine the quantities of FS generated and the typical characteristics of FS. In many cities, a variety of these technologies frequently exist side by side, and there is typically a predominance of various technologies in various geographic regions. The broad heterogeneity of reported FS features is related not only to the variety of onsite technologies utilized, but also to how the system is used, the storage duration (filling rates and collection frequency), inflow and infiltration, and the local climate. All of these criteria should be considered while evaluating FS characteristics.

Toilet usage

The variability of FS in the onsite containment technique is influenced by household patterns connected with toilet usage. The TS concentration is affected by factors such as whether the toilet is flushed or not, the volume of flush water used, the cleaning method ('washers' versus 'wipers,') and the inclusion or exclusion of grey water from bathing or cooking. With the addition of kitchen wastewater without properly maintained oil and grease traps, the concentration of fat, oil, and grease will rise, and odors will rise as well. The filling rate will grow when more waste streams enter the toilet and as more people use the toilet.

Storage duration

The type of technology, the standard of construction, how often toilets are used, and inflow and infiltration all affect the filling rate and storage duration. Due to the breakdown of organic matter during storage, the amount of time that FS is kept in onsite containment systems before being collected and transported will have a significant impact on the characteristics. For instance, a significant section of the population relies on heavily used public latrines in informal settlements, which require frequent emptying. In Kampala, there are often 30 people (or 7 houses) sharing one latrine (Gunther et al., 2011). 40% of the people in Kumasi, Ghana, rely on frequently-emptied, unsewered public toilets. As a result, FS collected from public toilets typically isn't stabilized and has significant levels of BOD and NH4+-N. (Strande et al., 2014). Septic tank emptying intervals can range from a few weeks to several years, depending on the volume and quantity of users. In comparison to FS from public toilets, FS that has been kept in a septic tank for a number of years will have undergone more stabilization. The FS compacts at the bottom during onsite containment system filling, making it denser overall. Since this FS is more challenging to pump out, it is frequently left at the bottom of the containment system without being emptied.

Inflow and infiltration

Additionally, the discharge of leachate into the environment and the infiltration of ground water into the system both have significant effects on the concentration and volume of FS. More leaching means a thicker FS and a slower filling rate for containment systems. Whether a containment system is unlined, partially lined, fully lined, connected to soakpits, or poorly constructed, all of these factors affect its permeability. Soil composition and groundwater table height will affect the rate of inflow and infiltration in permeable systems. Groundwater contamination can occur as a result of groundwater exchange with FS, which is intensified during periods of heavy and extensive rain. Pit latrines and septic tanks builders often originate from the informal sector in low-income countries, and they may not be aware of the dangers of FS seeping into ground water or may lack the tools to assess the situation.

Collection method

The FS collection method has an impact on its properties as well. FS at the bottom of containment systems that is too thick to pump will be collected only if it is manually emptied with shovels or if water is supplied to reduce the viscosity and allow pumping. Unlined or partially lined pit latrines usually require considerable volumes of water to be flushed in order to pump the FS, as liquid draining from the pit increases the thickness of the FS. FS removed by pumping is generally more dilute and less viscous than FS collected manually. Operators will often add water to the pit or tank as they break apart the solid masses with hand tools. The easy availability of water at the site will aid in the desludging process. If soak pits are utilized to infiltrate septic tank effluent, they may need to be emptied of sludge due to clogging.

Climate

Climate has a direct impact on FS properties, owing mostly to temperature and moisture. Tropical countries may have a single season of heavy rain, known as the wet season, although others may have a bimodal rainfall and/or dry season. Temperatures may be lowest during the rainy season and greatest during the dry season. Heavy rains cause overflowing and flooding of onsite systems, so collection and transport services are frequently in high demand during the rainy season. Temperature also affects biological degradation rates, which increase as temperatures rise.

2.2.2 Available Data on Characteristics of FS in Bangladesh

Inadequate information about the physiochemical characteristics of fecal sludge leads to ineffective treatment plant design and improper fecal sludge disposal, both of which contribute to environmental degradation. To determine the FS qualities, both the physicochemical and microbiological aspects of the FS must be examined. When developing an FS treatment system, it is essential to gather information about FS characteristics in particular locations. When it comes to Bangladesh, there is an inadequate amount of information on the characteristics of FS. Still, there is a lot of research going on in this area, and the combination of research results and real-world observations will continue to help us learn more about FS characteristics and get better at predicting them with less effort and more accuracy. However, Rahman (2018) reported physicochemical (primarily nutrient content) and microbial characteristics of raw pit sludge collected from rural areas of Bangladesh. UPM (2019) also had a report on characteristics of raw FS from pit latrines and septic tanks in Rohingya camps in Cox's Bazar.

Table 2.1: Physicochemical characteristics of pit sludge (Rahman, 2018)

District	**MC (ww%)**	**pH**	**EC (mS/cm)**	**TVS (dw%)**	**TOC (dw%)**	**N (dw%)**	**C/N**	**PO_4-P (dw%)**
Gazipur (n=8)	87.15 ±2.92	7.65 ±0.4	3.48 ±1.36	71.42 ±9.02	37.90 ±4.86	3.86 ±0.66	9.92 ±0.82	2.19 ±1.10
Khulna (n=6)	91.34 ±5.99	7.98 ±0.37	4.76 ±1.10	74.37 ±7.53	39.32 ±3.96	3.66 ±0.64	10.91 ±0.77	2.25 ±1.51
Noakhali (n=6)	91.77 ±2.94	7.32 ±0.10	5.14 ±2.72	73.31 ±3.81	38.77 ±2.10	4.04 ±0.99	10.15 ±2.62	2.28 ±0.59
Mymensingh (n=6)	83.43 ±8.73	7.73 ±0.28	3.51 ±1.32	68.09 ±9.89	36.01 ±5.19	3.15 ±1.45	12.83 ±4.01	1.67 ±0.82
Feni (n=6)	90.54 ±3.58	7.81 ±0.10	4.58 ±2.10	77.88 ±8.21	41.19 ±4.34	3.98 ±1.30	11.14 ±2.89	2.49 ±1.07
Mean ± STD (n = 32)	88.74 ±5.77	7.69 ±0.35	4.24 ±1.81	72.91 ±8.17	38.59 ±4.33	3.74 ±1.02	10.92 ±2.53	2.18 ±1.03

Table 2.2: FS characteristics from Rohingya camps in Cox's Bazar (UMP, 2019).

Source	pH	ES (mS/cm)	COD (mg/L)	TS (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_4^+-N (mg/L)	TKN (mg/L)
Pit Latrines n=13	7.0 ±0.3	5.42 ±1.8	21,182 ±10,208	12,947 ±6,032	5,094 ±1,977	7,853 ±5,458	413 ±341	2,168 ±387
Septic Tank (Top Layer) n=4	7.2 ±0.5	6.69 ±3.78	3,844	3,576 ±718	2,920 ±641	656 ±188	268	327 ±69
Septic Tank (Bottom Layer) n=4	7.3 ±0.3	7.03 ±4.0	26,708 ±7,760	6,453 ±4,766	3,672 ±566	2,781 ±5,221	958 ±104	451 ±232

2.3 Treatment and Processing of Dried Sludge

The primary goal of FS treatment is to protect human and environmental health. The law that specifies particular regulations for the treatment and discharge, enduse, or disposal of FS is thus required. However, in many situations, FS-specific legislation is borrowed from wastewater treatment regulations, such as the National Wastewater Discharge Standards or Environmental Protection Agency Guidelines, which fail to account for the fundamentally different nature of FS. Treatment goals for FS should be established based on the sludge's planned enduse or disposal aim, as well as the enduse or discharge of liquid effluents. A multi-barrier strategy is preferable to imposing prescriptive, target-based regulations to ensure the enduse of treatment products.

Dewatering (or "thickening") of FS is an important treatment goal since FS comprises a significant amount of liquid, and reducing this volume minimizes the expense of transferring water weight and simplifies future treatment stages. Pathogen reduction, organic matter and nutrient stabilization, and the safe enduse or disposal of treatment endproducts are all used to meet environmental and public health treatment goals.

Gravity settling, filter drying beds, and evaporation / evapotranspiration are all common methods for dewatering FS. In comparison to wastewater sludge, FS has different dewatering characteristics in that it foams upon agitation and resists settling and dewatering (Strande et al., 2014). The ability to dewater the sludge is also affected by the length of onsite storage and the age of the FS. Sand drying bed technology is best for drying digested or stabilized sludge that is not easily dewatered mechanically. Fresh (nearly undigested) sludge, in contrast, is difficult to dewater on drying beds because the majority of its water content is not free. As a result, direct drying of public toilet septage should be avoided because drying performance is frequently low and unpredictable (Heinss et al., 1998; Cofie et al., 2006). Cofie et al. (2006) found that the initial TS and TVS (total volatile solids) content, as well as the FS loads, all affect how well dewatering works. To increase the solids content, dewatering or thickening can also include the addition of dry materials such as sawdust. This is a common practice in processes such as composting, where the sawdust increases the carbon to nitrogen (C:N) ratio. The liquid stream produced during dewatering must also be treated because it contains ammonia, salts, and pathogens.

The planted drying bed or vertical-flow constructed wetland is a low-cost and effective FS dewatering technology. The process involves the use of selected emergent plants that are responsible for sludge dewatering by allowing high evapotranspiration (depending on climatic conditions) through the vegetation, while the root system facilitates water drainage and biofiltration (SSWM, 2013). The plants also help stabilize the sand surface, preventing erosion channels from forming. Plant selection criteria include the ability to grow a deep rhizome and root system, good multiplication in the presence of FS, tolerance of different water levels, variable pH or high salinity, and insect/pest resistance (Kengne et al., 2012).

2.3.1 Potential Use of Treated Sludge

In low- and middle-income countries, composting is frequently regarded as a low-cost and simple-to-implement technical option for sludge sanitization. Composting is a microbial degradation of organic solid waste process. It can be done under aerobic (with oxygen) or anaerobic (without oxygen) conditions, and it can even switch between the two. For dried FS composting, open/aerobic systems such as windrows and static piles (low cost) have been used to date. They are preferred over other methods because they allow composting temperatures to rise and material to be sanitized more quickly. Heat is still the most dependable sanitization method (Vinners 2007). Composting methods that do not result in a sufficient temperature increase (e.g., vermicomposting) should be avoided as much as possible because they necessarily require longer periods of sanitization for compost products. Dried FS can be co-composted with any organic material that contains a lot of carbon. However, the type of added material will influence the length of the co-composting process. Furthermore, incoming organics should not contain contaminants that have a long-term negative impact on the environment and human health. To ensure that the quality of the compost produced is acceptable, any heavy metal content must be confirmed to meet safety standards. According to current standards, FS contains acceptable levels of heavy metals under normal conditions, i.e. within the acceptable range for reuse (Nikiema et al. 2013; Cofie and Adamtey 2009; Kengne et al. 2009; Heinss et al. 1998). When co-composted with other waste types, however, care must be taken to ensure that the added material is also acceptable.

Dried fecal sludge or compost pelletization is intended to increase the marketability of FS-based products by addressing the technical, social, and environmental issues associated with FS. Pellets are small particles that are frequently formed by compressing the original material. The compost pellets must have the following properties: Durability: the ability to avoid being crushed during handling, particularly transportation. Malleability: Spreads easily, even mechanically, with no/little dust generation. The nutrient content is high and stable. Extrusion and compaction are the two main methods used to create pellets. Pelletization of vegetable compost has been practiced for many years in developing countries (e.g., Nigeria, India, and China). Pelletization of FS-based products, on the other hand, appears to be a new area, with only a few cases reported thus far. Binding material can be used during pelletization, but it is not always necessary. The binder prevents the pellets from breaking down until they are applied to the soil and is important when the material is difficult to pelletize (e.g. for sawdust co-compost). The decision to use a binder should be made with market behavior (e.g., are users willing to purchase the product even if it contains a certain percentage of fine particles) and cost implications in mind. Dry starch, dry sugars, beeswax, primary clay, secondary clay (bentonite), gums, alginates, and lignosulfonates are theoretical examples of binders.

2.3.2 Fuel Potential of Fecal Sludge

There is a market for FS treatment end products such as solid fuels, biogas, soil conditioner, protein, fertilizer, and compost (Diener et al., 2014; Gold et al., 2014). However, the majority of these markets are still untapped, with only limited use of treated FS as a soil conditioner (Diener et al. 2014). Energy-producing options have a higher revenue potential than other treatment end products in Sub-Saharan Africa (Diener et al. 2014) and can be recovered within urban markets, reducing transportation costs. The generated income could offset treatment costs. Because of their large and consistent fuel demands, large-scale industrial markets such

as cement or coal-fired power plants are especially promising.
For many years, wastewater treatment sludge has been used as a solid industrial fuel in cement industries and coal-fired power plants in Europe, the United States, China, and Japan (Werther and Ogada 1999; Spinosa 2011). In Germany, for example, power plants replace 3–10% of their coal consumption (by weight) with 10,000–100,000 tons of wastewater sludge dry matter (DM) per year (Richers et al. 2002). In Switzerland, one cement company uses approximately 15,000 tons of DM wastewater sludge per year, and in 2012, 27% of Swiss wastewater sludge was used as an industrial fuel in cement production (Tezcan 2013). The calorific value of FS ranges from 12.2 to 19.1 MJ/kg DM, which is comparable to wastewater sludge and other biofuels (Muspratt et al., 2014; Seck et al., 2015). Unlike wastewater sludge, however, dried FS fuel has not been evaluated for use as an industrial fuel (Werther and Ogada 1999; Luts 2000; Niwagaba et al. 2005). FS characteristics that influence combustion and adverse environmental impacts are currently understudied (Trezza and Scian 2005; Obernberger et al. 2006; WBCSD 2014). FS, unlike wastewater sludge, is collected from individual households and thus has highly variable properties (Niwagaba et al. 2014). This suggests that experience with wastewater sludge combustion is not directly transferable to FS.

According to Nower (2015), fuel capacity of dried FS sample of Satkhira and Khulna districts' fuel potential was calculated from Bangladesh's perspective. According to the findings of the fuel potential analysis, samples dried for 15 days appear to have a higher calorific value (7.1 MJ/kg) than samples dried for 21 days (4.32 MJ/kg). Additionally, it has been noted that the sample that was dried for 21 days contains more moisture and less fixed carbon. The findings thus imply that 15 days is sufficient for the sludge to be dried for use as fuel. The average calorific values for the 15-day and 21-day dried samples were found to be 7.1 and 4.32 MJ/Kg, respectively, indicating a decline in fuel potentiality with age.

2.4 Overview FSM in Bangladesh

The management of FS contained within on-site sanitation systems such as pit latrines and septic tanks is referred to as FSM. FSM is absolutely essential to the safe management of sanitation and the protection of public health. Without fecal sludge management, human waste can contaminate the environment and nearby drinking water sources. This makes it more likely that disease will spread in vulnerable populations. The collection, treatment, disposal, and reuse of fecal sludge are all part of a fecal sludge management system. Safe disposal of treated septage is an important part of efficient fecal sludge management. FSM services include using a suction pump or other mechanical solution to empty pits or tanks, collecting in a vacuum tanker, transporting the collected fecal sludge to a treatment plant, and finally treating the sludge into harmless end products (ITN-BUET, 2015).

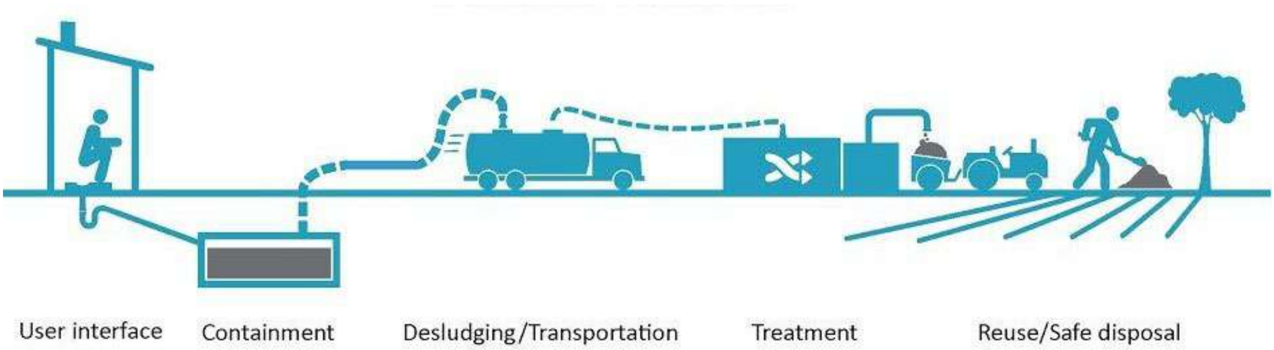

Figure 2.1: The elements of the entire FSM service chain

Over the past decade, Bangladesh has seen a dramatic increase in the number of individual sewage treatment systems. The elimination of open defecation among the lowest income quintile through the implementation of on-site sanitation (OSS) facilities represents the most significant improvement in urban sanitation during this time frame. However, sewage sludge treatment has not been a priority in the design of on-site sanitation systems in Bangladesh. The need for fecal sludge management (FSM) to keep on-site sanitation systems functional has increased significantly as their use has increased. Septic tanks and pits produce a vast amount of fecal sludge, which is typically improperly disposed of in low-lying regions, sewers, lakes, and canals due to a lack of reliable FSM services, resulting in severe environmental deterioration. While FSM-related issues are widespread, statistics and knowledge about FSM in urban settings are limited. There are substantial variations in institutional structure and FSM practices between and within cities and towns, and an accurate assessment of the situation is necessary before a functional FSM system can be designed.

2.4.1 FSM Framework in Bangladesh

Effluent discharge laws and norms have been passed in most less industrialized nations. The criteria typically apply to the treatment of both wastewater and fecal sludge. Due to the negative economic and institutional conditions present in many nations or regions, they are frequently too strict to be achieved. Effluent standards are frequently neither monitored nor enforced.

In order to establish any laws and regulations related to hygienic sanitation solutions, major decision-making bodies should concentrate on the following factors: affordable solutions for the problem of emptying ill-designed pits, septic tanks, and other containers; better pit emptying management; institutionalization of collection and transport processes; business models for FSM; more suitable treatment systems and capacities; and the requirement for improved reuse of treated FS.SDG Target 6.2 states that we will end open defecation and provide all people with access to sufficient and equitable sanitation and hygiene by the year 2030, paying particular attention to the needs of women, girls, and people in vulnerable situations. Indicator 6.2.1 shows the percentage of the population that uses sanitation services that are safely managed and include a sanitary sanitation solution. The government of Bangladesh and other relevant organizations take the required actions to create the Institutional and Regulatory Framework (IRF) for Fecal Sludge Management in order to meet this goal.

Bangladesh lacked a dedicated institutional and legal structure for FSM. Major obstacles to successful FSM include the lack of a clear institutional or legal framework and the lack of technology that has been demonstrated for the treatment and disposal of fecal sludge. The National Forum for Water Supply and Sanitation decided to create an institutional and regulatory framework for fecal sludge management on September 4, 2014. In order to establish the IRF, the working committee held a number of consultations, including 22 field consultations (11 in urban regions and 11 in rural areas). The government adopted and released the IRF for fecal sludge management (FSM) in October 2017. The Local Government Acts of 2009 served as the foundation for the development of the frameworks.

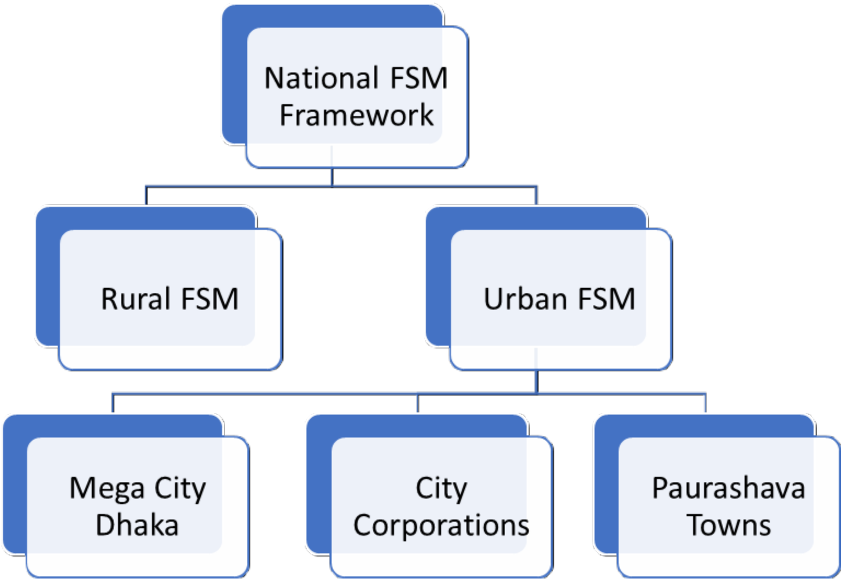

Figure 2.2: FSM Framework for Bangladesh

2.4.2 Overview of FSM services in Bangladesh

According to the IRF-FSM, City Corporations (in larger cities) and Pourashavas (in municipal towns) are responsible for FSM services in Bangladesh. The Pourashava authority in Bangladesh is responsible for implementing the complete FSM system in municipal towns. The Pourashava must take action to incorporate the FSM infrastructure (i.e., treatment facility) into their "master plan" for the implementation of City-Wide Inclusive Sanitation (CWIS) or FSM services. With help from different government agencies, development partners, and non-governmental organizations, several Pourashavas and City Corporations have introduced FSM services in their respective towns and cities. The cities were FSM services have been running for several years include Khulna, Chattogram, Mymensingh, Sakhipur, Laksmipur, Faridpur, Satkhira, Jashore, Kushtia, Jamalpur and Syedpur. A number of other cities have started or planning to start FSM services under projects being implemented by the Department of Public Health Engineering (DPHE). The FSTPs in these cities employ unplanted and planted drying beds for solid-liquid separation. A number of FSTPs are using the dried sludge for co-composting to produce soil conditioner. A few are also producing solid fuels from the dried FS.

In this study, raw and dried fecal sludge samples were collected from FSTPs in Satkhira Paurashava and Faridpur Paurashava. The FSM services in these two cities are discussed in the following section.

2.4.2.1 Overview of FSM in Sakhipur Paurashava

Sakhipur is a fast urbanizing paurashava in Tangail district's Sakhipur Upazila. It is around 96 kilometers from Dhaka, the capital city of Bangladesh. Sakhipur became a municipality in October 2000 and has a population of 42,760 people residing in a 27.6 km^2 residential area, resulting in a population density of 1,550 people per km^2 (Sakhipur Municipality, 2022). The total number of wards is nine, and the total number of households is 8,025. In recent years, it has confronted the challenges of an inadequate waste management system. Almost 80% of the fecal sludge from pits or tanks is discharged directly to the environment, either after manual emptying or by overflowing pipes. The lack of a treatment plant has clearly created a gap in the fecal sludge management system. Sweepers manually empty pits and tanks and transport garbage to disposal sites. Sludge from on-site sanitation units' overflows and discharges in neighboring open drains, water bodies, and forests due to a lack of effective maintenance, emptying, and collection services. This has a significant detrimental influence on public health and causes environmental damage. The town's solid waste management is likewise deficient. There are no trash cans or designated waste disposal areas. As a result, city inhabitants typically dispose of their domestic waste in ditches, along roadsides, or in drains. This has a significant detrimental influence on public health and causes environmental damage.

The municipality generates 6500 metric tons of FS and 3500 metric tons of home SW per year. Approximately 79% of the FS is dumped from pits or tanks, either manually or through pipelines that discharge directly to the environment (Al-Muyeed, 2017). WaterAid Bangladesh and the Bangladesh Association for Social Advancement (BASA) collaborated in 2015 to develop a co-composting plant in Sakhipur. The composting of two inputs, organic solid waste and fecal sludge, is referred to as "co-composting". For the co-composting plant, the municipality provided a 0.3-acre area of land outside of the city center. WaterAid provided technical and financial assistance, and BASA served as the project's implementation partner. Work on the plant began in 2015, and it became fully operational in January 2016. The treatment facility consists of ten (9 m^2) unplanted drying beds with a daily loading capacity of 8 m^3 of FS. Sakhipur Municipality has been operating the vacutug for FS collection and transportation since 2015, which is the only FS emptying and transportation vehicle in the municipality. The FSM system in Sakhipur Municipality covers all five components of the sanitation service chain: containment, emptying, transportation, reuse, and treatment. The co-composting plant's technology is a three-step process: 1) unplanted drying beds for fecal sludge; 2) wastewater treatment with a built wetland; and 3) aerobic decomposition (composting) of dried fecal sludge and organic solid waste. The treatment plant has a daily capacity of 5000 liters of sludge treatment. Currently, 1,200 MT of FS and 125 MT of solid waste is managed at the plant to produce 24 MT co-compost per year (ITN-BUET,2021). The co-composting plant requires a lot of effort, including a plant supervisor, two solid waste segregators, and two people working with the Vacutug. Previously, solid waste sorting was the most expensive activity. Since December 2018, a private entrepreneur has been contracted to collect solid waste from 1,000 homes and separate organic and inorganic waste.

The challenge for Bangladesh with this new approach is to change people's perceptions of compost. Sakhipur gives proof in the context of Bangladesh that human waste can be converted into fresh resources. The compost created at Sakhipur improves soil fertility, resulting in higher yields for farmers. The co-composting plant exemplifies how FSM can be used to successfully deal with solid waste and fecal sludge-induced environmental damage. The municipality intends to address the increased demand for FSM services. By 2024, the authority hopes to have safely managed all of the sludge. The vacutug's struggle with the tiny roads leading up to the residences. Furthermore, the need for pit emptying services is rapidly expanding. One vacutug is insufficient to accommodate the escalating demand.

Figure 2.3: Vacutug is used in Sakhipur for collection and transportation of FS

2.4.2.2 Overview of FSM in Faridpur Paurashava

Faridpur Municipality is one of the oldest municipalities in Bangladesh with a total area of 17.4 km². It was established as a municipality in 1869 and is situated between 89°47'4.17 and 89°51'18.09 east longitudes and latitudes of 23°33'34.10 and 23°35'52.87 north. From the capital city of Dhaka, it is 113 km away. There are 150,154 people living there in total, and on-site sanitation is offered right away. The coordination and resonance between a responsible local administration and a responsive citizenry at large are crucial components of a successful FSM system. By maintaining a strong regulatory and enforcement system, Faridpur Municipality continues to be at the forefront of ensuring that the FSM system is operational and sustainable. A Multi Stakeholder Steering Committee (MSSC) has been established by the municipality to serve as a general oversight and directing body for FSM services. This committee, which includes members from many stakeholders, is in charge of monitoring incentive management, party performance, and service level agreements.

A project to improve FSM in the Faridpur Municipality region was started in 2008–2009 by the international NGO Practical Action in Bangladesh with funding from the DGIS-supported Management of Digested Human Excreta Project. Since then, Practical Action has persisted in aiding the municipality through a number of programs and steadily enhancing the FSM service. The municipality now has five emptying and transportation vehicles, three of which are in use. The Faridpur Municipality's FSM system currently includes all stages of the sanitation value chain, including containment, emptying, transportation, treatment, and reuse. With a treatment capacity of 24 m3 per day and a target population of 130,000 people as beneficiaries. Faridpur's new fecal sludge treatment plant (FSTP) with both planted and unplanted drying bed technologies began operating in February 2017. It is funded by the Bill & Melinda Gates Foundation. There are 16 unplanted and 12 planted drying beds in the treatment. Six baffled tanks, several horizontal flow wetlands, and a maturation pond are used to treat the leachate. In the dried sludge storage shed, the sludge is pre-processed before being taken off-site to a co-composting plant for additional processing.

For FSM in Faridpur, a business plan has been created using a public-private partnership (PPP) strategy. Through the municipality, the sweepers' cooperatives, and the treatment plant operator, this model offers citywide consumer services at a reasonable cost. Useful Action Bangladesh is supporting the upkeep of the FSTP financially and technically. The desludging trucks, which are owned by the municipality but rented and managed by two sweeper associations, empty and transfer the sludge. The residents must contact the municipality to request desludging services, and the municipality will then contact one of the two associations. The pit-emptying business has been profitable since the first year, making the groups prosperous businesspeople. The tariff has been thoughtfully determined, taking into account a number of variables, including a safety net for low-income people. The municipality and the treatment plant operator, Society Development Committee, have a management agreement for the treatment facility. Compost production, use demonstrations, and marketing are the duties of the treatment plant operator. It also establishes a system for evaluating compost in order to uphold standards set by the government. This green business model, driven by the private sector, has been adopted by the Bangladeshi government as part of the Institutional and Regulatory Framework (IRF) for FSM for all secondary towns. This strategy will be expanded in several towns to transform the unofficial pit-emptying service into successful economic ventures and respectable livelihood possibilities.

The FSTP now receives very little FS and is not performing to its full potential. The FSTP received about 1600 m3 of FS in 2019, the year with the most trips (778) ever made, which is less than 25% of its overall capacity. As a result of the lack of FS supply, the FSTP is not being used to its full potential. The FSTP has difficulties due to the limited amounts of sludge discharged and the inconsistent filling of beds. Because generating revenue is given more weight than ensuring the long-term viability of the infrastructure, some of the drying beds are overloaded and the remainder are underutilized. The half of the unplanted drying beds is filled multiple times with all the incoming sludge, while the planted drying beds are hardly ever used. Their filter media will become clogged as a result of this. In order to adopt the best strategies to increase the amount of sludge being transported to the FSTP, it will be addressed where the sludge is exiting the FSM service chain. A new optimized operation plan that takes into account the dewatered sludge that is required for the co-composting operations as well as the long-term sustainable operation of both the planted drying beds and the unplanted drying beds should be implemented based on the current loading as well as the needs of the various stakeholders.

Figure 2.4: Schematic diagram of Faridpur FSTP (Source: Practical Action Bangladesh)

2.5 Summary

There is limited data on the characteristics of raw FS in the context of Bangladesh. Much of the reported data on FS characteristics are from African countries, where sanitation facilities and toilet usage are different from those in our country. A few research works have reported characteristics of raw FS based on analysis of samples that were collected directly from toilet pits or septic tanks (by the research teams). These characteristics may not represent the characteristics of FS that are emptied from containments by vacuum tankers and taken to FSTPs for treatment. The desludging methods often play an important role in the characteristic of the emptied sludge. Characteristics of emptied sludge is more relevant for the planning, design and operation of the FSTPs. It is therefore important to generate data on characteristic of emptied fecal sludge from the common types of onsite sanitation facilities in Bangladesh.

Most FSTPs in Bangladesh use unplanted or planted drying beds for solid-liquid separation. Characteristics of FS (e.g., solids content) are important for designing such drying beds. The design criteria available in the literature for the design of drying beds are commonly based on the characteristics of fecal sludge in African countries. It is important to assess how the expected different characteristics of local FS would affect the applicability of these criteria.

Like the raw FS, there is very limited data on the characteristics of dried FS. The processing and resource recovery options from dried FS primarily on its characteristics. It is therefore important to assess the characteristics of dried FS produced in different FSTPs in Bangladesh.

Chapter 3
METHODOLOGY

3.1 Introduction

The main objective of this study was to evaluate characteristics of fecal sludge from different types of onsite sanitation facilities, and to assess the effect of raw fecal sludge characteristics on the quality of dried sludge produced in unplanted drying beds. In this study, characteristics of raw fecal sludge was assessed through analysis of fecal sludge collected from vacuum tankers employed in Sakhipur Paurashava (where FSM service is supported by WaterAid Bangladesh) and in Dhaka (where desludging service is provided by Gulshan Clean and Care, an organization which provide professional cleaning service provider in Bangladesh). The FS samples were collected directly from vacuum tankers used for emptying fecal sludge, and for each sample the source of FS was recorded. The FS samples were analyzed for a wide range of parameters. At the Sakhipur FSTP site, raw FS samples were collected from vacuum tankers just before the loading of FS onto unplanted drying beds. After completion of the drying cycle, dried FS samples were collected from the top of the drying beds, and analyzed for selected parameters, including moisture and nutrient contents and calorific value. In addition, dried FS samples from the unplanted drying beds were collected from the FSTP at Faridpur FSTP (where technical support is provided by Practical Action Bangladesh) and analyzed for nutrients and calorific value.

The raw FS samples collected in this study were tested for a range of parameters including pH, EC, COD, TS, TDS, TSS, NH_4^+, NO_3^- and PO_4^{3-} following standard procedures (typically employed for wastewater). This chapter describes the methodologies followed to determine the characteristics of the raw fecal sludge samples. This chapter also presents the methodology of determining moisture content, organic content, heavy metal and calorific value of dried fecal sludge samples collected from Sakhipur and Faridpur. The calorific value was determined by a Bomb Calorimeter (Isoperibol Calorimeter Model C 3000, IKA, Germany) at the Environmental Engineering Laboratory at BUET. In addition, elemental composition of the dried FS samples was determined using a CNHS Elemental Analyzer at the Institute of National Analytical Research and Service (INARS), BCSIR, and calorific values of the dried FS samples were also estimated from the elemental composition.

3.2 Description of the Sampling Locations and Sampling Procedures

To evaluate the characteristics of raw fecal sludge from different types of onsite sanitation facilities and to assess the possible effects of raw fecal sludge characteristics on the quality of dried sludge, raw and dried FS samples were collected from Sakhipur, Faridpur and Dhaka. This section describes the sampling locations and details of the sampling procedures followed.

3.2.1 Sakhipur Municipality

Sakhipur is a town in Sakhipur Upazila, in the Tangail District of Bangladesh. The city is recognized as a Paurashava (Municipality) and consists of nine wards having an area of 27.60 sq.km. The number of households in Sakhipur Municipality is 8,025 and the total population of the Municipality is 42,760, (Sakhipur Municipality, 2022). According to a 2015 baseline report, it had 4,959 pit latrines and 288 septic tanks; the town was generating almost 15 m^3 of fecal sludge per day. The Sakhipur Paurashava is providing fecal sludge management (FSM) services since January 2016, and has a FSTP with a capacity of 8 m^3/day. It was designed by Water Aid Bangladesh (WAB), and BASA built it with financial assistance from WAB and the Municipality. The FS treatment process at the plant involves unplanted drying beds for drying of FS. The dried fecal sludge is subsequently used for co-composting. The effluent from the drying beds are treated using constructed wetlands and a polishing pond. The FSTP at Sakhipur has a total of 10 unplanted drying beds, each measuring 15 feet x 7 feet area. A 14-day cycle is used for the drying of fecal sludge at the Sakhipur FSTP. The drying beds are covered by a translucent celluloid sheet that protects the sludge from rain (Fig. 3.1).

Sakhipur Municipality now operates one vacutug (with a capacity of 1,000 liters) for FS collection and transportation. The FS collection from households is an on-demand process. Householders have to pay to the Municipality for the emptying service. Two personnel along with the 1000-liter capacity vacutug is dedicated to collect the liquid sample as per demand. On a typical working day, each vehicle can make a maximum of six journeys/trips. As a result, assuming five working days per week, one vehicle can accomplish a maximum of 1,500 trips each year. However, the vacutug remains inactive at times and there was no service on during repairs and maintenance. The total number of trips made by the vehicle (vacutug) in the Municipality over the last four years was 1991 (highest 523 in 2019, ITN-BUET, 2021). This implies that there was insufficient demand for emptying, given the capacity of the vacutug in terms of number of trips that can be made each day.

Figure 3.1: Unplanted drying beds at Sakhipur FSTP.

For this research work, raw FS samples were collected from the vacutug at the Sakhipur FSTP just before it was discharged into an unplanted drying bed (see Fig. 3.2). During each sampling, three 2-liter pre-washed plastic bottles were used to collect the raw FS samples from the vacutug. The bottles were sealed and transported to the BUET Environmental Engineering Laboratory on the same day for analysis. Raw FS samples were analyzed for a range of parameters, including pH, EC, COD, TS, TDS, TSS, NH_4^+, NO_3^- and PO_4^{3-} following the standard procedures used for the analysis of wastewater samples.

Figure 3.2: Raw sample collection at Sakhipur FSTP prior to discharge into the unplanted drying bed.

At the Sakhipur FSTP, the dried sludge is removed from the top of the drying beds at the end of the two-week drying cycle, and placed in a maturation bed for one week. For this study, dried FS samples were collected for analysis. Dried FS samples were collected in plastic bags and were stored at the plant before their transport to the Environmental Engineering Laboratory at BUET. These samples were analyzed for a range of parameters including moisture content, organic content, nutrients, heavy metal and calorific value. The effect of raw FS characteristics on quality of dried sludge were assessed based on the characteristic of the raw FS and the dried FS. Table 3.1 and Table 3.2 show the details of samples collection from Sakhipur.

Table 3.1: Details of the raw FS samples collected from Sakhipur FSTP

Sample ID	No. of Samples	Drying Bed No. to which FS was Loaded	Sample Source	Containment Type	Sampling Date
Sample-01	01	08	Public Septic Tank	Community Septic Tank	04.08.2019
Sample-02	03	05	Household	Pit Sludge	07.09.2019
Sample-03	03	03	Rakib Nagar Community	Community Septic Tank	02.11.2019
Sample-04	03	04	Rakib Nagar Community	Community Septic Tank	07.12.2019
Sample-05	03	07	Household	Pit Sludge	18.01.2020
Sample-06	03	05	Rakib Nagar Community	Community Septic Tank	02.02.2020

Table 3.2: Details of the Dried FS samples collected from Sakhipur FSTP

Sample ID	No. of Samples	Drying Bed No.	Sample Source	Containment Type	Sampling Date
Sample-01	03	08	Public Septic Tank	Community Septic Tank	07.09.2019
Sample-02	03	05	Household	Pit Sludge	02.11.2019
Sample-03	03	03	Rakib Nagar Community	Community Septic Tank	07.12.2019
Sample-04	03	04	Rakib Nagar Community	Community Septic Tank	18.01.2020
Sample-05	03	07	Household	Pit Sludge	02.02.2020

3.2.2 Dhaka City

Raw FS samples were collected from different places of Dhaka city where fecal sludge emptying service is provided by Gulshan Clean and Care (GCC), an organization which provides professional cleaning service. GCC provide water tank cleaning services, overhead tank cleaning, reserve tank cleaning, ETP cleaning, and pit and sewerage drain cleaning. They are also providing septic tank cleaning service at commercial and residential establishments since 2004. All raw samples were collected with support from GCC. The first raw FS sample was collected in prewashed plastic bottles from the holding tank of a vacuum tanker during the septic tank cleaning operation offered at Dhaka University's Institute of Energy by GCC personnel. The remaining samples were collected from the GCC operation terminal near Lake City Town in Khilkhet, Dhaka. GCC staff collected all of the samples from various locations throughout Dhaka city and gathered them at their operation terminal in Khilkhet. During collection of the samples from the holding tanks of vacuum tankers, the source of each sample was recorded. The samples were then taken to the Environmental Engineering Lab at BUET for analysis. The samples were analyzed for pH, EC, COD, TS, TDS, TSS, NH_4^+, NO_3^- and PO_4^{3-} Test. Table 3.3 (a) and Table 3.3 (b) shows the details of the raw FS samples collected from household septic tanks and community septic tanks, respectively, in Dhaka city.

Table 3.3 (a): Details of the raw FS samples collected from "household septic tanks" in Dhaka city

Sample ID	Sample Source	Collection Point	Sampling Date
Sample-01	Mirpur 11	GCC operation terminal	25.08.2020
Sample-02	Kalshi (TNT colony)	GCC operation terminal	01.09.2020
Sample-03	Mirpur 01	GCC operation terminal	02.09.2020
Sample-04	Mirpur 11	GCC operation terminal	03.09.2020
Sample-05	Mirpur 12	GCC operation terminal	04.09.2020
Sample-06	Banani	GCC operation terminal	04.10.2020
Sample-07	Baridhara	GCC operation terminal	05.10.2020
Sample-08	Banani DOHS	GCC operation terminal	07.10.2020
Sample-09	Uttara	GCC operation terminal	14.10.2020

Table 3.3 (b): Details of raw FS samples collected from "public septic tanks" in Dhaka city

Sample ID	Sample Source	Collection Point	Sampling Date
Sample-01	Dhaka University	Dhaka University	14.03.2020
Sample-02	A-Polar Ltd Station-01	GCC operation terminal	13.09.2020
Sample-03	A-Polar LtdStation-02	GCC operation terminal	14.09.2020
Sample-04	NZ Tex Group Tank-01	GCC operation terminal	17.09.2020
Sample-05	NZ Tex Group Tank-02	GCC operation terminal	18.09.2020
Sample-06	Nannu Textile Mills Limited Tank-01	GCC operation terminal	03.12.2020
Sample-07	Nannu Textile Mills Limited Tank-02	GCC operation terminal	03.12.2020
Sample-08	HSIA Terminal-01	GCC operation terminal	04.12.2020
Sample-09	HSIA Terminal-02	GCC operation terminal	04.12.2020

3.2.3 Faridpur Municipality

Faridpur is a city and district headquarters of Faridpur district in the Dhaka division. Total population of Faridpur Municipality is about to 159,150 (projected in 2020 as per BBS 2011 data). The city has an area of 17.40 sq. km. with a population density of about 9,157 per km^2. There are nine wards with a total of 30,815 holdings (ITN-BUET, 2021).

In Faridpur Municipality, 29.0% of the households had cistern-flush toilets, while the remaining households had pour-flush toilets. About 11.8% of houses either do not have any water seal or the water seal is broken, whereas 87.5% of households either have no vent pipes or the pipes are not working properly. A small number of houses in Faridpur Municipality (2.9%) do not have a containment system linked to their toilets and hence release feces directly into open drains or the open environment. About 53.3% of households with containments use septic tanks, 41.6% use single pits, and 2.2% use twin pits (ITN-BUET, 2021). In a few low-income communities, particularly in the slums of Faridpur Municipality, there are community toilets. There are 16 public toilets in the Municipality that are managed by the municipal authority.

In 2008-2009, Practical Action Bangladesh, an international NGO, began a project with Faridpur Municipality for the improvement of FSM in the municipal area with assistance from the Directorate General for International Cooperation (DGIS)-funded Management of Digested Human Excreta Project. They delivered a vacutug, a sludge gulper, and developed a sludge treatment plant. Since then, Practical Action has been assisting the municipality to improve the FSM service through many programs. At present, the FSM system in Faridpur Municipality covers all the components of the sanitation value chain: containment, emptying, transportation, treatment, and reuse. The fecal sludge treatment plant (FSTP) at Faridpur, which employs both planted and unplanted drying bed technologies. It was financed by the Bill & Melinda Gates Foundation and started functioning in February 2017 with a treatment capacity of 24 m^3 per day, targeting 130,000 households as beneficiaries. Currently, the municipality has five emptying and transportation vehicles, three of which are operating. The FSTP in Faridpur Municipality is not running at full capacity.

For this research work, dried fecal sludge samples were collected from Faridpur Fecal Sludge Treatment Plant at the end of the 14-day drying cycles. The samples were collected, marked and store by the plant operators. Subsequently the samples were transported to the Environmental Engineering Laboratory at BUET, where these were analyzed for moisture content, organic content, nutrients, heavy metals and calorific value. Table 3.4 shows the detail information of dried FS collection from Faridpur FSTP. It should be noted that the dried FS samples were collected during January to April 2021. However, the samples could be transported to the laboratory in August 2021 and analyzed. As a result, the moisture content of these dried FS samples should not be treated as the moisture content of the dried samples immediately after the drying cycle.

Table 3.4: Details of dried FS samples collected from Faridpur FSTP

Sample ID	Containment Type	Sampling Date	Sample Analyzed at Lab Date
Sample-01	Household Septic Tank	02.01.2021	14.08.2021
Sample-02	Community Septic Tank	07.01.2021	14.08.2021
Sample-03	Community Septic Tank	05.03.2021	14.08.2021
Sample-04	Household Septic Tank	08.03.2021	14.08.2021
Sample-05	Household Septic Tank	22.03.2021	14.08.2021
Sample-06	Community Septic Tank	24.03.2021	14.08.2021
Sample-07	Household Septic Tank	07.04.2021	14.08.2021
Sample-08	Household Septic Tank	14.04.2021	14.08.2021

3.3 Analysis of Raw and Dried FS Samples

The raw and dried FS samples collected in this study were analyzed for detailed characterization in the Environmental Engineering Laboratory of the Civil Engineering Department of BUET. Tests for elemental analysis (ultimate analysis) of dried FS samples were carried out at BCSIR.

3.3.1 Analysis of Raw FS Samples

The raw FS samples were tested for the following parameters: pH, EC, COD, TS, TDS, NH_4^+-N, NO^{3-}-N and PO_4^{3-} . pH was determined using a pH meter (WTW, Multi 3500i). Electrical Conductivity (EC) was determined by an EC meter (WTW, MultiLine P4). Nitrate, ammonia, phosphate and COD were determined using a Spectrophotometer. Nitrate (NO_3^-) concentration was determined using Cadmium Reduction Method (Method 8171), NH_4^+ was determined using USEPA Nessler Method (Method 8038), PO_4^{3-} was determined using USEPA PhosVer 3 (Ascorbic Acid) Method (Method 8048), and COD (Chemical Oxygen Demand) was determined using USEPA Reactor Digestion Method (Method 8000). TS and TDS were determined following Standard Methods.

3.3.2 Analysis of Dried FS Samples

Dried FS samples were analyzed for moisture content, organic content, nutrients (phosphate, ammonia and potassium), selected heavy metals (Pb, Cd, Cr, Cu, Ni, Zn), and calorific value.

The moisture content of dried fecal sludge was determined using the USEPA Gravimetric Method (Method 8271), and the organic content was determined using the USEPA Gravimetric Method (Method 2540 E). For the extraction of heavy metals (Pb, Cd, Cr, Cu, Ni, and Zn) from the dried fecal sludge sample, a mixture of 1:3 nitric acid and hydrochloric acid (known as aqua-regia) was used in the laboratory. Each sample was dried in an oven at 105°C for 24 hours. Then, the dish temperature was decreased to room temperature in a desiccator. Then 5 gm (about to) of each sample was taken into a 500-ml flask, where 2.5 ml of concentrated nitric acid and 7.5 ml of concentrated hydrochloric acid were added. The suspension was kept overnight for digestion, and then, after adding deionized water, it was refluxed for 2 hours in the Gerhardt Apparatus. After the digested sample cooled down, it was diluted to 500 ml with deionized water and kept in a plastic bottle. Finally, a Shimadzu AA-7000 FLAAS equipment were used to determine the heavy metal concentrations. Phosphate, ammonia and potassium were analyzed after extraction in a liquid medium. Potassium was determined using USEPA 200.9, SM 3111B Method. Phosphate and ammonia were determined with a Spectrophotometer (as noted above).

An IKA C3000 ISOPERIBOL Bomb Calorimeter (Fig. 3.3) was used to determine the calorific value of dried FS samples. The sample powder was created using approximately 2–3 grams of dried sample. A C-21 Pelleting press was used to press the powder to create a tablet. About one gram of a solid tablet was weighed out in a crucible and placed in the decomposition vessel- the so-called bomb. The sample in the crucible was connected to the ignition wire by a cotton thread. The vessel was then filled with oxygen, which was supplied from an external source, and the sample was combusted. During the combustion process, the core temperature of the crucible can increase to 1,000°C. This also increased the inside pressure. All organic material was burned under these conditions. When a combustion calorimeter was used, the heat that was created from a sample was measured during its combustion under controlled conditions. In the decomposition vessel, the sample was burned with an excess of oxygen. The resulting heat was given off into the environment and measured. To prevent disruptive external temperature influences, the system was surrounded with a jacket. The heat produced during the combustion process was on display. The measurement result was then designated as the calorific value.

Figure 3.3: Bomb Calorimeter used to determine calorific value of dried FS samples

For the ultimate analysis, a total of eight dried solid samples were crushed into powder manually and weighted around 20 grams. To get higher efficiency in powder form, a Ball Mill Grinder (Pulverisette 6) machine was used, which was available at the Department of Glass and Ceramic Engineering Laboratory. Then a sieve analysis was done using a #100 sieve to ensure the particle size of the sample was less than 100 µm. Finally, about 5-gram of each sample was weighed and preserved in zipper bags. Figure 3.4 shows the Ball Mill Grinder Machine and samples prepared for CHNS Elemental Analysis. After that, the samples were carried to the Institute of National Analytical Research and Service (INARS) of Bangladesh Council of Scientific and Industrial Research (BCSIR) for elemental analysis.

Figure 3.4: Ball-Mill grinder machine (left), and fine pulverized samples for CHNS/O test.

In CHNS elemental analyzer, results were given in the form of carbon, hydrogen, nitrogen and sulphur contents. Oxygen content was calculated by the difference of carbon, nitrogen, hydrogen, sulphur and ash from unity, as shown below.

$O = 100 - Ash - C - N - S - H$

Where, C = Carbon, weight %

H = Hydrogen, weight %

N = Nitrogen, weight %

S = Sulphur, weight %

O = Oxygen, weight %

Then five different mathematical models were used to estimate the theoretical calorific values of FS samples from the elemental (carbon, nitrogen, hydrogen, sulphur and oxygen contents) composition. Table 3.5 shows the mathematical formula used for estimation of the calorific values.

Table 3.5: Mathematical models for theoretical calorific values

Model	Mathematical Equation	Unit	Reference
Modified Dulong Formula	$HHV = 337(C) + 1419\ (H - \frac{O}{8}) + 93(S) + 23.26(N)$	kJ/kg	(Liu et al., 1996)
Steuer Formula	$HHV = 81(C - (\frac{3O}{8}) + 171\ (\frac{O}{8}) + 345\ (H - \frac{O}{10}) + 25\ (S) - 6\ (9H + W)$	kcal/kg	(Liu et al., 1996)
Scheurer–Kestner Formula	$HHV = 81\ (C - (\frac{3O}{4}) + 171\ (\frac{O}{4}) + 342.5\ (H - \frac{O}{10}) + 22.5\ (S) - 6\ (9H + W)$	kcal/kg	(Liu et al., 1996)
Niessen Formula	$HHV = 0.2322(C) + 0.7655(H) - 0.072(O) - 0.0419(N) + 0.0698(S) + 0.0262(Cl) + 0.1814(P)$	MJ/kg	(Tchobanoglous et al. 1993)

3.4 Estimation of Solids Loading Rate for Sakhipur FSTP

Solids loading rate is an important parameter that determines the efficiency of treatment (i.e., solid-liquid separataion) in unplanted drying beds. The solids loading rate (λ_s) is related to the characteristics of FS (in particular TSS concentration), FS loading depth, and drying cycle used at a particular plant. The solids loading rate (λ_s) was determined using the following formula:

$\lambda_s = Z.\ C_{TSS}.\ N_c$

where,

λ_s = solids loading rate in kg TSS/m^2/year

Z = loading depth of wet sludge in m;

N_c = number of complete drying cycles in a year (for each drying bed);

C_{TSS} = solids conc. of wet sludge (g/l or kg/m^3)

The loading depth (Z) and N_c was estimated based on the information collected from the Sakhipur FSTP. The average TSS concentrations of FS from different sources determined in this study were used for estimation of solids loading rate. The estimated values λ_s were compared with those commonly used in the design of FSTP (employing unplanted drying beds).

Chapter 4
RESULTS AND DISCUSSION

4.1 Introduction

The primary objectives of this study are to evaluate the characteristics of raw fecal sludge from different types of onsite sanitation facilities and to assess the effect of raw fecal sludge characteristics on the quality of dried sludge produced in unplanted drying beds that employ the same drying cycle. This chapter presents the detailed characteristics of fecal sludge collected from different sources in Sakhipur Paurashava (in Tangail district) and Dhaka. It also presents an assessment of FS loading on drying beds and the effects of FS characteristics on the quality (particularly moisture content) of treated sludge at the Sakhipur FSTP. This chapter presents the calorific value of dried fecal sludge produced in unplanted drying beds from FS coming from different sources. It also illustrates a comparison of theoretical calorific values of FS (derived from elemental composition) with experimental values (from Bomb calorimeter), and includes a discussion on the calorific value and possible resource recovery options for fecal sludge.

4.2 Characteristics of Raw Fecal Sludge from Different Sources

As described in Chapter 3, a total of 6 raw fecal sludge samples were collected from Sakhipur FSTP before their loading onto the unplanted drying beds, and an additional 18 raw fecal sludge samples were collected from the Dhaka region. Among the six samples from Sakhipur, 04 were from septic tanks connected to public toilets, while the remaining two were from household pits. Among the 18 samples collected from Dhaka, nine were from household septic tanks and nine from septic tanks connected to public toilets. It should be noted that information regarding the source of the FS were collected from the operators of the vacuum tankers. As mentioned earlier, all raw FS samples were tested for a range of parameters, including pH, EC, TS, TDS, TSS, COD, NH_4^+, NO_3^- and PO_4^{3-}.

Table 4.1 shows a summary of the characteristics of all the FS collected in this study. Here, the FS samples have been divided into four broad classes: (a) FS: Sakhipur Public Septic Tanks; (b) FS: Sakhipur household pits; (c) FS: Dhaka household septic tanks; and (d) FS: Dhaka public septic tanks. For each parameter, it shows the mean, standard deviation and the range of values. In general, significant variability is observed in the values of most of the parameters tested. The variability is particularly strong for certain parameters such as EC, COD and ammonia. However, such variability is not unusual for fecal sludge samples (Strande et al., 2014), primarily due to variability in the use of toilets, condition of containment (including possible inflow/infiltration), frequency of desludging, desludging methods, etc.

The mean pH values of the fecal sludge samples have been found to be in the neutral range, varying from 6.84 to 7.46. These values are similar to those reported by UPM (2019) for pH of FS from pit latrines (mean value 7.0) and from septic tanks (mean value 7.2) in Rohingya camps in Cox's Bazar. The pH of FS from septic tanks is normally in the range of 6.5 to 8.0 (Strande et al., 2014), but can vary greatly from 1.5 to 12.6 (USEPA, 1994). A pH outside the range of 6 to 9 usually indicates an upset in the biological process that will inhibit anaerobic digestion and methane production (Strande et al., 2014). Except for a FS sample from a Dhaka septic tank (which had a pH of 5.9), all pH values were within the range of 6-9.

The EC values of the FS samples varied over a wider range; from 2.68 mS/cm (for Dhaka public toilets) to 4.27 mS/cm (for Dhaka septic tanks). No clear trend is observed between type of containment and EC values. The mean TDS concentrations varied from 875 mg/l (for Sakhipur public toilets) to 1,315 mg/l (for Sakhipur pit toilets). The TDS values of the FS samples are not strongly correlated with the EC values (Pearson's correlation coefficient R^2=0.15 and p=0.52; see Fig. 4.4). This is probably due to the fact that a significant fraction of dissolved materials in the FS samples are likely to be non-ionized organic materials. UPM (2019) reported mean EC value of 5.42 mS/cm for pit FS and 6.69 mS/cm for septic tank FS. Scarcity of water and infiltration from pits could be possible reasons for higher EC values for the FS samples in Rohingya camps.

The total solids (TS) concentration of the FS samples varied over a wide range from 2,940 mg/l (for Dhaka public toilets) to 8,160 mg/l (for Sakhipur pit latrines). As before, no clear trend was observed between sources of the FS samples and these parameters. Strande et al. (2014) reported very high TS values of fecal sludge from African regions; reported values of TS for FS from public toilets varied from 30,000 to 52,000 mg/l, while that for FS from septic tanks varied from 12,000 to 35,000 mg/l. These high values are most likely due to the nature of these toilets (dry toilets, without pour flush) and their usage ("wipers" as opposed to "washers"). UPM (2019) reported mean TS values of 12,947 mg/l for pit FS and 3,576 mg/l for pit FS. The high TS value for pit FS samples in Rohingya camps could be due to low water use and higher infiltration from pits (UPM, 2019).

The mean TSS values of the FS samples from different sources also varied over a wide range. The average TSS concentrations of FS from public septic tanks in Sakhipur and Dhaka have been found to be 2,755 mg/l and 4,090 mg/l, respectively. On the other hand, average TSS of FS samples from pit toilet was much higher (6,845 mg/l). TSS concentration of FS from pits, especially those in ground with good infiltration capacity, are usually higher due to lower water contents. On the other hand, TSS contents of FS from septic tanks are often lower due to improper desludging that collects primarily FS from the top layer, leaving behind the thick (and often hardened) FS at the bottom of the tank. The even higher TSS values of FS (from toilet pits in Rohingya camps) reported by UPM (2019) is most likely due to fact that the FS samples were collected directly from the pit (not from vacuum tankers after desludging).

The mean COD values of FS from the four types of containment varied from 1,094 mg/l (for Dhaka household septic tank) to 3,689 mg/l (for Sakhipur public toilets). The highest mean COD value was found for septic tanks connected to public toilets in Sakhipur. The mean COD value of FS from pit toilets in Sakhipur was also relatively high (3,287 mg/l). However, these values are much lower than those reported in Stande et al. (2014) for African regions. Stande et al. (2014) reported COD concentration of 1,200 to 10,000 mg/l for FS from septic tanks, and 30,000 to 49,000 for FS from public toilets. As noted earlier, the nature of the toilets and their usage are probably responsible for these high values. UPM (2019) reported a mean COD of 21,182±10,208 mg/l for pit FS samples collected from Rohingya camps. As noted earlier, low water use and higher infiltration from pits could be responsible for these high COD values. UMP (2019) reported significant variation of COD (and also BOD) in FS samples collected from the top and bottom of a septic tank; the mean COD values varied by a factor of almost 7. Mean (n = 4) COD of FS samples collected from the top layer was 3,844 mg/l and that collected from the bottom layer was 26,708 mg/l (UPM, 2019). Collection of FS from the bottom layers of a septic tank often requires significant effort. It is possible that desludging operation in Sakhipur and Dhaka primarily collected FS from top layers and this has contributed to the relatively lower value of COD (and also TS) for these samples.

Table 4.1: Characteristics of raw fecal sludge of four different sources

Characteristics of Raw Fecal Sludge									
Source	**pH**	**EC (mS/cm)**	**COD (mg/L)**	**TS (mg/L)**	**TDS (mg/L)**	**TSS (mg/L)**	**NH_4^+-N (mg/L)**	**NO_3^--N (mg/L)**	**PO_4^{3-} (mg/L)**
Sakhipur Public Septic Tank n=04	7.35±0.38 6.60-7.85	3.62±1.50 1.50-6.50	3,689±1,619 1,300-5,850	3,630±2,985 1,170-9,610	875±380 300-1,500	2,755±3,105 200-9,210	281±108 150-450	3.4±2.2 1.0-8.0	208±95 90-340
Sakhipur Household Pit n=02	7.46±0.39 7.08-7.83	3.06±1.00 1.50-4.50	3,287±1,922 1,200-5,280	8,160±3,940 4,815-14,130	1,315±407 800-1,900	6,845±4,200 3,115-12,940	302±132 170-470	2.7±1.3 1.0-5.0	151±68 90-270
Dhaka Household Septic Tank n=09	7.04±0.48 5.90-7.45	4.27±2.13 1.95-7.55	1,094±982 500-1,100	-	1,176±657 520-2,500	-	223±158 70-460	4.6±2.4 2.0-9.0	158±44 110-220
Dhaka Public Septic Tank n=09	6.84±0.15 6.51-6.97	2.68±0.32 2.20-3.10	1,700±676 700-3,100	2,940±1,990 3,050-9,515	1,232±176 980-1,530	4,090±1,980 1,765-8,535	183±116 80-420	2.9±1.2 1.0-5.0	173±56 110-260
Overall Mean±STD Range n=24	7.15±0.42 5.90-7.85	3.44±1.51 1.50-7.55	2,405±1,692 500-5,850	4,470±3,530 700-14,130	1,127±454 300-2,500	4,220±3,350 200-12,940	244±131 70-470	3.4±2.0 1.0-9.0	170±65 90-310

Notes: (1) Mean, standard deviation, and range of parameter values are presented in the Table
(2) TS and TSS value of Dhaka household septic tank data are not reported due to a possible error in measurement.

The mean ammonia concentration in the FS samples varied from 183 mg/l (for public toilets in Dhaka) to 302 mg/l (for pit latrines in Sakhipur). As before, these values are relatively low compared to the values (150 to 5,000 mg/l) reported by Strande et al. (2014). Mean nitrate concentration in the FS samples varied from 2.9 mg/l to 4.6 mg/l. Strande et al. (2014) reported nitrate concentrations of 0.2 to 21 mg/l for FS from septic tanks. Mean phosphate concentrations in the FS samples varied from 151 mg/l to 208 mg/l. As before, no clear trend was observed between the characteristics of FS and type of containment. The following section presents a detailed assessment of each of the parameters of the FS samples collected from different sources.

4.2.1 pH

Figure 4.1 shows the pH values of all 24 FS samples collected and analyzed in this study. The mean value of pH in this study area varied from 6.84 to 7.46, with an average value of 7.15 for all 24 samples. These average values are within the pH range 6.5–8.0 for appropriate microbiological activity as reported by Bhagwan et al. (2008). Only one sample from a Dhaka household septic tank was found to have a low pH of 5.9. The pH value of all the other samples was in the neutral pH range (pH 6.51–7.85). The standard deviations for the sample groups from these four sources varied within the range of 0.15 to 0.48, indicating minor variation among the pH values.

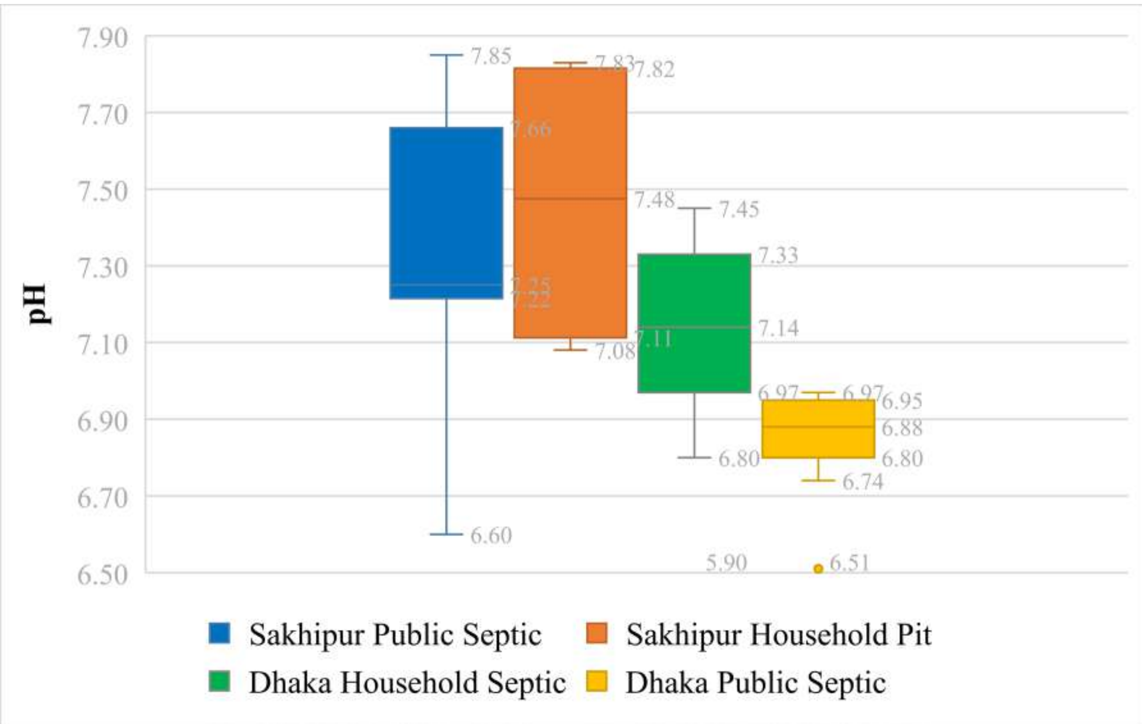

Figure 4.1: Box plot of pH of four different source of raw fecal sludge.

Figure 4.1 shows a “box plot” of pH values from the four different sources. Every box plot is divided into four major portions, each containing 25% of the sample data. From the data obtained from Sakhipur Public Septic Tank, 25% of the data points fell between 6.60 to 7.22, which means 25% of pH values were less than 7.22. In this box plot, 50% of the data points were found lying between 7.22 and 7.66, which means the interquartile range was 0.44 in this case. The observed median value for Sakhipur public septic tank samples was 7.25, and from the third quartile (q3) value, it can be observed that 25% of the data fell between 7.66 to 7.85. T-shaped whiskers reached the two extremes (6.60 and 7.85), which are still within 1.5 times the interquartile range (0.44).

From the Sakhipur household pit samples, it was observed that 50% of data points lied within 7.11 to 7.82, while the whiskers almost coincided with the first and third quartiles (q1 and q3, respectively). The median value was 7.48, which indicates 25% of samples had higher pH values than the median and another 25% had a pH value lower than 7.48. Considering the pH of all of the samples collected from this source, they were all found to be neutral to slightly alkaline.

From the data obtained from Dhaka household septic tank samples, 50% of data points were observed lying within the range 6.97 to 7.33. The median value was 7.14, with 25% of the data points above and 25% below this limit. One particular data point with a pH value of 5.90 (acidic) was out of the limit (1.5 times the interquartile range) and was hence considered an outlier.

From the data obtained from Dhaka public septic tank samples, 50% of data points were observed lying within the range 6.80 to 6.95. The median value was 6.88, with 25% of the data points above and 25% below this limit. One particular data point with a pH value of 6.51 (acidic) was out of the limit (1.5 times the interquartile range) and was hence considered an outlier.

4.2.2 Electrical Conductivity (EC) and Dissolved Solids (TDS)

Figure 4.2 shows the EC values of all FS samples collected in this study. The EC values of the samples varied from 2.68 to 4.27 mS/cm. The mean value of EC was 3.44 mS/cm for 24 samples, which is close to the value reported in another study by Nobela (2014). One of the samples from the Dhaka household septic tank had the highest EC value (7.55 mS/cm) and the lowest EC value was observed in a Sakhipur public septic tank and a Sakhipur household pit sample (1.50 mS/cm).

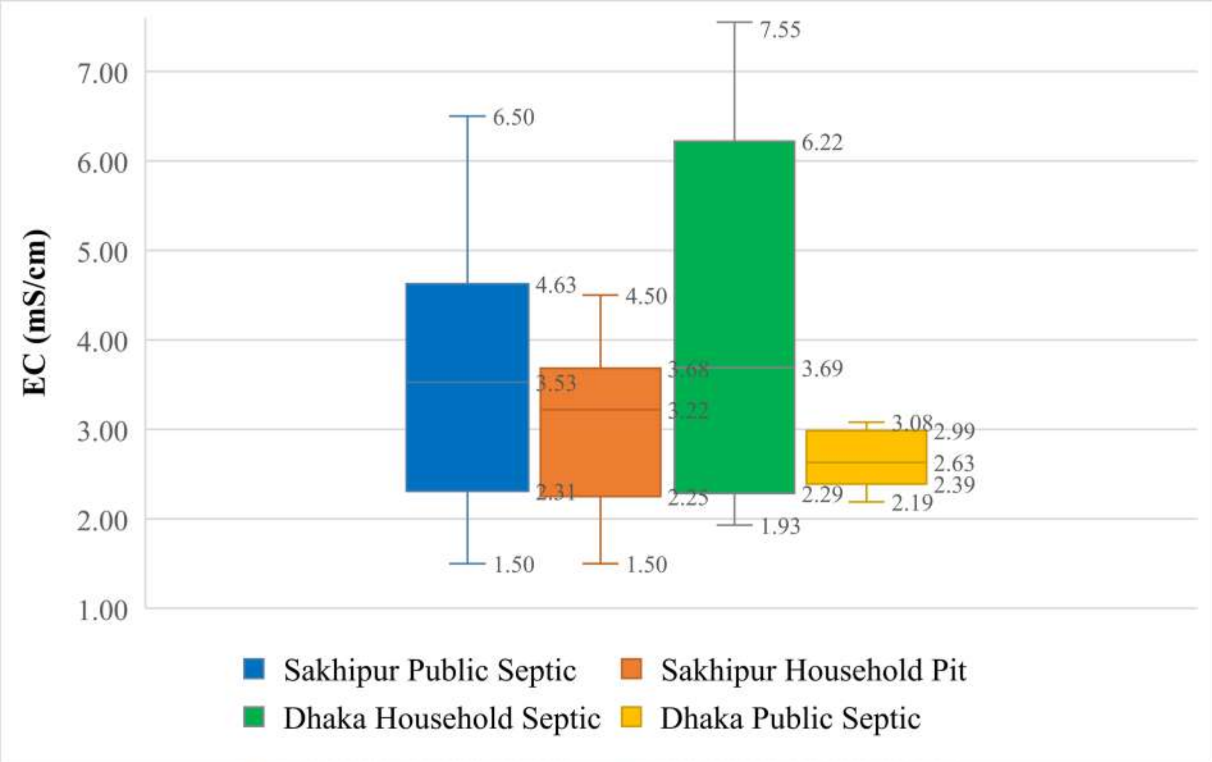

Figure 4.2: Box plot of EC of four different source of raw fecal sludge.

Figure 4.2 shows a "box plot" of EC values from the four different sources. Data from the Sakhipur public septic tank showed that 25% of data points fell between 1.5 mS/cm and 2.31 mS/cm, which suggests that 25% of EC values were lower than 2.31 mS/cm. The interquartile range in this box plot was 1.60 mS/cm since 50% of the data points were found to fall between 2.31 mS/cm and 4.63 mS/cm. The third quartile (q3) value shows that 25% of the data ranged between 4.63 mS/cm and 6.5 mS/cm. The observed median value for Sakhipur public septic tank samples was 3.53 mS/cm. The two extremes (1.5 mS/cm to 6.5 mS/cm), which are still within 1.5 times the interquartile range (1.60 mS/cm), were attained using T-shaped whiskers.

The median value for the Sakhipur home pit samples was 3.22 mS/cm, and 50% of the data points were within that range. This means that 25% of the samples had EC values that were higher than the median and another 25% had EC values that were lower than 3.22 mS/cm.

Fifty percent of the data points from the Dhaka household septic tank samples were found to fall between 2.29 mS/cm and 6.22 mS/cm. With 25% of the data points above and 25% below this limit, the median value was 3.69 mS/cm. The two extremes (1.93 mS/cm to 7.55 mS/cm), which are still within 1.5 times the interquartile range (3.33 mS/cm), were attained via T-shaped whiskers.

Fifty percent of the data points from the Dhaka public septic tank samples were found to fall between 2.39 mS/cm and 2.99 mS/cm. With 25% of the data points above and 25% below this limit, the median value was 2.63 mS/cm. Compared to the Dhaka household septic tank sample (1.93 mS/cm to 7.55 mS/cm), the two extremes of the public septic tank samples (2.19 mS/cm to 3.08 mS/cm) varied less.

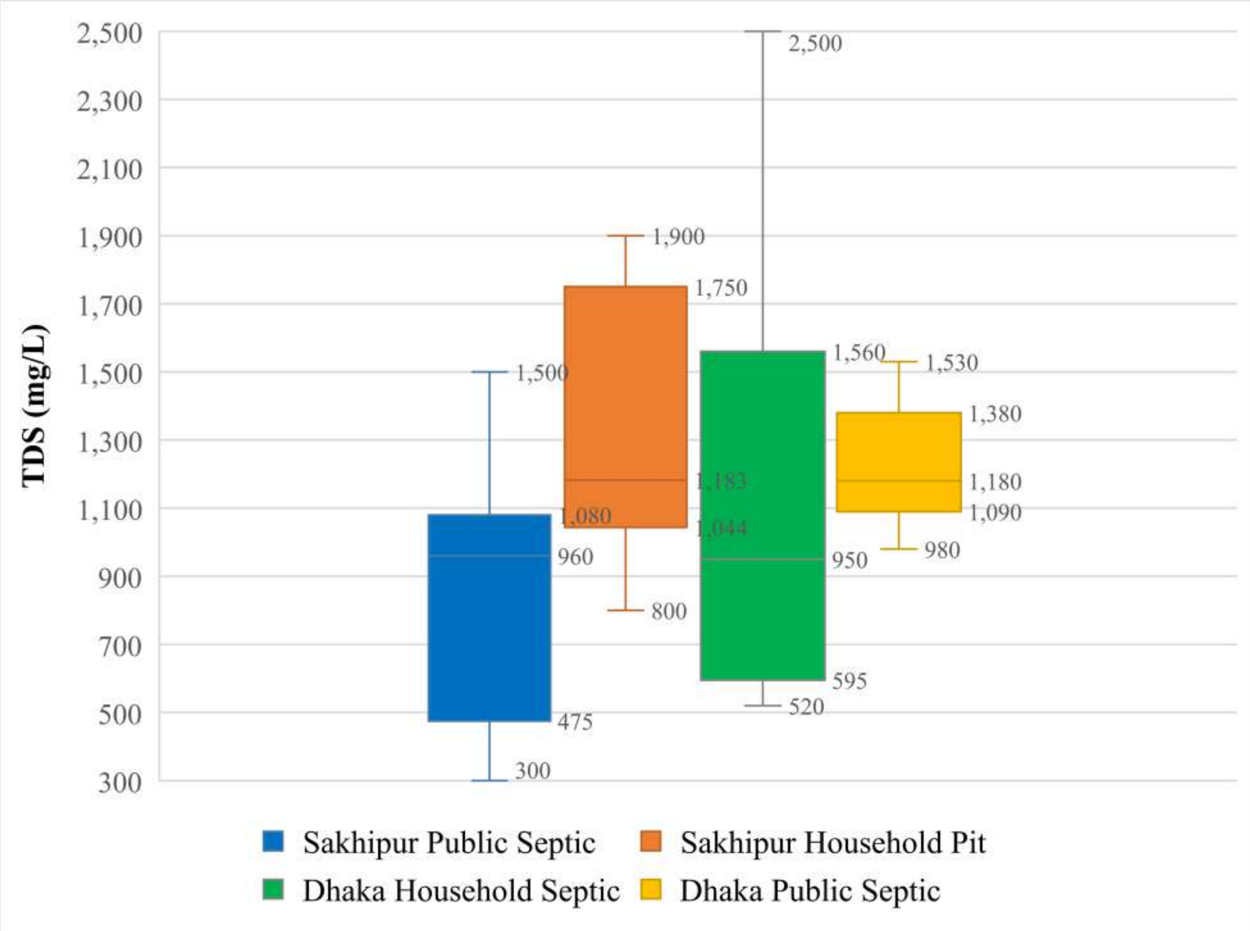

Figure 4.3: Box plot of TDS of four different source of raw fecal sludge.

Figure 4.3 shows the TDS values of the FS samples collected in this study, and it also shows a “box plot” of the TDS values. Total Dissolved Solid (TDS) values of FS samples from Sakhipur public septic tank ranged from 300 mg/L to 1,500 mg/L, with 25% of data points below 475 mg/L. In this box plot, 50% of the data points were between 475 and 1080 mg/L, making the interquartile range 410 mg/L. Sakhipur public septic tank samples had a median value of 960 mg/L and a third quartile (q3) range of 1080–1500 mg/L. T-shaped whiskers reached 300–1500 mg/L, which is 1.5 times the interquartile range (410 mg/L).

From the Sakhipur household pit samples, 50% of data points were between 1043 mg/L and 1750 mg/L, and the median value was 1182 mg/L, indicating that 25% of samples had TDS levels higher than the median and 25% lower.

50% of Dhaka household septic tank samples fell between 595 and 1560 mg/L. The median value was 950 mg/L, with 25% above and 25% below. T-shaped whiskers reached the extremes (520 mg/L to 2500 mg/L) within 1.5 times the interquartile range (915 mg/L).

Half of all the samples taken from public septic tanks in Dhaka had a concentration of between 1090 and 1380 mg/L. The value of 1180 mg/L was considered the median, with 25% above and 25% below. T-shaped whiskers achieved the highest levels, which were 980–1530 mg/L, which is 1.5 times the range of the interquartile range, which is 250 mg/L.

Electrical conductivity is an indirect measure of dissolved (ionic) solids. For the FS samples, EC values do not correlate well with dissolved solids (TDS) concentrations. One important reason for this could be that a significant part of the dissolved materials in FS are organic and possibly not ionized. Figure 4.4 shows a plot of TDS versus EC for the FS samples. It shows poor correlation ($R^2 = 0.269$ and $p = 0.52$) between TDS and EC.

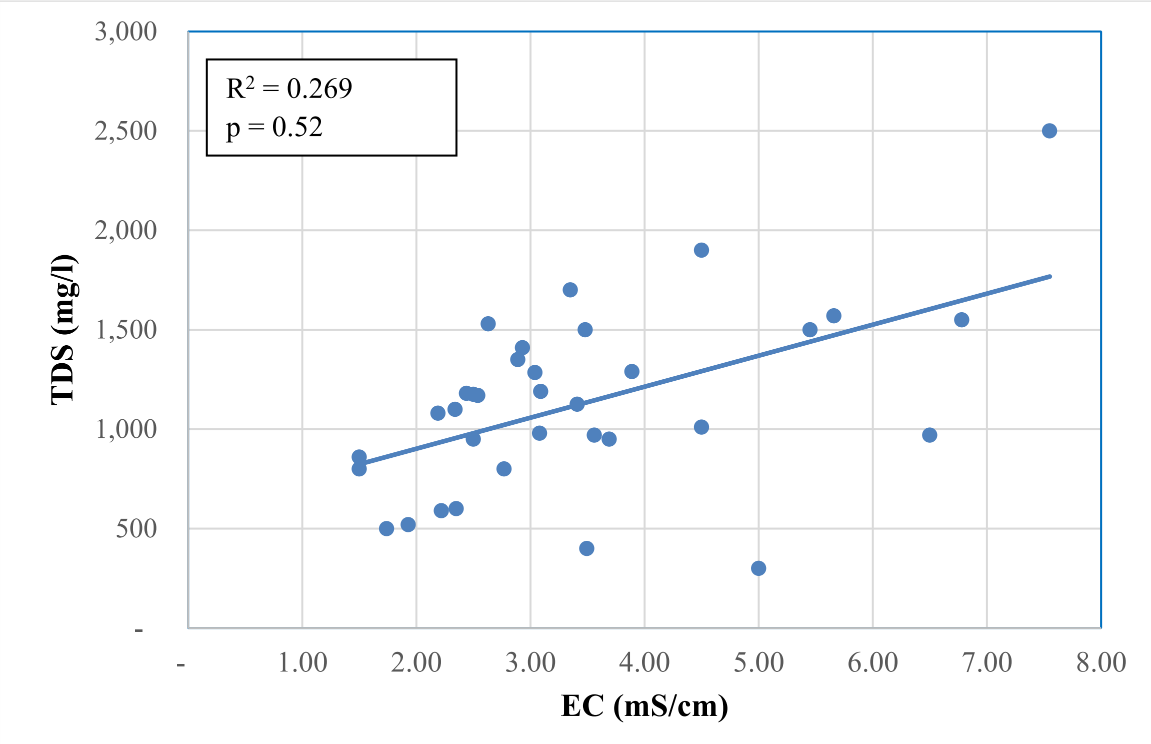

Figure 4.4: Relationship between TDS and ES value for all sample.

4.2.3 Total Solids (TS) and Total Suspended Solids (TSS)

Figure 4.5 shows the TS values of all FS samples and it also shows a “box plot” of these TS values. The Sakhipur public septic tank sample had the lowest TS value (1,170 mg/L) and the value of Dhaka household septic tank was kept out of discussion due to avoid possible error. The TS readings in Sakhipur household pit samples range from 4,815-14,130 mg/L are the most variable of any region.

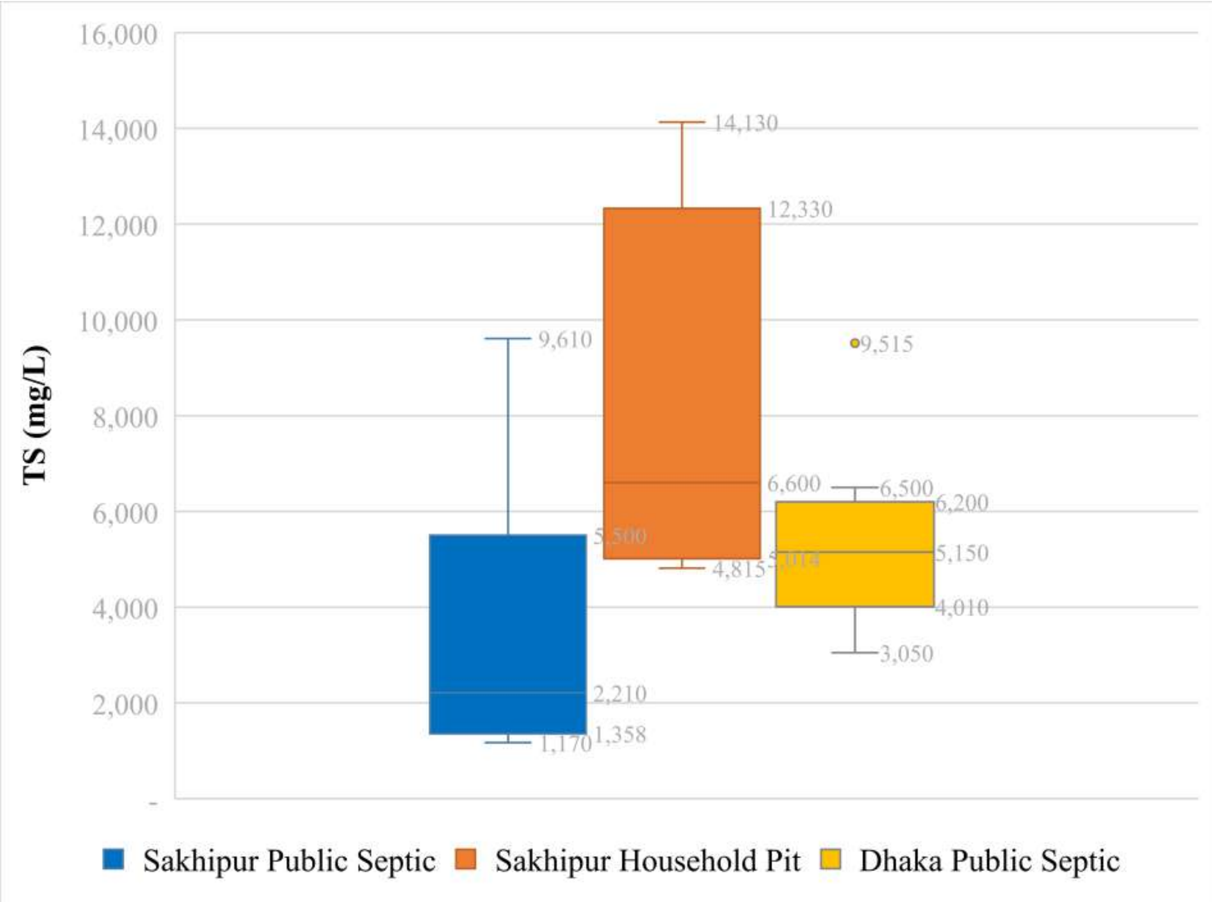

Figure 4.5: Box plot of TS of three different source of raw fecal sludge.

Total solids (TS) of FS from Sakhipur public septic tank ranged from 1,170 mg/L to 9,610 mg/L, with 50% of data points falling between 1,358 mg/L and 5,500 mg/L, implying that the interquartile range in this sample was 5,560 mg/L. T-shaped whiskers were found at both extremes (1,170 mg/L and 9,610 mg/L), with one data point (9,610 mg/L) falling outside of the interquartile range by 1.5 times and thus being designated an outlier.

The Sakhipur household pit samples showed that 50% of data points ranged from 5,014 mg/L to 12,330 mg/L, with the median value being 6,600 mg/L. 25% of samples had TS values higher than 12,330 and another 25% had TS values lower than 5,014 mg/L.

Total solids of FS samples from Dhaka public septic tank tests revealed that 50% of data points fell between the range of 4,010 mg/L to 6,200 mg/L. The median value was 5,150 mg/L, with 25% of the data points above and 25% below this limit. One particular data point with a TS value of 9,515 mg/L was out of the limit (1.5 times the interquartile range) and was hence considered an outlier.

4.2.4 Chemical Oxygen Demand (COD)

Figure 4.6 shows the COD concentrations of all FS samples. The highest COD value (5,850 mg/L) was found in one of the samples from the Sakhipur public septic tank, and the lowest COD value (500 mg/L) was found in a Dhaka household septic tank sample. The public septic tank at Sakhipur has the widest range of COD levels (5,850–1,300 mg/L).

25% of the data points for Chemical Oxygen Demand (COD) recorded from the Sakhipur public septic tank fell between 1300 mg/L and 2500 mg/L, indicating that 25% of the COD values were less than 2500 mg/L. 50% of the data points in this box plot fell between 2500 mg/L and 4972.50 mg/L, indicating that the interquartile range was 2472.5 mg/L. 25% of the data ranged between 4972.5 mg/L and 5850 mg/L, as shown by the third quartile (q3) value. The median value for Sakhipur public septic tank samples was 3925 mg/L. T-shaped whiskers reached both ends of the range (1300 mg/L to 5850 mg/L), which is still within 1.5 times the interquartile range (2472.5 mg/L). Fifty percent of the data points for the Sakhipur household pit samples fell between 1512.5 mg/L and 4987.50 mg/L, and the median value was 3430 mg/L, indicating that 25% of samples had COD levels higher than the median and another 25% had COD values lower than 1512.50 mg/L.

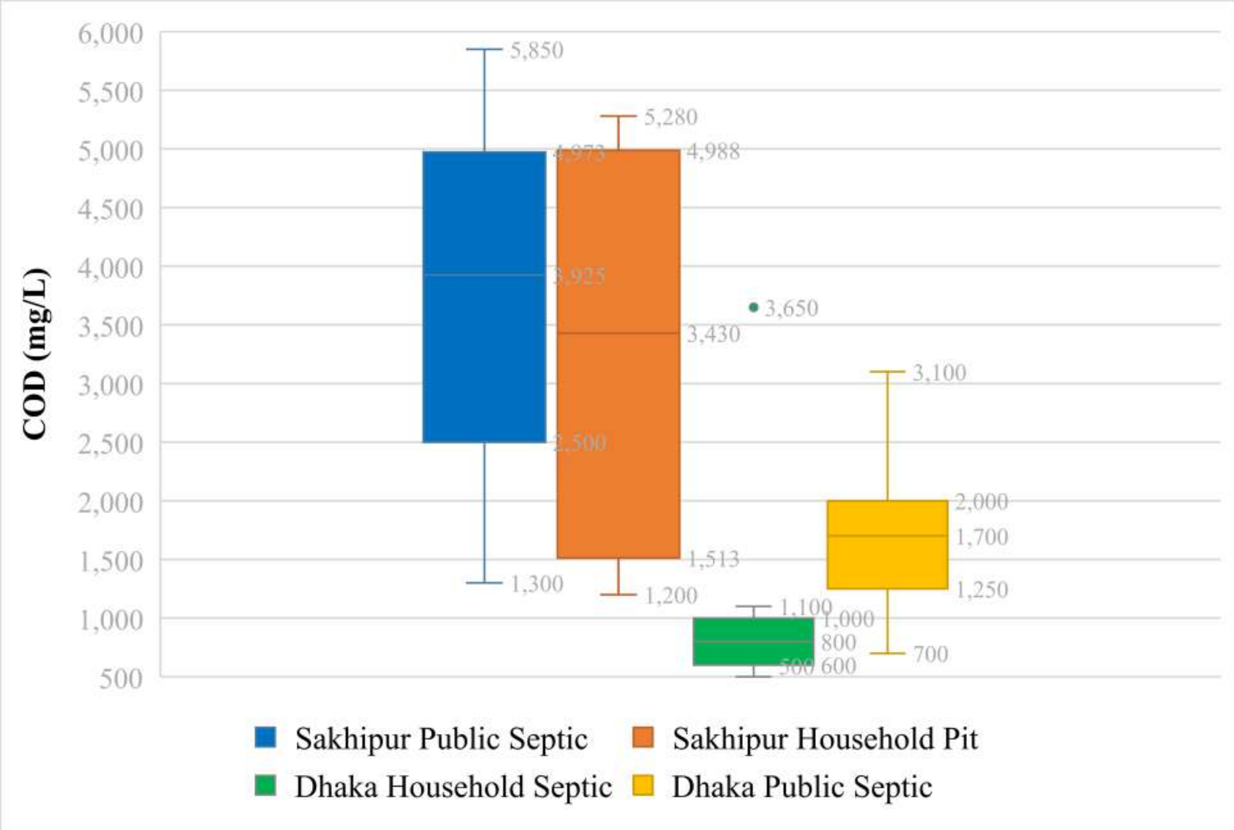

Figure 4.6: Box plot of COD of four different sources of raw fecal sludge.

Fifty percent of the data values collected from Dhaka household septic tank samples were reported to fall between 600 mg/L and 1,000 mg/L. The median value was 800 mg/L, with 25% of data points exceeding this threshold and another 25% falling below it. T-shaped whiskers reached the two extremes (500 mg/L to 1,100 mg/L), and one data point (3,650 mg/L) was outside 1.5 times the interquartile range, making it an outlier.

Fifty percent of the data values collected from Dhaka public septic tank samples were reported to fall between 1,250 mg/L and 2,000 mg/L. The median value was 1700 mg/L, with 25% of data points exceeding this threshold and another 25% falling below it. Still within 1.5 times the interquartile range (500 mg/L), T-shaped whiskers reached the two extremes (700 mg/L to 3,100 mg/L).

4.2.5 Nutrients (Ammonia, Nitrate, Phosphate)

Figure 4.7 shows the total ammonia (as NH_4^+-N) concentrations of all FS samples and it also shows a "box plot" of these ammonia concentration values. The samples from the household pit latrine in Sakhipur had the greatest ammonium value (470 mg/L), whereas the samples from the public septic tank in Sakhipur had the lowest ammonium value (70 mg/L). Samples from Dhaka household septic tanks show the widest range of ammonium concentrations (70-460 mg/L).

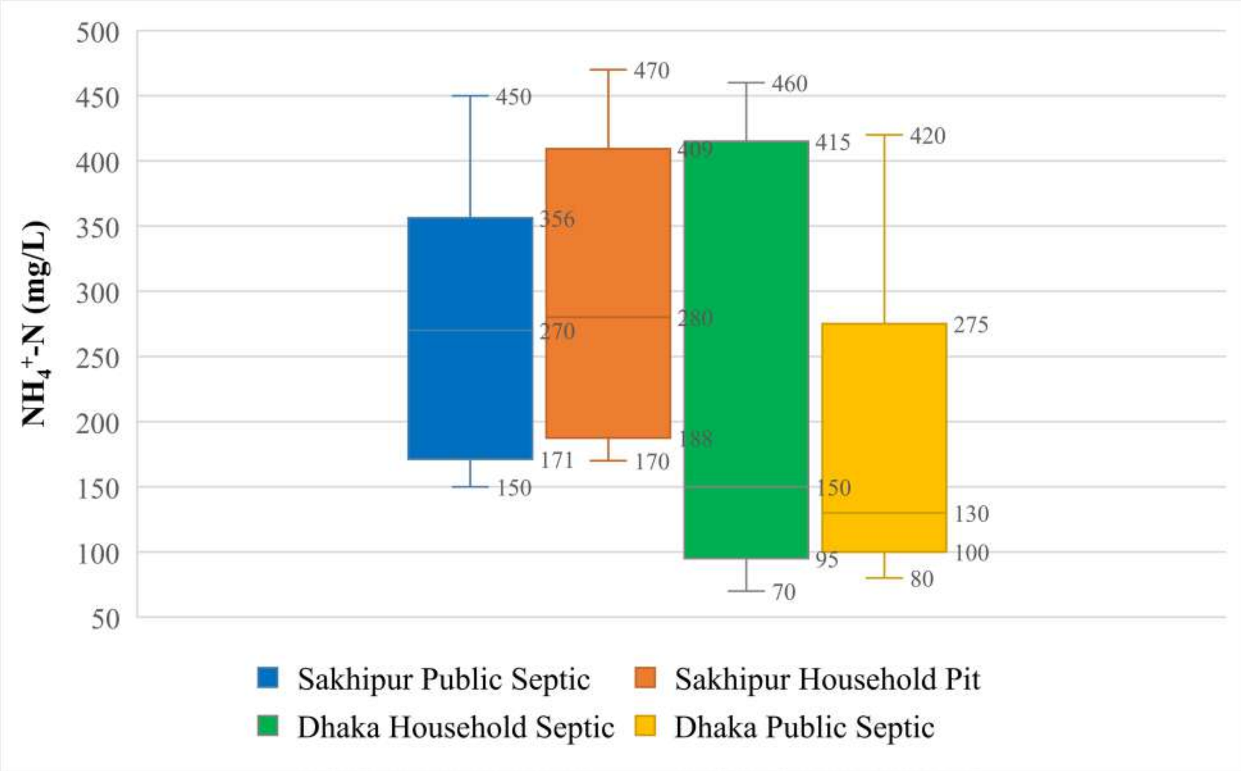

Figure 4.7: Box plot of NH_4^+-N of four different sources of raw fecal sludge.

Ammonia concentrations in the FS samples from Sakhipur public septic tanks varied widely, ranging from 150 mg/L to 450 mg/L. Twenty-five percent of the data points fell between 150 mg/L to 171.25 mg/L, which means 25% of values were less than 171.25 mg/L. In this box plot, 50% of the data points were found lying between 171.25 mg/L to 356.25 mg/L, which means the interquartile range was 172.5 mg/L in this case. The observed median value for Sakhipur public septic tank samples was 270 mg/L, and from the third quartile (q3) value, it can be observed that 25% of the data fell between 270 mg/L to 356.25 mg/L. T-shaped whiskers reached the two extremities (150 mg/L to 450 mg/L), which is still within 1.5 times the interquartile range (172.5 mg/L).

For the Sakhipur household pit samples, it was observed that 50% of data points lied within 187.50 mg/L to 409.25 mg/L and the median value was 280 mg/L, which indicates 25% of samples had higher ammonium ion values than the median and another 25% had a lower value than 187.50 mg/L.

For the FS samples from Dhaka household septic tanks, 50% of data points were observed lying within the range of 95 mg/L to 415 mg/L. The median value was 150 mg/L, with 25% of the data points above and 25% below this limit. T-shaped whiskers reached the two extremities (70 mg/L to 460 mg/L), which is still within 1.5 times the interquartile range (310 mg/L).

For the FS samples from Dhaka public septic tank samples, 50% of data points were observed lying within the range of 100 mg/L to 275 mg/L. Median value was 130 mg/L with 25% data points above this limit and another 25% data points were below it. T-shaped whiskers reached the two extremities (80 mg/L to 420 mg/L), which is still within 1.5 times the interquartile range (140 mg/L). Figure 4.8 shows the total nitrate (as NO_3^--N) concentrations of all FS samples and it also shows a "box plot" of these ammonia concentration values.

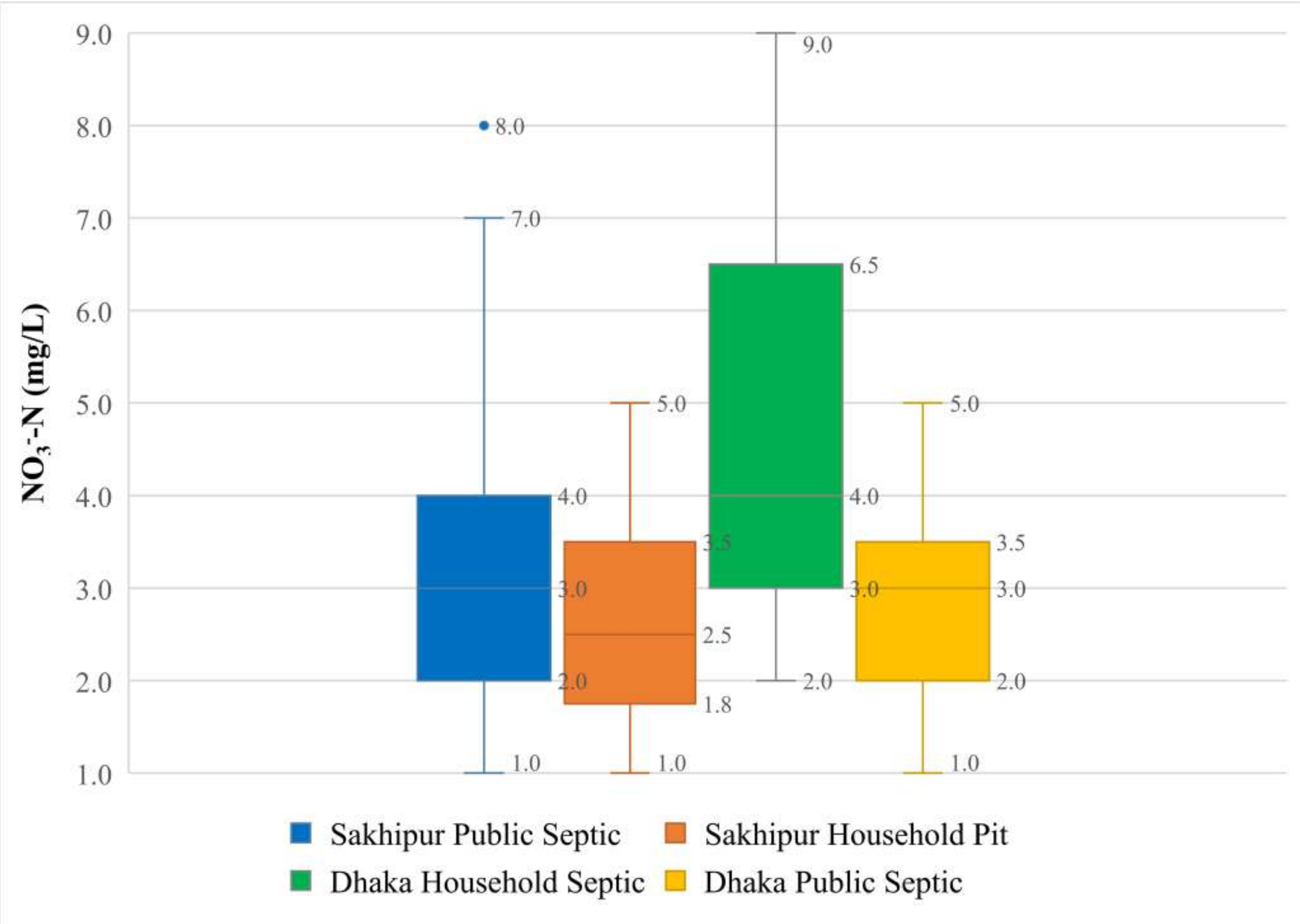

Figure 4.8: Box plot of NO_3^--N of four different sources of raw fecal sludge.

The highest Nitrate value was found in a sample from a Dhaka household septic tank (9 mg/L), and the lowest Nitrate value of 1.0 mg/l was found in a few samples. Nitrate levels vary the most in the FS samples from household septic tanks in Dhaka (1.0–9.0 mg/L).

Nitrate concentrations of FS samples from Sakhipur Public Septic tank ranged from 1.0 mg/L to 7.0 mg/L. Twenty-five percent of the data points were between 1.0 mg/L and 2.0 mg/L, which means that 25% of the values were less than 2.0 mg/L. In this box plot, 50% of the data points fell between 2.0 mg/L and 4.0 mg/L. This means that the range between the two middle points was 1.0 mg/L. The middle value of the samples from the Sakhipur Public Septic Tank was found to be 3.4 mg/L. The third quartile (q3) shows that 25% of the data fell between 3.0 mg/L and 4.0 mg/L. The T-shaped whiskers reached the two ends (1.0 mg/L and 7.0 mg/L), and one data point (8.0 mg/L) was more than 1.5 times the interquartile range, making it an outlier.

Half of the nitrate data points for the Sakhipur Household Pit samples were between 1.75 mg/L and 3.50 mg/L, and the median value was 2.50 mg/L. 25% of the samples had Nitrate ion values that were higher than 3.50 mg/L and 25% had values that were lower than 1.75 mg/L. Half of the nitrate concentration values of FS samples from the Dhaka Household Septic Tanks were found to be between 3.0 mg/L and 6.5 mg/L. The median value was 4 mg/L, and 25% of the data points were above this limit and 25% were below it. The two ends of the T-shaped whiskers (2 mg/L and 9 mg/L) are still within 1.5 times the interquartile range.

Half of the nitrate data points for the Dhaka Public Septic Tank samples were found to be between 2.0 mg/L and 3.5 mg/L. The median value was 3.0 mg/L, and 25% of the data points were above or below this limit. The two ends of the T-shaped whiskers (1 mg/L and 5 mg/L) are still within 1.5 times the interquartile range.

Figure 4.9 shows the total phosphate concentrations of all FS samples and it also shows a “box plot” of these phosphate concentration values. Phosphate concentrations in the FS samples varied from 90 to 340 mg/l. One sample from the Sakhipur family septic tank had the greatest Phosphate concentration (340 mg/L), whereas the lowest Phosphate concentration of 90 mg/l was found in a Sakhipur household pit and a Sakhipur public septic sample. Phosphate levels vary the most in Sakhipur household septic tank samples (90.00-340.00 mg/L).

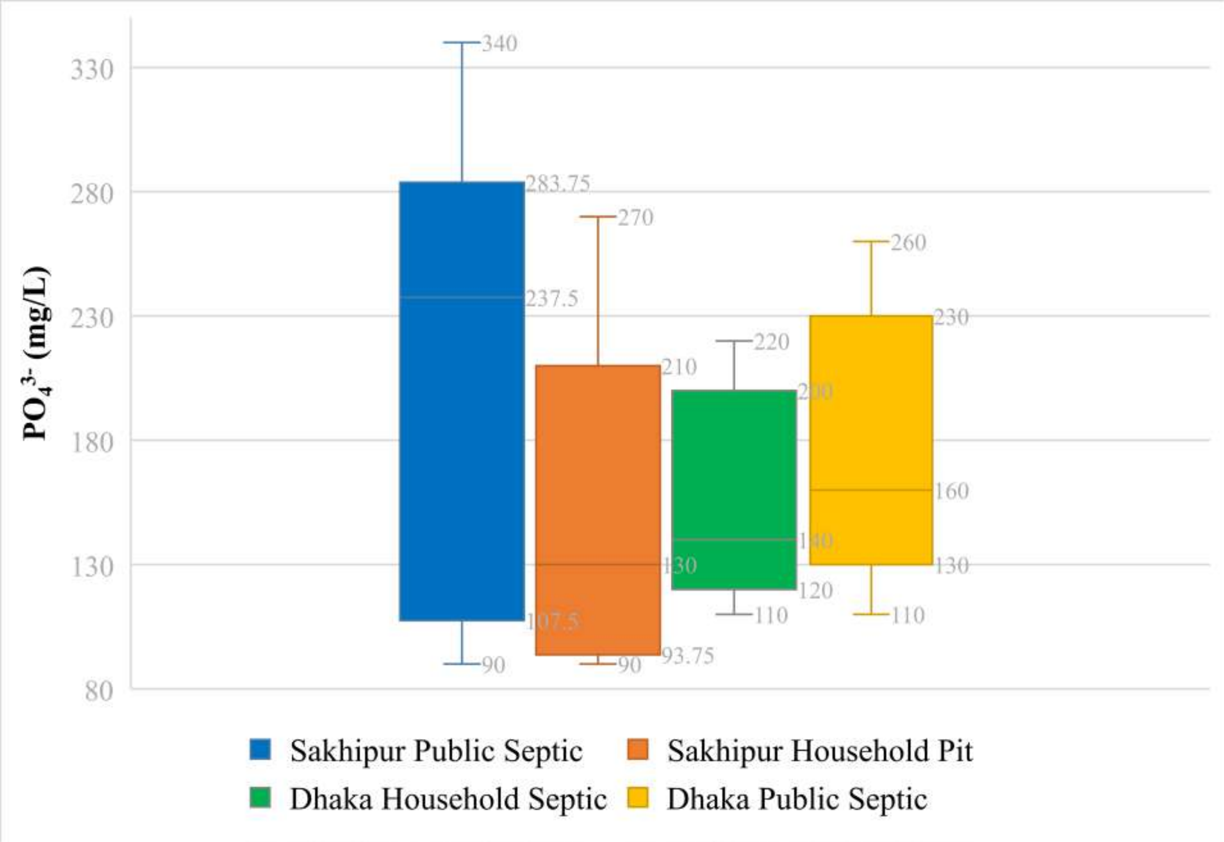

Figure 4.9: Box plot of PO_4^{3-} of four different sources of raw fecal sludge.

Phosphate concentrations in FS samples from Sakhipur Public Septic tank showed broad variations between 90 mg/L and 340 mg/L, with 25% of data points falling between 107.5 mg/L and 283.75 mg/L, meaning 25% of values were less than 107.50 mg/L. The interquartile range in this box plot was 150.00 mg/L since 50% of the data points were observed to fall between 107.50 mg/L and 283.75 mg/L. The third quartile (q3) value shows that 25% of the data fell between 283.75 mg/L and 340.00 mg/L, with the observed median value for Sakhipur Public Septic Tank samples being 237.50 mg/L. The two extremes (90 mg/L to 340 mg/L), which are still within 1.5 times the interquartile range (127.50 mg/L), were attained using T-shaped whiskers.

From the Sakhipur Household Pit samples, it was found that the median phosphate value was 130 mg/L and that 50% of the data points fell between 93.75 mg/L and 210 mg/L. 25% of the samples had phosphate ion values that were greater than 210 mg/L, while another 25% had values that were lower than 130 mg/L.

Data from Dhaka Household Septic Tank samples showed that 50% of the phosphate concentration values fell between 120 mg/L and 200 mg/L. With 25% of the data points over this threshold and another 25% below it, the median value was 140 mg/L. The two extremes (110 mg/L to 220 mg/L), which are still within 1.5 times the interquartile range (80 mg/L), were attained using T-shaped whiskers.

Fifty percent of the phosphate concentration values from the samples taken from the Dhaka Public Septic Tank were found to fall between 130 mg/L and 230 mg/L. With 25% of the data points over this threshold and another 25% below it, the median value was 160 mg/L. The two extremes (110 mg/L to 260 mg/L), which are still within 1.5 times the interquartile range (100 mg/L), were attained using T-shaped whiskers.

The values of nutrient concentrations in the FS samples indicates that there is a significant opportunity to recover these nutrients through composting for agricultural end uses.

4.3 Solids Loading Rate of Unplanted Drying Bed

Several design parameters should be taken into account when assessing the performance of an unplanted drying bed. Performance of an unplanted drying bed is directly influenced by the solids loading rate, among other factors. Wet sludge loading rate, volume of sludge loaded per day, solid concentration of wet sludge, number of cycles completed in a year, area of each bed, and other factors are taken into account to estimate the solid loading rate for raw FS sample.

The usual dewatering cycle for Sakhipur FSTP seems to last 14 days. For the FSTP, the highest number of trips operated by vacutags was 523, which was achieved in 2019 (ITN BUET, 2021). Considering five working days per week, the number of working days per year is 261 (= 365 – 2x52). Therefore, the average volume of sludge received at the Sakhipur FSTP (in 2019) is about 2.0 m^3 (= 523 x 1 m^3 ÷ 261 days). Assuming that one drying bed, with a surface area of 9 m^2 is loaded each day, the wet sludge loading rate was estimated at 0.222 meter (= 2 m^3 ÷ 9 m^2).

As discussed above, the average total suspended solid (TSS) concentration in FS from public septic tank and household pit latrine were as 2,755 mg/l and 6,845 mg/l, respectively. The following formula was used to compute the solid loading rate:

$$\lambda_s = Z.\ C_{TSS}.\ N_c$$

where,

λ_s = solids loading rate in kg TSS/m^2/year

Z = loading depth of wet sludge in m [= 0.222 m for Sakhipur FSTP];

N_c = number of complete drying cycles in a year (for each drying bed);

C_{TSS} = solids conc. of wet sludge (g/l or kg/m^3) [= 2.755 kg/ m^3 and 6.845 kg/ m^3, for public septic tank FS and pit FS, respectively]

For the Sakhipur FSTP, N_c has been estimated at 18 cycles per year. Using the estimated values of the parameters, the average solids loading rates for the unplanted drying beds of of Sakhipur FSTP are as follows:

λ_s = 11.0 kg TS/m^2/year (for public septic tank FS)

λ_s = 27.35 kg TS/m^2/year (for pit FS)

The comparatively lower solids loading rate for septic tank FS is due to the lower solids (TSS) contents of the FS. The possible reasons for higher TSS concentration of FS from pits have been discussed in Section 4.2.

For the design of unplanted drying beds, usually much higher solids loading rates are desirable for achieving higher efficiency (Taylor, 2018). In fact, if λ_s is less than about 100 kg/m^2/year, Taylor (2018) suggested use of solids-liquid separation techniques (e.g., use of settling-thickening tanks) to raise the solids content of wet sludge. Because of low solids (TSS) contents of emptied fecal sludge, the estimated solids loading rate is very low the Sakhipur FSTP. It appears that the treatment efficiency at the FSTP could be significantly improved through settling-thickening of the dilute FS the plant receives. Introduction of settling-thickening tanks, as a pre-treatment for dilute raw FS, could significantly reduce land requirements for FSTPs that employ drying beds for solid-liquid separation.

4.4 Dried Sludge from Sakhipur and Faridpur FSTPs

As described in Chapter 3, the raw fecal sludge samples collected from Sakhipur were treated at the fecal sludge treatment plant (FSTP) in Sakhipur Paurashava. At the FSTP, raw fecal sludge is first dried in unplanted drying beds, and the dried sludge are subsequently used for co-composting. As described in Chapter 3, the raw fecal sludge samples collected from Sakhipur were treated at the fecal sludge treatment plant (FSTP) in Sakhipur Paurashava. At the FSTP, raw fecal sludge is first dried in unplanted drying beds, and the dried sludge are subsequently used for co-composting.

In this study, samples of raw fecal sludge were collected (and analyzed) first (as discussed above), and then samples of dried fecal sludge were collected from the unplanted drying beds at the FSTP after the completion of a 14-day drying cycle. In addition, eight dried fecal sludge samples were collected from the Faridpur FSTP, where a 14-day drying cycle is also used. Among these, five were produced from fecal sludge from household septic tanks, and three were produced from fecal sludge from public septic tanks. It should be noted however, that the dried fecal sludge samples were in storage for periods varying from one to four weeks before their analysis.

Table 4.2 shows the characteristics (moisture content, organic content, ammonia, phosphate and potassium) of the dried fecal sludge samples. In this table, the twenty-three dried FS samples were divided into four categories depending of the source of the raw FS: (a) Sakhipur public septic tank; (b) Sakhipur household pit; (c) Faridpur household septic tank; and (d) Faridpur public septic tank.

Table 4.2: Characteristics of dried fecal sludge collected from Sakhipur and Faridpur

Source	Moisture Content %	Organic Content %	Nutrient: NH_4^+-N (mg/kg)	Nutrient: PO_4^{3-} (mg/kg)	Nutrient: K^+ (mg/kg)
Sakhipur Public Septic n=3	9.38±2.39 6.1-11.5	12.7±4.5 5.0-16.6	262±107 110-390	131±52 50-215	7.5±2.0 5.2-10.6
Sakhipur Household Pit n=2	10.3±0.80 9.4-11.5	12.7±1.2 11.1-14.1	173±60 95-250	104±42 40-165	6.3±0.9 5.1-7.2
Faridpur Household Septic n=5	8.21±1.43 6.7-10	8.6±2.8 5.2-12.6	178±72 80-270	100±26 55-117	8.2±1.4 6.6-10.2
Faridpur Public Septic n=3	9.48±0.47 9.0-9.9	14.5±3.8 10.2-17.2	223±31 190-250	133±54 73-180	7.7±0.7 7.0-8.4
Overall Mean±STD n=13	9.39±1.78 6.1-11.5	12.0±3.8 5.0-17.2	215±88 80-390	117±45 40-215	7.4±1.6 5.1-10.6

Note: Mean, standard deviation, and range of parameter values are presented in the Table.

Table 4.2 shows that the mean moisture (m/c) content of the dried fecal sludge samples varied from 8.2 to 10.3 percent. Since the dried FS samples were analyzed in the laboratory after a long storage time, these values m/c values should not be taken as the moisture content immediately after the completion of the 14-day drying cycle in unplanted drying beds. Typical m/c of dried fecal sludge from drying beds varies in the range of 70 to 80 percent (Tayler, 2018). The mean moisture content of 13 dried FS samples (after prolonged storage) is 9.4%. According to Tayler (2018), dry solids content should be at least 80% and preferably higher for energy recovery through combustion; while dry solids content should be in the range of 55 - 62% for composting. Results from this study suggest that significant reduction in moisture content could be achieved just through prolonged storage of dried fecal sludge from drying beds.

The mean organic content of dried FS from public septic tanks in Sakhipur and Faridpur and household pits from Faridpur varied over a relatively narrow range of 12.7 to 14.5%. Organic content of FS from household septic tanks of Faridpur was 8.6%. The average ammonium nitrogen concentration of dry FS for 13 samples was 215 mg/kg. In comparison to household samples, the overall value of the public septic tank sample was higher. The highest value was 390 mg/kg in the public septic tank at Sakhipur, and the lowest value was 80 mg/kg in the household septic tank at Faridpur. The average concentration of phosphate was 117 mg/kg, which is higher than the typical concentration found in animal manure and home compost, which ranges from 0.5 to 25 mg/kg of dry solid (Ecochem, 2014; Ghaly and MacDonald, 2012). Phosphate detergents in the water used to flush/clean latrines may contribute to the high concentration and fluctuation of phosphate in these samples. When compared to raw FS samples, these nutrient values (N, P, K, and micronutrients) indicate that nutrients may have been lost by leaching during the dewatering process. P and K insoluble fractions are soluble because of the production of acids during the breakdown of organic matter (Adi and Noor, 2009). But unlike these nutrients, the majority of lost nitrogen (N) is lost by volatilization as ammonia (NH_3) and other nitrogenous gases. Loss of N is also a major cause of odor generation during composting (Chen et al., 2010; Singh and Kalamdhad, 2012).

4.5 Heavy Metal Content of Dried FS

Heavy metals must be considered when using raw or dried fecal sludge as a soil additive in agriculture or to restore soil fertility in depleted soils. When utilized for agricultural purposes, immature compost may contain significant concentrations of heavy metals and organic acids that might harm plant development. It must be checked that any heavy metal content complies with safety regulations in order to guarantee that the compost generated is of an acceptable quality. A number of studies have reported that FS heavy metals are usually within the acceptable range that is suitable for reuse (Nikiema et al. 2013; Cofie and Adamtey 2009; Kengne et al. 2009; Heinss et al. 1998). The heavy metal contents of dried fecal sludge samples collected in this study from the Sakhipur and Faridpur Fecal Sludge Treatment Plants (FSTP) are summarized in Table 4.3.

Table 4.3: Heavy metal concentrations of dried FS samples and comparison with Bangladesh Standard for sludge substance.

Heavy Metal of Dried Sludge Mean (Range)						
Source	**Pb (mg/kg)**	**Cd (mg/kg)**	**Cr (mg/kg)**	**Cu (mg/kg)**	**Ni (mg/kg)**	**Zn (mg/kg)**
Sakhipur Public Septic n=3	192±63 (140-260)	2.5±0.6 (2.1-3.1)	22.6±12.2 (9.4-33.2)	239±54 (190-295)	26.0±10.6 (14.2-35)	1,360±135 (1,280-1,515)
Sakhipur Household Pit n=2	193±21 (180-210)	1.7±0.6 (1.2-2.1)	15.0±6.4 (10.5-19.5)	217±122 (130-305)	23.4±6.2 (19-27.8)	1,197±446 (880-1,510)
Faridpur Household Septic n=5	128±39 (70-170)	1.4±0.3 (1.0-1.7)	16.0±4.1 (11.6-22.8)	89±30 (55-135)	15.5±5.4 (8.1-22.5)	1,036±226 (760-1,350)
Faridpur Public Septic n=3	205±82 (140-300)	1.7±0.4 (1.3-2.1)	12.2±6.4 (8.2-19.6)	113±18 (90-125)	16.6±6.0 (11.1-22.4)	1,350±242 (1,165-1,625)
Mean±STD n=13	170±60 (70-300)	1.8±0.6 (1.0-3.1)	16.5±7.4 (8.2-33.2)	149±82 (55-305)	19.2±7.8 (8.1-35)	1,210±26 (760-1,625)
Bangladesh Standard for sludge (mg/kg)	900	10	900	800	200	2,500

Note: Mean, standard deviation, and range of parameter values are presented in the Table.

In general, the mean heavy metal contents of dried FS samples varied our a relatively narrow range, although high standard deviations suggest wide variability in the values. The dried FS samples from household septic tanks in Faridpur appear to have relatively lower concentrations of Pb, Cd, Cu, Ni and Zn. As noted earlier, these dried FS samples also had a relatively lower calorific value. The concentrations of heavy metals in the fecal sludges that were collected in Sakhipur and Faridpur are often lower than those found in industrial waste because fecal sludges have a tendency to include fewer heavy metals and refractory organics. When compared to the Bangladesh Standard for sludge (DoE, 2015), all of the values fall within the acceptable range. In fact, the heavy metal contents of dried FS are significantly lower than the corresponding standards, as shown in Table 4.3. When it is co-composted with other bulking agents such household solid waste, olive cakes, and sawdust, amongst other things, care must be taken to verify that the additional material is likewise suitable.

4.6 Relationship between Characteristics of Raw and Dried Sample

In Sakhipur FSTP, five raw samples (including 03 samples from public septic tank and 02 from household septic tank) and the corresponding dried FS samples (in the unplanted drying beds) were collected and analyzed to see possible effects of raw FS on the quality of dried FS. The TSS (for raw FS) and organic matter (for dried FS), and nutrient (ammonia and phosphate) contents of the raw and dried FS samples were compared. However, no clear trend was observed between the characteristics of raw FS and dried FS.

It appears that pit sludge had a substantially higher ammonia loss than the sample from the septic tank. The phosphate concentration also changed noticeably for all samples. The loss of nutrients is primarily due to the loss of dissolved nutrients through leaching during the process of solid-liquid separation in an unplanted drying bed.

4.7 Calorific Value of Dried Fecal Sludge

To assess the energy recovery options of dried sludge, the calorific values of dried fecal sludge samples are analyzed. The calorific value was determined using an IKA C3000 ISOPERIBOL Bomb Calorimeter following ASTM D2015 procedures. Five dried FS samples from Sakhipur FSTP and eight from Faridpur FSTP were analyzed for calorific value. Table 4.4 and Fig. 4.10 shows the calorific value (mean and standard deviation) of the dried fecal sludge samples.

Table 4.4: Calorific Value (experimental) of Dried FS Samples from Sakhipur and Faridpur

Source	Calorific value (MJ/kg)
Sakhipur Public Septic (n=3)	12.0±3.86
Sakhipur Household Pit (n=2)	9.5±1.03
Faridpur Household Septic (n=5)	8.7±1.88
Faridpur Public Septic (n=3)	13.4±1.25
Overall Mean±STD (n=13)	10.7±2.85

The calorific value of the dried FS samples ranged from 7.37 MJ/kg to 16.23 MJ/kg, and the mean value (of all 13 samples) was 10.68 MJ/kg. These values are within the range of values reported for fecal sludge and sewage sludge samples (Rose et al., 2015). The mean calorific values of the four categories of dried FS samples varied over a relatively narrow range of 8.7 to 13.4 MJ/kg. The dried FS samples from public septic tanks appears to have a slightly higher

calorific values than those from household septic tanks and pits.
It is important to note that fecal sludge's calorific composition varies widely. Higher ash content is associated with decreased calorific value because ash in feces is made up of indigestible components like vitamins and does not increase the heating value. This might explain why fecal sludge has a lower calorific value than sewage sludge, or biomass. Fecal sludge's high ash percentage reduces calorific value, causes more slagging and fouling, and makes it less effective as fuel.

However, since FS usually undergoes extensive biological, aerobic, and anaerobic breakdown or digestion inside a variety of containments, FS from onsite sanitation containments has significantly lower calorific value (often referred to as Higher Heating Value, HHVs) (Ward et al., 2015; Ostrem et al., 2004). The ash fraction of fecal sludge is predicted to rise with time as organic matter decomposes and releases gases. The difference in storage duration may account for the wide variation in HHV for fecal sludge in this study.

4.7.1 Ultimate Analysis of Faridpur Dried Sample

As previously stated, a total of eight dried fecal sludge samples were obtained from an unplanted drying bed at the Faridpur Fecal sludge treatment plant. The final analysis involved a determination of the amounts of carbon, hydrogen, oxygen, nitrogen, and sulfur in dried fecal sludge. The CNHS/O Elemental Analyzer was used for this analysis at the Institute of National Analytical Research and Service (INARS) of the Bangladesh Council of Scientific and Industrial Research (BCSIR). Table 4.5 shows the elemental composition of dried FS collected from Faridpur FSTP.

Table 4.5: CNHS Values of dried FS samples from Faridpur FSTP

Samples	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen Calculated (%)
Sample 1	24.40	3.76	2.74	1.14	27.31
Sample 2	27.70	4.06	3.01	0.72	40.11
Sample 3	29.20	4.18	3.00	0.62	33.51
Sample 4	22.90	3.28	2.67	0.30	30.81
Sample 5	22.20	3.34	2.39	0.36	30.19
Sample 6	32.20	4.64	3.15	0.96	12.16
Sample 7	13.40	1.96	1.47	0.32	30.58
Sample 8	17.30	2.51	1.89	0.48	14.44

Note: The analyses were carried out at BCSIR laboratory, Dhaka.

This carbon, hydrogen, nitrogen, sulphur and oxygen values were used to determine the calorific value of Faridpur dried sample using four different mathematical models, as discussed Chapter 3. Details of the calculations are presented in the Appendix (Tables A-9 to A-12). The calorific values of dried fecal sludge, as estimated by mathematical models and experimentation, have been found to be too low for FS to be used for energy recovery through combustion. Fecal sludge's low calorific values are comparable to other low-quality fuels such lignite coal (14.7–19.3 MJ/kg, ASTM D388–99) and sugar bagasse (18.61 MJ/kg) (Abd et al., 2016). Figure 4.10 shows a comparison of the calorific values of dried FS estimated from elemental composition (using four different models) and those determined in the laboratory. It is observed that the calculated calorific values from mathematical models were lower than the experimental values. Among the mathematical formulas, the modified Dulong formula appear to provide results closer to the experimental values. For both theoretical and experimental value, it was found that sample 6 had higher calorific value and sample 7 had minimum calorific value.

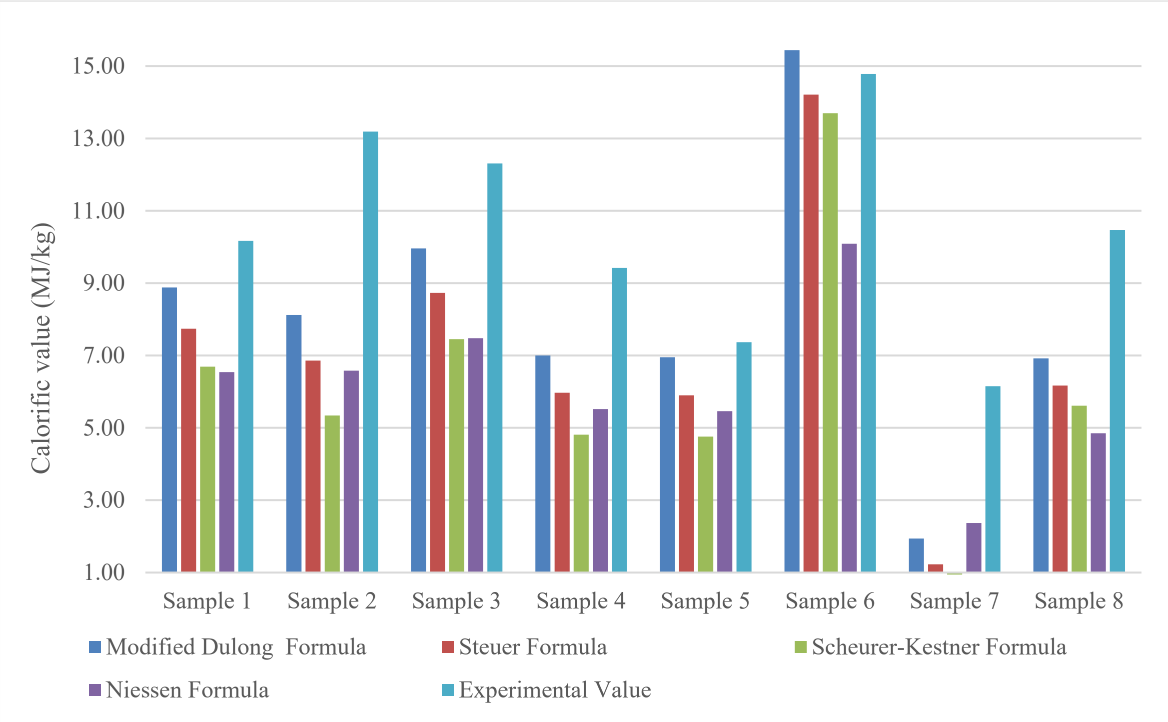

Figure 4.10: Comparison of Theoretical and Experimental Calorific Value of Faridpur Samples.

4.8 Possible End Use of Fecal Sludge

As discussed above, the calorific value of dried fecal sludge appears to be too low for FS to be used for energy recovery through combustion. For this reason, dried fecal sludge is often mixed with a biomass (e.g., wood chips) that has high energy value and low moisture content before combustion (for energy recovery). Such an approach has been adopted for energy generation from dried fecal sludge through incineration using "Omniprocessor" in different countries (including China). Such processes are yet to be implemented in Bangladesh. However, an "Omniprocessor" system is currently being constructed in Cox's Bazar that plans to utilize dried FS from the nearby Rohingya camps. Apart from, raw fecal sludge (along with solid wastes) has been used for generation of biogas. A facility has been recently built in Jashore for producing biogas from fecal sludge and solid waste.

Co-composting of fecal sludge (with suitable bulking materials) have been successfully used in several FSTPs in Bangladesh, including the FSTPs in Sakhipur, Faridpur, Kushtia. In order to decompose organic waste and create stable products, composting requires aerobic decomposition. The temperature of the compost is increased by aerobic microorganisms, which utilize oxygen to convert carbon to carbon dioxide and produce heat. If the temperature of the compost can be kept in the thermophilic range (40 - 70 °C) for a long enough period of time, pathogens in the composting material will be rendered inactive. The composting material's water content and C:N ratio must be kept within narrow limits in order to maintain the needed temperature, and there must be enough free air available to supply the necessary oxygen. The ideal C:N ratio is 25–35:1, and the ideal water content is 55–62%. In contrast, the typical C:N ratio of dewatered FS is often much lower (e.g., 6–11:1), while the typical water content is much higher (e.g., 70–80%). Because of this, FS is often mixed with an appropriate bulking agent, which is a substance having a high carbon (C) concentration and a low water content (e.g., solid waste, saw dust). The ultimate goal is to create a safe product by bringing pathogens down to acceptable levels. However, there are certain difficulties, such as the expensive and difficult pathogen screening. As a result, it is a common practice to check the temperature during the composting process and make necessary adjustments to guarantee that the required minimum temperatures and times are fulfilled. The ideal C:N ratio for composting is between 25 - 35 to 1. When the C:N ratio is less than 25, the temperature won't rise high enough to kill pathogens, and ammonia gas will probably develop instead, giving off an unpleasant odor. Lower temperatures and less microbial activity occur in compost when the C:N ratio is higher than 35. Table 4.16 shows that the C:N ratio for all samples ranges between 8.58 and 10.22 to1. Table 4.17 shows commonly available bulking agents that could be used for co-composting of fecal sludge. Municipal solid waste and sawdust have been successfully used as bulking agents for the co-composting of dried fecal sludge in several FSTPs in Bangladesh. Technically, co-composting of fecal sludge appears to be a feasible and promising option. However, financial/economic viability of such co-composting must be carefully assessed.

Table 4.6: C:N ratio of Faridpur dried fecal sludge sample.

Samples	Carbon (%)	Nitrogen (%)	C:N ratio
Sample 1	24.4	2.74	8.91:1
Sample 2	27.7	3.01	9.20:1
Sample 3	29.2	3.00	9.73:1
Sample 4	22.9	2.67	8.58:1
Sample 5	22.2	2.39	9.29:1
Sample 6	32.2	3.15	10.22:1
Sample 7	13.4	1.47	9.12:1
Sample 8	17.3	1.89	9.15:1

Table 4.7: Typical moisture content and C:N ratios of selected bulking agents (Tayler 2018).

Bulking Agent	Moisture Content (%)	C:N ratio
Vegetable waste	4-6	10-15:1
Grass clipping	60-80	12-25:1
Corn straw	9	30-60:1
Rice Husk	8-10	110:1
Leaves	9	170:1
Wood chips and sawdust	5-20	100-500:1

Bulking agents, which are high in carbon, can be employed to modify the moisture content of compost. Compost made from an appropriate mixture of dried fecal sludge and municipal solid waste impacts soil chemical qualities such as pH, acidity, conductivity, and overall nutrient retention capacity. Soil pH has a significant impact on nutrient availability for plants. With the exception of P, which is most available between pH 6 and 7, macronutrients (N, K, Ca, S, and Mg) are more available between pH 6.5 and 8, whereas most micronutrients (B, Cu, Fe, Mn, Na, Ni, and Zn) are more available between pH 5 and 7. (Singh et al. 2012). Municipal solid waste compost has a neutral or slightly alkaline pH and improves buffering capability in acidic soils. Composting can potentially have an impact on EC and salt levels. The EC of a soil solution, which correlates to the dissolved components of soil, is frequently used to determine soil salinity, and excess salts in soils are detrimental to plants. However, higher EC values decrease with time, most likely due to crop nutrient removal and leaching (Zhang et al. 2006). Compost application may impact not just pH and EC, but also soil cation exchange capacity

(CEC). CEC acts as a nutrient reservoir, restoring nutrients removed from soil water through plant uptake. Similarly, cations leached below the root zone by excess rainfall or irrigation water are replenished by cations already bound to the CEC.

Chapter 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The main objectives of this study was to evaluate the characteristics of raw fecal sludge from various types of onsite sanitation facilities as well as the effect of raw fecal sludge features on the quality of dried sludge produced in unplanted drying beds. Based the characteristics of raw FS, the solids loading rates on unplanted drying beds at Sakhipur FSTP have been estimated and its implications on treatment efficiency has been discussed. Dried FS samples have been collected from Sakhipur and Faridpur FSTP have been analyzed for a wide range of parameters, including organic, nutrient and heavy metal contents. The calorific values of dried FS samples have also been determined experimentally (directly and from elemental composition) possible resource recovery options from dried FS has been discussed. This chapter summarizes the key findings of the study and presents recommendations for future study.

5.2 Conclusions

The major conclusions obtained from the above study are as follows:

i. The overall characteristics of raw FS samples collected from septic tanks and household toilet pits did not vary significantly. However, for most of the parameters, there were significant variations in concentrations among samples from the same type of source (as evident from high standard deviations of parameters values).

ii. Compared to the reported raw FS characteristics from African regions (where dry toilets and use of toilet papers are common), the raw FS samples collected in this study are much more dilute. This is most likely due to the nature of water use (i.e., for flushing and cleansing) and local desludging practice.

iii. The pH of raw FS samples was mostly in the neutral range (with a mean pH of 7.15). The mean COD and TSS values were 2,405 mg/l and 4,220 mg/l, respectively. The ammonium (mean 244 mg/l) and phosphate (mean 170 mg/l) concentrations indicate that FS could be an excellent source of nutrient for use in agriculture.

iv. No clear trend was observed between the source of FS and their characteristics. However, the COD values of FS samples collected from public septic tanks and pits of Sakhipur were found to be significantly higher than those collected from containments in Dhaka. The TSS concentration of FS samples from household pits in Sakhipur were also found to be significantly higher, possibly due to leaching of water from pits.

v. Because of lower TSS contents of raw FS, the estimated solids loading rates for the unplanted drying beds in Sakhipur FSTP have been found to be significantly lower than those typically used in the design of unplanted drying beds. It appears that introduction of settling-thickening tanks, as a pre-treatment unit, could significantly improve treatment efficiency and reduce the land requirements for FSTPs employing drying beds.

vi. The organic content and nutrient contents of dried FS do not appear to be strongly correlated to the characteristic (TSS and nutrients) of raw FS.

vii. Significant moisture content reduction could be achieved through the storage of dried fecal sludge from drying beds. The ammonium nitrogen content (mean 215 mg/kg) and phosphate content (117 mg/kg) suggest that resource recovery from dried FS would be beneficial.

viii. Heavy metal (Pb, Cd, Cr, Cu, Ni, Zn) contents of the dried FS samples collected from Sakhipur and Faridpur are significantly lower than the corresponding Bangladesh standards for sludge.

ix. The mean calorific values of the four categories of dried FS samples varied over a relatively narrow range of 8.7 to 13.4 MJ/kg. The dried FS samples from public septic tanks appears to have a slightly higher calorific values than those from household septic tanks and pits.

x. Calorific values of dried FS calculated from different mathematical models were lower than the experimental values. Among the mathematical formulas, the modified Dulong formula appear to provide results closer to the experimental values.

xi. The relatively lower calorific values of dried FS appear to be a constraint for energy recovery through combustion. This constraint is usually addressed by mixing dried FS with a suitable biomass. Considering the characteristics of FS, co-composting, which is widely use in Bangladesh and elsewhere, is a good option for resource recovery from FS.

5.3 Recommendations for Future Study

The characteristics of FS in this study have been found to be significantly different from those reported in the literature from African countries. This has significant implications for FS management, particularly treatment. Because of the significant variability in the characteristics of FS, large-scale studies are needed to better understand the typical composition of FS from diverse types of sources (and uses) that are often emptied employing different techniques. The following recommendations are made for future studies:

i. In addition to the three places (Sakhipur, Faridpur, and Dhaka city) chosen for sample collection, other cities should be included for characterization of raw and dried fecal sludge.
ii. Research work is needed to assess possible improvement in treatment efficiency (and lower land requirement) through the introduction of settling-thickening tanks as a pre-treatment unit in FSTPs that employ drying beds.
iii. In addition to physicochemical properties, microbiological features of FS should be determined to assess a safe and hazard-free end product.
iv. To assess the fuel potentiality, further research work is required regarding combustion of dried FS and its economically viable and environment friendly end use.

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APPENDIX

Table A-1: pH values of FS samples collected from four different types of sources.

pH Values				
SL No.	Source Name			
	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	6.60	7.08	5.90	6.51
2	7.20	7.10	7.24	6.80
3	7.21	7.15	6.97	6.85
4	7.33	7.83	6.80	6.95
5	7.85	7.80	7.45	6.88
6	7.80	7.82	7.33	6.74
7	7.77		7.14	6.92
8	7.25		7.14	6.96
9	7.23		7.41	6.97
10	7.25			

Table A-2: EC values of FS from four different types of sources

EC (µS/cm)				
SL No.	Sakhipur Public Septic (mS/cm)	Sakhipur Household Pit (mS/cm)	Dhaka Household Septic (mS/cm)	Dhaka Public Septic (mS/cm)
1	1.74	4.50	7.55	2.63
2	1.50	3.41	2.35	3.04
3	3.50	3.35	2.22	2.93
4	3.89	2.50	1.93	2.44
5	6.50	3.09	6.78	2.34
6	3.48	1.50	5.66	2.19
7	2.50		5.45	3.08
8	4.50		2.77	2.54
9	3.56		3.69	2.89
10	5.00			

Table A-3: TDS values of FS samples from four different types sources

TDS Chart				
SL No.	Sakhipur Public Septic (mg/L)	Sakhipur Household Pit (mg/L)	Dhaka Household Septic (mg/L)	Dhaka Public Septic (mg/L)
1	500	1,900	2,500	1,530
2	860	1,125	600	1,285
3	400	1,700	590	1,410
4	1,290	1,175	520	1,180
5	970	1,190	1,550	1,100
6	1,500	800	1,570	1,080
7	950		1,500	980
8	1,010		800	1,170
9	970		950	1,350
10	300			

Table A-4: Variation of TS of four different sources of raw fecal sludge

TS Concentration (mg/l)				
SL No.	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	4,750	5,250	-	5,900
2	1,720	5,080	-	3,050
3	9,610	4,815	-	5,250
4	4,420	7,950	-	5,150
5	1,170	14,130	-	6,500
6	2,700	11,730	-	4,500
7	7,750		-	9,515
8	1,350		-	3,520
9	1,360		-	4,515
10	1,470			

Table A-5: COD concentrations of FS samples collected from four different types of sources.

COD Concentration (mg/l)				
SL No.	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	5,850	5,130	3,650	1,400
2	4,200	4,560	600	1,800
3	3,650	5,280	1,100	3,100
4	3,100	1,200	800	1,900
5	2,300	1,250	600	700
6	1,400	2,300	600	2,100
7	1,300		1,000	1,500
8	4,990		500	1,700
9	4,920		1,000	1,100
10	5,180			

Table A-6: NH_4^+-N concentrations of FS samples from four different types of sources

Total Ammonia as NH_4^+-N (mg/l)				
SL No.	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	160	470	100	110
2	150	430	150	250
3	175	350	90	420
4	310	210	70	115
5	250	170	420	90
6	275	180	410	80
7	265		460	155
8	325		160	30
9	450		150	130
10	450			

Table A-7: Variation of NO_3^--N of four different sources of raw fecal sludge

Nitrate as NO_3^--N (mg/l)				
SL No.	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	3.0	5.0	3.0	5.0
2	8.0	3.0	4.0	3.0
3	2.0	2.0	3.0	3.0
4	3.0	2.0	3.0	4.0
5	2.0	3.0	8.0	3.0
6	3.0	1.0	5.0	2.0
7	3.0		4.0	2.0
8	7.0		9.0	1.0
9	1.0		2.0	3.0
10	2.0			

Table A-8: Variation of PO_4^{3-} of four different sources of raw fecal sludge

PO_4^{3-} (mg/l)				
SL No.	Sakhipur Public Septic	Sakhipur Household Pit	Dhaka Household Septic	Dhaka Public Septic
1	120	90	130	260
2	275	270	120	130
3	220	130	110	230
4	340	190	140	160
5	310	95	200	240
6	260	130	220	110
7	255		220	140
8	110		160	120
9	100		120	170
10	90			

Table A-9: Calorific value calculation using modified Dulong formula.

a) Modified Dulong formula:				
$HHV = 337(C) + 1419\ (H - O/8\ ) + 93(S) + 23.26(N)$				
Sample 1	8,883.88	kJ/kg	8.88	MJ/kg
Sample 2	8,118.50	kJ/kg	8.12	MJ/kg
Sample 3	9,955.42	kJ/kg	9.96	MJ/kg
Sample 4	6,996.70	kJ/kg	7.00	MJ/kg
Sample 5	6,954.98	kJ/kg	6.95	MJ/kg
Sample 6	15,441.23	kJ/kg	15.44	MJ/kg
Sample 7	1,936.86	kJ/kg	1.94	MJ/kg
Sample 8	6,919.10	kJ/kg	6.92	MJ/kg

Table A-10: Calorific value calculation using Steuer's formula.

b) Steuer's formula:				
HHV = 81(C − (3*O/8)) +171*(O/8) +345(H-O/10) +25(S) -6(9H+W)				
Sample 1	1,851.08	kcal/kg	7.74	MJ/kg
Sample 2	1,639.28	kcal/kg	6.86	MJ/kg
Sample 3	2,085.70	kcal/kg	8.73	MJ/kg
Sample 4	1,427.15	kcal/kg	5.97	MJ/kg
Sample 5	1,410.68	kcal/kg	5.90	MJ/kg
Sample 6	3,395.58	kcal/kg	14.21	MJ/kg
Sample 7	293.51	kcal/kg	1.23	MJ/kg
Sample 8	1,473.87	kcal/kg	6.17	MJ/kg

Table A-11: Calorific value calculation using Scheurer–Kestner formula.

c) Scheurer–Kestner formula:				
HHV = 81 (C − (3*O/4) +171(O/4) +342.5(H-O/10) +22.5(S)-6(9H+W)				
Sample 1	1,599.86	kcal/kg	6.69	MJ/kg
Sample 2	1,276.36	kcal/kg	5.34	MJ/kg
Sample 3	1,780.48	kcal/kg	7.45	MJ/kg
Sample 4	1,148.61	kcal/kg	4.81	MJ/kg
Sample 5	1,137.26	kcal/kg	4.76	MJ/kg
Sample 6	3,275.18	kcal/kg	13.70	MJ/kg
Sample 7	20.23	kcal/kg	0.08	MJ/kg
Sample 8	1,340.05	kcal/kg	5.61	MJ/kg

Table A-12: Calorific value calculation using Niessen formula.

d) Niessen formula: HHV = 0.2322(C)+0.7655(H)-0.072(O)-0.0419(N) +0.0698(S) +0.0262(Cl) +0.1814(P)		
Sample 1	6.54	MJ/kg
Sample 2	6.58	MJ/kg
Sample 3	7.48	MJ/kg
Sample 4	5.52	MJ/kg
Sample 5	5.46	MJ/kg
Sample 6	10.09	MJ/kg
Sample 7	2.37	MJ/kg
Sample 8	4.85	MJ/kg