



SLUDGE DRYING

TECHNOLOGY AND ECONOMICS





SLUDGE DRYING

TECHNOLOGY AND ECONOMICS

Authors: Jyoti Parsad Dadhich and Umra Anees
Research support and guidance: Sumita Singhal
Reviewer: Rajarshi Banerjee
Editor: Rituparna Sengupta
Cover and design: Ajit Bajaj
Graphics: Vineet Tripathi
Layouts: Kirpal Singh and Surender Singh
Production: Rakesh Shrivastava and Gundhar Das

Acknowledgement:

Uttar Pradesh Jal Nigam
Directorate of Town Panchayats, Tamil Nadu
Jhansi Nagar Nigam
Odisha Water Supply and Sewerage Board
Nagar Palika Lalsot
Periyanaickenpalayam Town Panchayat
Karunguzhi Town Panchayat
Divija Construction Pvt Ltd, Jaipur
Inch Enviro Technologies Private Limited
Indian Institute for Human Settlements (IIHS)
Purna Pro Enviro Engineers Pvt Ltd
CDD Society, Bengaluru
Tide Technocrats Pvt Ltd
Keystone Foundation



© 2025 Centre for Science and Environment

Material from this publication can be used, but with acknowledgment.

Citation: Jyoti Parsad Dadhich and Umra Anees 2025, *Sludge Drying Technology and Economics*, Centre for Science and Environment, New Delhi

Published by

Centre for Science and Environment

41, Tughlakabad Institutional Area

New Delhi 110 062

Phone: 91-11-40616000, Fax: 91-11-29955879

E-mail: sww-aeti@cseindia.org, Website: www.cseindia.org

CONTENTS

1. INTRODUCTION	9
1.1 Sludge Drying: What and Why?	9
1.2 Aim	10
1.3 Objective	10
1.4 Scope	11
1.5 Methodology	12
2. NATURE-BASED SLUDGE DRYING TECHNOLOGIES	13
2.1 Unplanted Drying Beds (UDBs)	13
Case studies	16
2.1.1 Unplanted drying bed-based Faecal Sludge Treatment Plant at Lalsot, Rajasthan	16
2.1.2 Unplanted drying bed-based Faecal Sludge Treatment Plant at Bhubaneswar, Odisha	20
2.2 Planted Drying Beds (PDBs)	23
Case study	26
2.2.1 Planted drying beds-based 18 KLD FSTP at Jhansi, Uttar Pradesh	26
3. ELECTRO-MECHANICAL SLUDGE DRYING TECHNOLOGIES	30
3.1 Belt dryer	30
Case studies	34
3.1.1 Belt dryer-based Faecal Sludge Treatment Plant at Warangal, Telengana	34
3.2 Greenhouse Solar Dryers (GHSD)	37
Case studies	40
3.2.1 GHSD-based Faecal Sludge Treatment Plant at Karunguzhi, Tamil Nadu	40
3.2.2 GHSD-based Faecal Sludge Treatment Plant at Devanahalli, Karnataka	44
3.3 Screw press and solar/sun drying or GHSD	49
Case studies	52
3.3.1 Screw press and GHSD-based FSTP at Periyanaickenpalayam (PNP), Tamil Nadu	52
3.3.2 Screw press and drying bed based Faecal Sludge Treatment Plant at Loni, Uttar Pradesh	56

4. ALTERNATIVE SLUDGE DRYING TECHNOLOGIES	61
4.1 Paddle dryer	61
4.2 Geotube dewatering system	64
5. FINDINGS AND RECOMMENDATIONS	67
6. ANNEXURES	74
6.1 Questionnaire for primary data collection	74
6.2 Compost quality standards as per Solid Waste Management Rules, 2016; Fertilizer Control Order, 2009; and Fertilizer Control Order, 2013	75
References	76

LIST OF FIGURES

Figure 1. Categorization of water available in sludge	10
Figure 2. Steps involved in conducting research study	12
Figure 3. Schematic diagram of unplanted drying bed	13
Figure 4. Process flow diagram of the Lalsot FSTP	17
Figure 5: Process flow diagram of the Bhubaneswar FSTP	21
Figure 6: Schematic of a planted drying bed	23
Figure 7. Operational cycle of PDB	24
Figure 8. Process flow diagram of the Jhansi FSTP	27
Figure 9: Schematic diagram of belt dryer	31
Figure 10: Process flow diagram of the Warangal FSTP	35
Figure 11: Process flow diagram of the Karunguzhi FSTP	41
Figure 12: Process flow diagram of the Devanahalli FSTP	46
Figure 13: Schematic diagram of screw press	50
Figure 14. Process flow diagram of the Periyanaickenpalayam (PNP) FSTP	53
Figure 15. Process flow diagram of the Loni FSTP	57
Figure 16. Schematic diagram of paddle dryer	61

1. INTRODUCTION

In India, several states have successfully implemented faecal sludge treatment plants (FSTPs) and co-treatment plants to manage faecal sludge. However, despite this progress, one of the major challenges that remains is managing the by-products of these plants, especially biosolids.

The drying process is a key step in preparing the sludge for safe and beneficial reuse. Properly dried sludge ensures the elimination of pathogens, making it safe for storage and further use. However, if the sludge remains moist, pathogens can multiply during storage, leading to unhygienic conditions and posing public health risks.

At present, many cities in India face challenges in selecting suitable sludge drying technologies due to a lack of sufficient knowledge and technical guidance. Cities need a comprehensive guidance that outlines different sludge drying technologies, their efficiency, and the economics of each technology. Such a guidance note will help the authorities make informed decisions about selecting technology that is most suited for their specific needs.

This study aims to identify the various sludge drying technologies currently employed across India. It will also provide insights into both the capital expenditure (CapEx) and operational expenditure (OpEx) involved with each technology and operations and maintenance related challenges cities face in implementing these technologies. By understanding these costs, cities can better plan their budgets and choose solutions that are both economically and operationally feasible. Furthermore, the study will explore the potential for reusing dried sludge, considering factors such as performance quality, pathogen removal, and cost-efficiency.

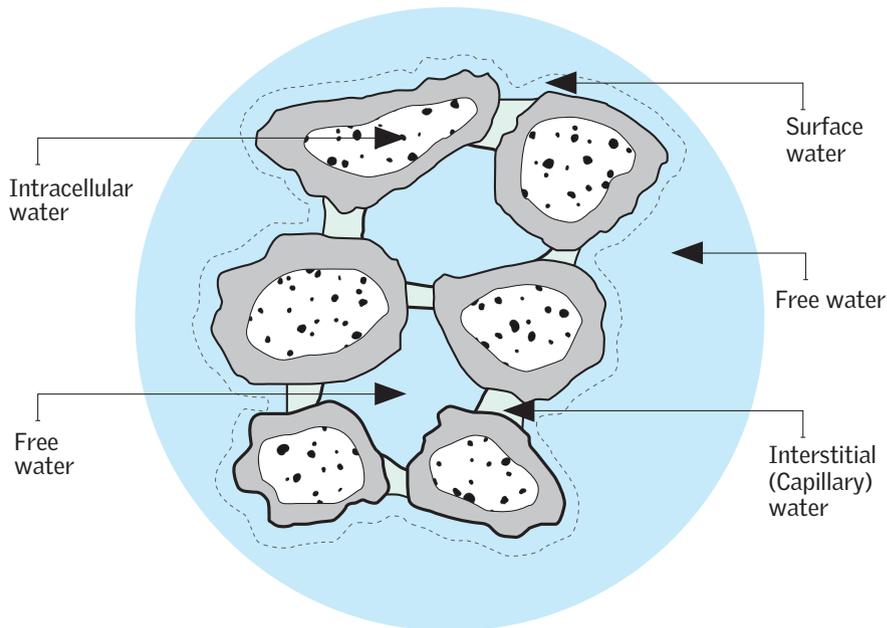
1.1 SLUDGE DRYING: WHAT AND WHY?

Faecal sludge is primarily composed of water¹. The water in sludge can be classified into two main forms: free water and bound water. Alternatively, this classification can be further broken down into free water, intracellular water, interstitial (capillary) water, and surface water². Figure 1 illustrates these different categories of water in sludge.

Free water is the moisture that is loosely held within the sludge and can be easily removed using methods like filtration, centrifugation, or dewatering. This type of water makes up a large portion of the total water content and is the primary target for reduction during treatment to reduce the volume of the sludge. In contrast, bound water is tightly held within the sludge's cellular and organic structures through chemical or physical bonds. Removing bound water is more challenging and typically requires energy-intensive processes such as thermal drying or advanced stabilization. Drying of sludge to remove bound water offers several benefits:

- Deactivation of pathogens: Drying helps to eliminate harmful microorganisms.
- Reduction of mass and volume: Less waste means lower transport and storage costs.

Figure 1: Categorization of water available in sludge



Source: www.researchgate.net/figure/Different-categories-of-water-in-sludge_fig2_362061751

- Increase in calorific value and nutrient value: Dried sludge has a higher energy and nutrient content, making it more valuable as a biofuel³ and to be reused in the agriculture. However, if the sludge is overheated and undergoes thermal degradation, the nutrient value of the final product may be compromised.⁴

Faecal sludge is highly viscous, but its viscosity decreases when shear forces are applied. The sludge reaches peak stickiness at about 50 per cent moisture content, which is an important factor to consider when designing drying units. Drying the sludge to around 30 per cent moisture content is ideal because most pathogens cannot survive at this dryness level. Additionally, removing more moisture beyond this point would require excessive energy due to the strong binding of the remaining water⁵.

Controlling the temperature during drying is important, as it significantly affects both moisture removal and pathogen elimination. Higher temperatures can speed up drying and kill pathogens more effectively, but temperatures exceeding around 50°C can damage the solid structure of the sludge.

1.2 AIM

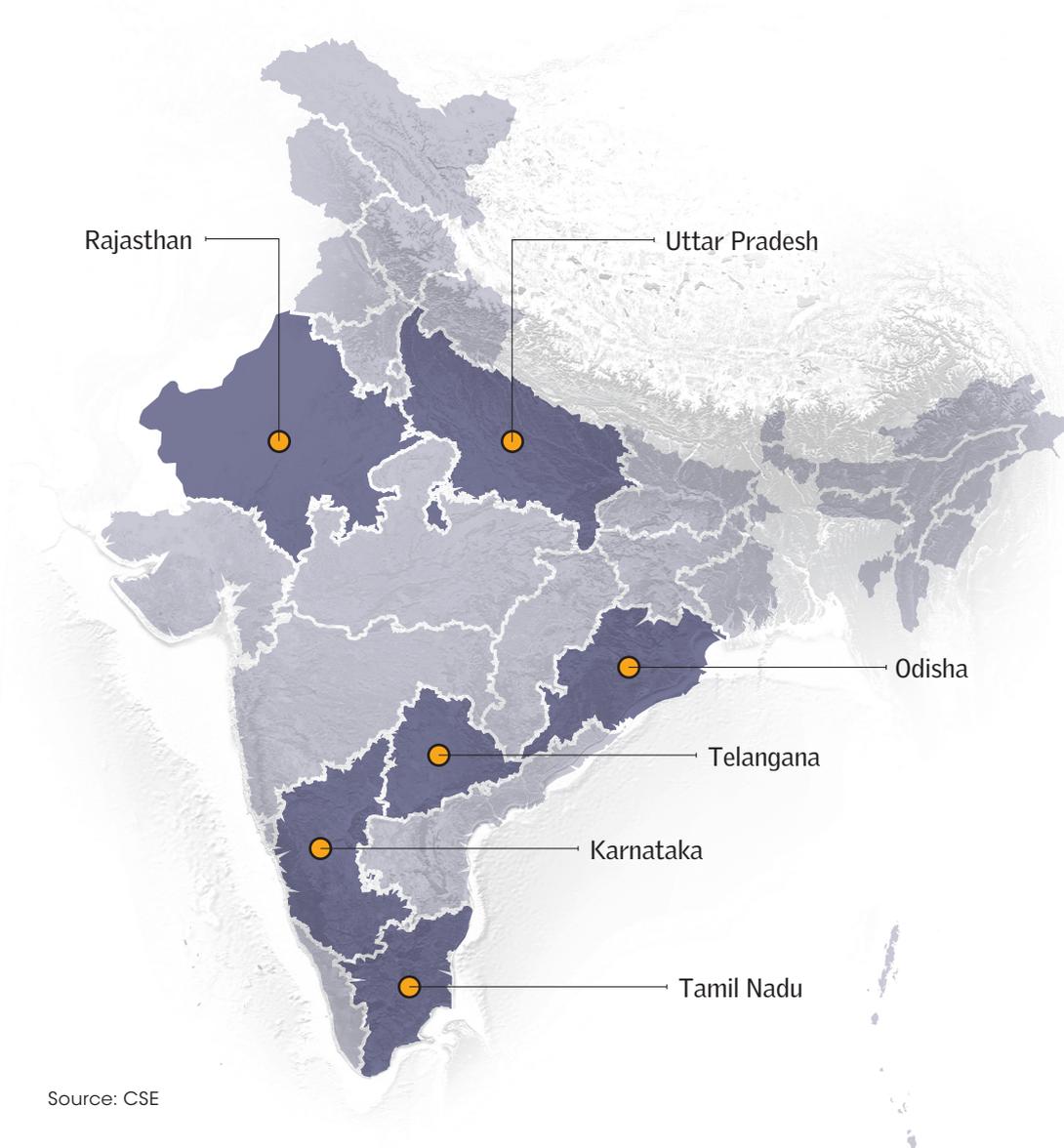
The research aims to evaluate the effectiveness and cost-efficiency of various sludge drying technologies being used in India for drying faecal sludge in diverse geo climatic conditions.

1.3 OBJECTIVE

- Identifying faecal sludge drying technologies predominantly being used in India
- Assess current issues and challenges with sludge drying

- Understanding effectiveness and economic feasibility of different sludge drying technologies
- Identifying potential reuse of dried sludge produced from different technologies for agriculture

Map 1: Map representing states covered for the study



1.4 SCOPE

The research primarily examines faecal sludge drying technologies utilized in various regions of India, assessing their performance, efficiency, and economic viability. These drying technologies are typically implemented following dewatering processes, and in

certain instances, they may be integrated or extended as part of the dewatering operation. Both of the types of drying solutions—natural and electro-mechanical—are considered.

1.5 METHODOLOGY

This study assesses the sludge drying technologies employed in various FSTPs located in different Indian states, each representing a distinct geo-climatic region. The study has been conducted based on secondary and primary research. We have selected one case study each in Rajasthan, Odisha, Karnataka and Telangana while two in Uttar Pradesh and Tamil Nadu.

The selection of these towns was the result of thorough secondary research on multiple FSTPs employing diverse sludge drying technologies. The research team engaged with technology providers, site operators, and coordinators, conducting key informant interviews to gather detailed information. After cross-verifying the data from various secondary sources, the team selected these eight sites for further assessment. Another key criterion for selecting these sites was the availability of data related to dried sludge. This study also references the 2023 research conducted by the Centre for Science and Environment (CSE) on the evaluation of FSTPs across India⁶, which provided valuable insights for this assessment.

To collect the primary data from sites, research team visited all the selected places and collected in-depth information from the ground. The data collected from different sources has been cross verified with different stakeholders involved.

Figure 2: Steps involved in conducting the research study



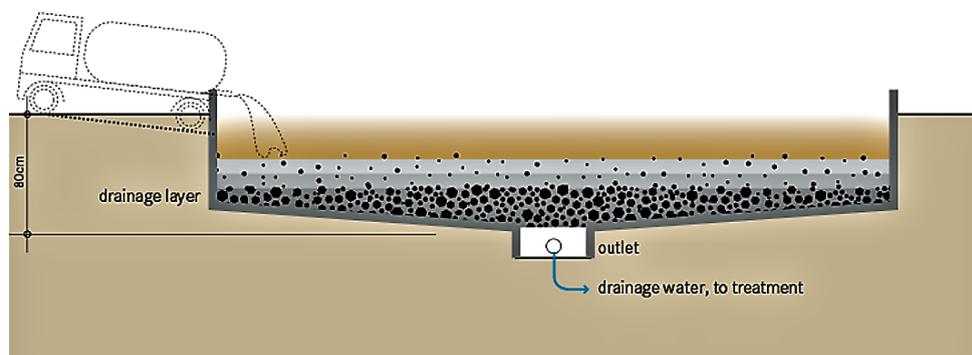
2. NATURE-BASED SLUDGE DRYING TECHNOLOGIES

Nature-based sludge drying technologies utilize natural processes to treat and manage sludge, often relying on natural biological, physical, and chemical processes to treat sludge effectively. Also, such technologies don't require any energy input or additives and work entirely on the basis of gravity. This section comprises two technologies— Unplanted Drying Beds (UDBs) and Planted Drying beds (PDBs).

2.1 UNPLANTED DRYING BEDS (UDBs)

Unplanted drying beds are shallow filters filled with sand and gravel with an under-drain at the bottom to collect leachate. Sludge is discharged onto the surface for dewatering. The drying process in a drying bed is based on drainage of liquid through the sand and gravel to the bottom of the bed, and evaporation of water from the surface of the sludge to the air. The design as well as the operation of the drying bed is fairly straightforward, provided the sludge loading rate is well selected and the inlet points for depositing the sludge onto the bed are properly designed. Depending on the faecal sludge (FS) characteristics, a variable fraction of the sludge volume drains off as a liquid (or leachate), which needs to be collected and treated prior to discharge⁷. After reaching the desired dryness, the sludge is removed from the bed manually or mechanically. Further processing for stabilization and pathogen reduction may be required depending on the intended end-use option. When considering the installation of a drying bed, the ease of operation and low cost needs to be considered against the relatively large footprint and odour potential.

Figure 3: Schematic diagram of unplanted drying bed



Source: Septage Management - A Practitioner's Guide by CSE

Treatment principle

The drying process is based on two principles. The first principle is percolation of the leachate through sand and gravel. This process is significant with sludge that contains large volumes of free water, and is relatively fast, ranging from hours to days. The second process, evaporation, removes the bound water fraction and this process typically takes place over a period of days to weeks⁸. Reported removal of 50 to 80 per cent by volume due to drainage, and 20 to 50 per cent due to evaporation in drying beds with FS.

Factors affecting drying and performance

While designing a drying bed, several factors must be considered, as they can vary depending on the location. These factors can be grouped into two main categories: climate conditions and the type of sludge being treated. Additionally, key parameters like the sludge loading rate, the thickness of the sludge layer, and the total surface area of the bed also play a crucial role in the effectiveness of the sludge drying process.⁹

1. Climate factors

The following climatic factors affect the performance efficiency of the unplanted drying beds:

- **Humidity:** High humidity hinders the evaporation process, slowing down the drying rate.
- **Temperature:** Higher temperatures, also in combination with relatively low humidity and high wind, will enhance the total amount of water removed via evaporation.
- **Rainfall:** In areas with frequent and prolonged periods of intense rainfall, a drying bed may not be practical. To manage during the rainy season, the beds can either be left unused or covered with a roof. Rainfall may rewet the sludge, the intensity of which depends on the phase of drying.

2. Sludge loading rate

The sludge loading rate (SLR) is measured in kilograms of Total Solids (TS) per square meter per year (kg TS/m²/year). It represents the amount of solid material dried on one square meter of the drying bed over the course of a year. According to Pescod (1971), providing a precise number that links the total sludge volume to the SLR, bed surface area, and sludge depth is challenging due to significant variations in local conditions. However, a typical range for SLRs in tropical climates falls between 100 and 200 kg TS/m²/year, with 100 being for less favorable conditions and 200 for optimal conditions.

3. Thickness of the sludge layer

Sludge is typically applied in a layer 20 to 30 cm deep, with 20 cm being the preferred depth. While it might seem advantageous to apply a thicker layer to increase the amount of sludge treated in one bed, this actually leads to longer drying times and reduces the number of times the bed can be used in a year. Pescod (1971) found that increasing the sludge layer by just 10 cm can extend the drying time by 50 to 100 per cent, even under the same weather conditions.

Innovations and adaptations in sludge drying beds

Drying beds could potentially be modified in order to increase drying rates and reduce sand loss. Aspects that have been investigated include the installation of piping systems, drying in greenhouses, the use of wedge wire, mixing and coagulants. These are discussed in the following sections.

A. Piping systems

This type of system uses solar heating to heat up sludge prior to applying it onto sludge drying bed in order to enhance the drying process. The study found that sludge treated on a standard bed dried from 96 per cent to 33 per cent moisture over a period of 18 days, but when dried on this modified bed using water heated to 70°C, the same result could be achieved after only 10 days of drying¹⁰. Such systems were used in Jordan.

B. Greenhouse Solar Dryer

It is experimented with covering beds with glass panels in order to enhance the drying of sludge. A reduction in the drying time of 25–35 per cent was reported¹¹. It is important to note that any system involving covering of the beds needs to be well ventilated, either actively or passively, in order to facilitate the transport of the water saturated air away from the bed. Drying in greenhouses is also a technology actively applied for sludge, often combined with an active mixing device and blowers to enhance the drying process (Huber Technology, 2013). These types of system are used in various FSTPs in India like Devanahalli, Karunguzhi, Periyanaickenpalayam (PNP), Dhenkenal etc.

C. Wedge wire system and hollow blocks as surface

The use of stainless-steel wedge wire and hollow blocks as a surface enhances sludge drying and drainage. It also helps in reducing the amount of sand that partitions with the sludge upon removal¹². Such systems have been used in many FSTPs in India such as in Lalsot, Phulera, Devanahalli etc.

D. Additives to the sludge to enhance drying

As per Pescod (1971) report¹³, adding alum (potassium aluminium sulphate) can increase the rate of drying of sludge. This study found that conditioning with alum should only be carried out during the wet season, as there was no significant advantage in conditioning the sludge during the dry season.

CASE STUDIES

2.1.1 Unplanted drying bed-based Faecal Sludge Treatment Plant at Lalsot, Rajasthan

The 20 KLD capacity Faecal Sludge Treatment Plant (FSTP) in Lalsot has been operational since November, 2019. This FSTP was built under the grant from Asian Development Bank and designed to serve urban municipal areas, which is divided into 25 wards, but currently it also receives sludge from nearby villages through cluster approach. The town has approximately 7,710 households, with a total population of around 45,319 people. The plant was implemented under Build Operate and Transfer (BOT) contract which was signed among Lalsot Nagar Palika, Rajasthan Urban Infrastructure Development Project (RUIDP) and the contractor (Divija Construction Pvt Ltd).



The FSTP in Lalsot operates based on natural processes that are known to be cost-effective, energy-efficient and chemical free treatment. The plant consists of a series of roofed unplanted drying beds with fiber sheets. The drying beds are used for dewatering FS as well as drying the dewatered sludge.



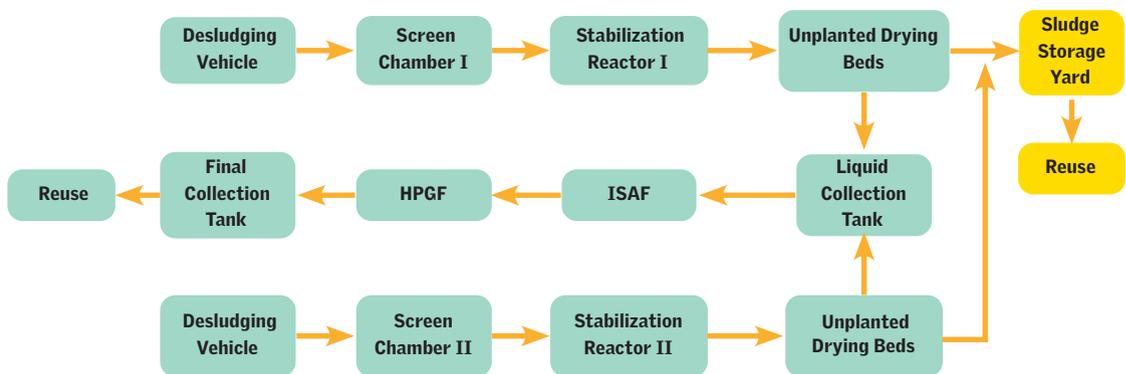
Unplanted drying beds with coverings at Lalsot FSTP

The treatment process consists of two parallel rows of screening chambers, stabilization reactors and eight unplanted drying beds in each row.

The faecal sludge is initially directed through two screening chambers to retain coarse materials and solid waste found in the septage. The liquid sludge is then conveyed to two stabilization reactors to remove the degradable organic substance and improve its dewatering

ability. The solids, collected as slurry at the bottom of the stabilization reactor, are pumped to the covered sludge drying beds through a pump located in the third chamber. The sludge undergoes solid-liquid separation and also drying on the sludge drying bed. The sludge drying beds are covered with fiber sheet to increase the drying. The retention time of the sludge in stabilization reactor and unplanted drying bed was observed to be 10 and 14 days respectively. The dried sludge from the drying beds is removed periodically and transferred to the sludge storage yard located within the premises and the rest of the part which is the liquid effluent is conveyed to the collection tank after which it is pumped to the Integrated Settler and Anaerobic Filter (ISAF). The effluent is then treated in two stages (primary and secondary stage) in Decentralized Waste Water Treatment System (DEWATs). The treated water is collected into a final collection tank from which it is used for the landscaping within the FSTP premises.

Figure 4: Process flow diagram of the Lalsot FSTP



*HPGF- Horizontal Planted Gravel Filter

Climatic conditions

Lalsot has subtropical steppe climate and falls under the Semi-Arid Eastern Plains Agro-Climatic Zone. May is the least humid month in Lalsot, with an average relative humidity of 16 per cent. The summer seasons are long, starting in March and ending in June. Temperatures range from a minimum of 3°C in winter and can rise up to a maximum of 50°C in summers. Lalsot experiences rainfall primarily due to the southwest monsoon, occurring between July and September. Annual average rainfall is 552 mm. Main months of rainfall in Lalsot are July, August and September during which it receives about 95 per cent of rainfall.

Being a natural treatment process, the drying of sludge get affected by temperature variations, rainfall and humidity. However, the drying beds are covered with the polycarbonate sheet so the direct impact of rainfall on sludge has not been observed. Usually, the sludge drying period is 7–10 days in summer and 10–12 days in winter. But in rainy days, due to the high humidity and reduced sunlight, the sludge takes more time to dry, sometimes even more than 15–20 days.

Performance quality

The data presented in Table 1 is derived from two CSE reports published in 2023^{14,15,16}, highlighting the changes in concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was within acceptable limits, but it fell below the recommended range after drying. As a result of natural drying, the moisture content significantly decreased from 95.2 per cent to 37.7 per cent, which does not comply to the acceptable limit specified by Fertilizer Control Order (FCO, 2009). The carbon-to-nitrogen (C:N) ratio seems to fall outside the range recommended by the FCO. However, microbial analysis indicates that pathogen levels are within the limits, showing that sunlight penetration during drying was sufficient to effectively kill pathogens. The data shows approximately 99.01 per cent pathogen reduction due to natural drying.

Table 1: Characteristics of raw FS and dried sludge for FSTP at Lalsot

Parameters	Raw FS	Dried sludge	FCO/WHO/USEPA standards
pH	7.2	5.9	6.5–7.5
TS %	4.8	62.3	-
Moisture %	95.2	37.7	<10%
C:N ratio	-	9:1	20:1–30:1
Faecal coliform (MPN/g)	30182.50	296	1000

Source: CSE

Energy consumption

The FSTP at Lalsot uses minimal energy as it relies entirely on natural processes. Only two pumps are being used for lifting FS from stabilization reactors to unplanted drying beds. The total cost of energy consumption is around INR 4,000 per month, while energy consumption related to pumps come around INR 3,000 per month.

Economics (CapEx, OpEx, Ease of O&M)

CapEx includes expenses incurred for the treatment plant, ancillary infrastructure and procurement of desludging vehicle that comes around INR 39.7 million.

OpEx includes expenses incurred for the regular operations and maintenance of the equipment as well as salaries. Currently, the contractor (Divija Construction Pvt Ltd) who has built the FSTP is looking after O&M.

Nature-based treatment system requires less skilled workers, it can be operated by a person with basic understanding of regular O&M requirements. Such systems don't require any specific input for its operations. The sludge removal from beds requires manpower on periodic basis.

Table 2: CapEx and OpEx of the plant and drying process for FSTP at Lalsot

Parameters	Cost in INR
CapEx of the plant	397 Lakhs
CapEx incurred for drying process	52.64 Lakhs
CapEx incurred for drying process/ KLD	2.63 Lakhs
OpEx of the plant	9.6 Lakhs/year
OpEx incurred for drying process	1.2 lakhs/ year
OpEx incurred for drying process/ KLD	0.06 Lakhs/ year

Source: CSE

Reuse of by-products

Currently, the treated water from the FSTP is being reused for landscaping within the premises and the treated bio-solid is being stored at a designated place. Only a small portion of treated bio-solids is being taken by the local farmers which further reuses it for soil conditioning purposes in their agricultural fields.

The villages surrounding Lalsot are agriculturally prosperous, presenting a strong potential for reusing treated bio-solids.



Bio-solids at FSTP Lalsot

2.1.2 Unplanted drying bed-based Faecal Sludge Treatment Plant at Bhubaneswar, Odisha

The 75 KLD capacity Faecal Sludge Treatment Plant in Basuaghai in the outskirts of Bhubaneswar was implemented under the AMRUT scheme and has been operational since 2017. A population of 2,20,000 has been covered by the project. The present capacity of 75 KLD is proposed to be expandable up to 150 KLD in future.



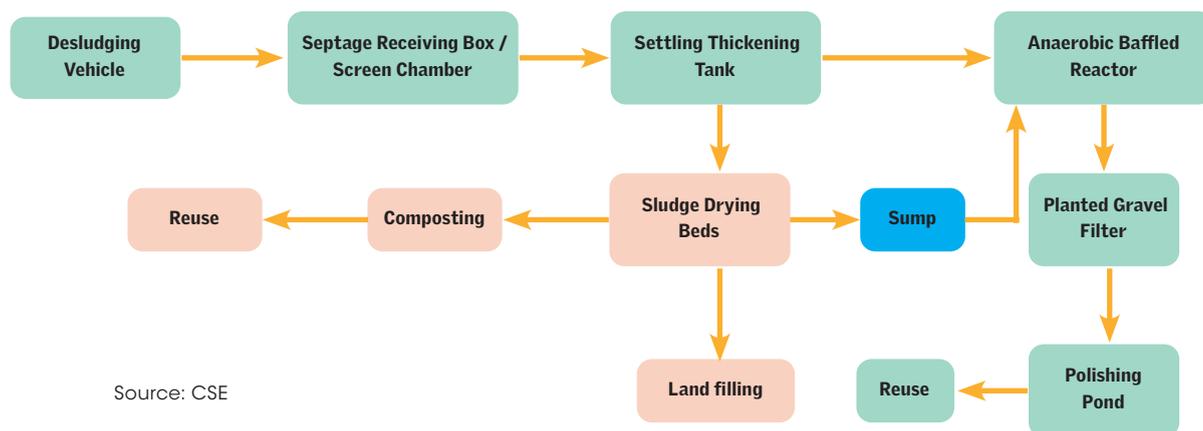
The FSTP covers an area of 2.47 acres out of which 1.3 acres have been utilized for landscaping and plantation. The area covered by eight sludge drying beds is 1,070 sq m.



Unplanted drying beds with sliding roof at Bhubaneswar FSTP

The plant involves a series of treatment steps to first separate the liquids from the solids, and then treat both the liquid and solid streams separately. Faecal sludge is emptied into a sludge receiving box, then it further goes into a screen chamber. After passing through the screens, the influent flows into the Settling-Thickening tanks to increase the solid content, facilitating easier dewatering. Thickened sludge is taken out of tanks after a period of 10 days and the supernatant goes into DEWATs for further treatment. The thickened sludge is pumped into sludge drying beds where they are kept until they are fully dried under direct sunlight. The drying beds are equipped with a sliding aluminum roof to prevent direct rainfall from falling onto the beds.

Figure 5: Process flow diagram of the Bhubaneswar FSTP



Source: CSE

Climatic conditions

Bhubaneswar has a tropical savanna climate with temperatures ranging from 11°C–44°C. July and August are the wettest months of the year with an average annual rainfall between 1,400–1,600mm. Being, a coastal town, the climate plays a very important role in sludge drying. Heavy rains cause floods inside the FSTP, sometimes flooding the drying beds. During cyclonic incidents, the sludge remains moist and becomes contaminated. Usually, the sludge drying period is 7–10 days in summer and 10–15 days in winter. On rainy days, the high humidity and reduced sunlight cause the sludge to take longer to dry, sometimes requiring more than 15–20 days.

Performance quality

The data presented in Table 3 is derived from two CSE reports published in 2023, highlighting the changes in concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was within acceptable limits, but it fell below the recommended range after drying. As a result of natural drying, the moisture content significantly decreased from 99.3 per cent to 6.4 per cent, which complies with the acceptable limit specified by the Fertilizer Control Order (FCO, 2009). The carbon-to-nitrogen (C:N) ratio appears to be outside the range suggested by the FCO. However, microbial analysis indicates that pathogen levels are within the limits, showing that sunlight penetration during drying was sufficient to effectively kill pathogens. The data shows approximately 99.99 per cent of pathogen reduction due to natural drying.

Table 3: Characteristics of raw FS and dried sludge for FSTP at Bhubaneswar

Parameters	Raw FS	Dried sludge	FCO/WHO/USEPA standards
pH	7.3	5.1	6.5–7.5
TS %	0.7	93.6	-
Moisture %	99.3	6.4	<10%
C:N ratio	-	8:1	20:1–30:1
Faecal coliform (MPN/g)	2,02,142.85	13	1,000

Source: CSE

Economics (CapEx, OpEx, Ease of O&M)

Total CapEx includes expenses incurred for the treatment plant, ancillary infrastructure and procurement of machineries. However, CapEx incurred for drying process includes cost of Settling thickening tank, eight sludge drying beds with cover and sludge storage yard.

OpEx includes expenses incurred for the regular operations and maintenance of the equipment, energy consumption as well as salaries. Currently, the plant is operated and maintained by a women’s self-help group (SHG) under the guidance of Bhubaneswar Municipal Corporation.

Table 4: CapEx and OpEx of the plant and drying process for FSTP at Bhubaneswar

Parameters	Cost in INR
CapEx of the plant	354 lakhs
CapEx incurred for drying process	120 lakhs
CapEx incurred for drying process/ KLD	1.6 lakh
OpEx of the plant	21.84 lakhs/year
OpEx incurred for drying process	9.6 lakhs/year
OpEx incurred for drying process/ KLD	0.13 lakhs/year

Source: CSE

The FSTP is managed by a team of four semi-skilled sanitation workers who have been trained in the basic operation and maintenance of the plant. Their regular task is removing and shifting dried sludge from the drying beds every 15 days. During the rainy season, they also adjust the sliding roof over the beds to protect them from rainwater.

Aside from these routine duties, the drying beds require occasional upkeep, such as replacing the filter media or fixing any wear and tear, which is typically done once a year or as needed. This ensures smooth and efficient operations of the plant.

Energy consumption

The FSTP primarily operates using natural methods that require minimal or negligible energy inputs, though some pumps need to be operated regularly. The plant consumes an average of 1,700 units energy per month from main energy source i.e. grid power supply, however the plant is also equipped with a 10 KW solar



Dried sludge stored at Bhubaneswar FSTP

system that generates green energy of approx. INR 12 lakhs annually. The solar power generated is used to offset the energy consumption of the pumps and other ancillary needs. As a result, the overall energy consumption of the plant is often minimal or even negligible.

Reuse of by-products

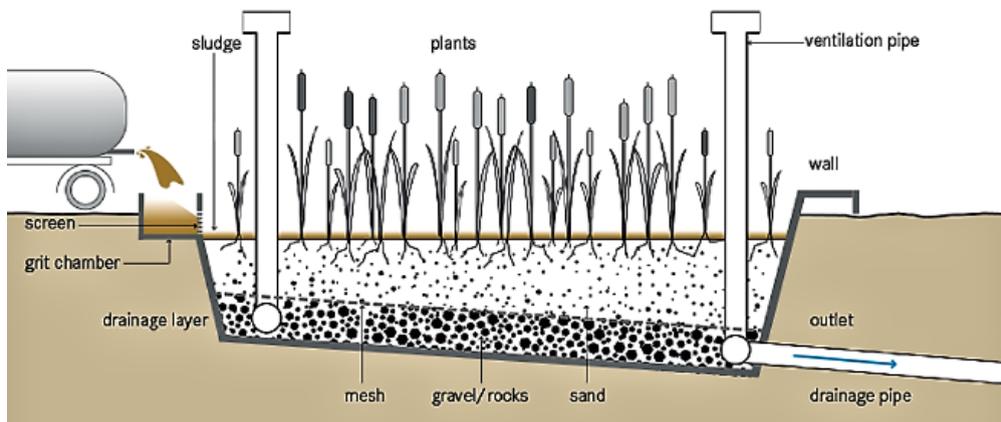
Currently, the facility generates approximately 2,800 kg of treated bio-solid each month from eight beds. However, only a small fraction, around one to two per cent is being repurposed by Water Corporation of Odisha (WATCO) and Bhubaneswar Municipal Corporation (BMC) for use in their nurseries and roadside plantation. The majority of the bio-solid remains either stored within the premises or used for landfilling purposes. Additionally, the treated water produced by the facility is being reused to maintain the landscaping within the plant premises, ensuring a more sustainable operation by reducing the need for external water sources.

2.2 PLANTED DRYING BEDS

Planted drying beds (PDBs), also sometimes referred to as planted dewatering beds, vertical-flow constructed wetlands and sludge drying reed beds, are beds of porous media (e.g. sand and gravel) that are planted with emergent macrophytes. PDBs are loaded with layers of sludge that are subsequently dewatered and stabilized through multiple physical and biological mechanisms.

A planted drying bed is similar to an unplanted drying bed, but has the added benefit of transpiration and enhanced sludge treatment due to the plants. It is a sealed shallow pond filled with several drainage layers and designed for the separation of the solid from the liquid fraction of (faecal) sludge from latrines, septic tanks, biogas reactors, trickling filters, etc. Sludge is dried naturally by a combination of percolation and evaporation. The key improvement of the planted bed over the unplanted bed is that the filters do not need to be desludged after each feeding/drying cycle. Fresh sludge can be directly applied onto the previous layer; the plants and their root systems maintain the porosity of the filter.¹⁷

Figure 6: Schematic of a planted drying bed



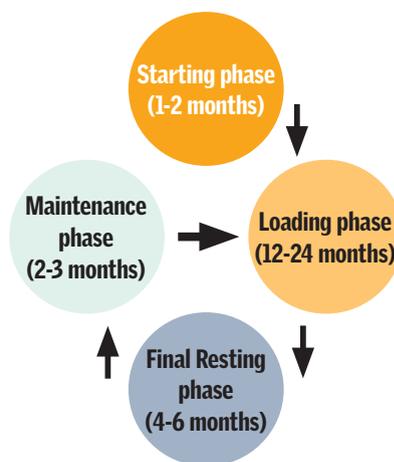
Source: Septage Management - a Practitioner's Guide by CSE

Solid loading rate for planted drying beds in tropical climates should be in the range of 180–250 kg TS/m²/year. With up to 15–20cm of faecal sludge per loading.

The minimum time between two successive loadings should be 6–8 days. The accumulated sludge from PDB needs to be removed during non-monsoon period and sun-dried so that it is free of moisture.¹⁸

The dried sludge from PDB can be directly applied to the soil as a conditioner with necessary precautions.

Figure 7: Operational cycle of PDB



**Assumptions for PDB phases are on the basis of observations from PDB pilot implementations.*

Source: CDD India

Factors affecting drying in planted drying beds

Drying beds, particularly planted drying beds are used for dewatering and stabilizing sludge. The drying process in these beds is influenced by a variety of factors that can be broadly categorized into environmental, design, and operational factors. Here’s a detailed look at these factors:

Environmental factors

- *Temperature:* Higher temperatures increase evaporation rates, leading to faster drying.
- *Humidity:* Lower humidity levels facilitate more effective drying due to a greater potential for evaporation.
- *Rainfall:* Excessive rainfall can saturate the bed, slowing down the drying process.
- *Wind speed:* Wind can enhance evaporation by removing the moisture-laden air from the surface of the sludge.
- *Seasonal variations:* Changes in weather patterns across seasons can significantly impact drying rates. For instance, winter conditions can slow down the drying process due to lower temperatures and reduced solar radiation.

Design factors

- *Type of vegetation:* The choice of plants affects the drying process. Plants with high evapotranspiration rates, such as certain reeds or grasses, can significantly enhance drying. Root structure also plays a role; deep-rooted plants can create channels in the sludge, improving aeration and drainage.
- *Bed construction:*
 - Bed depth: Shallower beds allow for faster drying but may require more frequent sludge applications.
 - Filter media: The type and arrangement of layers (e.g., gravel, sand) impact drainage and the capillary rise of water.
 - Slope and drainage: Proper sloping and drainage systems ensure that excess water is efficiently removed.
 - Bed area: Larger bed areas provide more surface exposure, facilitating better evaporation and drying.

Operational factors

- *Loading rate:* The amount of sludge applied per unit area affects drying time. High loading rates can lead to thicker sludge layers, slowing down the drying process.
- Frequency and timing of sludge application also play a role. More frequent applications can maintain a more consistent drying cycle.
- *Sludge characteristics:*
 - Solid content: Sludge with higher solid content dewateres more efficiently than sludge with lower solid content.
 - Composition: Organic and inorganic content, as well as the presence of fibrous material, can impact drying rates.
 - Particle size: Finer particles may settle more compactly, impeding drainage and slowing drying.
 - Maintenance: Regular maintenance of the bed, including cleaning and removal of dried sludge, ensures that the bed functions efficiently.
 - Managing plant health and ensuring that the vegetation is thriving is crucial for optimal evapotranspiration.

Additional considerations

- *Water table level:* A high-water table can negatively impact the drainage capacity of the drying bed.
- *Contaminants:* Presence of contaminants in the sludge can affect the health of plants and the overall efficiency of the drying process.
- *Hydraulic conductivity:* The permeability of the filter media and the sludge layer itself influences how quickly water is removed from the sludge.

By optimizing these factors, the efficiency and effectiveness of planted drying beds can be significantly improved, leading to better management of sludge and wastewater treatment processes.

Economics (CapEx, OpEx)

The capital and operational costs of planted drying beds (PDBs) can vary significantly depending on several factors, including the size of the facility, local labor and material costs, climate and specific design choices. For a 100 sq m planted drying bed the estimated total capital costs is approximately INR 1.74– 7.9 lakhs and the total operational costs (annually) will be approximately INR 0.37–0.8 lakh.

Pros

- This technology is effective at decreasing the sludge volume (down to 50 per cent) through decomposition and drying, which is especially important when the sludge needs to be transported elsewhere for end-use or disposal.
- Can handle high loading
- Better sludge treatment than in unplanted drying beds
- Easy to operate (no experts, but trained community required)
- Can be built and repaired with locally available materials
- Relatively low capital costs; low operating costs
- No electrical energy required

Cons

- Because of their area requirements, planted drying beds are most appropriate for small to medium cities with populations up to 100,000 people, but they can also be used in bigger cities.
- Drying beds are not adapted for regions with heavy rainfalls and frequent flooding or where the water table is high.
- Odours and flies may be noticeable
- Long storage times
- Labour-intensive removal
- Requires expert design and construction supervision
- Leachate requires further treatment

CASE STUDY

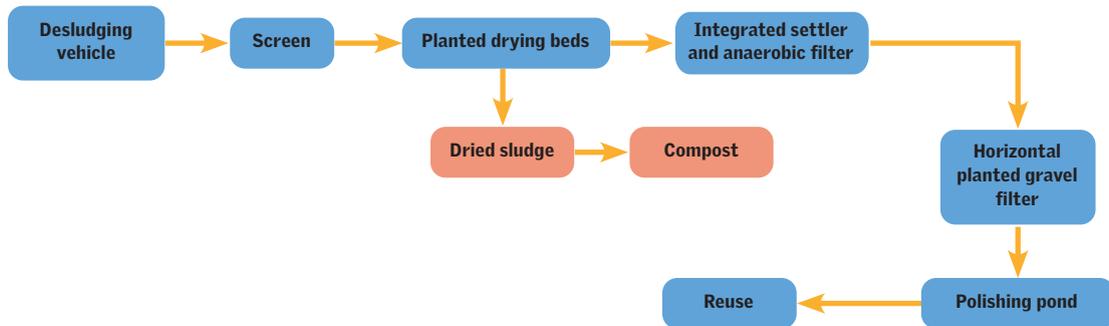
2.2.1 *Planted drying beds-based 18 KLD FSTP at Jhansi, Uttar Pradesh*

In 2018, Jhansi became the first city in Uttar Pradesh to set up a Faecal Sludge Treatment Plant (FSTP) with a capacity of six kilolitres per day (kld) at the Bijoli industrial area, located about 12 km south of the city center. In 2021, the plant was expanded with the addition of 12 more planted drying beds, increasing its total capacity to 18 kld (6 kld + 12 kld).¹⁹

The 18 kld design capacity FSTP has been constructed on the technology of planted drying beds for sludge stabilization/dewatering and Integrated Settler and Anaerobic Filter and Horizontal Planted Gravel Filter for the treatment of liquid steam. At the plant, the sludge is directly applied to the planted drying beds (PDBs) that are loaded with



Figure 8: Process flow diagram of the Jhansi FSTP



Source: CSE



Planted sludge drying beds at Jhansi FSTP



layers of sludge to get dewatered and stabilized through multiple biological and physical mechanisms.

Land requirement: The plant is constructed in a total area of one acre. Out of this, one planted drying bed covers an area of 44.7 m². The total area covered by 18 PDB's is 804.6 m² (0.2 acre).

Climatic condition

Jhansi is located on the rocky plateau and the weather is generally dry and is prone to extreme weather conditions and temperature fluctuation throughout the year. Peak summers are extremely hot with mercury soaring up to 45–47 degrees during the peak months of summer and an average daily temperature of 36 degrees with very high humidity. In contrast, winter temperatures can drop as low as two degrees Celsius in December. Jhansi experiences a southwest monsoon in December. Monsoons are relatively longer of three and a half months during June through September. The average rainfall is 900 mm per year. This rainfall affects the planted drying beds, as all the beds are uncovered, thereby increasing the sludge drying period.

Drying period

Under typical conditions in hot and semi-arid regions like Jhansi, the drying period for faecal sludge in summer usually ranges from 10 to 20 days. However, during the monsoon or humid seasons, the drying period extends to 20 to 40 days or more, due to reduced evaporation rates and higher humidity.

Performance quality

The data presented in Table 5 is derived from two CSE reports published in 2023, highlighting the changes in sludge concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was a little above the acceptable limits, both before and after drying. As a result of natural drying, the moisture content significantly decreased from 96.3 per cent to 9.9 per cent, falling right inside the acceptable limit specified by the Fertilizer Control Order (FCO, 2009). The carbon-to-nitrogen (C:N) ratio appears to be outside the range suggested by the FCO.

In addition, microbial analysis indicates that pathogen levels are significantly higher than the FCO limits, showing that sludge drying was not happening in a proper manner and is insufficient to effectively kill the pathogens. The data shows approximately 93.98 per cent pathogen reduction due to natural drying.

Table 5: Characteristics of raw FS and dried sludge for FSTP at Jhansi

Parameters	Raw FS	Dried sludge	FCO/WHO/USEPA standards
pH	7.8	7.8	6.5-7.5
TS %	3.7	90.1	-
Moisture %	96.3	9.9	<10%
C:N ratio	-	9:1	20:1–30:1
Faecal coliform (MPN/g)	13,82,252.16	83,205	1,000

Source: CSE

Energy consumption

The monthly expenditure in Jhansi FSTP on electricity is approximately INR 10,000 mainly used for operation of the crusher machine. For street lighting, 3 KWh solar panels have been installed.

Economics (CapEx, OpEx, Ease of O&M)

The total capital cost of the 6 kld plant is two crore. The capital cost was funded through Jhansi Nagar Nigam’s own funds from the 14th Central Finance Commission. In addition, the total capital cost of the 12 kld plant is 3.1 crore. Which shows that for 18 kld a total capital cost of 5.1 crore has been invested.

The plant is operated and maintained by a private contractor, namely, Purna Pro Enviro Engineers Pvt Limited. Currently, the plant is running at its full design capacity. The private operator has deployed six staff members at the plant; two guards, two workers, one supervisor and one service engineer for maintenance. However, the overall supervision is done by Jhansi Nagar Nigam (Zonal Sanitary Officer).

The total operational cost of the plant is INR 55.44 lakhs/year. Jhansi Nagar Nigam pays 4.62 lakhs INR/month (INR 2.62 lakhs for 6 kld and INR 2 lakhs for 12 kld) from their own funds for the operation and maintenance (O&M) of the plant. O&M expenses for the plant is borne by the operator and is generated through desludging fees collected from the community.

Table 6: CapEx and OpEx of the plant and drying process for FSTP at Jhansi

Parameters	Cost in INR
CapEx of the plant	510 lakhs
CapEx incurred for drying process	100 lakhs
CapEx incurred for drying process/ KLD	5.5 lakhs
OpEx of the plant	55.44 lakhs/year
OpEx incurred for drying process	16.6 lakhs/year
OpEx incurred for drying process/ KLD	0.9 lakhs/year

Source: CSE

The plant has six staff members, four guards, one supervisor and one service engineer for maintenance. Jhansi Nagar Nigam (JNN) has also provided PPEs to all staff members.

However, as mentioned by the private operator, due to 30–40 per cent of the desludging services to government institutions being provided on a pro-bono basis, the plant is unable to meet desludging expenses and the cost is being compensated from the funds provided for the FSTP O&M.

Reuse of by-products

180 metric tonnes (180,000 kgs) of biosolids is generated every year. The treated biosolids are used for plants in parks and road medians. For further use of the nutrients of biosolids and developing a revenue model, Jhansi Nagar Nigam (JNN) installed a crusher machine in 2022, for converting the dried biosolids into a fine powder. These can be further packed and sold for reuse as manure. Recently, JNN has partnered with an NGO (National Jan Kalyan Trust) for the sale of biosolids at the rate of 32 paisa per kg.

3. ELECTRO-MECHANICAL SLUDGE DRYING TECHNOLOGIES

Electro-mechanical sludge drying technologies are advanced systems that use mechanical equipment, chemical additives and electrical energy to dewater and dry faecal sludge. These technologies require skilled workforce and significant O&M expenses to handle its routine O&M activities. This section comprises of three technologies such as, Belt Dryer, Green House Solar Dryers (GHSD), Screw Press or Volute press with Sun Drying.

3.1 BELT DRYER

Belt dryers comprise a conveyer belt which is fed with the dewatered sludge. The sludge solids are slowly transported by the belt through a stream of heated air, generally at 80–180°C. They permit an additional element of process control to the usual parameters of sludge feeding rate and heat input, since the belt speed can be adjusted to change the dryer residence time.

Belt dryers are widely used for drying various materials, including sludge from wastewater treatment, due to their continuous and controlled drying process.

Several factors influence the efficiency and effectiveness of drying using a belt dryer. These factors can be grouped into material properties, operational parameters, and environmental conditions.

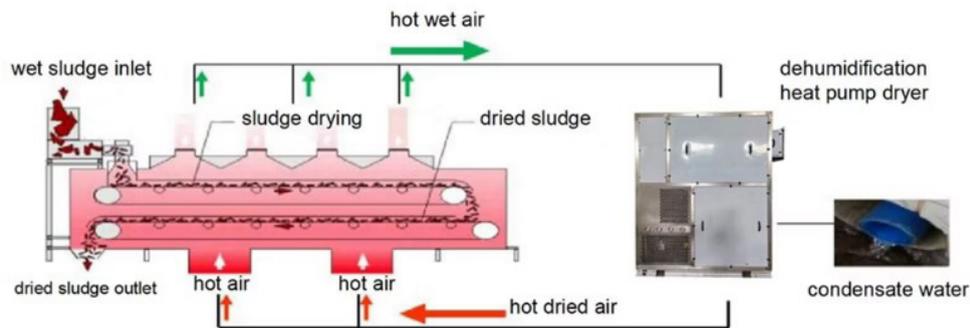
Factors affecting drying using belt dryer

Material properties

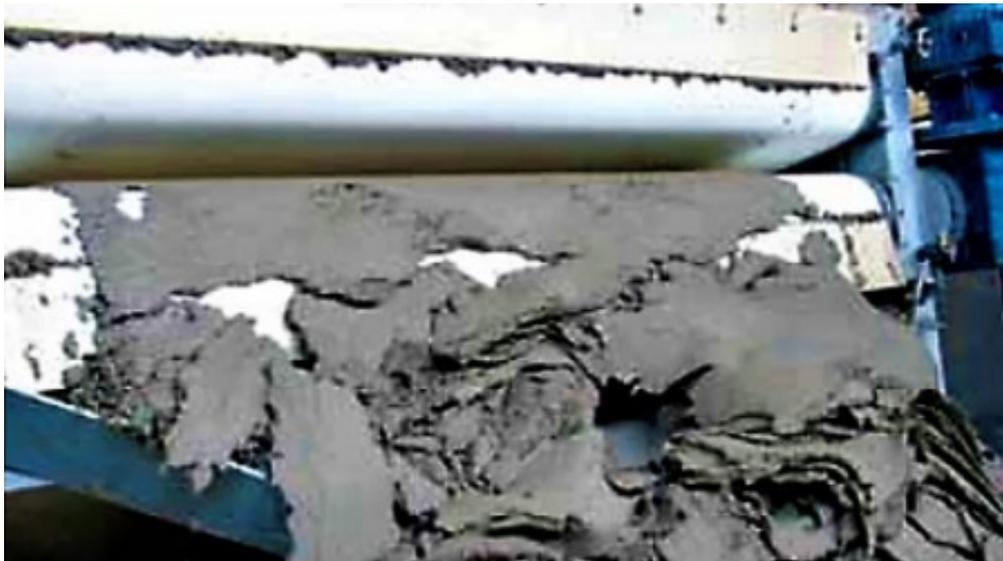
- Moisture content:
 - Initial moisture content: Higher initial moisture content requires more drying time and energy.
 - Moisture distribution: Uniformly distributed moisture allows for more consistent drying.
- Particle size and shape:
 - Size: Smaller particles dry faster due to a larger surface area relative to volume.
 - Shape: Irregularly shaped particles may have more surface area, enhancing drying, but can also complicate uniform drying.

- Higher bulk density materials retain more moisture, requiring more energy and time to dry.
- Materials that are sensitive to heat require careful control of drying temperature to avoid degradation.
- The use of certain polymers can form a coating on sludge particles, potentially reducing efficiency of drying processes such as belt drying.

Figure 9: Schematic diagram of belt dryer



Source: <http://kintep.vn/en/shop/low-energy-consumption-hmi-control-panel-sludge-dryer/>



Dried sludge after processing it through belt dryer¹⁹

Operational parameters

- Belt speed: The speed at which the belt moves determines the residence time of the material in the dryer. Slower speeds increase residence time, allowing for more thorough drying.
- Belt load: The thickness of the material layer on the belt affects drying efficiency. Thicker layers take longer to dry.
- Drying temperature: Higher temperatures generally increase drying rates but must be balanced against the risk of damaging heat-sensitive materials.

- **Airflow:**
 - **Air velocity:** Higher air velocity enhances moisture removal by carrying away moisture-laden air.
 - **Air distribution:** Uniform air distribution ensures consistent drying across the belt.
- **Humidity of drying air:**
 - Lower humidity in the drying air increases the driving force for moisture evaporation.
 - Control of inlet and outlet air humidity is crucial for optimizing the drying process.
- **Heat source:** The type and efficiency of the heat source (e.g., gas, steam, and electric) impact the drying rate and energy consumption.

Environmental conditions

- Higher ambient temperatures and lower ambient humidity improve drying efficiency.
- Seasonal variations can affect the performance of the belt dryer and may require adjustments in operational parameters.

Design factors

- **Belt material:**
 - The material of the belt should be heat-resistant and compatible with the material being dried.
 - Perforated belts can improve airflow and drying efficiency.
- Multi-stage dryers can offer more controlled and gradual drying, improving overall efficiency and product quality.
- **Insulation and sealing:**
 - Proper insulation of the dryer reduces heat loss, enhancing energy efficiency.
 - Effective sealing prevents air leakage, maintaining optimal drying conditions.
- Efficient removal of moist air from the drying chamber is crucial to maintain the drying rate and prevent condensation.

Additional considerations

- **Energy consumption:**
 - Monitoring and optimizing energy use can reduce operational costs and improve sustainability.
- **Maintenance and cleaning:**
 - Regular maintenance and cleaning ensure that the belt dryer operates efficiently and prevents issues such as clogging or material buildup.
- **Automation and control systems:**
 - Advanced control systems can optimize drying parameters in real-time, enhancing efficiency and consistency.

By understanding and optimizing these factors, the performance of belt dryers can be significantly improved, leading to more efficient and effective drying processes.

Performance quality

Pathogen removal in sludge using a belt dryer is a complex process influenced by

temperature, residence time, moisture content, airflow, and pathogen type. By carefully controlling these factors, belt dryers can effectively reduce pathogen levels in sludge to meet regulatory standards and ensure safe handling and disposal or beneficial reuse of the dried bio-solids.

Pathogens in sludge, such as bacteria, viruses, and parasites, can be inactivated or killed when exposed to high temperatures for sufficient periods. Different pathogens have varying sensitivities to heat. For example, most bacteria, including *E. coli* and *Salmonella*, are killed at temperatures around 70–80°C with sufficient exposure time.

The moisture content of sludge is a critical factor in the drying process. Initially, sludge is typically dewatered to reduce its water content. In a belt dryer, the moisture content is further reduced to 30-40 per cent, which not only decreases the volume and weight but also helps in the reduction of pathogens. Dry environments are less conducive to the survival of pathogens, further aiding in their removal.

Economics (CapEx, OpEx)

The price of a belt dryer can vary widely depending on several factors, including the size and capacity of the dryer, the specific design and features, the manufacturer, and the intended application.

Pros

- High thermal efficiency: Optimized process air circulation.
- Modular design: Expandability for higher throughput/water evaporation capacity.

Cons

- High initial investment cost: Belt dryers often have a high upfront cost compared to other drying technologies. They may also require significant infrastructure investments, including building modifications, installation costs, and setup of ancillary equipment (e.g., conveyors).
- Energy consumption: Belt dryers generally consume a significant amount of energy, particularly when drying materials with high moisture content. The need to maintain continuous airflow and heating can lead to high operational costs.
- Maintenance requirements: The moving parts of a belt dryer, such as conveyor belts, motors, and fans, are subject to wear and tear, requiring regular maintenance and sometimes costly repairs.
- Complexity of operation: Proper operation of a belt dryer requires trained personnel who understand the system's controls and processes.
- Slow drying process: Belt dryers typically operate with relatively long residence times compared to other drying methods. This slower process may not be suitable for applications requiring rapid drying.
- The operation of belt dryers can produce exhaust gases that need to be managed and treated, especially if dealing with hazardous materials or odors.
- Belt dryers need sawdust as an additive to increase the surface area of the sludge for efficient drying. The cost of sawdust places an additional burden —20 kg of sludge will require 100 kg of sawdust.

CASE STUDY

3.1.1 Belt dryer-based Faecal Sludge Treatment Plant at Warangal

A 15 kld FSTP was set up in Warangal in 2018 by Tide Technocrats, technology being Pyrolysis and MBBR clubbed with filtration. This is the first FSTP of the Telangana state.

This FSTP was constructed on a PPP model. While GWMC provided land for the construction of the FSTP, Bill and Melinda Gates Foundation (BMGF) funded the CapEx. Private partner Tide Technocrats was responsible for the construction and O&M of the FSTP. Around 30–40 loads are decanted at the pyrolysis based FSTP on an average in a month.



Belt dryer technology at Warangal FSTP

The septage is received at the screen chamber and stored in two holding tanks, each with a capacity of 20 kld. From there, it is pumped into a mechanized dewatering machine called a volute press/screw press, which separates the solids from the liquid. The dewatered sludge is then mixed with sawdust in a 1:5 ratio before being fed into a belt dryer for drying. The belt dryer, followed by a pyrolizer; with a feeding capacity of 200 kg per day, produces approximately 15–20 kg of biochar daily after eight hours of operation. Excess sludge is transferred to a composting site for natural drying, where windrow composting is currently practiced at the Warangal FSTP.



Sawdust and polymer uses at Warangal FSTP

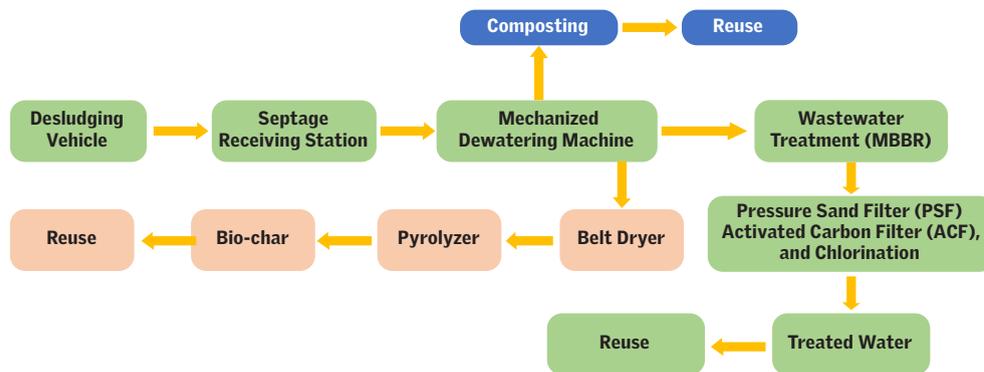
The belt dryer completes one cycle in 40 minutes, operating at a temperature of 70–80°C to achieve the desired moisture content in the sludge.

Special feature: After dewatering, the dewatered sludge forms agglomerates and is hard to spread on the belt. Subsequently the drying doesn't happen evenly. To break the agglomerates and to increase the drying efficiency, the saw dust is mixed with the dewatered sludge.

Land requirement

The total area covered by the plant is 0.9 acre, whereas the area occupied by the equipment used for dewatering and sludge drying is 400 sq ft. Sludge dewatering and drying machines have been installed in a multilevel container which ultimately saves space.

Figure 10: Process flow diagram of the Warangal FSTP



* PSF: Pressure Sand Filter
*ACF: Activated Carbon Filter

Climatic conditions

The climate in Warangal district is generally dry. Summers are hot, sometimes touching 50°C. The temperature dips to 13°C in winters, during the months of December and January. Warangal district receives maximum rainfall through the South–West monsoon, during the months of July, August and September. Normal annual rainfall is 994 mm. However, this plant does not affect much with the rainfall because of its container-based design. Only the composting area gets wet during rainfall days and increases the moisture content of the bio-solids.

Performance quality

The data presented in Table 7 is derived from a CSE report published in 2023 as well as from the primary research, which highlights the changes in concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was found to be higher than the acceptable limits but within the limit for dried sludge. As a result of mechanized dewatering followed by mechanical drying through belt dryer, the moisture content significantly decreased from 97.3 per cent to 38 per cent, which is not within the acceptable limit specified by the Fertilizer Control Order (FCO, 2009). Hence, the dried sludge is further getting

Table 7: Characteristics of raw FS and dried sludge for FSTP at Warangal

S.No.	Parameters	Raw FS	Dried sludge	FCO/WHO/USEPA Standards
1	pH	8.0	7.2	6.5-7.5
2	TS %	2.7	62	-
3	Moisture %	97.3	38	<10%
4	C:N ratio	-	-	20:1–30:1
5	Faecal coliform (MPN/g)	24,81,481.48	-	1,000

Source: CSE

treated through pyrolysis and producing bio-char as by-product. The data of pathogen levels were not available for the dried sludge after processing it through belt dryer.

Energy consumption

The primary energy source is the government power supply, which frequently disrupts the treatment process due to common power outages. To address this, a 15 KVA capacity DG set has been installed as a backup. The energy requirements for the various modules used in the drying process are as follows:

- Dewatering system: 2.6 kWh
- Dryer: 9 kWh

The overall monthly power consumption of the whole plant is around 1800 Units that cost around Rs. 16,000–18,000 per month. One interesting thing in this plant is that, the counter flow heat exchanger recuperates the heat generated from pyrolysis and is reused back within the system which ultimately reduces the requirements of additional external heat source.

Economics (CapEx, OpEx, Ease of O&M)

CapEx includes expenses incurred for the treatment plant, ancillary infrastructure and procurement of desludging vehicle.

OpEx includes expenses incurred for the energy consumption, salaries of the trained manpower, additives requirement such as polymer and saw dust and regular operations and maintenance of the plant.

As the Warangal FSTP relies heavily on electro-mechanical equipment, it necessitates a skilled and well-trained operator, along with consistent attention to its routine operations. The dewatering unit can process approximately 3,000 liters per hour (LPH) when handling septage with lower solids content. However, as solids content increases, the flow rate decreases to around 1,000 LPH. Due to fluctuations in solids concentration, the operator must adjust the polymer dosing, volute press speed, and conveyor and blower speeds to maintain stable operations.

Table 8: CapEx and OpEx of the plant and drying process for FSTP at Warangal

Parameters	Cost in INR
CapEx of the plant	200 lakhs
CapEx incurred for drying process	40.74 lakhs
CapEx incurred for drying process/kld	2.7 lakhs
OpEx of the plant	30.6 lakhs/year
OpEx incurred for drying process	6 lakhs/year
OpEx incurred for drying process/kld	0.4 lakhs/year

Source: CSE

Reuse of by-products

The 15 kld capacity Warangal FSTP produces three by-products: biochar, compost, and treated water. Some part of the dewatered sludge is dried on the belt dryer and subsequently used into the pyrolyzer to convert in biochar while the rest of the quantity is co-composted further. Currently, the compost is provided free of charge to nearby farmers who use it in their fields. The biochar is mostly stored in a storage room, with only a small portion being used by farmers as a soil conditioner. However, there is currently limited interest among farmers in adopting biochar. In the future, its usage could expand, given that 81 per cent of the district’s population lives in rural areas where agriculture is the primary livelihood.



Compost and bio-char for reuse at Warangal FSTP

3.2 GREENHOUSE SOLAR DRYERS (GHSD)

Greenhouse solar drying is a method for treating faecal sludge, utilizing solar energy to dehydrate and sanitize waste. This method is particularly advantageous in regions with abundant sunlight and limited access to conventional waste treatment infrastructure. Careful design, operation, and maintenance are crucial to maximize its effectiveness and ensure safety.²⁰

Process mechanism

1. Loading into drying beds:
 - o The sludge is loaded onto drying beds within a greenhouse structure. These beds are typically lined to prevent leachate from contaminating the groundwater.



Exterior view of Greenhouse solar dryers

- o The thickness of the sludge layer is controlled to optimize drying efficiency.
- 2. Greenhouse design:
 - o The greenhouse is designed to maximize solar radiation capture. It often features transparent roofing and walls made of materials such as polycarbonate or polyethylene.
 - o Ventilation systems are incorporated to allow moisture to escape, which can include natural ventilation (vents, louvers) or forced ventilation (fans).
- 3. Solar drying:
 - o Solar radiation heats the sludge, promoting evaporation of moisture. The greenhouse effect raises the internal temperature, accelerating the drying process.
 - o Depending on the climate and design, drying can take several days to a few weeks.
- 4. Monitoring and maintenance:
 - o Regular monitoring is essential to ensure even drying and to prevent issues such as odour or pest infestation.
 - o Periodic mixing or turning of the sludge can enhance drying efficiency.
- 5. Final product:
 - o The dried faecal sludge is significantly reduced in volume and weight. It can be further processed or used directly, depending on its intended use.
 - o Potential applications include use as soil conditioner, compost, or even fuel if properly sanitized and processed.

Factors affecting drying using GHSD

- 1. Climatic dependence:
 - o Effectiveness is highly dependent on local climate, particularly solar radiation and ambient temperature.
 - o Inconsistent weather conditions can prolong drying times or reduce efficiency.
- 2. Initial investment:
 - o Initial setup costs for greenhouse construction can be significant, though offset by lower operating costs over time.
- 3. Operational expertise:
 - o Requires trained personnel to monitor and manage the drying process to ensure safety and efficiency.

- o Regular maintenance of the greenhouse structure and ventilation systems is necessary.

Performance quality

1. Drying efficiency:

- o Greenhouse sludge drying can reduce sludge moisture content from around 80 per cent to below 20 per cent.

2. Drying time:

- o Drying time can vary from a few days to several weeks, depending on the climate (temperature, humidity, and sunlight intensity), sludge characteristics, and the design of the drying system. Under optimal conditions, drying time can be as short as 10-12 days.

3. Dry solid content:

- o The goal is typically to achieve a dry solids content of 60–90 per cent, depending on the desired end-use of the dried sludge.

4. Processing capacity:

- o The capacity depends on the size of the greenhouse and the initial moisture content of the sludge. For example, a 500 sq m greenhouse can process approximately 10–20 cubic meters of sludge per batch, depending on the initial sludge characteristics and climatic conditions.

Economics (CapEx, OpEx)

For a greenhouse sludge drying system assuming a 500 sq m facility, the estimated total capital costs is approximately INR 27–72 lakhs and the total operational costs (annually) will be approximately INR 10.5–26.5 lakhs.

Pros

- Efficient sludge drying technique, approximately 40 per cent faster
- Minimizes greenhouse gas emissions compared to conventional sludge treatment methods
- Reduction in the volume and weight of faecal sludge, making transportation and disposal easier and cheaper
- High temperatures achieved in the greenhouse can reduce pathogens including, Helminths inactivation, making the sludge safer for handling and potential reuse as soil conditioner or co-fueling, etc.
- Design optimization with high quality materials; can be built and maintained with locally available materials and labour.
- 40 per cent SDBs' land reduction (when included in planning stage)
- Utilizes renewable solar energy, reducing reliance on fossil fuels
- Lower operational costs due to reduced energy requirements

Cons

- Drying efficiency depends on climatic conditions and seasons
- The need to use additional heat sources
- Suitable at locations where there is land availability
- Possibility of odours emission released during drying the sludge.
- Labour intensive process requiring manual handling at each stage

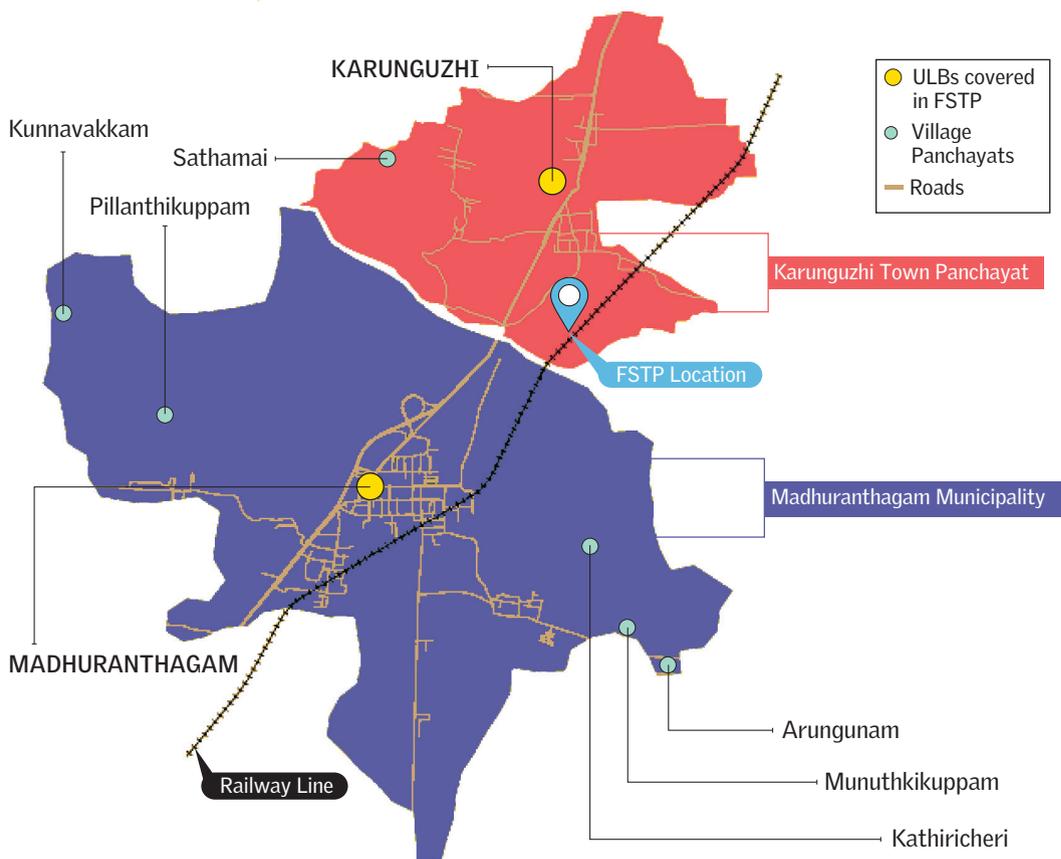
CASE STUDIES

3.2.1 FSTP at Karunguzhi, Tamil Nadu

Karunguzhi, a Grade I Town Panchayat in the Chengalpattu district of Tamil Nadu, was selected by the Government of Tamil Nadu to showcase septage management. A pilot FSTP was constructed in Karunguzhi to serve the needs of Karunguzhi and the adjacent municipality of Maduranthagam (as part of the cluster approach) in 2017.²¹



Map 2: Karunguzhi FSTP cluster map



Source: CSE

A 23.4 kld FSTP has been setup in Karunguzhi with the technical assistance of Indian Institute of Human Settlements (IIHS). The FSTP treats septage collected from about 3,500 households (12,485 people) in Karunguzhi, and about 7,000 households in Maduranthagam. The treatment process consists of 20 unplanted drying beds of which 10 have greenhouse solar drying system.

Seven people are employed for the O&M of the plant: two plant operators, supervisor, and four sanitation workers for dry sludge collection, co-composting, etc. The plant has no foul odor and people treat it as a recreational area.

Land requirement: The total built up area of the plant is 8,093 sq.m (two acre). Out of this, one unplanted drying bed is covering an area of 49.2 m². The total area covered by 20 sludge drying beds is 984 m² (0.24 acre). The area covered by the sludge storage yard is 35 m².

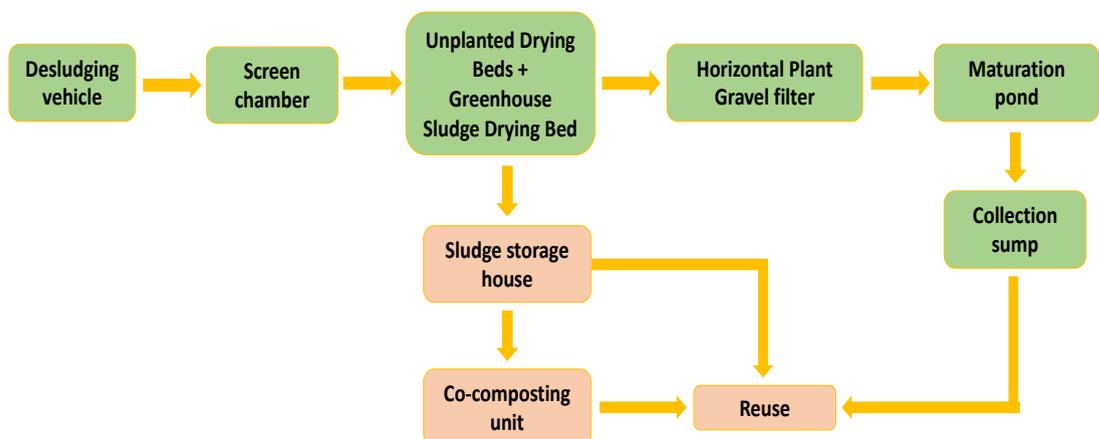


Unplanted drying beds with GHSD set up at Karunguzhi FSTP



Interior view of GHSD at Karunguzhi

Figure 11: Process flow diagram of the Karunguzhi FSTP



Source: CSE

Climatic condition

Karunguzhi experiences a tropical wet and dry climate. This type of climate is characterized by a distinct wet season and a dry season, with relatively high temperatures throughout the year. Summers in Karunguzhi are typically hot, with daytime temperatures ranging from 28°C to 38°C (82°F to 100°F). During peak summer months, temperatures can occasionally rise above 40°C (104°F). The humidity levels during summer can be quite high, especially in the afternoons, which can make the heat feel more intense. Winters in Karunguzhi are mild and pleasant, with temperatures ranging from 18°C to 28°C (64°F to 82°F). The nights can be cooler, with temperatures occasionally dipping to around 16°C (61°F).

The monsoon season brings significant rainfall to Karunguzhi, primarily due to the southwest monsoon.

The town receives a moderate amount of rainfall during this period, with an average annual rainfall of about 1,200 mm (47 inches). This contributing to its lush greenery and agricultural activities.

As the 10 sludge drying beds are covered from top but not from the sides, it increases the drying period of the sludge. However, the remaining 10 GHSD beds (with polycarbonate sheets) remain unaffected.

Performance quality

The data related to raw faecal sludge which is presented in Table 9 is derived from one of CSE’s report published in 2020, highlighting the changes in sludge concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was within acceptable limits before the treatment, however the data for dried sludge could not be found. However, as a result of natural drying, the moisture content significantly decreased from 99.75 per cent to less than 10 per cent, which falls under the acceptable limit specified by the Fertilizer Control Order (FCO, 2009).

The data shows approximately 90 per cent moisture reduction is happening in this FSTP due to the monitored temperature in the beds because of the presence of greenhouse sheds.

Table 9: Characteristics of raw FS and dried sludge for FSTP at Karunguzhi

Parameters	Raw FS	Dried Sludge	FCO/WHO/USEPA standards
pH	7.14	-	6.5–7.5
TS %	0.25	90	-
Moisture %	99.75	<10	<10%
C:N ratio	-	-	20:1–30:1
Faecal coliform (MPN/g)	4,44,00,000	-	1,000

Source: CSE

Drying period

In the 10 unplanted drying beds (with steel sheets) the sludge takes approximately 20–25 days to dry in the Karunguzhi FSTP, however, in the greenhouse solar drying sheds (with polycarbonate sheets) the sludge dries approximately 10–12 days only. The maximum temperature difference observed is between 15–20°C.

Factors affecting drying

In the 10 unplanted drying beds, which are covered only from the top but open on all other sides, a lot of leaves fall into the beds. Additionally, during the rainy season, water accumulates in the beds, leading to an extended drying period. However, there is no impact of leaves or rains on the remaining 10 GHSD beds (with polycarbonate sheets).

Energy consumption

The greenhouse solar drying sheds requires electricity for basic activities like running exhaust fans, regulators etc for which the operator has been trained. The plants consume 830 KWh monthly, for running the GHSDs. This demand is met by the solar panels installed by M/S Covestro (India) Pvt. Ltd. over the greenhouse solar drying sheds. Rest of the plant is non-mechanized and gravity based which only requires energy to run the pump.

Economics (CapEx, OpEx and Ease of O&M)

Total capital cost of the FSTP is approximately 493 lakhs, additional 60 lakhs were used for the installation of GHSD sheds (with polycarbonate sheets) which was funded by M/S Covestro (India) Pvt. Ltd.

The FSTP is easy to operate and requires minimum expenditure. Total operational cost of the plant is approximately 9.64 lakhs annually which is divided in a 70:30 ratio by Maduranthagam and Karunguzhi Municipalities respectively. Out of this amount, 7.6 lakhs is utilized for the salaries of the seven staff members at the plant.

Tipping fees is of INR 200 and user charges collected are INR 1,000 per trip which is operated by the municipality. Of the INR 1,000 for user charges, INR 700 is given to operators and INR 300 is kept by the municipality to run operations.

Table 10: CapEx and OpEx of the plant and drying process for FSTP at Karunguzhi

Parameters	Cost in INR
CapEx of the plant	493 lakhs for entire plant 60 lakhs for GHSD
CapEx incurred for drying process	15.97 lakhs (SDBs + Sludge storage tank) + 60 lakhs GHSD
CapEx incurred for drying process/ KLD	3.25 lakhs
OpEx of the plant	9.64 lakhs/ year
OpEx incurred for drying process	5.8 lakhs/ year
OpEx incurred for drying process/ KLD	0.25 lakhs/ year

Source: CSE

Reuse of by-products

In Karunguzhi FSTP, the bio-solids and co-composted sludge is being reused and a revenue is generated of approximately 20000 Rs per month. Both the bio-solids and the co-composted manure from the FSTP are sold to the farmers to be used as agricultural fertiliser. For 1.5 tonne of manure, 1000 Rs are being charged. The farmers finds the crop yield to be better after using this manure. The remaining bio-solid stored in the sludge storage yard is used for gardening in the FSTP premises.



Dried sludge at Karunguzhi FSTP

In the co-composting unit, windrow composting is being practices, where each pile gets composted for 45 days. Approximately 2.5 tonne waste is sent for co-composting which produces 500kg of manure (1 cycle of 45 days) which is sold for 10Rs per kg.



Co-composting Process at Karunguzhi FSTP

In addition, to raise awareness among citizens about the benefits of this manure, the town panchayat also set up stalls to display the manure packets, explain their advantages, and sell them to citizens at minimal charges.

3.2.2 FSTP at Devanahalli, Karnataka

Devanahalli is a town located near Bengaluru in Karnataka. It is located 40 kilometers (25 mi) to the northeast of Bengaluru and is spread over an area of 16 km² (6 sq mi) where approx. 28,051 people reside. Assuming an estimated growth rate of around two per cent per year, the population in 2024 can be roughly projected to be around 36,000 to 40,000 people. The estimated wastewater generation in Devanahalli is approximately four million liters per day (MLD).



In 2015, Devanahalli was the first planned town-scale Faecal Sludge Treatment Plant (FSTP) in the country with a treatment capacity of six kilo litres per day (KLD). The FSTP was handed over to the Devanahalli Town Municipal Council in April 2019 and they have been able to operate it with minimal expert supervision.

The plant receives a minimum of three truck-loads weekly. All trucks of 3–3.5 cubic metre capacity.

To enhance/optimize the drying time of the SDB, the usage of greenhouse solar drier sheds (GHSDs) was adopted in 2019. GHSDs even helps to get enhanced moisture removal.²²



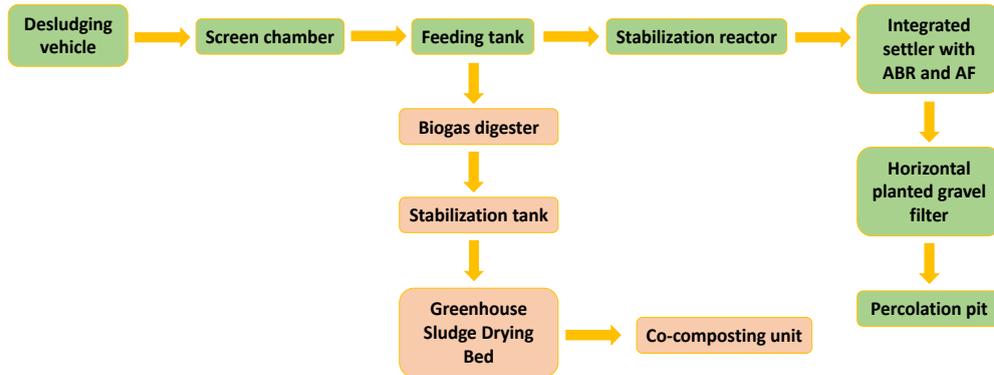
Unplanted Drying Beds with GHSD at Devanahalli FSTP

This helped in maintaining a high temperature inside the unit (maximum temperature of 60°C for approximately 5–6 hours a day) thus leading to the reduction of pathogens and simultaneously drying the sludge (approximate moisture content of 50–60 per cent). Between the 15–18th day of loading, the sludge cakes become dry enough to be taken out and co-composted.²³

Technology: Unplanted drying beds with greenhouse solar dryers, Integrated Settler and Anaerobic Filter and Horizontal Planted Gravel Filter.

Land requirement: The total built up area of the plant is 625 sq.m (0.15 acre). Out of this, one sludge drying bed covers an area of 10 m². The total area covered by 10 SDB's is 100 m² (0.02 acre).

Figure 12: Process flow diagram of the Devanahalli FSTP



Source: CSE

Climatic condition

Devanahalli enjoys a moderate climate throughout the year, with no extreme temperatures. The relatively mild winters and the cooling effect of the monsoon rains make it a comfortable place to live or visit for most of the year. The summer season in Devanahalli is typically warm, with daytime temperatures ranging from 25°C to 35°C (77°F to 95°F). Occasionally, temperatures can reach up to 38°C (100°F) on particularly hot days. Humidity levels are moderate during this time. Winters in Devanahalli are mild and cool, with temperatures ranging from 14°C to 26°C (57°F to 79°F). Occasionally, temperatures can drop to around 10°C (50°F) during early mornings and late nights, but this is relatively rare.

The monsoon season brings most of the annual rainfall to Devanahalli. The area receives moderate to heavy rainfall due to the southwest monsoon. The average annual rainfall is around 900 to 1,000 mm (35 to 39 inches). This climate does not affect the drying of sludge in the FSTP due to the presence of greenhouse solar sheds.

Performance quality (% reduction)

The data presented in Table 11 is derived from primary survey, highlighting the sludge concentration after the sludge drying process. The pH of the raw fecal sludge (FS) was unknown, but it remained under the FCO recommended range after drying. Even after using greenhouse sheds and drying under a monitored temperature, the moisture content of the dried sludge lies above the acceptable standards specified by the Fertilizer Control Order (FCO, 2009). The Carbon-to-Nitrogen (C:N) ratio appears to be outside the range suggested by the FCO. However, microbial analysis indicates that pathogen levels are just a little higher than the accepted standards, showing that heat penetration during drying was insufficient to effectively kill pathogens. The data also shows that approximately 70 per cent pathogen reduction is happening using this technology.

Table 11: Characteristics of raw FS and dried sludge for FSTP at Devanahalli

Parameters	Raw FS	Dried sludge	FCO/WHO/USEPA standards
pH	-	7.4	6.5–7.5
TS %	4.2	69.8	-
Moisture %	95.8	30.2	<10%
C:N ratio	-	12:1	20:1–30:1
Faecal coliform (MPN/g)	-	>1600	1000

Source: CSE

Drying period

Operations of the Devanahalli FSTP for the first year indicated that the drying time of sludge (approximately 23 days) in the sludge drying beds was not consistent with the design drying time of 15 days. Percolation in the filter media i.e. through sand (1.5 mm particle size) was slow and it retained moisture for a longer time. After the installation of greenhouse solar drying sheds, the drying time has now reduced to approximately 18 days from the earlier 23 days. Maximum temperature difference observed is 15 °C – 20 °C.

Energy consumption

The greenhouse solar drier requires electricity for basic activities like running exhaust fans, for which the operator has been trained. The plants consume 830 KWh monthly, for running the GHSDs.

Economics (CapEx, OpEx and Ease of O&M)

The total capital cost of the Devanahalli FSTP is 110.90 lakhs. A total of 20 lakhs have been invested in the construction of the unplanted drying bed, including the installation of greenhouse solar drying (GHSD) sheds, with 8.5 lakhs allocated specifically for the greenhouse solar drying sheds. The ancillary units for a co-composting plant costs approximately 40 lakhs.

The total operational cost of the FSTP is 5.33 lakhs/year, out of which 4.2 lakhs are for salaries of the staff members. Breakup of the operational costs include desludging operations (45 per cent), co-composting operations (30 per cent) and FSTP operations (25 per cent). The plant has one plant manager, one operator and three support staff. The same operator has been operating and maintaining the plant from the time the plant was commissioned in 2015. Only INR 250–300 per month is the maintenance cost of the blower and exhaust.

The ULB generates revenues from various sources like from user fees a total of five lakhs is earned annually, from sale of co-compost a total of 4.4 lakhs is earned annually and 0.76 lakhs is earned through charging tipping fees and registration of truck from private operators.

Table 12: CapEx and OpEx of the plant and drying process for FSTP at Devanahalli

Parameters	Cost in INR
CapEx of the plant	110.91 lakhs
CapEx incurred for drying process	20 lakhs (SDB and GHSD)
CapEx incurred for drying process/kld	3.3 lakhs
OpEx of the plant	11.7 lakhs/year
OpEx incurred for drying process	3.9 lakhs/year
OpEx incurred for drying process/kld	0.65 lakhs/year

Source: CSE

1. Few and simple activities for regular and periodic operations as well as maintenance
2. O&M tasks require basic skills and technical knowledge (An unskilled operator, rather than an engineer, can be trained to handle the operation and maintenance (O&M) of the treatment plant)
3. No moving parts installed in the FSTP (faecal sludge moves from one module to another either through gravity or through the pressure exerted by generated biogas)
4. No chemicals required through the treatment process

Reuse of by-products

The FSTP was intended to produce a safe, dry and nutritive by-product. There are three by-products obtained from the Devanahalli FSTP: compost, treated wastewater and biogas.

1. The compost is being sold to farmers; it serves as a safer alternative to the untreated faecal sludge that they had been using. Additionally, it costs them a fraction of what they were paying for chemical fertilizers.



Dried sludge at Devanahalli FSTP

2. Biogas generated from the treatment process, is being used on-site as fuel for cooking by the plant's operator.
3. The treated wastewater is being used for irrigation at the plant itself. Additionally, the farmers have expressed interest in procuring the treated wastewater too but presently it is not being supplied to them.

Devanahalli, situated in an agricultural region, has a readily available market for a nutritious soil conditioner. Additionally, farmers were already familiar with using untreated FS in their fields, provided they followed certain safety precautions. Combining these two requirements defined the demand and supply for a safe, natural and nutrient-rich version of soil conditioner.

Dried faecal sludge was co-composted with segregated municipal wet waste using the Windrow method, which helped in the inactivation of pathogens by maintaining a high stable temperature (approximately 65–70°C for a period of 3–5 days). Additionally, it provided carbon content to the by-product. This technology intervention helped to produce a by-product that had moisture content in the range of 25–30 per cent making it easier for packaging and field application. In addition, the by-product has a C:N ratio of <20 as per the Fertiliser Control Order (FCO) recommendations. The compost samples tested were found to be negative for Helminth eggs, which makes it safe for handling and field application.

A randomized block trial was designed to conduct an experiment in a scientific manner to compare the efficacy of co-compost against other soil conditioners by comparing plant growth characteristics. It was found that field beans grown under co-composted faecal sludge had a comparatively higher yield and showed improved growth in other physical parameters.

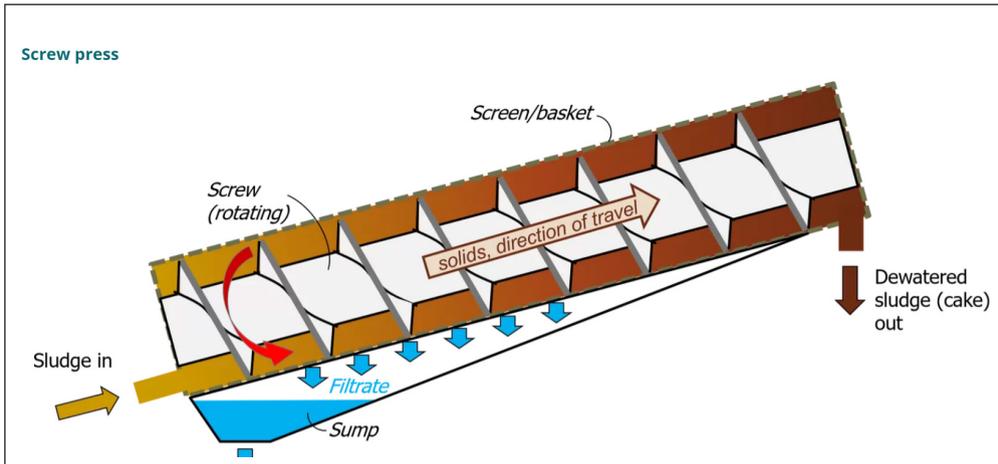
3.3 SCREW PRESS AND SOLAR/SUN DRYING OR GHSD

Screw press: Mechanized dewatering system

A screw press provides sludge dewatering by conveying the sludge along the inside of a permeable cylinder. It is based on a slowly-rotating (~5 RPM) Archimedean screw within a cylindrical screen (otherwise termed drum filter/screen or basket). It is normally inclined by ~20° to the horizontal to assist with the draining of water into the sump. The screen generally has an aperture rating below 0.5 mm and is based on wedge-wire or occasionally perforated metal. The screens are less susceptible to clogging than the filter media used for other thickening and dewatering processes. Consequently, spray-cleaning is applied only intermittently for around 2-4 per cent of the operating time.²⁴

As with all thickening and dewatering processes, the output product (dried sludge or sludge cake) content is dependent on the feed water sludge quality. The cake solids content has been shown to be inversely proportional to the volatile solids (VS) of the feed sludge. Screw press requires addition of polymer in significant amount to enhance dewaterability of the input sludge.

Figure 13: Schematic diagram of screw press



Source: CSE

Working principle of screw press

The screw press operates in two key zones:

1. **Thickening zone:** Water separation from sludge occurs as the shaft-driven screw compresses the sludge. The moving and fixed rings prevent blockages.
2. **Dewatering zone:** Increasing pressure squeezes out water, resulting in dryer sludge cakes. The self-cleaning mechanism ensures uninterrupted operation.

Multi Plate Screw Press (MPSP)

The Multi Plate Screw Press is an advanced dewatering system that surpasses traditional methods. Here are its key features:

1. **Continuous sludge processing:** The MPSP enables automatic and continuous sludge flocculation, thickening, dewatering, and filtrate discharging.
2. **Wide solid concentration range:** Exclusive pre-thickening allows for a solid concentration ranging from 10,000 mg/l to 50,000 mg/l.
3. **Efficiency and small footprint:** High efficiency with minimal space requirements.
4. **Low power consumption:** Consumes less than five per cent of what a centrifuge does.
5. **Minimal water usage:** Less than one per cent of an equivalent belt filter press.
6. **Self-cleaning:** No blocking or backwash water needed.
7. **Versatility:** Handles oily and fibrous sludge effectively.
8. **Sealed system:** No odors or bad smells.
9. **Wear-free:** Longer service life.
10. **Exclusive screw shaft:** Optimized for sludge thickening and inorganic material.

Solar/sun drying

Solar/sun drying is an option for increasing the solids content of sludge to the desired levels. However, as pathogen reduction also occurs along with drying of sludge, this method is considered here as an option for pathogen reduction. Solar drying can be done in two ways—either with or without a transparent covering sheet. Many of the FSTPs as well as STPs are dependent on sun drying of sludge obtained after dewatering.



Natural sun drying in UDB covered with Polycarbonate Sheet

Process mechanism

- Solar drying relies entirely on evaporation to remove moisture. The transparent covering (if provided) prevents the entry of rain and increases the temperature of the air above the sludge through sunlight, hence increasing the evaporation rate.
- Ventilation is required to remove moist air from above the beds and replace it with drier air, so maximizing the evaporation that can be achieved. Natural wind-based ventilation, based on wind, will have some effect, but most solar drying systems incorporate fans to circulate air and prevent warm air from rising.
- The sludge must be regularly turned. Turning brings wet sludge to the surface, thereby increasing the potential for evaporation.

Pros and cons

The effectiveness of the drying process depends mainly on the degree of solar exposure on drying location. It also depends on the initial method of sludge dewatering, its amount and the type of technology applied. Due to the fact that drying by using sunlight is most effective in the spring-autumn period, in winter and rainy season, there might be a need for an additional source of heat, e.g. underfloor heating, greenhouse solar sheet etc. Also, natural drying process may cause odour emission, this is linked to an additional investment in a system of filters. The major disadvantage is that drying efficiency completely depends on the degree of sunlight and temperature, which varies throughout the year.

Screw press in combination with solar drying is used for the sludge drying in most of the FSTPs in India. Screw press reduces the volume of sludge by squeezing out the free water from the sludge particles and subsequently reduces the moisture from the raw faecal sludge from approximately 95 per cent to 80–75 per cent.

The dewatered sludge is further sundried to bring down the moisture and pathogen levels in the sludge.

CASE STUDIES

3.3.1 Screw press and GHSD-based FSTP at Periyanaickenpalayam (PNP), Tamil Nadu

Periyanaickenpalayam is an industrial city and one among the suburb of Coimbatore in the Indian state of Tamil Nadu. The town is located at a distance of 22 kilometers to the north of Coimbatore. Periyanaickenpalayam Town Panchayat is a Selection Grade Town Panchayat. The extent of the Town Panchayat is 9.37 Sq.km. The population of the town was 32,647. Assuming an annual growth rate of about two per cent, the population in 2024 would be approximately 40,000 people.



The Periya Naicken Palayam (PNP) FSTP at present can operate at a maximum capacity of 50 kilo litres per day (KLD). The plant has been operational since October 2019. 25 KLD capacity plant was constructed in 2019 by BMGF and later an additional 25KLD was constructed in 2022 by 5 Urban Local Bodies. The plant follows a cluster approach where it caters to 5 ULBs namely PNP, Narasimhanaickenpalayam (NNP), Idigarai, Veerapandi, and Gudalur. This is the first mechanical FSTP of the state. The plant was constructed, commissioned, and operated and maintained under the Tamil Nadu Urban Sanitation Support Programme (TNUSSP). The plant receives around 5,23,000 litres of septage/month which is 70 per cent of its design capacity.

Total capacity of the plant is 50 KLD which generates 600kg of sludge per day and 40,000 litres of treated water.



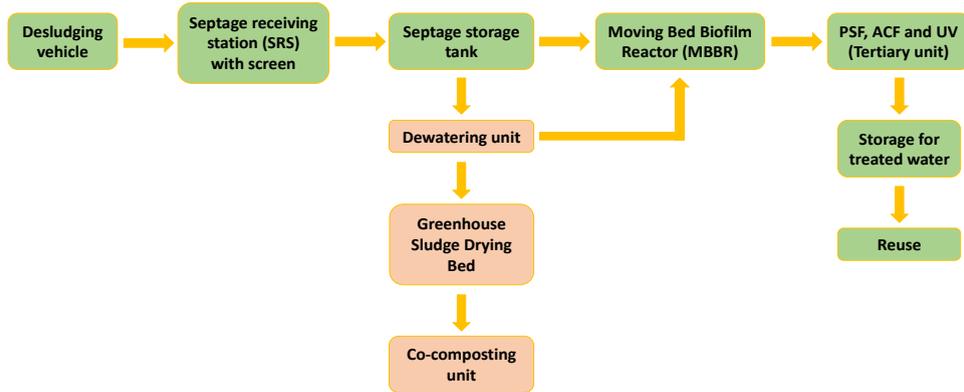
GHSD process at PNP FSTP



Technology: Greenhouse solar drying with dewatering unit (Screw press and dozing), Moving Bed Biofilm Reactor, Pressure Sand Filter (PSF), Activated Carbon Filter (ACF) and Ultraviolet (UV) Filtration.

Land requirement: The plant is constructed in a total area of 1.5 acres (0.45 acres built up). Out of this, the total area of the sludge drying beds is 74.3 sq.m. (0.02 acres).

Figure 14: Process flow diagram of the Periyanaickenpalayam (PNP) FSTP



Source: CSE

- **Step 1:** Screening of floatables and settlement of grit at the septage receiving station (SRS).
- **Step 2:** Homogenisation of the septage in the storage tank (with baffles).
- **Step 3:** Pumping of settled sludge from the collection tank to the sludge holding tank. The supernatant overflows to the MBBR tank by gravity.
- **Step 4:** Pumping of sludge from the sludge holding tank to the dewatering unit. The dewatering unit consists of: Polymer mixing system, Polymer maturation tank, Polymer dosing system, Dewatering – volute press (2 nos.)
- **Step 5:** Conveyance of the dewatered solids to the greenhouse sludge drying bed. After drying in GHSD, the sludge is conveyed to composting yard for further composting with the Municipal Solid Waste organic fraction. The filtrate from the volute flows to the MBBR.
- **Step 6:** Treatment of the overflow from holding tank, and filtrate from volute in the Moving Bed Biofilm Reactor (MBBR), the outlet from the MBBR is fed into the Sand & Carbon and the UV and stored in the treated water tank for reuse.



Mechanized dewatering machine at PNP FSTP

Climatic condition

The temperature in PNP is cool and humid throughout the year because of the location, viz., foothill of Nilgris, except during summers. The average rainfall is 50cm in a year. However, this does not affect the drying of sludge as the screw press and dozing unit are installed under a covered place and the rain doesn't even affect the final sludge drying due to the presence of greenhouse solar sheds.

Drying period

The sludge takes three days to dry in summers, however it takes around 4-5 days to dry in rainy seasons. The overall turn-around time for septage is 4-5 days, from the day of receipt into the FSTP. In the greenhouse sheds, the temperature is maintained at 56 per cent with a humidity of 85-99 per cent.



Sludge drying process through GHSD Mechanism at PNP FSTP

Performance quality (% reduction)

The data presented in Table 13 is derived from two CSE reports published in 2023, highlighting the changes in sludge concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) was within acceptable limits, but it rose above the recommended range after drying. As a result of natural drying, the moisture content significantly decreased from 99.66 per cent to 32 per cent, though it still exceeds the acceptable limit specified by the Fertilizer Control Order (FCO, 2009). The Carbon-to-Nitrogen (C:N) ratio appears to be outside the range suggested by the FCO. However, microbial analysis indicates that pathogen levels are extremely higher than the FCO limits, showing that sludge drying is not happening in a proper manner and it was insufficient in effectively killing the pathogens. The data shows approximately 91.99 per cent pathogen reduction due to natural drying.

In this FSTP it was also found that the value of faecal coliform and *E. coli* is the same which indicates that *E. coli* is the predominant bacteria present among the fecal coliforms. The result may also suggest that the contamination is largely due to *E. coli* and no other fecal coliform bacteria. This can be an indicator that the fecal contamination is recent or from a source where *E. coli* is the dominant bacteria.

Table 13: Characteristics of raw FS and dried sludge for FSTP at PNP

Parameters	Raw FS	Dried Sludge	FCO/WHO/USEPA Standards
pH	7.9	8.1	6.5–7.5
TS %	0.34	68	-
Moisture %	99.66	32	<10%
C:N ratio	-	8:1	20:1–30:1
Faecal coliform (MPN/g)	441176.5	35296	1000

Source: CSE

Economics (CapEx, OpEx, Ease of O&M)

The total capital cost of the PNP FSTP is divided into two sections:

1. Treatment process till the screw press was funded by the Bill and Melinda Gates Foundation which cost INR 2.82 cr.
2. Treatment process from MBBR to sludge drying beds by ULBs which cost INR 86 lakhs.

The total operational cost of the FSTP is 1.42 lakhs per month (which includes salaries of three staff members). This is borne by the five ULBs together.

Polymer mixing in dosing unit per 1,000 litres of faecal sludge is two kilograms. It costs INR 385 per kg.

ULB handles the O&M of the plant. However, they believe that the staff capacity needs to be increased.

Table 14: CapEx and OpEx of the plant and drying process for FSTP at PNP

Parameters	Cost in INR
CapEx of the plant	367 Lakhs
CapEx incurred for drying process	50 lakhs
CapEx incurred for drying process/ KLD	1 lakh
OpEx of the plant	17.04 lakhs/year
OpEx incurred for drying process	12 lakh/year
OpEx incurred for drying process/ KLD	0.24 Lakhs/year

Source: CSE

Energy consumption

The plants consume 1,600 units monthly, this generates an electricity bill of approximately INR 20–25,000 per month.

Reuse of by-products

The PNP FSTP site is producing 400 kg of sludge daily that is collected by a screw press dewatering machine. The collected sludge is dried and used for a co-composting process by mixing it with municipal solid waste that consists mostly of vegetable waste. Windrow composting method has been employed that takes 45–60 days total for the completion of the composting process. Windrow composting is an aerobic composting method in which series of composting platforms (windrows) are constructed on plain cement concrete with a slope of about 1 per cent to drain the excess water (leachate).

However, the utilization of co-compost has not been initiated yet. Moreover, FSTP site is facing some issues in conducting the composting process. Firstly, there is space constrain to carryout composting for such huge amount of biosolid. Also, there is random mixing of biosolid and vegetable waste as ratio of mixing of both has not been optimized yet. Plant is also not providing the proper sunlight exposure to bio-solid that is essential to make it free from micro-organisms. However, besides this, the plant produces 200kgs of compost daily.



Co-composting process at PNP FSTP

3.3.2 Screw press and drying bed based Faecal Sludge Treatment Plant at Loni, Uttar Pradesh

Loni, a town in Ghaziabad district of Uttar Pradesh state is located on the Gangetic plains of North India lying between major cities of Moradabad and Ghaziabad. To address the issues of waste generated from the on-site sanitation systems, municipality had undergone a project of implementing a 32 KLD capacity FSTP under AMRUT funding. The plant was designed to serve a population of 5.8 lakhs and is operational since 2021. The plant is equipped with hybrid technology which was adopted to improve the efficiency as well as lessen the land footprint. The total area required for the FSTP is 5830 sq m whereas treatment modules used for sludge drying process covered an area of 350 sq m which is six per cent of total area.

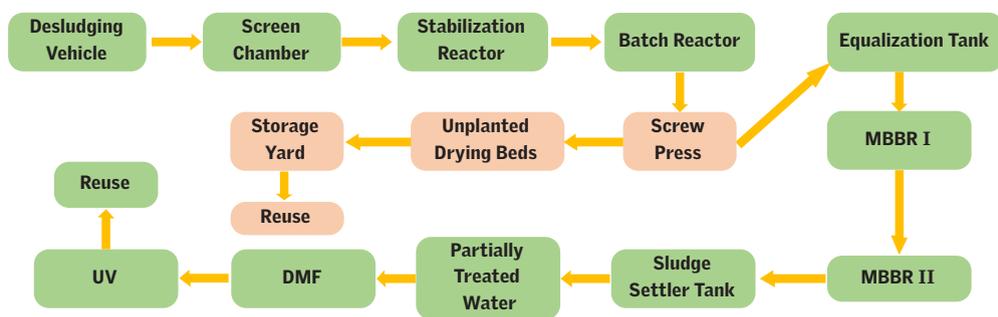




Mechanized dewatering and natural sun drying at Loni FSTP

The Loni FSTP operates on a hybrid system, combining nature-based processes with electro-mechanical equipment. Septage is first received in the screen chamber and then flows into a 64 KLD anaerobic stabilization reactor, where it is stabilized or homogenized with the help of a stirrer. The stabilized sludge is then transferred to a 32 KLD batch reactor, from where the slurry-like sludge is pumped to a screw press for dewatering. To increase the dewaterability of sludge, a polymer dosing is required in the screw press. The screw press can handle 3,000 liters of sludge per hour, with a daily operating time of four hours, producing 2,400 kg of sludge each day. The dewatered sludge is spread on sludge drying beds, while the separated liquid is directed to the MBBR system for further treatment. The drying process occurs on two drying beds. The liquid filtrate from these beds is also pumped to the Moving Bed Biofilm Reactor (MBBR) system. To further enhance the quality of treated water, it is passed through the Dual Media Filter (DMF) and Ultraviolet (UV) system.

Figure 15: Process flow diagram of the Loni FSTP



Source: CSE

Climatic conditions

In Loni, the hot season lasts for 2.8 months, from 14 April to 7 July, with an average daily high temperature above 35.5°C. The hottest month of the year in Loni is June, with an average high of 38.3°C and low of 28.3°C. The wetter season lasts 3.0 months, from 15 June to 13 September, with a greater than 30 per cent chance of a given day being a wet day.

The month with the wet days in Loni is July, with an average of 16.7 days with at least 0.04 inches of precipitation. The dewatered sludge from screw press at Loni FSTP requires further drying which is being taken place in drying beds. As, the drying beds are not covered with a roof, the sludge directly gets affected due to rainfall and humidity. In the summer, sludge takes about 15 days to dry, 20–25 days in winter and during the rainy season. After each drying cycle, the dried sludge is moved from the drying beds to a storage yard, where it is eventually provided to nearby farmers free of charge.



Dual Media Filter at Loni FSTP

Performance Quality
(% reduction)

The data presented in Table 15 is derived from two CSE reports published in 2023, highlighting the changes in concentration before and after the sludge drying process. The pH of the raw fecal sludge (FS) as well as dried sludge was found to be higher than the acceptable limits suggested by FCO, 2009. As a result of mechanized dewatering followed by natural sun drying, the moisture content significantly decreased from 98.5 per cent to 6.8 per cent, which is within the acceptable limit specified by the Fertilizer Control Order (FCO, 2009). The carbon-to-nitrogen (C:N) ratio appears to be outside the range suggested by the FCO. However, microbial analysis indicates that pathogen levels are much higher than the acceptable limit suggested by WHO and USEPA, which could be a sign of unsafe bio-solids. The data shows approximately 98 per cent reduction in the pathogen which may require further treatment.

Table 15: Characteristics of raw FS and dried sludge for FSTP at Loni

S.No.	Parameters	Raw FS	Dried Sludge	FCO/USEPA/WHO Standards
1	pH	7.8	8.0	6.5–7.5
2	TS %	1.5	93.2	-
3	Moisture %	98.5	6.8	<10%
7	C:N ratio	-	12:1	20:1–30:1
11	Faecal coliform (MPN/g)	1436400	25753	1000

Source: CSE

Energy consumption

The energy required for operating FSTP is being sourced by Solar system installed within the premises. This system costs INR 25 lakhs for its installation. There is no arrangements for power back-up, hence the machineries in plant faces disruptions many a times. There is no monthly bills against electricity uses as it is totally dependent upon the solar energy.

Economics (CapEx, OpEx, Ease of O&M)

CapEx includes expenses incurred for the treatment plant, ancillary infrastructure and procurement of desludging vehicle.

OpEx includes expenses incurred for the regular operations and maintenance of the equipment as well as salaries.

Table 16: CapEx and OpEx of the plant and drying process for FSTP at Loni

Parameters	Cost in INR
CapEx of the plant	465 Lakhs
CapEx incurred for drying process	50 lakhs
CapEx incurred for drying process/ KLD	1.56 lakhs
OpEx of the plant	18 lakhs/year
OpEx incurred for drying process	12 lakhs/year
OpEx incurred for drying process/ KLD	0.37 Lakhs/year

Source: CSE

The plant, equipped with electro-mechanical machinery, requires skilled and well-trained operators and workers. The mechanized dewatering machine demands regular polymer dosing. There are currently five workers on site, each handling different roles and responsibilities. The majority of the operation and maintenance (O&M) expenses are



Dried sludge and treated water reuse for horticulture within the premises

associated with the mechanized dewatering machine. The primary issue they encounter is clogging in the pipe from the screw press to the equalization tank. Additionally, the ring in the screw press needs to be replaced periodically, which incurs significant costs.

Reuse of by-products

Currently, the bio-solid is not being sold due to limited interest from farmers. Only a small quantity is being taken by nearby farmers free of charge. However, the municipality plans to sell it to farmers at approximately INR 12 per kg in the near future.

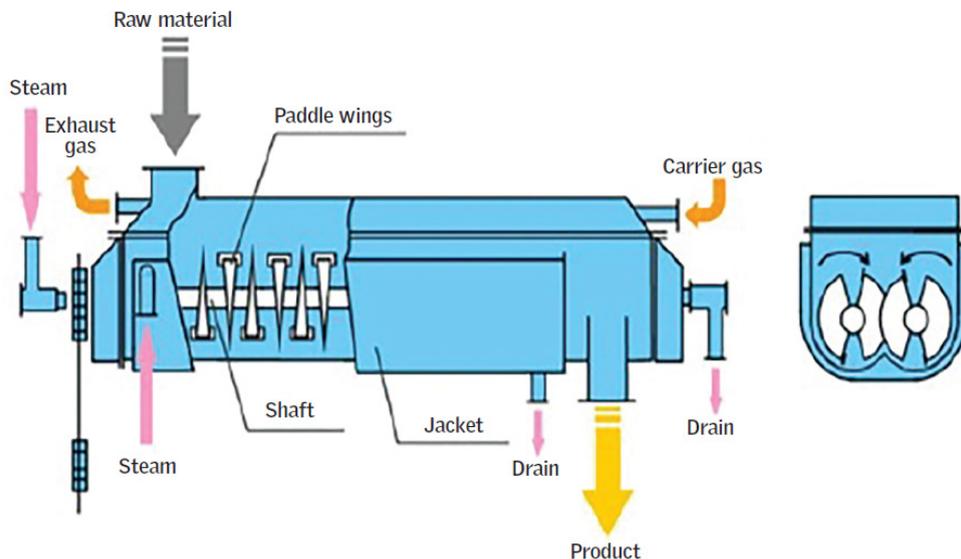
4. ALTERNATIVE SLUDGE DRYING TECHNOLOGIES

4.1 PADDLE DRYER

A paddle dryer is often used to dry wet materials like sludge, pastes, and thick mixtures. It works by heating hollow paddles and the walls of the dryer using steam or hot oil. When the wet material touches the heated paddles and walls, it starts to dry. The paddles are designed to clean themselves, so the material doesn't stick to them. As the product moves through the dryer, moisture is gradually removed.

This type of dryer is very useful for drying sludge, especially from equipment like volute presses, screw press, decanters (Centrifuges), mono belt presses, or filter presses. Wet sludge with about 85 per cent moisture can be fed directly into the paddle dryer, which can reduce the moisture content to less than five per cent. This method makes the process easier by eliminating the need for sun drying or storing the sludge on-site, helping improve waste management efficiency.²⁵

Figure 16: Schematic diagram of paddle dryer



Source: CSE

Process mechanism

It is a safe method of treating the pathogenic sludge. In the jacket shell body of paddle dryers there are two parallel shafts that have interleaved paddles. Each shaft has several hollow fan-shaped paddles which interleave with a certain spacing. There are two kinds of paddles: feed shear plane and return shear plane; the shaft rotates at low speed. A heating medium enters the hollow rotary shafts and paddles through a universal revolving joint. After heat transfer and drying, it is discharged through the revolving joint. The height of overflow weir can be changed to adjust residence time. In addition to this, the steam produced in the drying process is discharged through the escape hole with trace amounts of air.

This type of dryer is commonly used for drying dewatered sludge. Sludge with 20–25 per cent solids is fed into the dryer for thermal drying. The material is continuously introduced into the equipment, where it is agitated and mixed near the paddles. The paddle dryer features dual counter-rotating shafts with paddles, which are hollow to allow heat to transfer through them, causing the sludge above to begin evaporating. These shafts with paddles rotate counter direction to produce uniform heating and high rate of transfer rates. At the same time, the material is gradually dried by the heat conduction of paddle and jacket. Outlet sludge has less than 10 per cent moisture. Exhaust gases coming out can be treated by scrubber. Temperature of 100–140 degree is maintained for sterilization and hygienic treatment. Dry solids coming out can be used for making brick and in agriculture manure. This technology has been used in two FSTPs (Uppal and Kamareddy) in India to treat FS biosolids.

The paddle dryer at Uppal FSTP is equipped with IR de-contamination unit.



Paddle dryer at Uppal FSTP

Decontamination unit

In the de-contamination unit the sludge comprising 60–65 per cent are reduced to dried form by heating via IR-radiation which will ensure the pathogens and helminth eggs both will be destroyed, without taking away the nutrition value in the sludge. The unit consists of pulverize followed by hot air unit with conveying and IR radiation heads to heat up the sludge.



IR decontamination unit

Performance

Pathogen removal efficiency:

The solids content of the dried sludge produced by paddle dryer is typically in the range of 90–95 per cent. Its pathogen content should be undetectable so that solids dried using a rotary dryer should achieve Class A biosolids status.

Recommendations for improving performance: A sludge feed with a water content of around 60–65 per cent is required in paddle dryers to allow the sludge to move through the dryer without sticking.

Features of a paddle dryer²⁶

- Efficient drying of sludge and paste through direct contact
- Capacities up to 2.5 tonne per hour
- Low running and maintenance cost
- Compact construction–less floor area
- Minimum exhaust air quantity; no elaborate air cleaning equipment needed.

Table 17: Specifications of paddle dryer

Configuration Option

Capacity	60 sq. ft. to 3000 sq. ft. Heat Transfer Area
Heating Medium	Steam or Thermal Fluid Via Gas/Diesel, etc.
Energy Source	Electric, Wood, Coil, LPG, LDO
Material options	MS, SS, 304, SS, 316
Power Supply	3 phase, 50 Hz/60Hz, 415/380 Volt (as per area)

Source: CSE

Advantages of paddle dryer²⁷

- High thermal efficiency
- The heat transfer medium does not come into contact with the product
- Gas is not used to convey the product; off-gas flow is minimal
- Precise control of temperature
- Uniform product quality, thorough mixing and movement of the product
- Continuous process on a once-through basis
- High heat transfer area to process volume ratio, reduced floor space
- Pre-conditioning with recycle is typically not required
- Easy to operate, requiring minimal attention
- Safer than direct drying when processing combustible material
- Simple durable design for easy and low maintenance
- Enclosed process contains odours and hazardous materials

4.2 GEOTUBE DEWATERING SYSTEM

Geotube dewatering systems are prefabricated using high strength and quality seaming techniques into tubular, bag-like, or other forms with filling ports or other provisions for site filling. The systems are custom sized to save land space and are ideal for areas where space is a constraint. Geotubes are designed to optimize the solids retention and effluent discharge rate and quality making it a highly efficient and environment-friendly solution for various sludge dewatering applications.²⁸



Geotube sludge dewatering system at 10 KLD Warangal FSTP

Working principle and process mechanism²⁹

Dewatering with Geotube technology is a three-step process:

Step 1: Filling

Sludge (slurry material) is pumped into the Geotube. Environmentally-safe polymers are added to the sludge, which makes the solids bind together and water separate.

Step 2: Dewatering

Clear effluent water simply drains from the Geotube through the small pores in the specially engineered textile. This results in effective dewatering and efficient volume reduction of the contained materials. The volume reduction allows for repeated filling of the Geotube. Over 99 per cent of the solids are captured, and clear filtrate can be collected and recirculated through the system. The decanted water is often of a quality that can be reused/returned for processing or returned to native waterways without additional treatment.

Step 3: Consolidation

After the final cycle of filling and dewatering, the solids remain in the bag and continue to densify due to desiccation as residual water vapour escapes through the fabric. Volume reduction can be as high as 90 per cent. When full, the Geotube and contents can be deposited at a landfill, remain on-site, or the solids can be removed and land-applied when appropriate.

Performance

A study conducted by Banka Biloo Pvt Ltd on the 10 kld Warangal Faecal Sludge Treatment Plant (FSTP) highlighted the performance and efficiency of the Geotube dewatering system. The incoming septage, with an average Total Solids (TS) concentration of 29,615 mg/l, was reduced to 2,000 mg/l in the Geotube effluent, and further to around 1,300 mg/l in the final treated effluent.

Similarly, the average Total Dissolved Solids (TDS) of the septage, initially measured at 8,500 mg/l, dropped to 1,400 mg/l in the Geotube effluent and reduced further to approximately 1,000 mg/l in the polished effluent. The system's efficiency increased progressively, ranging from 70 per cent to 92 per cent, depending on the concentration of the influent.

Advantages of Geotube:

- Highly effective technology that produces high volume reduction and retention of solids
- High effluent discharge rate with clear filtrate that can be recirculated through the system
- Custom-sized tubes save expensive and limited land space
- Easy removal and disposal of solids
- Efficient, versatile and environmentally friendly solution reduces carbon footprint
- Reliable in all weather conditions and reduces risks in operational safety
- Cost effective, low maintenance and saves time.

Disadvantages:

- It is restricted to single time use and needs to be discarded after
- When stacking Geotube dewatering tubes, there are safety concerns related to deployment, pumping, and cleaning. These include walkway space, access to drainage channels, and getting up onto the tubes.
- Trained personnel are required for the Geotube process.
- Equipment needs to be washed and disinfected daily
- The larger the tube units, the greater the number of units, and the higher the stack, the greater the risk of issues.
- Requires large area to install.

5. FINDINGS AND RECOMMENDATIONS

This study examines five different sludge drying technologies implemented at FSTP sites across various geo-climatic regions of India. Due to differences in their working mechanisms, these technologies are not directly comparable—some operate through natural processes, while others incorporate electro-mechanical systems. The analysis focuses on factors such as performance efficiency in terms of reducing the moisture content and pathogens, economic viability, land requirements and operational ease.

The findings and recommendations of the study are as follows:

5.1 FINDINGS

This study, based on limited available data, aims to provide initial insights into the performance of various drying technologies for faecal sludge treatment in different climatic conditions across India. Due to the intermediate nature of sludge drying in the overall faecal sludge treatment process, data availability for dried sludge was found to be a challenge.

We selected four key performance indicators (KPIs) for our analysis:

- Moisture reduction percentage
- F. coli reduction percentage
- Capital expenditure (CapEx) per kiloliter (KL) of dried sludge
- Operational expenditure (OpEx) per kiloliter (KL) of dried sludge

While this preliminary investigation doesn't identify the optimal drying technology, several key observations emerged:

1. Performance efficiency of sludge drying technologies

Nature-based technologies generally outperformed electromechanical systems in terms of F. coli reduction. However, mix results are found in case of moisture reduction.

Bhubaneswar FSTP demonstrated good performance, likely due to its unique design as well as effective O&M and monitoring that enhanced sludge drying efficiency and reduced pathogen levels, particularly in challenging weather conditions.

Table 18: Comparative analysis of different sludge drying technologies

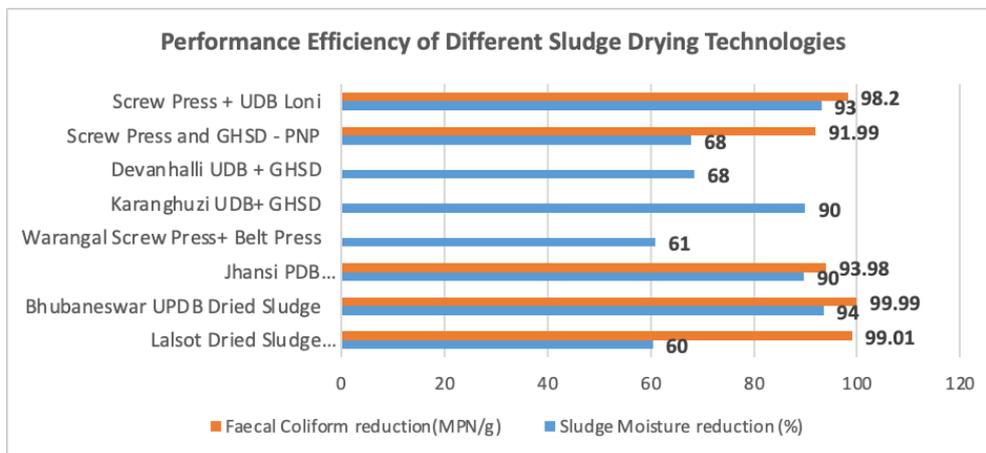
S. No.	Technology	Town	Capacity (in KLD)	Area required for sludge drying units	CapEx			OpEx			Drying Period	Moisture reduction (%)	Faecal Coliform Reduction (%)	Current Bio-solids Reuse Status (Yes/No)
					CapEx of the plant	CapEx incurred for drying process	CapEx incurred for drying process / KLD	OpEx of the plant	OpEx incurred for drying process	OpEx incurred for drying process / KLD / year				
1	Nature-based sludge drying technologies	Bhubaneswar	75	1070 Sq-m	3.54 Cr	1.2 Cr	1.6 Lakhs	21.84	9.6	0.12 Lakhs	Summer: 7-10 Days Monsoon: 15-20 Days	99.99%	Yes	
2		Laisot	20	1100 Sq-m	3.97 Cr	52.64 Lakhs	2.63 Lakhs	9.6	1.2 Lakhs	0.06 Lakhs	Summer: 7-10 Days Monsoon: 10-15 Days	99.01%	No (Planning stage)	
3	Electro-mechanical sludge drying technologies	Jhansi	18	804 sq.m.	5.1 Cr	1 Cr	5.5 Lakhs	55.44	16.6	0.9 Lakhs	Summer: 10-20 Days Monsoon: 20-40 Days	93.98%	No (Planning stage)	
4		Loni	32	350 Sqm	4.65 Cr	50 Lakhs	1.56 Lakhs	18	12	0.37 Lakhs	Summer: 12-15 Days Monsoon: 20-25 Days	98.20%	No (Planning stage)	
5		PNP	50	74.3 sq.m.	3.67 Cr	50 lakhs	1 lakh	17.04	12	0.24 Lakhs	Summer: 3 Days Monsoon: 4-5 Days	91.99%	Yes	
		Warangal	15	37 Sq-m	2.0 Cr	40.74 Lakhs	2.7 Lakhs	30.6	6	0.4 Lakhs	40 Mins for one cycle	-	No (Planning stage)	
		Devanahalli	6	100 sq. m.	1.11 Cr	20 lakhs	3.3 lakhs	11.7	3.9	0.65 Lakhs	16-18 Days	-	Yes	
		Karunguzhi	23.4	984 sq.m.	5.53 Cr	76 lakhs	3.25 lakhs	9.64	5.8	0.25 Lakhs	UDB: 20-25 Days GHSD: 10-12 Days	-	Yes	

Source: CSE

Lalsot and Warangal FSTPs encountered difficulties achieving satisfactory moisture reduction, even with additional set-ups such as polycarbonate shed and mechanised dryer respectively. Further investigation is needed to understand the reasons for high moisture content.

Jhansi FSTP, despite lacking a polycarbonate shed, showed good drying capacity but struggled to meet faecal coliform reduction standards.

Graph 1: Performance efficiency of different sludge drying technologies



Source: CSE

A. Climate and weather conditions play a crucial role in the sludge drying process.³⁰

Some FSTPs have adopted advanced technologies like greenhouse solar dryers to maintain optimal temperatures in unfavorable conditions. The drying period varies across locations, largely depending on the geo-climatic characteristics of each region. For instance, although Bhubaneswar and Lalsot use the same technology, their drying times differ due to their distinct climates. In summer, sludge dries in 7-10 days at both sites, but during the monsoon season, the drying period extends to 15-20 days in Bhubaneswar and 10-15 days in Lalsot. Similarly, Karunguzhi experiences a significantly shorter drying period compared to Devanahalli, even though both FSTPs utilize the same drying technology.

B. Belt dryer technology, when used alone, is not achieving the desired drying results and requires additional processing.

The drying process resulted in moisture reduction in sludge varying between 60 per cent and 93 per cent across different locations. The highest reduction was achieved at the Bhubaneswar FSTP, which uses the fully nature-based technology known as Unplanted Drying Beds. Conversely, the Warangal FSTP, employing an electro-mechanical process, achieved lower moisture reduction. Consequently, sludge dried using the belt dryer at Warangal requires additional treatment through pyrolysis, an incineration method.

QUESTIONABLE FINDING

Can natural sun drying provide more pathogen reduction than greenhouse solar drying? Also, can pathogen reduction be more in humid region than semi-arid region in case of same technology?

The extent of pathogen reduction in dried sludge correlates with the effectiveness of the drying process and the drying period. This study reveals that the highest pathogen reduction occurs at the Bhubaneswar FSTP (99.9 per cent), followed by the Lalsot (99.01 per cent) and Loni (98.2 per cent) FSTPs. The top two FSTPs utilize fully nature-based drying systems, while the Loni FSTP operates with a hybrid system. On the other side, sludge dried using greenhouse solar dryers showed lower pathogen reduction than natural sun drying. The team was unable to get the relevant data of 3 FSTPs such as Devanahalli, Warangal and Karunguzhi.

The team also found some contradictory findings with respect to moisture reduction. The moisture reduction at Bhubaneswar FSTP was found to be more than the Lalsot FSTP which actually is a contradictory situation against climate. Being a town of semi-arid region, Lalsot FSTP should have shown more reduction in moisture.

2. Economic feasibility of sludge drying technologies

Nature-based systems generally exhibited lower capital expenditure (CapEx) and operational expenditure (OpEx) compared to electromechanical technologies.

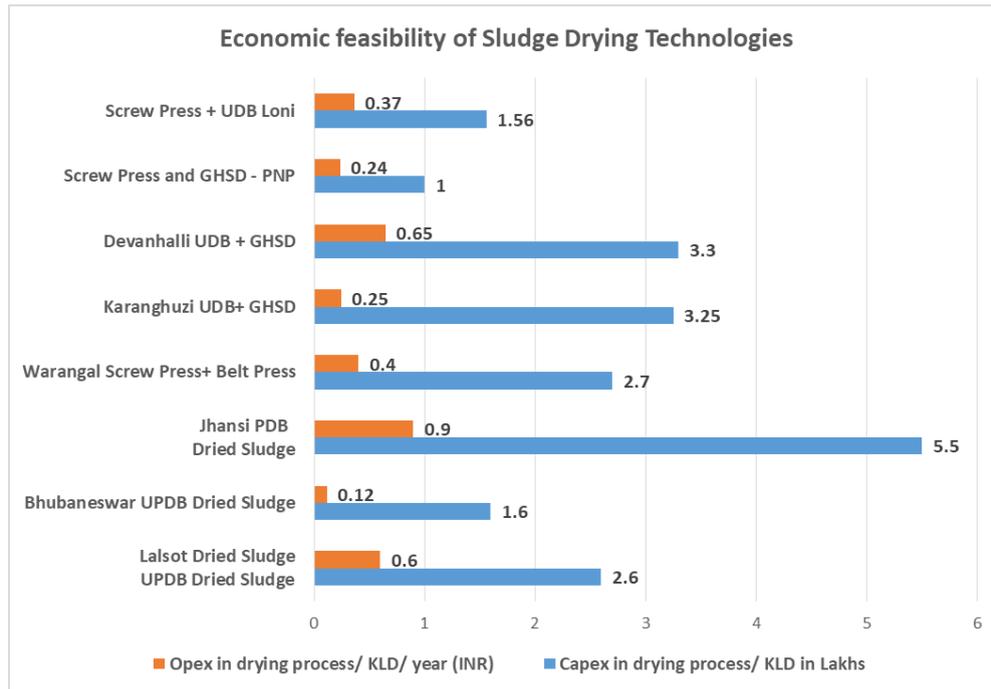
Electromechanical technologies typically have higher CapEx and OpEx. However, optimized designs and resource management, as seen in the PNP and Loni cases, can help mitigate these costs. (see Graph 2)

Following factors determine the capex and opex of the drying technologies.

A. *Capex of civil construction work of UDBs/PDBs will always be higher than hybrid and electro mechanical infrastructure. But in exceptions where high cost and advanced drying technologies are undertaken, the reverse may be true.*

- The data indicates that nature-based technologies, such as Unplanted Drying Beds (UDB) and Planted Drying Beds (PDB), require more land compared to electro-mechanical drying technologies like the screw press with sun drying, greenhouse solar dryers (GHSD), and belt dryers. Land availability plays a crucial role in determining the most suitable technology. The highest land requirements were observed at FSTPs in Lalsot (Rajasthan) and Bhubaneswar (Odisha), both utilizing UDB technology. In contrast, the Warangal FSTP (Telangana), which uses an electro-mechanical belt dryer, had the smallest land footprint.
- The capital expenditure (CapEx) for setting up an FSTP is largely influenced by the nature of the implementation, with more civil construction leading to higher costs. Among the five technologies studied, two rely entirely on civil construction for the

Graph 2: Economic feasibility of sludge drying technologies



Source: CSE

drying process, while the others use machinery that can be installed more quickly and with lower CapEx. The data shows a comparison of CapEx per KLD for different sludge drying technologies, revealing that nature-based technologies (UDB, PDB) have significantly lower costs (except few cases like Jhansi). The PNP FSTP, which uses a hybrid approach combining nature-based and electro-mechanical methods, has the lowest CapEx per KLD.

B. OpEx of similar natural sun drying technologies (PDB and UDB) varies greatly. This is not related to the process, but to the cost of labour operations varying in different plants.

- The operational expenditure (OpEx) for any sludge drying technology is influenced by various factors, including costs for human resources, routine and periodic maintenance of civil and electro-mechanical systems, energy consumption, additives, and wear and tear. Nature-based and electro-mechanical technologies differ significantly in terms of operational requirements; electro-mechanical systems typically demand more frequent daily maintenance, while nature-based systems require less daily effort but may involve more intensive periodic or long-term maintenance. Among the five technologies studied, the highest OpEx was reported at the Jhansi FSTP (6+12 KLD), followed by the Devanahalli FSTP, which uses a hybrid process with unplanted drying beds covered by a greenhouse sheet. The Bhubaneswar FSTP, which operates on a nature-based system, had the lowest operational costs for its operation and maintenance.

- However, the OpEx incurred by Planted drying beds at Jhansi FSTP is debatable because other FSTPs with similar technologies are running on way lesser OpEx. For example, Jhansi FSTP's O&M is INR 55 lakhs per annum whereas Chunar FSTP's OpEx is only INR 5 lakhs per annum which is 10 times lower than the Jhansi FSTP. This shows that the O&M contract of Jhansi has been done on higher costs than what is required actually. Also, if we compare two nature-based technologies (UDB and PDB), the data shows that Planted Drying Beds require highest OpEx and the Unplanted Drying Beds requires Lowest OpEx but the difference in O&M activities of both is not much. On the other hand, electro-mechanical technologies should have incurred more OpEx as it consumes more energy, requires skilled manpower and also requires regular maintenance of machineries but this analysis shows opposite picture.

C. Improper combination of sludge treatment modules at an FSTP

- Where two units or modules perform the same function but operate in different modes. Such setups can unnecessarily increase both the capital expenditure (CapEx) and operational expenditure (OpEx) of the plant. For example, at Loni FSTP prior to sludge drying, screw press and drying beds both dewater the sludge while only screw press can serve the purpose and drying beds could have been replaced with simple drying platforms.

5.2 RECOMMENDATIONS

1. There is a need to rationalize the OpEx, factorization to be done for cost incurred for human resources for arriving at some realistic per KL OpEx.³¹
2. **Lessons on re-designing of natural sludge drying beds** - Many FSTPs in India are running under capacity (as less as 30 to 40 per cent), so standby drying beds for sludge could be reduced to two or three, instead of six beds. A draft advisory issued by Central Public Health and Environmental Engineering Organisation (CPHEEO) for the design of FSTPs in small and medium towns also suggest economical design which avoids to have excess and ancillary infrastructures.³²
3. The choice of sludge drying technology should be based on whether it provides desired outcomes or not? Be it moisture reduction or pathogen reduction.
4. Repetitive modules serving the same purpose should be avoided towards achieving cost effectiveness as well as avoiding extra burden on regular operations and maintenance.
5. Selection of the drying technology NBS systems or hybrid should be based on the climatic conditions and land availability. NBS systems can be highly efficient in drying faecal sludge, especially in regions with favorable climatic conditions (high temperatures and low humidity). Areas having high rainfall can opt for having polycarbonate shed for better drying of sludge. If land is plentiful, a solar drying system may be a viable option, as it can be relatively space-efficient. However, in areas with limited space, a hybrid system that combines solar drying with mechanical components might be more suitable.

5.3 CONCLUSION

The study concludes that the choice of sludge drying technology must consider factors such as land availability, CapEx, OpEx, climatic conditions, and desired moisture reduction levels. Each technology has its strengths and weaknesses, making site-specific requirements critical in determining the most suitable solution.

Sludge drying is not a treatment of sludge, it is a process of preparing sludge ready for reuse or further treatment (if required). The Pathogen reduction as well as reuse potential depends on the extent of drying.

Therefore, sludge drying is also important for reuse for a circular economy. The most critical aspect of sludge drying is the cost effectiveness.

The study also reveals inconsistencies in operational costs, particularly among nature-based technologies, indicating potential inefficiencies in contract management and operational practices. Overall, these findings call for a more nuanced approach to technology selection, one that balances land requirement, financial viability, and environmental sustainability, while ensuring adaptable solutions for diverse geo-climatic conditions.

This study found unplanted drying beds with coverings as most prominent technology considering different factors like – OpEx, moisture reduction and pathogen reduction. It is also cost effective and appropriate for hot climatic regions.

6. ANNEXURES

6.1 QUESTIONNAIRE FOR PRIMARY DATA COLLECTION

Name of Town/Location _____

Capacity of FSTP _____

Technology _____

Coordinates _____

O&M Agency _____

Table 19: Performance quality (dried sludge)

Parameters	Dried sludge	Raw FS
Moisture content %		
Pathogen (F.Coli, E. Coli)		
Heavy metals		
C:N ratio		
pH		
TS (mg/l)		

Table 20: Parameters to evaluate

Drying period	
Factors affecting drying and performance	
CapEx of plant CapEx of drying units CapEx of drying units/KLD	
OpEx of Plant OpEx of drying units OpEx of drying units/KLD	
Energy consumption Total energy consumption Energy consumption in drying process	
Ease of O&M	
Possible reuse option	
Land requirement Total land required Land required by drying units	
Pros	
Cons	

6.2 COMPOST QUALITY STANDARDS AS PER SOLID WASTE MANAGEMENT RULES, 2016; FERTILIZER CONTROL ORDER, 2009; AND FERTILIZER CONTROL ORDER, 2013

Sl no.	Parameter	Organic compost FCO* 2009	Phosphate-rich organic manure FCO (PROM) 2013
1	Arsenic (mg/kg)	10.001	10
2	Cadmium (mg/kg)	5	5
3	Chromium (mg/kg)	50	50
4	Copper (mg/kg)	300	300
5	Lead (mg/kg)	100	100
6	Mercury (mg/kg)	0.15	0.15
7	Nickel (mg/kg)	50	50
8	Zinc (mg/kg)	1.000	1000
9	C/N ratio	<20	Less than 20.1
10	pH	6.5-75	(1.5 solution) maximum 6.7
11	Moisture % by weight, maximum	15.0-25.0	25.0
12	Bulk density (g/cm ³)	<1.0	Less than 1.6
13	Total organic carbon, % by weight minimum	12.0	79
14	Total nitrogen (N), % by weight, minimum	0.8	0.4
15	Total phosphate (P ₂ O ₅), % by weight minimum	0.4	10.4
16	Total potassium (K ₂ O), % by weight minimum	0.4	--
17	Colour	Dark brown to black	--
18	Odour	Absence of foul odour	--
19	Particle size	Minimum 90% material should pass through 4.0 mm IS sieve	Minimum 90% material should pass through 4.0mm IS sieve
20	Conductivity (as dsm ⁻¹), not more than	4.0	8.2

Note : FCO: Fertilizer control order; Tolerance limits 35 per FCO: compost : The sum of nitrogen, phosphorus and potassium nutrients shall not be less than 1.5 per cent in compost. For FROM : No. such directive.

REFERENCES

1. Walid Alalayah, Ayhan Demirba , Gaber Edris 2017. *Sludge production from municipal wastewater treatment in sewage treatment plant*. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. Accessible at: https://www.researchgate.net/publication/316172618_Sludge_production_from_municipal_wastewater_treatment_in_sewage_treatment_plant
2. F G Kootenaai, N Mehrdadi, R Nabi et al 2022. *Improvement of Sludge Dewatering by Ultrasonic Pretreatment*. International Journal of Environmental Research. Accessible at: https://www.researchgate.net/publication/362061751_Improvement_of_Sludge_Dewatering_by_Ultrasonic_Pretreatment
3. O Cofie, D Koné, S Rothenberger et al 2009. *Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics*. Water Research. Accessible at: https://www.researchgate.net/publication/222326560_Co-composting_of_faecal_sludge_and_organic_solid_waste_for_agriculture_Process_dynamics
4. A. Murray Muspratt, T. Nakato, C. Niwagaba, H. Dione et al 2014. *Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal*. Journal of Water Sanitation and Hygiene for Development. Accessible at: https://www.researchgate.net/publication/263788858_Fuel_potential_of_faecal_sludge_Calorific_value_results_from_Uganda_Ghana_and_Senegal
5. S Septien, J Pocock b, L Teba 2018. *Rheological characteristics of faecal sludge from VIP latrines and implications on pit emptying*. Journal of Environmental Management. Accessible at: <https://pmc.ncbi.nlm.nih.gov/articles/PMC6189870/>
6. Sunita Narain, Vinod Vijayan et al. 2023. *Evaluation of FSTPs and STP Co-treatment Systems across India: An insight into technology and performance*. Centre for Science and Environment, New Delhi. Accessible at: <https://www.cseindia.org/evaluation-of-fstps-and-stp-co-treatment-system-across-india-11712>
7. E. Tilley, L. Ulrich, C. Lüthichrome et al. *Compendium of Sanitation Systems and Technologies*. EWAG, Zurich. Accessible at <chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.iwa-network.org/wp-content/uploads/2016/06/Compendium-Sanitation-Systems-and-Technologies.pdf>
8. Pierre-Henri Dodane and Mariska Ronteltap 2014. *Unplanted Drying Beds*. Faecal Sludge Management Alliance. Accessible at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fsmttoolbox.com/assets/pdf/66.FSM_Ch07_Drying_Beds.pdf
9. Anon 2006. *Biosolids Technology Fact Sheet: Heat Drying*. Environmental Protection

Agency, USA. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.epa.gov/sites/default/files/2018-11/documents/heat-drying-factsheet.pdf>

10. J A Radaidah and Kamel K. Alzboon 2011. *Increase the Efficiency of Conventional Sand Drying Beds by using Intensive Solar Energy: A case study from Jordan*. 2nd International Conference on Environmental Science and Technology IPCBEE, Singapore. Accessible at: https://www.researchgate.net/publication/228450039-Increase_the_Efficiency_of_Conventional_Sand_Drying_Beds_by_using_Intensive_Solar_Energy_A_case_study_from_Jordan
11. Laura Thomson 2022. *Improving Sludge Drying Processes with a Solar Greenhouse*. AZoCleantech. Accessible at: <https://www.azocleantech.com/article.aspx?ArticleID=1552>
12. A A Elbaz, Ahmed Aboufotoh, E H Elgohary et al, M T Reham 2020. *Review Classification of sludge drying beds SDB (conventional sand drying beds CSDB, Wedge-wire, Solar, and Vacuum assisted and paved drying beds PDB)*. Journal of Materials and Environmental Sciences. Accessible at: https://www.researchgate.net/publication/340004077_Review_Classification_of_sludge_drying_beds_SDB_conventional_sand_drying_beds_CSDB_Wedge-wire_Solar_and_Vacuum_assisted_and_paved_drying_beds_PDB
13. Pierre-Henri Dodane and Mariska Ronteltap (n.d). *Unplanted Drying Beds*. Faecal Sludge Management Alliance. Accessible at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fsmttoolbox.com/assets/pdf/66.FSM_Ch07_Drying_Beds.pdf
14. Sunita Narain, Vinod Vijayan et al. 2023. *Evaluation of FSTPs and STP Co-treatment Systems across India: An insight into technology and performance*. Centre for Science and Environment, New Delhi. Accessible at: [http___cdn.cseindia.org_attachments_0.94973600_1683089188_evaluation-of-fstps-and-stp-co-treatment-systems-across-india-report-web%20\(6\).pdf](http___cdn.cseindia.org_attachments_0.94973600_1683089188_evaluation-of-fstps-and-stp-co-treatment-systems-across-india-report-web%20(6).pdf)
15. Sunita Narain, Vinod Vijayan, Arvind Singh Senger 2023. *Biosolids: A Report*. Centre for Science and Environment, New Delhi
16. Megha Tyagi and Vinod Vijayan 2023. *Best practices and strategies for pathogen-free compost production*. Centre for Science and Environment, New Delhi
17. Pierre-Henri Dodane and Mariska Ronteltap (n.d) *Unplanted Drying Beds*. Faecal Sludge Management Alliance. Accessible at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fsmttoolbox.com/assets/pdf/66.FSM_Ch07_Drying_Beds.pdf

18. Anon 2021. *Guidance document for design of FSTP based on drying bed technology*. Consortium for DEWATS Dissemination Society, Bangalore. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://cddindia.org/wp-content/uploads/FSTP-guidance-document-2021.pdf>
19. Anon (n.d). *Belt dryers*. Sludge Processing. Accessible at: <https://www.sludgeprocessing.com/process-and-operation/thickening-dewatering-drying/drying/belt-dryers/>
20. Girija R, Hiranya T, Krishna K, Ganapathy PG 2023. *Greenhouse Solar Dryers: A Cost-Effective Solution to Ensure Safe Application of Faecal Sludge in Agriculture*. African Water and Sanitation Association (AfWASA). Accessible at: extension://efaidnbmnnnibpcajpcgclefindmkaj/https://afwasakm.afwasa.org/wp-content/uploads/2023/06/GREENHOUSE-SOLAR-DYERS_-A-COST-EFFECTIVE-SOLUTION.pdf
21. Anon 2019. *Fecal Sludge Treatment in Karunguzhi, The FSTP Story*. Tamil Nadu Urban Sanitation Support Programme. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://tnussp.co.in/wp-content/uploads/2020/10/karunghuzhi-photo-story.pdf>
22. Anon 2020. *Insights from Faecal Sludge Management in Devanahalli- Five years of operations*. Consortium for DEWATS Dissemination Society, Bangalore. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj>
23. AMoorthy, RPradeep and RPai. *Improving the Performance of Unplanted Sludge Drying Beds (USDB) at Devanahalli, India*. Consortium for DEWATS Dissemination Society, Bangalore. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://cddindia.org/wp-content/uploads/2019/04/Sludge-Drying-Beds-Devanahalli.pdf>
24. Anon 2020. *Screw presses for sludge dewatering*. Sludge Processing. Accessible at: <https://www.sludgeprocessing.com/sludge-dewatering/screw-press/>
25. Anon (n.d). *Paddle/Sludge dryer*. Chemin Enviro Systems Pvt. Ltd. Accessible at: <https://cheminenvirosystems.com/products/paddle-dryer/>
26. Anon (n.d). *Sludge dryer (Paddle dryer)*. SNP Water Infra. Accessible at: <https://snpwaterinfra.com/sludge-dryer-paddle-dryer/>
27. Anon (n.d). *Paddle Dryers*. Indiamart. Accessible at: <https://www.indiamart.com/proddetail/paddle-dryers-22714601462.html?srltid=AfmBOopqkyTgBgUduDcEK1g2atPYJ-cH4z82PexdtX7Recz1XPbNyifc>
28. <https://www.tencategeo.us/en-us/products/GeoTube-systems/GeoTube-dewatering>

29. <https://www.tencategeo.eu/en/products/tencate-geotube/Dewatering-Geotube>
30. Anon 2021. *Faecal sludge and septage management in urban areas*. Niti Aayog. Accessible at: <chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.niti.gov.in/sites/default/files/2021-08/NITI-NFSSM-Alliance-Report-for-digital.pdf>
31. Depinder Singh Kapur, Pavan Kumar and Jyoti Parsad 2023. *Operation and Maintenance Cost of Faecal Sludge Treatment Plants in Uttar Pradesh*. Centre for Science and Environment, New Delhi. Accessible at: <https://www.cseindia.org/operation-maintenance-cost-of-faecal-sludge-treatment-plants-in-uttar-pradesh-11679>
32. CPHEEO draft advisory on FSSM in small and medium towns

Sludge management remains a critical challenge in India, with many cities struggling to select the most suitable sludge drying technologies. This report provides a comprehensive assessment of both nature-based and electro-mechanical sludge drying solutions, examining their efficiency, economic feasibility, and operational challenges.

Through case studies across multiple states, it presents a comparative analysis of various drying methods - including unplanted and planted drying beds, belt dryers, screw press with solar drying and greenhouse solar dryers. By offering a matrix-driven decision framework, the report serves as a valuable resource for engineers, planners and decision makers, ensuring informed technology selection and promoting sustainable sludge management practices across the country.



Centre for Science and Environment

41, Tughlakabad Institutional Area, New Delhi 110 062

Phone: 91-11-40616000 Fax: 91-11-29955879

E-mail: cse@cseindia.org Website: www.cseindia.org