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A comprehensive study on the physicochemical characteristics of faecal sludge from septic tank and single pit latrine facilities in a typical semi-urban Indian town: a case study of Rajasthan, India

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Faecal sludge (FS) generated from onsite sanitation (OSS) systems has become a significant pollutant that negatively impacts the environment. Environmental contamination results from the disposal of untreated FS. In semi-urban areas where numerous toilets are linked to OSS systems, such as septic tanks and single pits, faecal sludge management (FSM) becomes crucial to ensure a safe sanitation service chain. Integral to the faecal sludge management framework, treating FS is imperative, ensuring safe disposal and resource recovery. FS characterization plays a significant role in designing FS treatment plants. This case study characterized FS samples of OSS collected from Pilani, Rajasthan, India. The pH, temperature, electrical conductivity, total solids, chemical oxygen demand, faecal coliforms, total nitrogen, total phosphorus, and capillary suction time varied from 4.64 to 7.93, 20.6 to 27.5 °C, 1.857 to 6.315 mS cm^{-1}, 3430 to 95 393.33 mg l^{-1}, 4406 to 160 000 mg l^{-1}, 10^3 to 10^9 CFU ml^{-1}, 81.7 to 709.2 mg l^{-1}, 285 to 4471 mg l^{-1}, and 149 to 1256.8 seconds, respectively. The significant factors influencing the key FS characteristic parameter COD are found to be the FS age ($p < 0.001$) and type of OSS ($p = 0.044$), and for total solids, the factors affecting are identified as the FS age ($p < 0.001$), type of OSS ($p = 0.002$) and greywater dilution ($p = 0.011$). This case study can assist FSM stakeholders in designing FS treatment plants in Indian semi-urban towns and other developing nations with infrastructure, geographical and demographic factors, sanitation types, and FSM models similar to those in Pilani.

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Water impact

The Swachh Bharat Mission (SBM) in India, launched in 2014, built 110 million toilets (including public and individual household toilets) to eradicate open defecation. In India, 90% of the population relies on onsite sanitation (OSS). In addition to that, due to the SBM, there was a rapid increase in the usage of OSS. Consequently, if untreated, the rise in faecal sludge (FS) from OSS poses a significant pollution risk to surface and groundwater. This case study characterized FS to aid sanitation stakeholders in designing treatment systems in Indian towns and comparable nations globally, ensuring efficient treatment and resource recovery and protecting water quality, directly contributing to achieving SDG6.

1. Introduction

On-site sanitation (OSS) involves collecting, storing, or treating excreta and wastewater at the exact location where they are produced. Currently, 2.8 billion people in the urban centers of low and middle-income countries rely on OSS. A significant portion of excreta generated from this OSS in low- and middle-income countries is not treated and safely managed. By 2030, the number of people using OSS is expected to increase to 5 billion,[1] highlighting the urgent need for effective treatment and safe management of excreta to prevent the looming sanitation crisis. The storage of excreta and blackwater mixtures, with or without greywater, in OSS containment systems produces faecal sludge (FS), which is raw or partially digested, a slurry or semisolid.[2–4] FS contains many faecal coliforms, organic matter, and total solid content, due to which septic tank overflows and the irresponsible release of FS into open spaces harm groundwater quality, water bodies, irrigation fields, open drains, and areas outside villages. The FS leachate leaches

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into the soil surface and reaches the groundwater table, which affects the groundwater quality. Disposal of untreated FS into open fields makes the soil infertile and unfit for agriculture. If FS is discharged in or near waterbodies, it will affect the surface water quality, negatively impacting public health and the environment by spreading excreta-related diseases. Excreta-related diseases are becoming more common through direct contact due to improper disposal techniques and the use of untreated FS. As a primary cause of illness and mortality for children under five in low- and middle-income countries, diarrhoea results from inadequate sanitation, a severe public health concern.[5] The existing faecal sludge management (FSM) model is struggling to safeguard public health in many developing and middle-income countries due to the lack of proper FS collection, treatment, disposal, and resource recovery. Thus, robust localized FSM is needed for an hour to achieve a sustainable sanitation service chain and meet SDG6 goals. Even though more individuals have access to sanitation systems globally, appropriate FSM is still a significant issue in low- and middle-income countries. These regions often lack infrastructure and adequate and systematic FSM service chains, *i.e.*, FS collection, FS treatment, and resource recovery.

Wastewater is water generated from domestic, commercial, and industrial sources containing chemicals and heavy metals. FS is entirely different from usual wastewater since FS is a sludge that accumulates in OSS systems, such as septic tanks, pit latrines, and composting toilets. Thus, the characteristics of wastewater and FS differ widely, even if they are produced in the same geographical location. The overall concentrations of total solids, organic content, ammonia, total nitrogen, and helminth eggs are 10–100 times more in FS than they are in wastewater sludge.[2,3,6] Thus, FS treatment is an essential aspect of FSM for its safe disposal and resource recovery from FS. Co-treatment with sewer-based wastewater treatment technology is one option for treating FS. However, most wastewater treatment plants in low-income nations have failed because of improper loading rates and greater FS strength compared to municipal wastewater.[7] Thus, faecal sludge treatment plants (FSTPs) are essential for treating FS from OSS for safe disposal, especially in low-income countries. FS characterization plays a vital role in choosing/designing FS treatment technologies. However, FS raw data are highly location-specific and less uniform compared to wastewater data.[8]

FS is higher in chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids (TS), total nitrogen (TN), nutrients, and pathogen content. The large variability in FS and various OSS in use, such as pit latrines, septic tanks, and dry toilets, makes it difficult to assess the FS generation rate and the average FS characteristics.[9] For example, a study in Bangangte, Cameroon[10] found that the TS value of FS was higher in pit latrines (15.90 g l^{-1}) compared to septic tank FS (1.92 g l^{-1}). Similarly, another study in Vadgaon Maval, Maharashtra[11] analysed septic tank FS samples by age and found that the TS and COD in FS increase with age. A study in Chennai, India[12] found that the total solid content of FS is 1.6 times more in the winter than in the summer. The cleaning frequency of OSS is influenced by demographic factors like population density, household size, socioeconomic status, and urbanization levels, which affect the volume of FS generated and the size of the OSS system. Inputs like excreta, blackwater, greywater, and additives, factors like the type of containment (septic tanks, single pits, cesspool, dry toilets, *etc.*), demographic factors (urban, rural, cleaning frequency), and environmental factors (climate, topography) affect the FS characterization.[13]

As of 2023, India remains the most populous country, and many Indians face serious health issues due to contaminated soil and water resulting from inadequate sanitation practices.[14] The Sustainable Development Goals (SDG) of UN 2015 include SDG 6, which aims to provide everyone with clean water and safely managed sanitation systems. The Swachh Bharat Mission (SBM) is a country-wide campaign by the Government of India to eradicate open defecation and make open-defecation-free towns and villages. Under the SBM, 110 million toilets (including public and individual household toilets) have been built in towns and villages nationwide to combat open defecation.[15] The stages in constructing 110 million toilets nationwide under the SBM are shown in Fig. 1.

Policy impact leads to increased OSS nationwide and an increase in the FS generation rate. According to estimates from the consulting firm Energy Alternatives India, India produces approximately 0.12 million tonnes of FS daily,[16] which will be further increased due to increased OSS usage. But most of the emptied FS from OSS is dumped without treatment, posing environmental pollution through groundwater degradation and spreading faecal pathogenic diseases. For example, according to a report by the Centre for Science and Environment (CSE) in 2019, 94% of the FS in 66 cities of Uttar Pradesh, India's most populous state, was left untreated.[17] India initiated the establishment of FSTPs to treat the generated FS in different towns and urban areas of India. Since treatment technologies for FS depend upon its characteristics, an in-depth characterization study and data are necessary in Indian towns. This case study aims to analyse the FS characteristics in a semi-urban, tier-III (population range of 20 000 to 49 999) Indian town and identify the factors affecting them in a localized context. The insights of this study can be used to analyse FS characteristics and design FS treatment systems in similar tier-III Indian towns for safe FSM. A case study defines the situation through data collecting and empirical facts, allowing researchers to highlight the particular issues the victims experience. Therefore, empirical data were gathered for this case study through questionnaire interviews with FSM stakeholders and laboratory characterization in Pilani to learn about the factors impacting the FS characteristics. The novelty of this study lies in its comprehensive approach, which combines laboratory characterization with

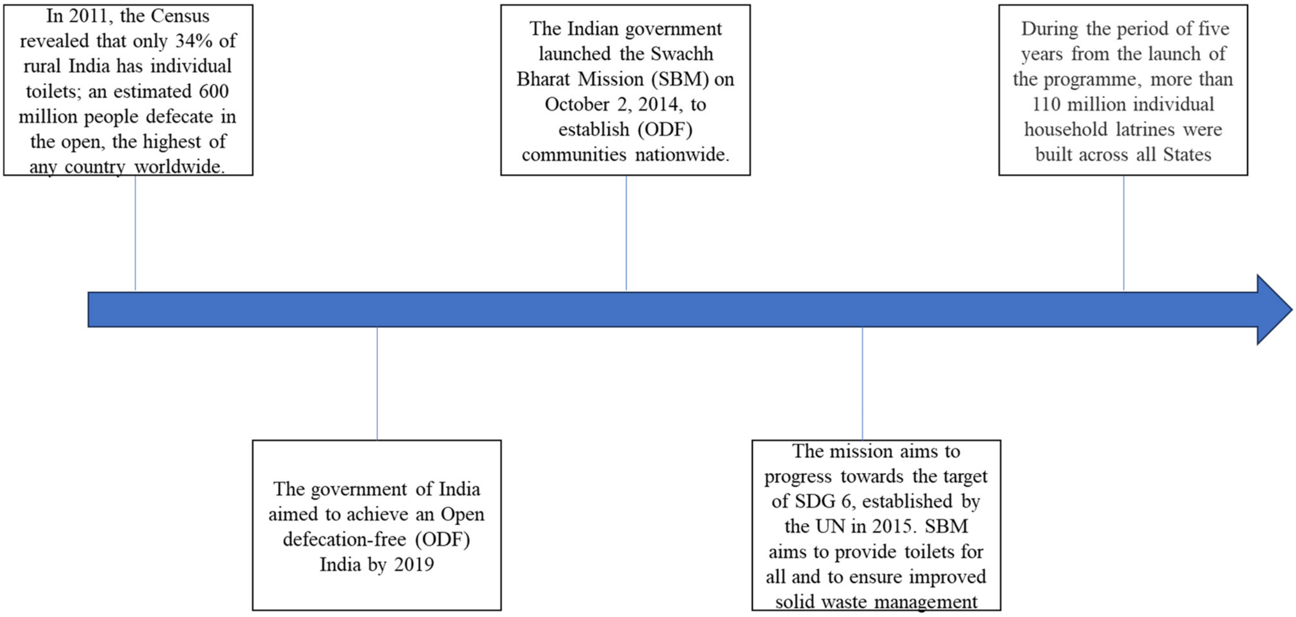


Fig. 1 Stages of the SBM in providing toilets to households.

questionnaire methodology, specifically in the Indian context. While previous research has focused on the characterization of raw FS, our study expands upon this by examining FS under various conditions such as age, the type of on-site sanitation system (OSS), inflow and outflow dynamics, household behavioural changes, and the role of OSS emptiers as discussed in the subsequent paragraphs. Furthermore, the existing literature predominantly explores septage rather than FS, and studies are often confined to metropolitan areas. In contrast, this study addresses the gap by encompassing semi-urban and rural environments. Also, this paper suggests a treatment system for FS based on its characterization.

1.1. Septic tank and single-pit latrine

In the Indian context, septic tanks and single-pit latrines are the major OSS systems. Septic tanks are underground concrete chambers through which excreta, blackwater, greywater, and other domestic wastewater flow for anaerobic digestion. Solids settle at the bottom and form an accumulation of FS which is an anaerobic sludge also called septic, whereas the scum layer floats at the top. These septic tanks are lined at the bottom with a concrete layer to prevent the contamination of surrounding soil and groundwater. A septic tank should have at least two chambers. When waste enters the first chamber, the thick solid particles settle at the first chamber, whereas the scum oil layer floats in the liquid part and moves to the second chamber. A single pit latrine, as the name indicates, is a pit system that collects excreta, urine, and blackwater. As the single pit latrine fills, three processes control the rate of accumulation of FS and the process of digestion, which are leaching, consolidation, and degradation. Unlike septic tanks, pit latrines have no multi-chamber system and lining at the bottom, allowing water and urine parts to leach into soil layers. Indian sanitation systems should follow a code for installing septic tanks, IS 2470-(1985). However, most Indian households' septic tanks do not follow the code, where the soak pit and secondary chamber are not connected to another treatment. But most septic tanks have a lining and chamber. In Indian systems, a pit latrine system is a collection of excreta and wastewater in a pit without lining, whereas concrete structure tanks with lining layers and chambers are septic tanks.

2. Materials and methodology

2.1. Study area information

Pilani (latitude: 28.36137°N, longitude: 75.60037°E), a tier-III (population range of 20 000 to 49 999) semi-urban town (population range of 10 000 to 99 999) in Rajasthan, India, is selected for the study, shown in Fig. 2. The population of Pilani was 29 741 in the 2011 census, and it has since grown to 40 000, according to municipality data, with approximately 5000 families. According to the 2011 census, Pilani is a moderately densely populated town with a population density of 1983 km^{-2} with a total area of 15 km^2. The climate of Pilani is semi-arid, which experiences a hot and dry summer from March to July, followed by monsoon months of August, September, and October; from post-October to February, Pilani has temperature-drop winters with dry conditions. Regarding FSM, Pilani does not have any FSTPs for treating FS, so the collected FS from Pilani's OSS is dumped in the dumpsite without treatment.

2.2. Sample collection

The sampling process was conducted in July 2023 and continued till November 2023, covering summer, monsoon,

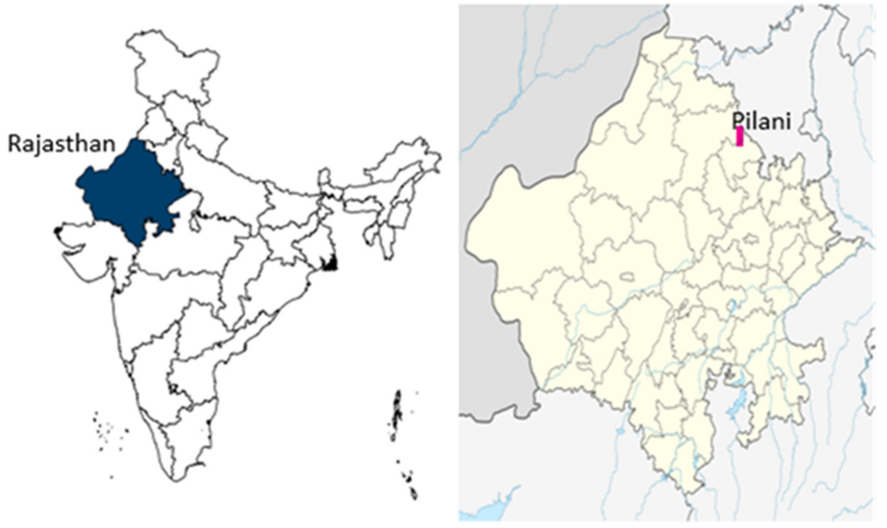


Fig. 2 Study area, Pilani located in the state of Rajasthan, India.

and winter. During sample collection, OSS/septic tank emptying and transporting operators provided the required assistance. The sampling objective is to characterize the FS that would be delivered for treatment. Thus, sampling was conducted when the emptying operators were cleaning the OSS. FS samples were collected immediately after emptying events by vacuum trucks at locations within a 5 km radius of Pilani, including its rural surroundings. The heterogeneous matrices that exhibit properties that change over time and space can be sampled representatively using composite samples.[18] Typically, the composite sample is obtained by obtaining one sample at the start of the discharge, two in the middle, and one at the end.[19] Thus, composite FS samples were collected while emptying the vacuum truck, *i.e.*, by collecting samples during the discharge of FS into a dumpsite at different discharge timings. The samples were collected in polypropylene bottles, kept in an icebox, and transported to the laboratory for testing. The sample size (n) is calculated using the Cochran W. G. formula,[20] as shown in eqn (1).

$$n = \frac{Z^2 p(1-p)}{\text{MOE}^2} \tag{1}$$

Here, Z is a score based on the confidence interval, whereas p is the population proportion, a portion of a population with a specific characteristic that can be represented as a percentage, fraction, or decimal of the entire population. MOE is the margin of error, which reflects the degree of uncertainty present and is influenced by the sample size, degree of confidence, and data variability. Within a selected confidence interval, the confidence level expresses the degree of certainty on how well a sample represents the population under study. In this study, a % confidence level of 95% is used, and the corresponding Z score is 1.96 from the standard normal distribution table. The population proportion p is taken to be 90.53% since 90.53% of the Indian population uses the non-sewer sanitation facility type (*i.e.*, OSS) as per the joint monitoring programme of the World Health Organization and UNICEF.[21] MOE is the margin of error, which is taken to be 0.1(10%). Thus, by substituting the values, Z = 1.96, p = 90.53%, and MOE = 10% in eqn (1), 33 samples (n) are required from the households to analyse the characterization of FS in the Pilani town. 33 composite samples were collected from the OSS system in different regions of the town. Due to social constraints (people's disinterest in cooperation and OSS was inaccessible for sample collection), choosing the sites for sample collection is problematic. Thus, in this study, septic tank emptying and transportation operators were identified, and help was asked for with sample collection. These emptying and transportation operators contacted the authors when a household required emptying services and allowed the authors to participate in the emptying event for sampling. Thus, sampling was done when households cleaned the OSS and FS samples were collected immediately after emptying events by vacuum trucks at different locations in Pilani. Samples of 33 OSS systems were collected from 30 different household locations, and 3 samples were collected directly from the disposal site, as shown in Fig. 3.

2.3. Questionnaire

The questions were asked to households, shops, and property owners of the site where FS samples were collected. As mentioned earlier, due to social constraints (households' disinterest in revealing personal information), the head of the family mostly answered the questions, which was a man in most cases, since they only knew the details about the OSS type, cleaning frequency, dimensions, and water pipelines connecting OSS. A few women (3 cases) also answered the questions regarding OSS. With the few available responses, the interviewees' ages range from 32 to 54. Since the

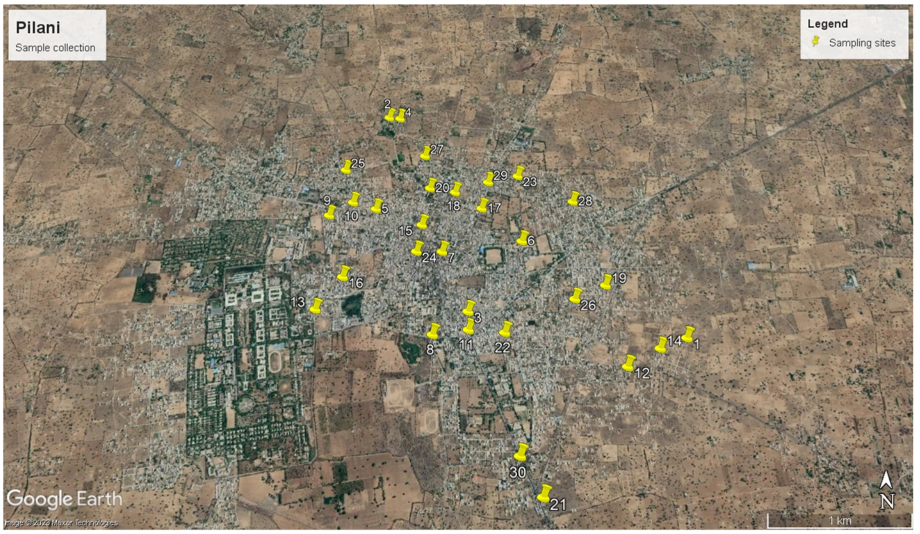


Fig. 3 Sample collection locations in the study area.

sampling events were based on cleaning operations, the interviewees were interviewed using a random sampling method; this will also ensure a representative cross-section of the population. The questionnaire was designed to gather information for analysis of FS characterization. The questionnaire included the following questions for households: what is the source of FS, *i.e.*, the type of building, whether it is a residential house, cluster of blocks, or commercial building like shops, hotels, or complexes, was noted. Then, the type of OSS containment, whether a septic tank, a single pit, or any other OSS, was recorded. Components of OSS, like chamber counts in septic tanks, lined pits, or unlined pits, were also noted. This was followed by questions about the dimensions of the OSS and its shape, such as the pit shape and depth. The previous OSS cleaning year was enquired to know the age of FS in the containment so that the present age of FS can be calculated from that. The type of input to containment other than FS was also noted (*i.e.*, mixing of greywater, kitchen wastewater, and any other wastewater into OSS was recorded). Additionally, it was inquired whether any water or chemicals were added during emptying the OSS containment.

2.4. Sample preservation

The FS sample is a biohazard that changes its composition over time. Thus, proper preservation is required to ensure that there is no change in characterization before testing. Samples were tested as much as possible immediately after sampling. Whenever storage was required, samples were stored in a refrigerator at 4 °C. No preservatives were added during storage since they affect the properties of FS. All laboratory tests were initiated on the day of sampling, and analysis was completed within three days of collection (some analyses, like total solids and BOD, can't be completed in a single day) with samples stored in the refrigerator merely as a backup. The sampling bottles were washed with deionized water initially, followed by detergent washing. Then, the bottles were soaked in bleach, a disinfectant. Lastly, the bottles were sterilized at 120 °C for 10 min.

2.5. Sample preparation

The main composite samples were homogenized, and from these, the sub-samples were prepared and further homogenized using orbital shakers to ensure consistency. Due to the higher COD and TS concentration, FS samples require dilution so that their concentration is within the measurable quantification range. Since the sample collection and analysis were conducted on the same day, the process followed was consistent throughout the study. This included these steps in the order of sample collection, dilution, and analysis initiation, ensuring uniformity and reliability in the results. It is important to avoid adding small FS volumes into larger volumes for dilution. If the difference between the two volumes is more than two orders of magnitude, a series of dilutions should be utilized instead.[22] Thus, for 1 : 1000 dilution, 1 mL was added into 9 mL of Millipore water (deionized pure water) for 10 mL diluted sample volume, which was repeated three times to make a 1 : 1000 diluted FS sample. Due to the high variability of FS characterization, because of an effluent zone and a sludge zone, three subsets of the FS sample were prepared from the single composite sample. For faecal coliform analysis, the main composite sample was used. Since it is expensive and difficult to measure all the pathogens, a common practice of measuring faecal coliform indicators to know the pathogen content level has been employed. Common faecal coliform indicators such as *Escherichia coli* (*E. coli*), *Klebsiella pneumoniae*, and *Serotype enteritidis* have been measured.

2.6. FS characterization

Physical–chemical parameters such as temperature, pH, total suspended solids (TSS), total dissolved solids (TDS), TS, COD, BOD, total phosphorus, total nitrogen (TN), and faecal coliform count were analysed for the FS samples. Physical examination of the FS colour was performed to assess the degree of decomposition of organic matter in FS due to anaerobic decomposition. All the parameters were tested following the 23rd edition of Standard Methods for Examination of Water and Wastewater, which is a joint publication by the American Public Health Association, American Water Works Association, and Water Environment Federation (APHA-AWWA-WEF).[23] Important indicator faecal coliforms, including *Klebsiella pneumoniae*, *Serotype enteritidis*, and *Escherichia coli* (*E. coli*), are measured in this study using coliform count plates that include agar and tryptose culture media and are incubated at 44 °C for 24 hours to calculate the colony forming unit per milliliter (CFU ml^{-1}). Each composite sample was subdivided into three sub-composite samples and tested in triplicate for accuracy and understanding of the variations in the sub-samples. The characterization results of a total of FS samples from 33 independent OSS systems, which were subdivided into 86 sub-samples, are presented in this article. The testing method and the standardization methods adopted are mentioned in Table 1. The methodology of the study is presented in Fig. 4. The red-coloured section of the methodology diagram outlines and describes the laboratory analysis process, including sampling, dilution, and testing. The yellow-coloured part in the methodology picture highlights the responses regarding the OSS system. The blue-coloured section shows the analysis of characterization results, considering the questionnaire response, and includes suggestions for safe FSM. This is the methodology followed for the case study and will also serve as the article's structure explaining the questionnaire responses, FS characterization analysis, suggestions, and FS treatment in the subsequent sections.

3. Results and discussion

3.1. Questionnaire results

Investigation of 30 sampling locations on the OSS type gave the following results in Table 2. The questionnaire responses indicate that the OSS types prevalent in the study area include two-chamber septic tanks, single-chamber septic tanks, and single-pit latrines. 16 samples were collected from two-chamber septic tanks, 14 FS samples from single-pit latrines, and 3 from single-chamber septic tanks. Samples of FS emptied from OSS of residential houses and commercial establishments, such as shops, hotels, and bakeries, were collected for characterization analysis. The age of the FS was determined by inquiring about the number of years since the last cleaning of the OSS systems, which varied from 1 to 16 years in this study. Households were surveyed to investigate how the presence or absence of lining in OSS systems impacts the FS characteristics. Findings from the survey indicate that except for a few, most single pit latrines in this study were found to be without lining. It was explored to analyse the external water content entering on-site sanitation systems, apart from FS and blackwater (comprising urine and anal cleansing water). The investigation revealed that in residential dwellings, the inflow consisted of FS and blackwater. However, in commercial complexes such as hotels and shops, greywater (kitchen wastewater) was observed to intermingle with FS and blackwater. A sample of FS was collected from a vacuum truck, encompassing a blend of FS samples from two distinct OSS systems. The Pilani municipality depends on OSS systems to manage excreta. This aligns with the observations from the government of Rajasthan report,[24] indicating that 70% of the Rajasthan state relies on the OSS system for managing generated FS.

Table 1 Methods/instruments for FS characterization analysis

S. no	Parameters	Analysis methods/instruments	Standardization methods
1	Temperature, pH & EC	pH meter and electrical conductivity meter	Calibration standard solutions
2	Total dissolved solids	Benchtop meter	Calibration standard solutions
3	Total solids	Volumetric and gravimetric methods by oven drying	Analysis protocol: the oven was maintained at 105 to 110 °C. The crucible was preheated and dried before testing
4	Total suspended solids	Oven drying method/digital meter	
5	Chemical oxygen demand	Closed reflux titrimetric method	Potassium hydrogen phthalate (KHP) stock solution with a theoretical COD value of 400 mg l^{-1}
6	Biochemical oxygen demand	Winkler's method/5-day method	Titration of sodium thiosulfate with standard potassium iodate and Millipore water solution results in consistent and reproducible results of less than 0.05 ml
7	Total nitrogen	Total nitrogen analysers	Standard calibration curve
8	Total phosphorus	Vanadomolybdate yellow color method	Standard phosphorus stock solutions
9	Faecal coliform	Sample ready culture medium-coliform count plates	—
10	Capillary suction time (CST)	Capillary suction timer	Calibrated by the manufacturer

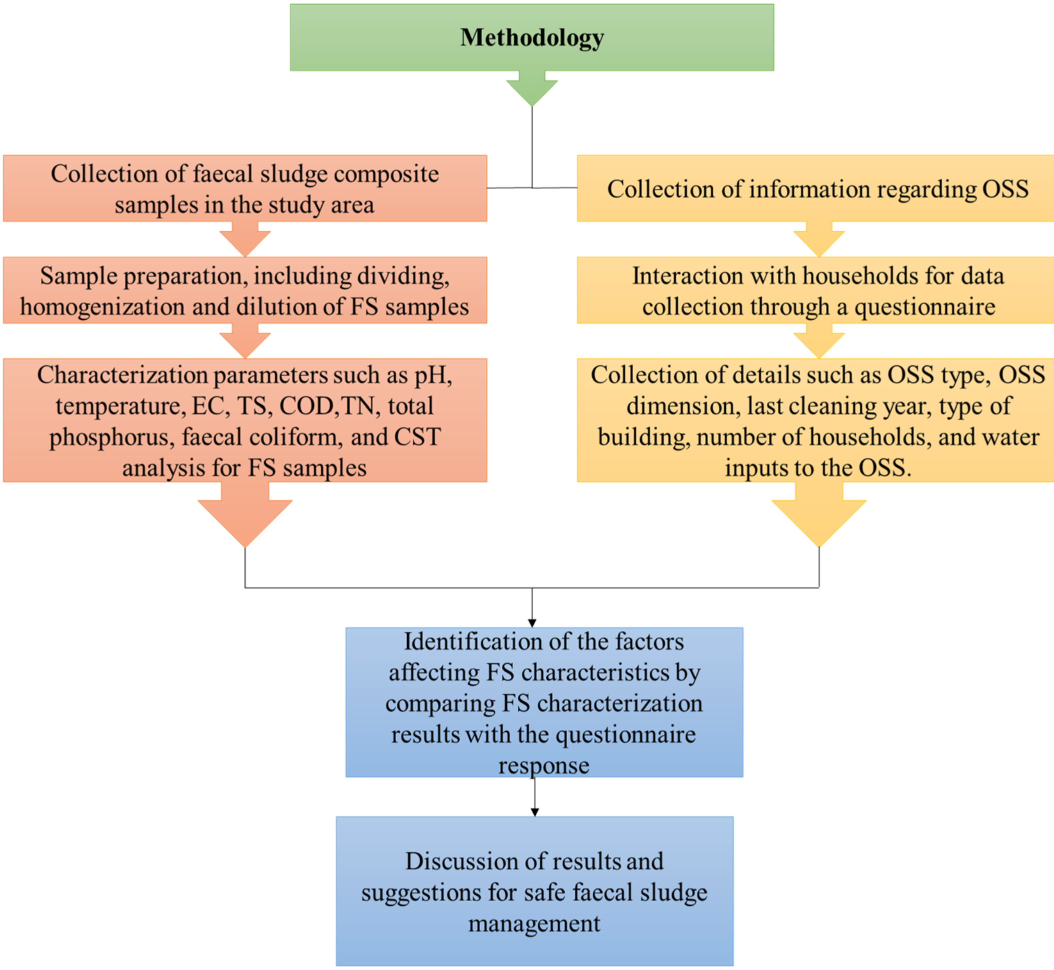


Fig. 4 Methodology of the case study.

Three private companies operate in the town to empty the OSS system. In the study area, there are no FSTPs; instead, all the collected FS is disposed of in dumpsites, which may cause adverse environmental effects. The authors' direct participation in OSS emptying events verified the questionnaire responses. Physical participation in OSS emptying events enables the verification of the responses. The OSS type and design have been verified by checking the layout of the building plans where they are available. In some cases, the last OSS cleaning date has been written on the top of septic tanks, which can be useful for cross-verification.

3.2. Physical examination of faecal sludge samples

Physical examination of the FS colour was performed to assess the degree of decomposition of organic matter in FS due to anaerobic decomposition. The colour of FS, ranging from brown to black, indicates varying degrees of decomposition, with darker colours suggesting more advanced degradation. This qualitative analysis helps infer the biochemical status of FS, providing essential information on its stabilization level. Additionally, this observation forms a preliminary examination of FS. The faecal sludge colour can vary during different phases of digestion and can reveal information about the stages of the FS digestion process. FS with an age range of a year or less than two years exhibits a yellow colour, as shown in Fig. 5(a), representing a relatively natural state before the start of organic matter digestion. During the intermediate stages of digestion of FS in OSS containment, the colour transforms from yellow to a greenish-brown or dark brown shade, as shown in Fig. 5(b), indicating the breaking down of organic matter of FS, as noted in FS samples aged between five and eight years. Following a residence time of 10 years in the on-site OSS, FS samples were discovered to have a fully dark brown or black colour, as shown in Fig. 5(c), signifying the comprehensive breakdown of FS organic matter and the mineralization of FS.

3.3. Temperature, pH, and electrical conductivity

The effectiveness of the anaerobic digestion process in a septic tank heavily depends on both temperature and pH levels. Septic tanks are classified as mesophilic environments because they work best in a moderate temperature range,

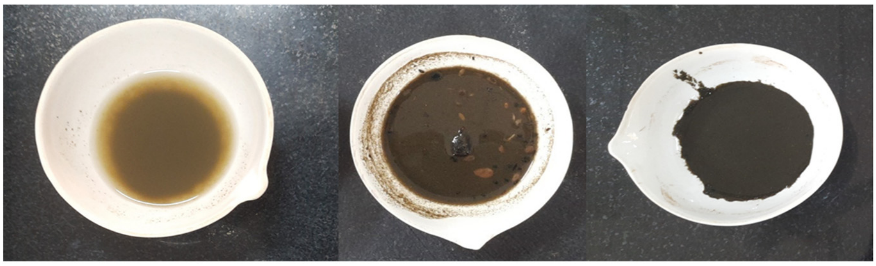
Table 2 Details of collected FS samples

FS samples	Sample set number	Type of OSS	Type of building	Dimensions of OSS	Age of FS sample	Type of sample	No. of people in the household	Remarks
1	1	Single pit	House	0.9 m × 0.9 m × 8 m	>1 year	Yellowish liquid	7	Lined pit
	2							FS + blackwater
	3							
2	4	Single pit	House	4 m depth with 0.6 m diameter	1.5 years	Yellowish liquid to slurry	6	Lined pit
	5							FS + blackwater
3	6	Two-chamber septic tank	House	1 m × 1.4 m × 1.8 m	2 years	Greenish-black liquid	5	FS + blackwater
	7							
	8							
4	9	Single pit	House	4 m depth with 0.7 m diameter	2 years	Yellowish-black liquid	6	Lined pit
	10							FS + blackwater
	11							
5	12	Square	House	3.5 m depth with 3 m × 3 m surface area	2 years	Brownish-yellow thick slurry	7	Lined pit
	13	Single pit						FS + blackwater
	14							
6	15	Two-chamber septic tank	House	2 m × 1.7 m × 1.6 m	2 years	Black liquid	5	FS + blackwater
	16							
	17							
7	18	Single pit	House	4 m depth with 1 m diameter	2.5 years	Greenish black slurry	2	FS + blackwater
	19							
	20							
8	21	Two-chamber septic tank	Hotel	2 m × 2.7 m × 2.5 m	3 years	Dark black liquid	15 workers + moving population	FS + blackwater + greywater
	22							
	23							
9	24	Two-chamber septic tank	Bakery	1.5 m × 2.5 m × 2.1 m	3 years	Light yellow liquid	5	FS + bakery wastewater
	25							
	26							
10	27	Septic tank	House	2 m × 3.1 m × 1.5 m	3 years	Yellow liquid	3	FS + blackwater
	28							
	29							
11	30	Two-chamber septic tank	Sweet shop	2 m × 1 m ×1.8 m	3.5 years	Yellowish-black liquid sample	5 workers	FS + blackwater + greywater
	31							
12	32	Two-chamber septic tank	House	1.8 m × 1.6 m × 2 m	3.5 years	Yellowish black liquid	8	FS + blackwater
	33							
	34							
13	35	Two-chamber septic tank	Hotel	2.1 m × 3.1 m × 1.5 m	4 years	Light yellow liquid	10 workers + moving population	FS + blackwater + kitchen wastewater
	36							
	37							
14	38	Single pit	House	5 m depth with 1 m diameter	4 years	Dark green slurry	4	Unlined pit
	39							FS + blackwater
	40							
15	41	Single pit	House	7 m depth with 0.6 m diameter	5 years	Dark yellowish-brown slurry	6	Unlined pit
	42							FS + blackwater
	43							
16	44	Two-chamber septic tank	Complex shops	2.2 m × 3.1 m × 2 m	6 years	Dark brown slurry	5	FS + blackwater
	45							

Table 2 *(continued)*

FS samples	Sample set number	Type of OSS	Type of building	Dimensions of OSS	Age of FS sample	Type of sample	No. of people in the household	Remarks
	46							
17	47	Two-chamber septic tank	Shop	2.1 m × 1.8 m × 1.9 m	6 years	Yellowish black slurry	—	FS + blackwater + greywater
	48							
	49							
18	50	Single pit	House	4.5 m depth with 0.8 m diameter	6 years	Greenish slurry	4	FS + blackwater
	51							
	52							
19	53	Single pit	House	7 m depth with 0.8 m diameter	7 years	Yellowish brown slurry	5	Unlined pit
	54							FS + blackwater
	55							
20	56	Composite sample	—	—	Composite sample of 7 years and 1 year	Greenish yellow slurry	—	FS + blackwater + greywater
	57							
	58							
21	59	Single chamber septic tank	House	1.5 m × 1.5 m × 1 m	8 years	Dark green slurry	6	Unlined tank
	60							FS + blackwater
	61							
22	62	Single chamber septic tank	House	1.8 m × 1.5 m × 1.2 m	8 years	Greenish black slurry	8	FS + blackwater
	63							
	64							
23	65	Composite sample	—	—	Composite samples of 9 years and 1 year	Greenish-yellow slurry	—	FS + blackwater
	66							
	67							
24	68	Single pit	House	5 m depth with 0.9 m diameter	9 years	Dark blackish slurry	7	FS + blackwater
	69							
	70							
25	71	Single pit	House	10 m depth with 0.8 m diameter	10 years	Greenish-yellow slurry	4	Unlined pit
	72							FS + blackwater
	73							
26	74	Single pit	House	6 m depth with 1 m diameter	10 years	Dark greenish colour, thick slurry	9	Unlined pit
	75							FS + blackwater
	76							
27	77	Composite sample	—	—	Composite samples of 11 years and 8 years	Greenish-black slurry	—	FS + blackwater + greywater
	78							
	79							
28	80	Two-chamber septic tank	House	2.2 m × 1.8 m × 1.5 m	12 years	Brownish black liquid	10	FS + blackwater
	81							
	82							
29	83	Two-chamber septic tank	House	2.6 m × 2.6 m × 2 m	13 years	Yellowish-brown slurry	3	FS + blackwater
	84							
30	85	Single pit	House	12.1 m depth with 0.7 m diameter	16 years	Dark black slurry	4	Unlined pit
	86							FS + blackwater

usually between 30 and 35 °C.[25] The temperature of the FS samples in this particular case study varied between 20.6 and 27.5 °C, as shown in Fig. 6(a). Because of the lower atmospheric temperatures in the study area in August and November, the OSS system in this case study does not meet the mesophilic temperature requirements. The pH range for



(a) (b) (c)

Fig. 5 Stages of FS decomposition (by physical examination interpretation).

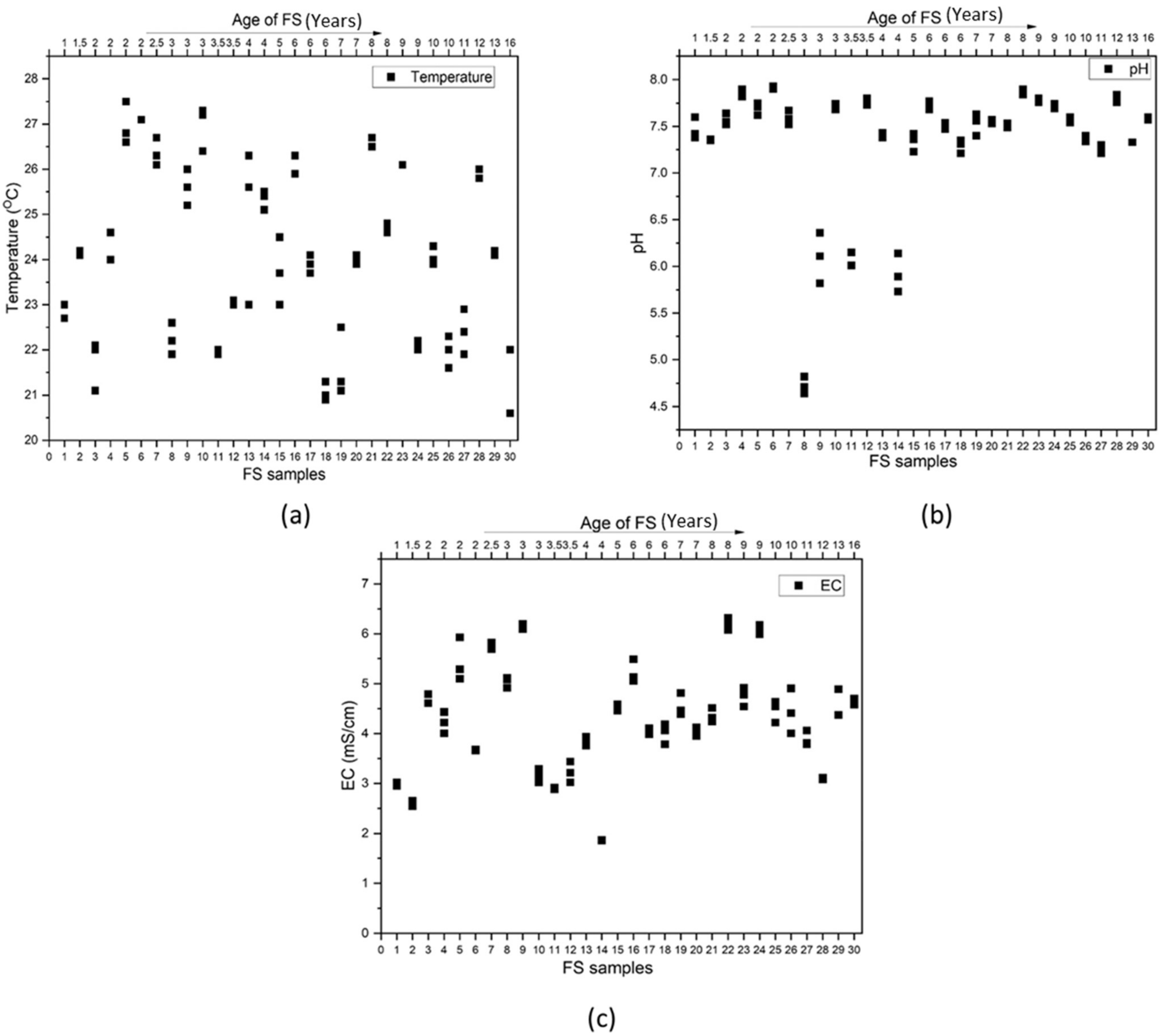


Fig. 6 Temperature, pH, and EC of FS samples collected from Pilani, Rajasthan.

ideal anaerobic digestion was identified to fall between 6.5 and 7.5.[26] The pH levels observed in the study area for FS samples varied between 4.64 and 7.93, as shown in Fig. 6(b). All FS samples fall within the pH range appropriate for

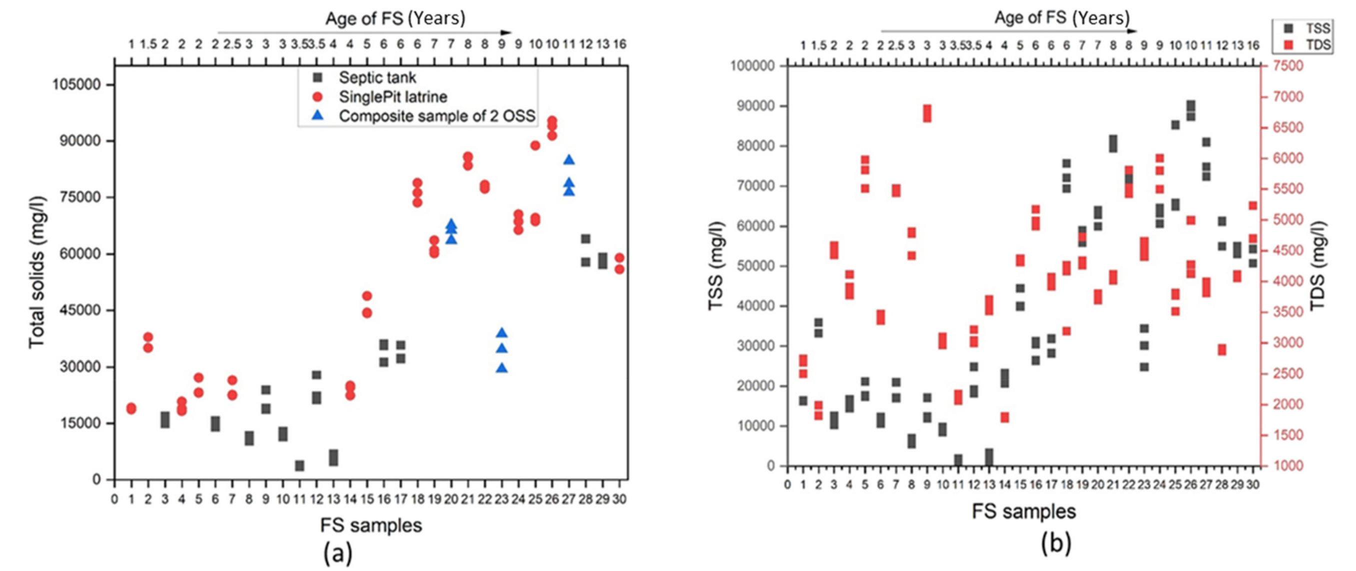


Fig. 7 TS, TSS, and TDS of FS samples collected from Pilani, Rajasthan.

anaerobic digestion, with few exceptions. FS samples from bakeries and hotels that include kitchen wastewater have an acidic pH, possibly because of the organic acids produced from food residues. The ions dissolved in the FS are measured by electrical conductivity (EC). In this study, the EC of FS samples varied from 1.857 to 6.315 mS cm^{-1}, as shown in Fig. 6(c). Similar EC values are observed for almost all samples with minimal variations. Due to increased solid content, samples from single-pit latrines demonstrate a slightly elevated electrical conductivity compared to septic tank FS samples.

3.4. Total solids

TS analysis data are valuable for designing, operating, and monitoring FS treatment plants. TS measurement determines the total amount of suspended (TSS) and dissolved (TDS) particles in FS. This study measures TS by drying an FS sample in a heated oven at 103 to 105 °C for 24 hours.[9] The TS in this study area varied from 2033.33 to 95 393.33 mg l^{-1}, as shown in Fig. 7(a). The TS value was directly proportional to age, probably due to increased organic matter accumulation. However, there are exceptions to this trend because of the OSS system type and water content of FS. FS samples from unlined single pit latrines exhibit higher TS values than FS samples from septic tanks because of urine and blackwater leaching, resulting in thicker and more concentrated FS. FS samples with greywater possess lower TS values than other FS samples of the same age because of the dilution effect of greywater, which comes from kitchen wash water. TS was further divided into TSS and TDS; this will provide more information about the composition of solids in FS samples. TSS contributes to a significant portion of TS and varies from 1098 to 90 400.33 mg l^{-1}, as shown in Fig. 7(b), indicating that all the organic matter is in the form of solids. TDS shows a strong correlation with EC with an R square of 0.92393 by linear regression analysis, as shown in Fig. 8, confirming the significant impact of organic materials and dissolved ions on the FS's electrical conductivity.

3.5. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD)

Understanding the COD and BOD concentrations in FS is essential for designing FS treatment technologies. A concentration of organic pollutants is indicated by COD values, which also provide information about the degree of contamination and possible effects on the environment. COD is measured by oxidizing FS samples with a strong oxidizing agent, potassium dichromate ($K_2Cr_2O_7$). The COD of FS in this study area ranged from 4406 to 160 000 mg l^{-1}, as shown

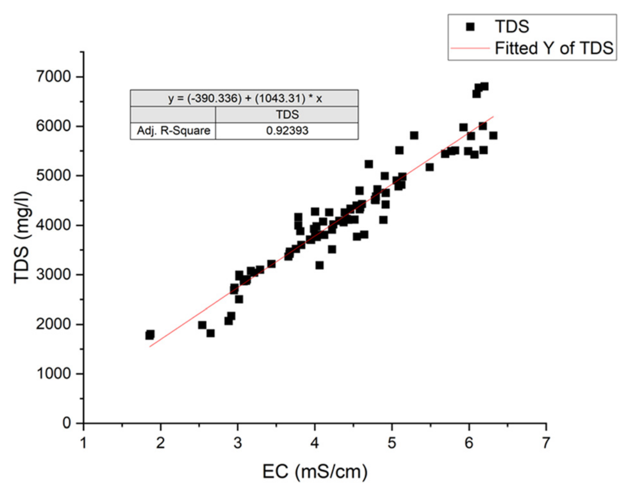


Fig. 8 EC–TDS correlation of FS samples collected from Pilani, Rajasthan.

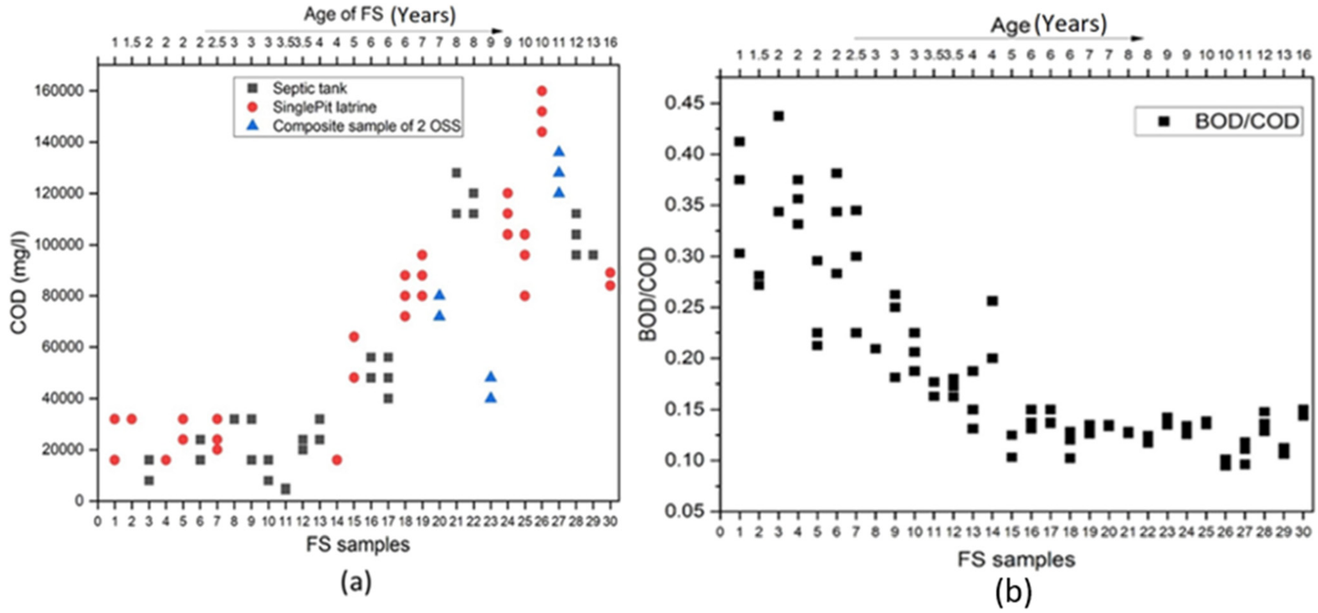


Fig. 9 COD, COD & TS correlation and BOD/COD ratio of FS samples from Pilani, Rajasthan.

in Fig. 9(a). As the FS in the OSS system ages, due to microbial decomposition, microorganisms break the complex organic matter into simpler forms and produce inorganic compounds, *i.e.*, mineralization, which may increase COD. Similar to the case of TS, COD was also in higher concentration in single-pit latrines than in septic tanks. This was verified by performing a linear regression analysis and plotting COD and TS in the X and Y axes, respectively. The model revealed a strong correlation between COD and TS with an R square of 0.90078, as shown in Fig. 10. One of the most crucial parametric indicators in the characterization of FS is the BOD to COD ratio since it establishes whether the FS can be biologically treated.[27] The average BOD/COD ratio of 86 FS samples in this study area is 0.1896, ranging from 0.095 to 0.4375. As the FS ages, the BOD/COD ratio tends to decrease, as shown in Fig. 9(b). This indicates that FS with more residence time in the OSS system has less biodegradable organic matter due to mineralization, making the treatment of FS more complex. COD measures the oxygen needed to chemically oxidize organic matter in FS, while BOD measures the oxygen microorganisms require to decompose the organic matter in FS biologically. Thus, COD also measures the oxygen requirement of microorganisms, which can decompose the organic matter. BOD represents a biodegradable portion of COD, indicating that BOD is the subset of COD. Due to this, COD and BOD show a strong correlation, as verified by linear regression analysis, plotting COD and BOD in the X and Y axes, respectively. The model revealed a strong correlation between COD and BOD with an R square of 0.87531, as shown in Fig. 11.

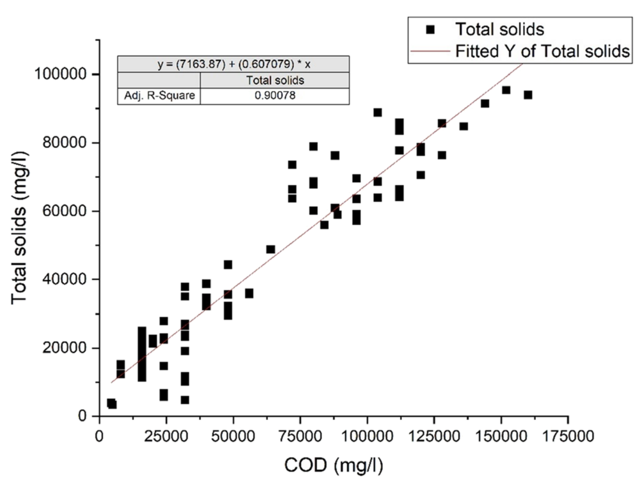


Fig. 10 COD & TS correlation of FS samples from Pilani, Rajasthan.

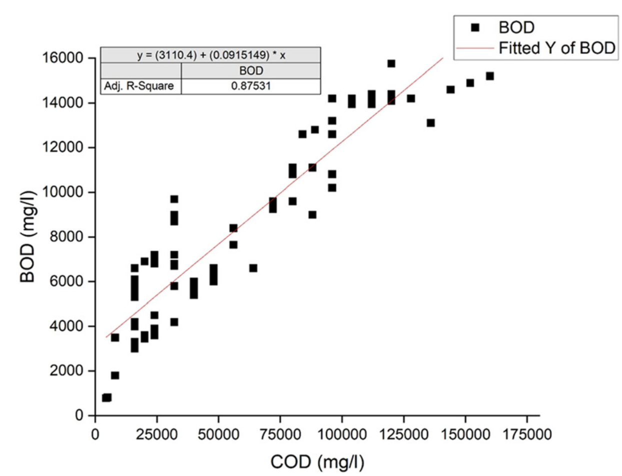


Fig. 11 COD & BOD correlation of FS samples from Pilani, Rajasthan.

3.6. Faecal coliform

The presence of faecal coliforms in FS is a key indicator which indicates faecal contamination.[9,28] The concentration of faecal coliforms in FS is a key indicator of potential contamination by waterborne disease-causing organisms. In this present study, important faecal coliforms such as *Klebsiella pneumoniae, Serotype enteritidis, and Escherichia coli* (*E. coli*) are determined in colony forming unit per ml (CFU ml^{-1}) using coliform count plates with agar and tryptose culture media, incubated at 44 °C for 24 hours. *E. coli* varied from 10^5 to 10^9 CFU ml^{-1}, the *Klebsiella pneumoniae* count ranged from 10^4 to 10^8 CFU ml^{-1}, and *Serotype enteritidis* varied from 10^3 to 10^9 CFU ml^{-1}, as shown in Fig. 12(a). The faecal coliform count was almost stable in all ages of FS with minimal variations, probably because of the continued input of fresh FS into the OSS system.

3.7. Total nitrogen

Exceeding TN discharge standards may lead to diverse environmental consequences, including eutrophication, the proliferation of algal blooms, groundwater contamination, and drinking water contamination. TN in FS exists in various forms, including ammonia, nitrate, and nitrite. In this study, the TN concentration varied from 81.7 to 709.2 mg l^{-1}, as shown in Fig. 12(b). The decrease in TN concentration observed with an extended retention time of FS in the OSS system can be due to multiple factors, including microbial decomposition, volatilization of ammonia, denitrification (nitrate to N_2 gas), and the leaching of liquid effluent.

3.8. Total phosphorus

Human waste contains phosphorus, an important mineral found in FS. Though human faeces and urine produced in a

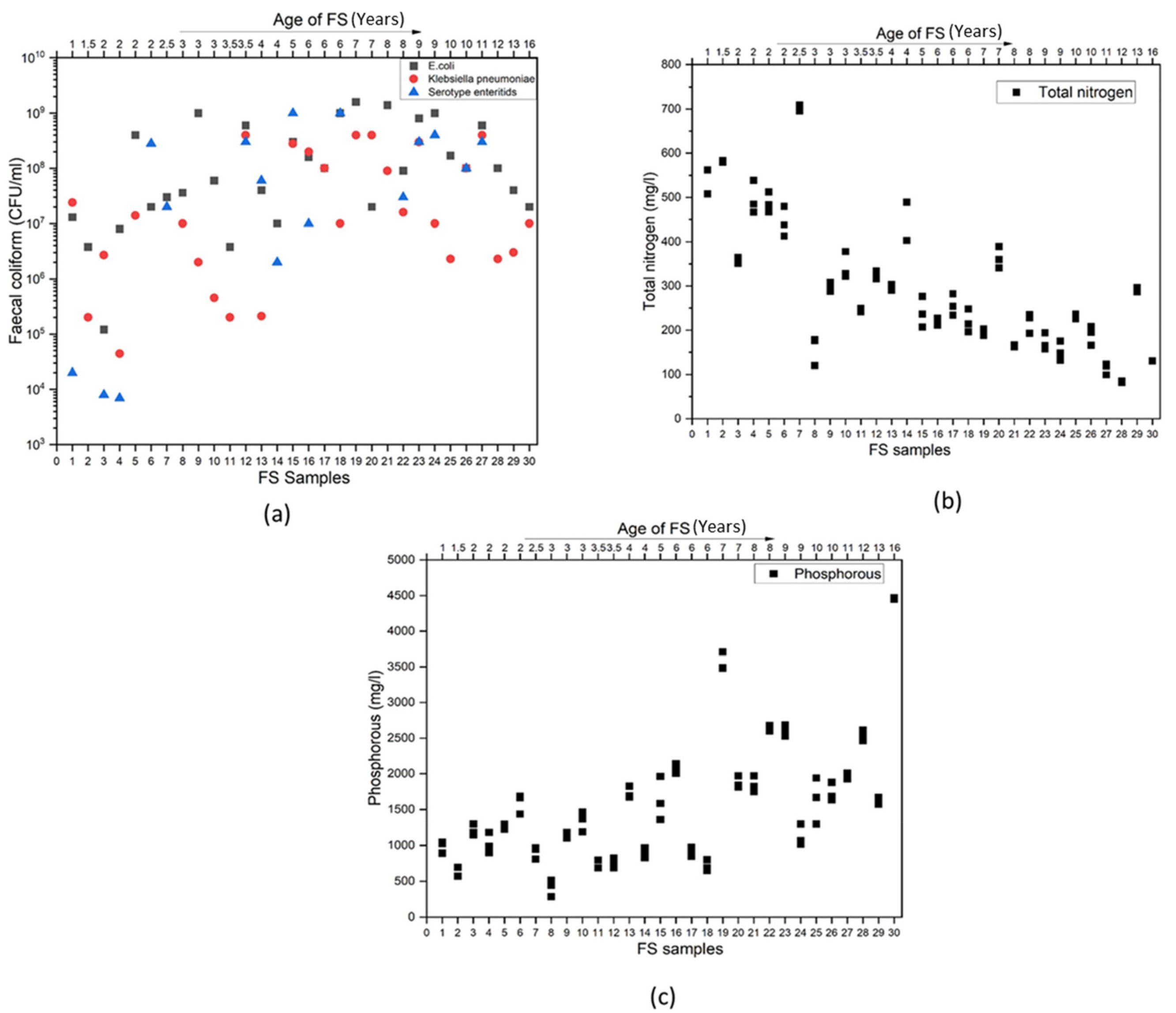


Fig. 12 Faecal coliform count, TN concentration, and TP concentration in FS samples from Pilani, Rajasthan.

year by a person contain the nutrient requirement (nitrogen and phosphorus) required for producing 250 kg of cereals,[29] their release into the environment could harm surface and groundwater resources if FS is untreated. Thus, it's critical to evaluate phosphorus for safe and efficient reuse in compost for agriculture. The TP content in this study ranged from 285 to 4471 mg l^{-1}, as shown in Fig. 12(c). Since the phosphorus content in FS depends upon the dietary habits of households and geographical and cultural factors, no significant trends were observed. However, dilution of FS with other water inputs shows lower TP values in some cases than others.

3.9. Capillary suction time (CST)

Dewatering FS, *i.e.*, liquid–solid separation, is an important aspect of FS treatment. The term "dewaterability" refers to effectively removing liquid from sludge. Capillary suction time (CST) measures the rate at which water is drawn from FS. CST is a valuable tool in designing drying beds for sludge because it provides insights into the dewatering characteristics of the FS. A lower CST value indicates better dewaterability or the FS's increased ability to release water.[30] The CST value also determines the speed at which FS can be filtered, the moisture level of the FS cake, and the degree of water bonding to the FS solids.[22] In this study, the dewaterability rate was determined using the capillary suction time (CST) test, using a CST instrument, which has an acrylic filtration unit with electrodes and a timer, as shown in Fig. 13(a). According to manufacturer instructions, a 5 ml raw FS sample was used for testing, and CST values were recorded in seconds. The CST value varied from 149 to 1256.8 seconds, as shown in Fig. 13(b), for the FS samples in this study. The CST value increased with an increase in the age of FS, indicating that more time is required for dewatering, which may be because of FS's mineralization over time, making FS thicker and less porous. The CST of FS is also affected by its temperature; for example, at higher temperatures, the viscosity of the water in the FS will be reduced, allowing it to move more easily through the sludge matrix. This typically results in shorter CST, as water moves out easily from FS at higher temperatures. In this study, the temperature of the FS samples didn't vary much since the standard deviation is 1.916; however, samples with a high temperature showed shorter CST than very low-temperature FS samples. Also, a single pit latrine produces thicker FS than septic tank FS, exhibiting high CST values and indicating low dewaterability due to the solid FS composition (high TS).

4. FS treatment options

In this case study, FS is found to be a high COD waste, ranging from 4406 to 160 000 mg l^{-1}, correlated with total solids by an R square of 0.90078. Thus, it is essential to trap total solids from FS, which will also remove COD. Removing a liquid particle from any sludge waste is called dewatering. After dewatering, FS should be treated for separated solid particles and sludge leachate parts. The process of FS treatment methodology is given in Fig. 14. FS should undergo dewatering followed by sludge stabilization and leachate treatment. The site-specific FS treatment system is discussed in this section.

4.1. Site-specific FS treatment system

4.1.1. FS dewatering methods. Dewatering treatment methods include drying beds, settling tanks, Imhoff tanks, and mechanical dewatering technologies. Drying beds can be either unplanted or planted in which macrophytes are planted. Drying beds are sand- and gravel-filled pits or tanks connected to a gutter for leachate collection. For dewatering purposes, FS is poured on the top layer.[31] The sludge loading

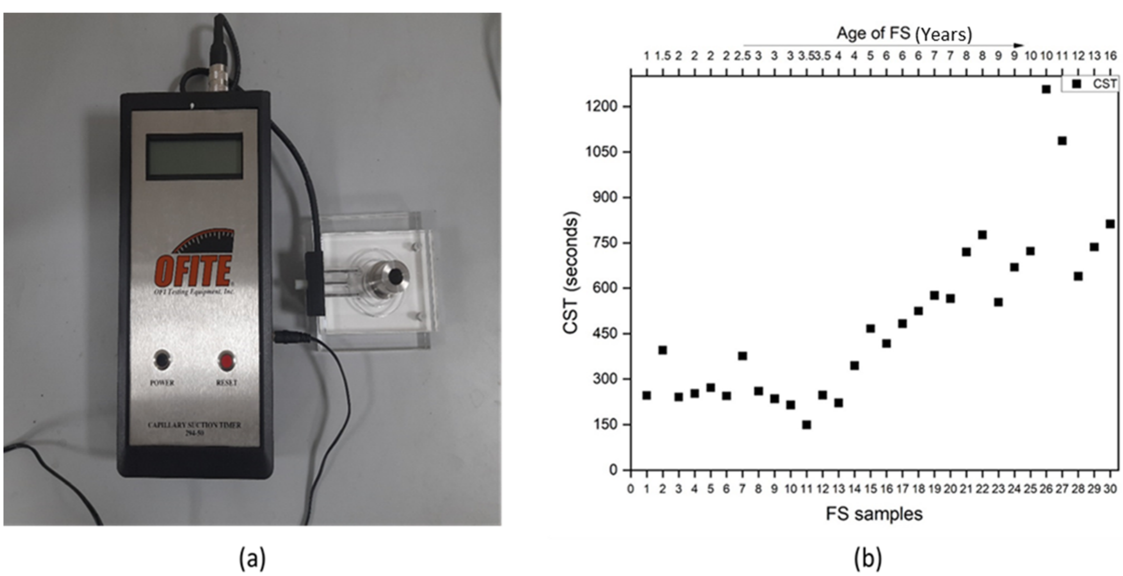


Fig. 13 CST apparatus and CST values measured for FS samples from Pilani, Rajasthan.

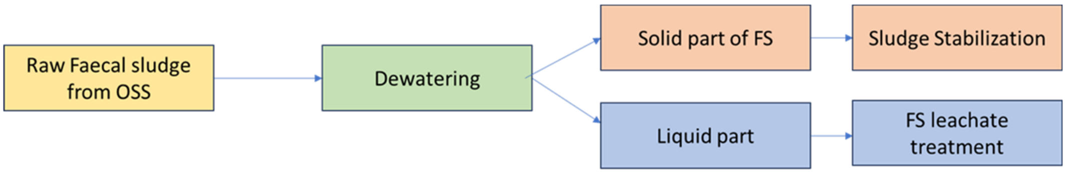


Fig. 14 FS treatment methodology.

rate, expressed in kg TS m^{-2} per year, is the mass of FS dried in a drying bed in a year, varying from 50 to 300 kg TS m^{-2} per year.[32] The primary mechanism behind drying beds is the natural evaporation and absorption of organic matter by media (sand and gravel). Along with TS, drying beds are also capable of removing COD and BOD due to the correlation with TS, which is in accordance with case studies of Ouagadougou (Burkina Faso), Nègrepelisse (France), and Yaoundé (Cameroon).[33–35] The leachate collected and the solid parts dried on the top of drying beds can be processed for next-level treatments.

Settling and Imhoff tanks are other types of dewatering techniques in which FS treatment starts by separating solid FS and liquid parts using settling and thickening tanks. In Imhoff tanks, the mechanism involved is anaerobic digestion and settling; these principles combine to treat FS.[31] Mechanical dewatering consists of a belt filter press, screw press, and centrifuge. This equipment removes water from sludge and produces a thick, dried sludge cake. The removal efficiencies and loading rates of various dewatering techniques available from the literature are given in Table 3.

In the Pilani context, a semi-urban, arid tier-III town, an effective dewatering method can be a drying bed. Mechanical dewatering involves the establishment of high-cost equipment along with power motors to dewater the sludge, which cannot be suitable for the Pilani context because of more initial investments. Operation and maintenance costs will also be high due to the high electricity requirement and skillful labor. Settling and thickening tanks require an initial construction cost and more land, which is unsuitable for dense tier-III towns. Pilani is an arid region where the maximum temperature can reach around 45–48 °C, so drying beds can be a viable and sustainable option for dewatering in Pilani because more sunny days can increase the efficiency of drying beds. Also, planted/unplanted drying beds involve direct dumping of FS on the top surface, so electricity and motors are not required for the functioning of drying beds, which indicates less operation and maintenance cost.

4.1.2. Stabilization treatment for dried FS. After the dewatering of FS, stabilization treatment for dried faecal sludge (DFS) is required to ensure the complete removal of faecal coliforms. Composting, co-composting, deep row entrenchment, vermicomposting, incineration, and lime treatment are the stabilization methods for DFS.[38] Composting DFS with organic municipal solid waste, agriculture waste, and bulking agents like rice husk, sawdust, and earthworms has good potential for use as compost for agriculture and to increase soil fertility. This compost can increase the growth of plant crops.[39,40] Deep-row entrenchment is dumping DFS in deep trenches and covering them with soil. This may stabilize the DFS, but the drawback is faecal coliforms, which can contaminate groundwater. Incineration is the burning of DFS in an incinerator at 800 to 900 °C, which can be used as a fuel for industrial use.[41,42]

In Pilani's local context, composting can be a viable option since it is a cheaper and more efficient method. Agriculture is a significant occupation in the local context of most tier-III Indian towns, so producing manure from FS makes a sustainable FSM model.

4.1.3. FS leachate treatment. FS leachate from the dewatering process must be treated for disposal or domestic use since it is a faecal coliform. A study from Tanzania[43] has shown that FS leachate has a mean total coliform count of 7.7×10^5 CFU ml^{-1}. A stabilization pond, coagulation, anaerobic baffled reactors, and wetlands are options for treating FS leachate. Hybridization of coagulation with a drying bed can be a viable option in the local context. FS leachate contains high suspended solids and turbidity; the TSS in this case study varied from 1098 to 90 400.3, indicating that FS leachate may contain high TSS. Coagulation efficiently removes suspended solids and turbidity.[44,45] Thus, natural coagulants such as plant seeds, chitosan, and other natural coagulants can be used in the local context. Sludge settled can be composted along with DFS.

The treatment system suggested based on the characterization of FS for treating FS in the local context of Pilani and other tier-III towns can be hybridization of a drying bed, composting, and coagulation, as shown in Fig. 15. A zero FS discharge model can be achieved in which

Table 3 Removal efficiencies of various dewatering methods

Dewatering methodology	Sludge loading rate	Removal efficiency
Belt filter press	218–272 kg TS h^{-1} m^{-1}	80–90% TS removal[36]
Unplanted drying beds	196 to 321 kg TS m^{-2} y^{-1}	80% TS, 69% COD and 76% BOD removal[32]
Settling tank	0.16 m^3 m^{-3}	60–70% of TSS removal[37]
Planted drying bed	300 kg TS m^{-2} y^{-1}	90% BOD and 77% COD removal[33]

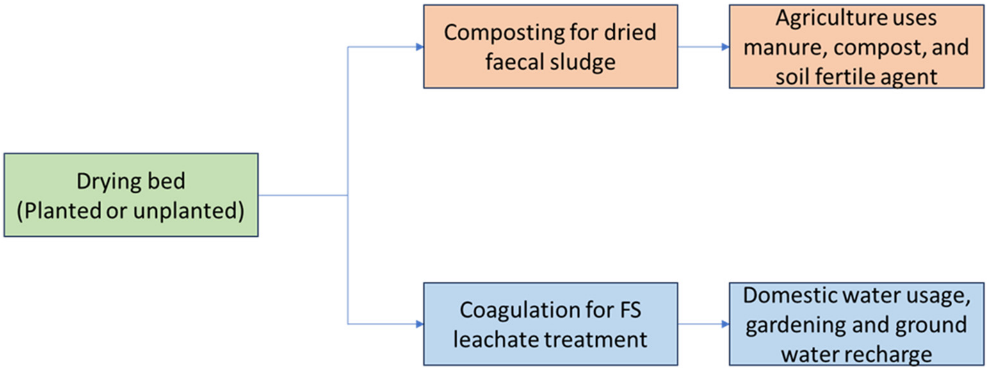


Fig. 15 Suggested line of treatment for FS in this case study.

treated FS can be used as manure and treated leachate can be used for domestic water consumption. Zero waste discharge can make the FSM service chain safe and sustainable.

5. Summary

The FS characteristics measured in this case study were highly variable and unevenly distributed. A summary of characterization results is presented in Table 4. Temperature and pH showed a small standard deviation, indicating that anaerobic conditions are similar among various OSS systems in the study area. The average TS value in the study area is 42 468.027 mg l^{-1}, with a high standard deviation of 27 028.47 mg l^{-1}, which indicates that TS has greater variability among the FS characteristic dataset because of different OSS types, water content, and FS age. The lower quartile value of COD is 20 000 mg l^{-1}, the 25th percentile, meaning 75% of the FS samples collected in Pilani show a COD value of more than 20 000 mg l^{-1}, higher than the safe disposal limit of 250 mg l^{-1}. This is in accordance with the findings in Ghana,[32,37,46,47] with COD values of 49 000 mg l^{-1}, 67 500 mg l^{-1}, 48 000 mg l^{-1}, and 201 200 mg l^{-1}, respectively. The findings in Thailand[8,48] also show similar COD values of 49 000 and 39 000 mg l^{-1}, respectively. The mean COD value of FS samples from this case study is 58 440.73 mg l^{-1} with a larger standard deviation of 42 283.094 mg l^{-1}, which indicates significant dispersion among datasets because of factors like the containment type, FS age and total solid content of FS. The faecal coliform count varies from 10^3 to 10^9 CFU ml^{-1}, with a mean of 10^8 CFU ml^{-1} for all coliforms measured in this study. The average TP content is 1590.437 mg l^{-1} in the FS samples, which suggests phosphorus recovery potential from FS if FS is properly treated. The mean CST is 503.6531 seconds, which varies from 149 to 1256.8 seconds, suggesting that FS has a slower dewatering time, *i.e.*, a slower water-releasing rate from the sludge's solid part.

An interesting observation was noted by comparing the previous characterization results: septage exhibits less COD and total solids than FS. Septage is limited to septic tanks, whereas FS belongs to the wider range of organic waste from OSS, not only from septic tanks but also from pit latrines and other OSS. Numerous types of dangerous organic waste are found in FS, and the factors influencing OSS practices are impacting the concentration levels of these contaminants. These variables include how often the OSS is cleaned, the age of the sludge, the type of sanitation system, the climate, the

Table 4 Summary of characterization results of 86 FS samples collected from 33 OSS systems of Pilani, Rajasthan

S. no	Parameters	Minimum	Maximum	Lower quartile	Upper quartile	Median	Mean	Standard deviation
1	Temperature (°C)	20.6	27.5	22.425	26	24.1	24.15	1.916
2	pH	4.64	7.93	7.352	7.737	7.54	7.316	0.702
3	EC (mS cm^{-1})	1.857	6.315	3.696	4.915	4.346	4.305	1.064
4	Total solids (mg l^{-1})	3430	95 393.33	18 988.33	66 442.49	34 836.66	42 468.027	27 028.47
5	TSS (mg l^{-1})	1098	90 400.3	16 186.14	62 371.7	30 273.8	38 371.042	26 865.758
6	TDS (mg l^{-1})	1773	6807	3432.5	4767	4100.5	4111.25	1154.66
7	COD (mg l^{-1})	4406	160 000	20 000	96 000	44 000	58 440.73	42 283.094
8	BOD (mg l^{-1})	780	16 200	5550	12 600	7000	8409.886	4132.499
9	BOD/COD	0.0095	0.4375	0.12857	0.225	0.14586	0.19136	0.0889
10	*Escherichia coli* (CFU ml^{-1})	1.2×10^5	1.6×10^9	2×10^7	5.5×10^8	9.5×10^7	3.24×10^8	4.75×10^8
11	*Klebsiella pneumoniae* (CFU ml^{-1})	4.4×10^4	4×10^8	2.3×10^6	1.5×10^8	10^7	1.03×10^8	1.51×10^8
12	*Serotype enteritidis* (CFU ml^{-1})	7×10^3	10^9	8×10^6	3×10^8	8×10^7	2.38×10^8	3.29×10^8
13	Total nitrogen (mg l^{-1})	81.7	709.2	192.7	364.9	248.8	297.894	148.917
14	Total phosphorus (mg l^{-1})	285	4471	996.7	1957.281	1362.43	1590.437	840.3370
15	CST (s)	149	1256.8	248.4	661.55	442.6	503.6531	272.0384

inflow and outflow to the OSS, chemical additions like toilet cleaners and acids, the FS collection method, user behavior, *etc.* All septage is a faecal sludge but all faecal sludge may not be a septage. A study from Chennai,[12] India analysed septage characteristics and found a COD value of 6656 mg l^{-1}. Similarly, another study in the Indian context from Maharashtra analysed FS from septic tanks,[11] *i.e.*, septage, and the COD values varied from 960 to 6080 mg l^{-1}. This case study results contradict some Indian septage characterization analysis studies since this study measured raw FS characterization while emptying the OSS. The characterization values of septage and FS from other previous studies are shown in Table 5. This study's results align with the study from Ghana,[47] in which raw FS shows the maximum COD value of 201 200 mg l^{-1}. Another study from Ghana[37] has also shown a similar COD value of 49 000 mg l^{-1}, where FS was collected from public toilets. Faecal coliforms measured in previous studies are similar in all studies, with 10^5 to 10^9 CFU ml^{-1}. Another interesting trend observed in this study is that total nitrogen values decrease with increasing age of FS, which was not observed in any of the studies, which may be due to microbial decomposition of organic matter and denitrification (Fig. 12b). Also, the BOD/COD ratio found to decrease with an increase in age may be due to organic matter mineralization (Fig. 9b); this is also not mentioned in any previous study. CST, which measures the FS dewaterability index, was also found to increase with the increase in age due to the solidification of thick FS by mineralization (Fig. 13b).

5.1. Factors influencing the variations in faecal sludge characteristics

The assessment of factors with the greatest influence on the faecal sludge characteristics reveals that three significant explanatory variables were the predominant sources of the variation in the COD, total solid, total nitrogen, and CST values of FS. They are as follows: the age of FS, the type of onsite sanitation system, and inclusion of greywater. The Statistical Package for the Social Sciences (SPSS) software is used to analyse the statistical significance of the data attributed to these factors. A one-way ANOVA test is performed with the FS age, type of OSS (septic tank or single pit latrine), and greywater inclusion (with and without greywater) as independent variables, and FS characteristic parameters depend on the independent variables using a statistical measurement known as the *p*-value. The statistical significance of the observed difference increases with decreasing *p*-value. Generally speaking, anything is statistically significant if the *p*-value is 0.05 or below. The age of FS significantly affects the COD ($p < 0.001$), total solids ($p < 0.001$), total nitrogen ($p < 0.001$), and CST ($p = 0.005$). This is because as the age of FS in OSS increases, microbial breakdown of organic matter occurs, producing an inorganic compound, *i.e.*, mineralization, which will increase COD. Due to a strong correlation with COD, TS also increases as the age of FS increases. The total nitrogen value also tends to be significant with the age of FS ($p < 0.001$) due to microbial decomposition and denitrification. Also, the CST value increases with an increase in FS age ($p < 0.005$), mainly due to the solidification of FS due to mineralization.

From the ANOVA test, it is also observed that COD and total solids also vary based on the OSS type with *p*-values of 0.044 and 0.002, respectively, indicating that the OSS type significantly affects the FS characteristics. The OSS type also affects the BOD and total nitrogen, which can be observed from *p*-values of 0.007 and 0.016, respectively. Surprisingly, the OSS system did not affect pH, possibly due to the same anaerobic conditions observed in Pilani among all OSS. Also, the BOD/COD ratio was not affected by the OSS type, which suggests that, irrespective of the OSS type, as the age of the FS increases, the BOD/COD ratio tends to decrease because of the less biodegradable organic matter due to mineralization. Greywater inclusion into the OSS also affects the FS characteristics, mainly because FS dilution reduces the total solids ($p = 0.011$). It is observed that the pH value was also affected due to the inclusion of greywater because of the mixing of acidic kitchen wastewater with the OSS ($p < 0.01$). In assessing differences in FS characteristic parameters with independent variables, the FS age, OSS type, and greywater content of FS significantly affected at least some of the FS characteristic parameters, as shown in Table 6 of *p*-values from the one-way ANOVA test. The statistically significant *p*-values ($p < 0.05$) are highlighted in bold.

Table 5 FS key characterization parameters in this study and other studies

Study description	COD (mg l^{-1})	BOD (mg l^{-1})	Total solids (mg l^{-1})	Faecal coliforms
FS characteristics in Ghana[37]	49 000	7600	52 500	—
FS characteristics in Thailand[48]	39 000		8240–123 100	
FS characteristics in Ghana[47]	201 200	56 836		132×10^6 CFU ml^{-1}
FS (septage) characteristics in India[11]	960–6080	—	1000–123 000	Total coliform of 10^5–10^9 No L^{-1}
Septage characteristics in India[12]	6656	1896	17 467	—
FS characteristics in Ghana[46]	48 000	5280	55 800	—
FS characteristics in Burkina Faso[19]	12 437	2126	13 349	
This present case study of Pilani	4406–160 000	780–16 200	3430–95 393.33	*E. coli* – 3.24×10^8 CFU ml^{-1} *K. pneumoniae* – 1.03×10^8 CFU ml^{-1} *S. enteritidis* – 2.38×10^8 CFU ml^{-1}

Table 6 *p*-Values of the one-way ANOVA test of faecal sludge parameters with independent factors

Variables compared	pH	Temperature	TS	COD	BOD	BOD/COD	TN	CST	EC	TP
Age of FS (1–16 years)	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Type of OSS system (septic tank *vs.* single-pit)	0.458	**0.001**	**0.002**	**0.044**	**0.007**	0.844	**0.016**	0.624	0.699	0.963
Grey water inclusion (with or without greywater)	**<0.001**	0.406	**0.011**	0.223	**0.045**	0.517	**0.033**	0.064	0.554	0.097

6. Discussions and suggestions

In assessing FS characterization, the OSS emptying frequency (FS age), the type of OSS containment, and water inputs are the major factors affecting the FS characterization. Also, other factors like the addition of water during emptying, OSS dimensions, and the number of households influence the FS characterization.

6.1. FS age

In this case study, the residence time of FS in the OSS system, *i.e.*, FS age, plays a crucial role in FS characterization. As the age of FS increases, TS and COD tend to increase, and the BOD/COD ratio decreases due to organic matter accumulation by time and mineralization. Emptying or desludging the OSS system was more challenging when emptying was performed after four years. This is because TS increases rapidly after three years, making the desludging process more difficult due to bottom sludge accumulation, which is in accordance with a study in Maharashtra, India.[11] Thus, it is recommended that the FS be emptied from the OSS system at a regular frequency of three years for safe FSM. This practice facilitates easy cleaning and minimizes the pollutant load, including TS and COD, for subsequent treatment.

6.2. Type of OSS containment

Only two OSS systems were identified in the study area: the septic tank and the single-pit latrine. Septic tanks have two chambers; anaerobic digestion occurs in the first chamber, and FS settles and accumulates in the second chamber. The two-chamber treatment process in septic tanks typically results in lower TS and COD levels than single-pit latrines. In unlined single-pit latrines, water content, urine, and greywater leach through soil and thicker FS, increasing COD and TS and making desludging difficult. Thus, adopting the twin toilet system is recommended for safe and effective FSM. A twin pit toilet consists of two pits, with the first pit serving as the initial receptacle for excreta. Once the first pit reaches capacity, the second pit becomes available for excreta storage. This will ensure better decomposition of FS for converting into manure and reduce the load for anaerobic digestion compared to a single pit latrine.

6.3. Water input to OSS

OSS containment generally stores excreta and blackwater (anal cleansing water + urine + toilet flush water), and may or may not include greywater. In this study area, most residential OSS has only FS and blackwater, whereas commercial buildings like hotels include greywater. Containment with a greywater input shows reduced TS and COD than OSS containment without greywater because of the dilution effect of low-solid greywater. Even though polluting parameters are lower, the larger volume creates more handling challenges. Handling larger volumes is practically difficult regarding transportation, treatment, and disposal. Dewatering of FS becomes complex and time-consuming for liquid FS and may require additional treatment for separation. Thus, it is suggested to separate the greywater line from OSS, which can be linked with the public sewer line.

6.4. Addition of water during emptying

During the sampling campaign, in some cases, it was observed that water was added during emptying events. Water addition during emptying also plays an important role in FS characteristics. If thick and concentrated solid FS accumulates in the bottom of the OSS, it would be difficult to pump it for the vacuum truck. Thus, to make FS thin and loose, water is added to OSS containment during emptying, making FS dilute and easily pumpable. Due to the dilution effect, FS collected from OSS, where water is added, possesses a lower concentration of TS despite the unknown quantity of water added.

6.5. Other factors

It was anticipated that the number of households in the house or building would influence the characteristics of the FS, but no significant impact on its characteristics was observed. This is in accordance with the findings in the study of Sircilla, India,[49] which observed no significant difference in the FS parameters with the number of OSS unit users. The dimensions of the OSS system exhibit a minor influence on characterization, primarily through variations in retention time. The larger the size, the larger the retention time, which allows more time for FS to settle and microbial breakdown. FS with more residence time (age) shows reduced biodegrading capacity (decrease in the BOD/COD ratio) due to mineralization followed by microbial decomposition. This case study highlights that a single-chamber septic tank is unsuitable for heavy FS loads due to its lack of separation, leading to the high concentration of COD and TS. Thus, a two-chamber septic tank must be preferred over a single one.

6.6. Socio-economic aspects

Although treated FS compost contains vital nutrients, treated FS leachate is suitable for domestic uses, and there are many barriers to utilizing those resources. The study in Bhubaneshwar, India[50] has shown that fear of infection, bad odour, and socio-cultural/religious beliefs are the key factors influencing the negative perceptions of urban households practicing kitchen gardening. Another socio-economic barrier in FSM is the unscientific application of untreated FS in agricultural lands in Indian villages, which leads to the accumulation of faecal coliforms in the food chain.[51] This necessitates the FS treatment, which requires a characterization study of FS. Another study in Vellore,[52] India has revealed that anxiety about getting mocked by others is a problem in using FS fertilizers by farmers. Also, people's willingness to buy crops and vegetables grown using FS fertilizers is very low. All this shows that general awareness of FSM is required among the Indian people. Another socioeconomic barrier to the failure of FSM models is the inhumane handling of FS in hands. Manual OSS emptying in India is based on the caste system, which is practiced by lower socio-economic classes.[53] In this study, the authors also observed that OSS cleaners handled FS with naked hands without any protection. This will lead to widespread infection in the community, nullifying the efforts made for safe FSM. Another study from Karnataka, India[54] found that in rural India, caste hierarchies and customs continue to influence the waste economy; however, policies that support sustainable "business" models for safe reuse fail to recognize this. Caste practices in the waste economy should be openly acknowledged in current efforts to formalize the reuse sector; otherwise, the scale and extent of the caste-based informal sector may continue, which leads to the failure of the FSM resource recovery model.

6.7. Suggestions specific to the study area

The case study reveals that 100% of the FS generated by the town is unsafely managed since it is discharged in open lands without treatment. This is not only the case in Pilani; most tier III towns in India face the same problem. This is mainly due to the lack of awareness among local-level stakeholders, *i.e.*, people, local municipalities, and OSS cleaners. Due to household ignorance about cleaning and emptying the OSS, the FS becomes more challenging to treat (increase in COD and total solids). In this study, it is observed that the COD value increases as the age increases. Thus, awareness should be created among local households in Pilani to clean the OSS at regular intervals of 3 years. Similarly, it is observed that OSS cleaners do not follow any precautionary and safety measures while cleaning the septic tank, which may lead to the community's spread of diseases; this implies that OSS cleaners of Pilani require a workshop to learn about safety measures while cleaning OSS.

Because of low construction costs, households opt for single-pit latrines, which produce FS with more COD and TS than septic tanks. The maximum COD of FS generated from a single pit is 160 000 mg l^{-1}, while the maximum COD of FS generated from a septic tank is 128 000 mg l^{-1}. Also, it is observed that the FS of single pits, which were cleaned in one year, exhibits more COD and TS than the FS of septic tanks, which were cleaned in five years, mainly due to the leaching of blackwater. It is suggested that people should go for septic tanks or twin-pit latrines, which produce comparatively lower COD and TS than single-pit latrines. In 3 cases, it was found that a single chamber septic tank was used instead of a two-chamber septic tank; due to shock loading of FS and the absence of a soak pit, the breakdown of organic matter in FS will be slow, producing more COD, so it is recommended that single chamber septic tanks should be avoided, instead double chamber septic tanks should be used. In commercial complexes, it was found that kitchen wash water (greywater) dilutes the COD, as observed in FS with greywater, and produces less COD than FS without greywater. Still, it was noted during cleaning that one vacuum truck was insufficient to empty the OSS with greywater due to the larger volume, which will create handling problems and increase the load to treatment. Thus, commercial shops in Pilani are suggested to separate the greywater from OSS and link it with the public sewer.

6.8. Challenges associated with recommendations

While interacting with households of Pilani, it is clear that they lack knowledge about FSM. It is observed that households empty the OSS only when it is full, so to make them clean their OSS regularly, awareness should be made about safe and sustainable FSM. FSM stakeholder roles and responsibilities are unclear at the local stage, making FSM unsuccessful. The emptied OSS contents are dumped into the open field, which causes more groundwater, surface water, and land pollution. Thus even though when the pits and septic tanks are emptied regularly, the FS from the OSS container will be discharged without treatment. In hotels and complexes, the greywater sewer line is attached to OSS for easy maintenance; separating the greywater line from OSS and connecting with public sewers requires an initial cost investment from property owners. Hotels and complexes produce a large amount of greywater daily because of the moving population; linking the greywater line from hotels to public sewers creates a shock loading and more pollution load. A lack of awareness was observed among all stakeholders, such as municipal authorities, OSS cleaners, and households, making FSM success difficult. Construction of twin-pit latrines instead of single-pit latrines requires land and an initial investment from households.

6.9. Role of faecal sludge management in achieving SDG6

FSM significantly contributes to achieving SGD6 goals by addressing several key targets within the goal. SDG6 aims to ensure the availability and sustainable management of water and sanitation for all. FSM ensures safe and sustainable management of on-site sanitation facilities, including single pits and septic tanks, which are predominantly found in Pilani and other Indian towns. FSM ensures efficient treatment of FS and sustainable resource recovery from FS. This will help address the inequalities in access to sanitation, achieving target 6.2. Resource recovery from FS, followed by treatment of FS, produces valuable resources such as compost from the drying process, and treated leachate can be used for domestic water requirements, achieving target 6.4 of increasing water use efficiency and sustainable water management. Localized FSM involves the participation of local-level key stakeholders such as households, OSS cleaners, and municipality staff in improving sanitation management, achieving target 6. b. Direct disposal of FS into water bodies affects the water ecosystem and increases the pollution load of rivers and lakes. Also, disposal of untreated FS into open lands leads to leaching and contaminates the groundwater ecosystem. Robust FSM involving efficient treatment of FS removes the organic pollution load from FS, making FS fit for disposal and resource recovery. This will help achieve target 6.6, protecting and restoring the water-related ecosystem, and target 6.3, *i.e.*, improving water quality. Also, protecting water resources ensures access to safe drinking water for all, achieving 6.1. A well-structured FSM model can expand international cooperation and capacity building to support sanitation-related activities and programs, achieving 6. a. Thus, well-developed FSM can significantly contribute to the nation's health and well-being by achieving the targets of SDG6. The contribution of FSM to SDG6 is shown in Fig. 16.

7. Limitations of the study

The case study emphasized various factors influencing FS characterization. However, due to social reasons, it didn't address how FS characteristics change according to people's lifestyles, particularly their food habits and income levels. Due to inaccessibility, the characterization of leachate from FS percolating through soil in an unlined pit was hindered. This leachate characterization would provide insights into its effect on groundwater quality. The study did not consider the influence of toilet cleansing agents on the characterization of FS. The planned collection of FS samples from public toilets was hindered by challenges related to inaccessibility and social constraints, leading to the unavailability of the intended samples. FS sampling from public toilets will provide a comparative analysis between public toilets and other household sources.

8. Conclusion

Faecal sludge management contributes significantly to the country's development and well-being, ensuring public health and a healthier population. FS treatment is an important aspect of FSM as it minimizes the negative impact of FS on the environment and helps resource recovery. The present study characterized FS at the local level for parameters like TS, COD, TN, and faecal coliforms, which range from 3430 to 95 393.33 mg l^{-1}, 4406 to 160 000 mg l^{-1}, 81.7 to 709.2 mg l^{-1}, and 10^3 to 10^9 CFU ml^{-1}, respectively. The age of FS, the type of containment, water added during emptying, and water

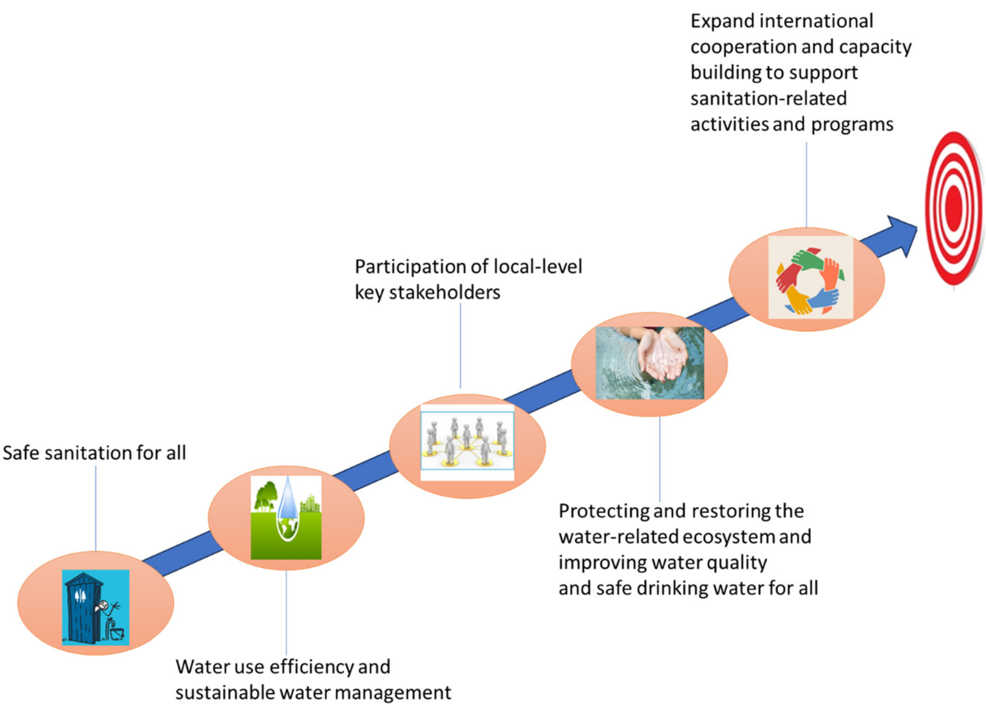


Fig. 16 Contribution of FSM to SDG6: clean water and sanitation.

input (blackwater and greywater) to OSS significantly impact FS characteristics. The age of FS causes mineralization and tends to increase COD and TS. Pit latrines produce thicker FS because of the leaching of water content, resulting in thicker FS, *i.e.*, higher TS concentration than septic tanks. The insights into FS characteristics and analysis discussed in this case study can assist FSM stakeholders in designing effective FS treatment plants in Indian towns or towns with similar contexts.

Disclosures and declarations

Ethics approval and consent to participate

All authors of the manuscript certify that this manuscript fully complies with the ethical standards of this journal and that there is no conflict of interest among the authors to publish the manuscript. They are in full agreement with this publication.

Availability of data and material

All required data supporting the findings are available in the manuscript. If the readers require any additional data, the same will be shared electronically by the authors whenever required.

Disclosure statement

The authors declare that there is no potential competing interest and the authors do not have any financial and/or business interests.

Data availability

The authors verify that the manuscript contains all relevant data. However, if readers require any further data related to this study, the same shall be made available on reasonable request.

Author contributions

Both authors have contributed, as given below, with respect to conceptualization, methodology development, data collection, investigation and modeling, original draft preparation, writing, and editing. The authors certify that there is no conflict of interest. Harishvar Jothinathan: sampling, conceptualization, methodology, investigation, data collection, interpretation, analysis, original draft preparation, writing, and editing. Ajit Pratap Singh: conceptualization, methodology, data collection, interpretation, investigation and analysis, validation, visualization, writing – original draft, review and editing, supervision, correspondence.

Conflicts of interest

The authors declare that no personal relationships or known competing financial interests could have influenced the work reported in this manuscript.

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