STREAMLINING PATHOGEN MANAGEMENT IN FSTPs

Effective Technologies and Operational Guidelines

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Preface

The Swachh Bharat Mission was launched by the Prime Minister of India in 2014 with the objective of achieving the status of an open-defecation-free (ODF) country. The Mission was deemed successful when India declared itself open-defecation-free (ODF) in 2019. The country is now focusing on achieving ODF+ status that includes ensuring the sustainability of the ODF status, as well as the ODF++ status that ensures safe collection, conveyance, treatment and disposal of all faecal sludge and sewage in the country. Keeping this in mind, many faecal sludge treatment plants (FSTPs) have been constructed or are under construction in the country. The FSTPs are constructed for treating faecal sludge and septage (FS&S) that is generated from the onsite sanitation systems namely, septic tanks and pit latrines. A performance evaluation of FSTPS conducted by CSE shows that the liquid effluent generated from several FSTPs is non-compliant with existing Indian regulations (MoEF&CC, 2017) for COD, TKN and faecal coliform. It was observed that the solid residue generated from many FSTPs is high in pathogen content. Keeping this in consideration, the current report focuses on the reduction of pathogens in FSTPs by providing operational guidelines and best practices for the efficient use of treatment technologies so that the FSTP effluents/products are safe for reuse or disposal.

1. Introduction

Waste management is essential for the development of a nation. The management of human excreta, especially, is extremely important as it is rich in pathogens, posing risks to public health and the environment. Developing countries like India depend primarily on onsite sanitation systems (OSS) for the management of human excreta (faecal sludge [FS] and septage). An estimated 60 per cent of the households in urban India are connected with OSS to contain the FS and septage. Additionaly, a large number of toilets were constructed under the Swachh Bharat Mission (SBM) since its inception in 2014.[1] To manage the waste generated from the OSS and recently constructed toilets, several faecal sludge treatment plants (FSTPs) have been constructed or are under construction across the country. These FSTPs have been constructed by adopting diverse technologies depending on requirement.[2] CSE's study on the performance evaluation of FSTPs in the country has revealed that liquid effluent and biosolids generated from several FSTPs have pathogen content that is above the safe levels specified by the existing Indian and or global standards and is too high to be disposed into the environment or be used.[3,4] Hence, the current report focuses on measures that can be taken by the FSTP operators/managers to improve reduction in FS liquid effluent and biosolids in FSTPs. The report aims to provide operational guidelines for the efficient performance of treatment technologies to generate products that are safe for reuse.

All septage and FS treatment processes produce a liquid effluent and sludge residue that is referred to as biosolid. Both components need to be treated separately to reduce pathogen content which is particularly necessary when there is direct or indirect human exposure. Efficient and well-established pathogen removal technologies are already available for FS treatments, many of which were adapted from technologies used for sewage treatment.[5] FSTPs in India adopted most of these technologies, especially for liquid treatment. The report discusses, in detail, most of the technologies used in FSTPs in India,[6,7] a few additional efficient technologies used for pathogen removal in FS elsewhere,[8] their pathogen removal efficiency, advantages, limitations, and factors associated with pathogen removal, as well as measures to be taken to improve treatment performance. The study has identified promising technologies for pathogen removal, as well as their limitations. The study also identifies potential factors that can lead to treatment failure, and the measures to be taken to mitigate them.

2. Pathogens present in faecal sludge

Faecal Sludge (FS) contains four major groups of pathogenic organisms, including pathogenic bacteria, viruses, parasitic protozoa and helminths. These pathogens occur in raw FS and septage, and liquid effluent and biosolids generated from FSTPs. When humans come in contact with polluted water or food, these pathogenic organisms can cause illnesses. This poses a worldwide concern. Diarrhoea, hepatitis and fever are some of the illnesses that can affect humans from contact with pathogenic organisms. Such waterborne and foodborne diseases become a problem when using improperly treated effluent water and biosolids from FSTPs for irrigation and as a fertilizer respectively for agricultural crops because they are potential spreaders of pathogenic microorganisms. Research has shown that FS treatments are not efficient enough to bring pathogens down to safer levels in the sludge before using it for agricultural purposes.[9] Hence, it is important to know about the diverse groups of pathogenic organisms present in FS and the diseases caused by them in order to understand the potential health risks they impose on humans. A list of commonly excreted pathogens in human faeces and the diseases/symptoms caused by them in humans is given in Table 1. A brief description of two important pathogens present in faecal sludge that are of public health concern, *Salmonella* and *E. coli*, are provided below.[10]

2.1 *Salmonella*

Salmonella spp. are rod-shaped, highly-motile, Gram-negative, non-spore-forming, facultatively anaerobic bacteria. This group consists of a range of very closely related bacteria that belongs to the genus *Salmonella* and the family *Enterobacteriaceae*. *Salmonella* spp. are frequently found in sewage. They are also the most prevalent bacterial pathogens of public health concern.

Pathogenicity: From insects to mammals, *Salmonella* spp. can cause diseases in all organisms. Enteric fever is a collective term given to invasive infections caused by *S. typhi* and *S. paratyphi* that cause typhoid and paratyphoid fever respectively. *S. typhi* is a pathogen that only uses humans as its natural host. Several other *Salmonella* serotypes cause salmonellosis, a food-borne diarrhoeal disease.

Properties of significance in sewage treatment: *Salmonella* spp. exhibit psychrotrophic properties and actively grow within a wide temperature range (10–54°C). *Salmonella* spp. are resistant microorganisms that readily adapt to extreme environmental conditions and have the ability to survive under hostile environmental conditions. These characteristics make them the indicator of choice for monitoring the effectiveness of biosolid pathogen reduction (US EPA 1995).

2.2 *Escherichia coli* O157:H7

Escherichia coli (*E. coli*) is a rod-shaped Gram-negative bacterium, which belongs to the family *Enterobacteriaceae*. They are facultative, oxidase-negative anaerobes and produce gas from glucose. *E. coli* is a member of the physiological gastrointestinal flora bacterium species for humans and warm-blooded animals.

Pathogenecity: *E. coli* belongs to the normal intestinal flora and is a facultative pathogen for human beings. However, some *E. coli* serotypes are pathogenic, among them is the enterohaemorrhagic strain *E. coli* (EHEC) O157:H7 which causes gastrointestinal disorders such as bloody diarrhoea, cramping and abdominal pain and the infectious "hemolytic uremic syndrome". The infectious dose of *E.coli* O157:H7 is only 10 cells and it is able to survive in an environment for a long time without a host.

Table 1: Selected pathogens that may be excreted in faeces, and related disease symptoms[11]

Type of pathogen	Pathogen name	Disease/disease symptoms caused by the pathogen in humans
Bacteria	*Aeromonas* spp.	Enteritis
	Campylobacter jejuni/coli	Campylobacteriosis - diarrhoea, cramping, abdominal pain, fever, nausea, arthritis, Guillain-Barré syndrome
	Escherichia coli (EIEC, EPEC, ETEC, EHEC)	Enteritis. For EHEC there are also internal haemorrhages that can be lethal
	Salmonella typhi/paratyphi	Typhoid/paratyphoid fever – headache, fever, malaise,anorexia, bradycardia, splenomegaly, cough
	Salmonella spp.	Salmonellosis – diarrhoea, fever, abdominal cramps
	Shigella spp.	Shigellosis – dysentery (bloody diarrhoea), vomiting,cramps, fever; Reiters syndrome
	Vibrio cholera	Cholera – watery diarrhoea, lethal if severe and Untreated
Virus	Adenovirus	Various; respiratory illness, here added due to enteric types (see below)
	Enteric adenovirus types 40 and 41	Enteritis
	Enterovirus types 68-71	Meningitis; encephalitis; paralysis
	Hepatitis A	Hepatitis – fever, malaise, anorexia, nausea, abdominal discomfort, jaundice
	Hepatitis E	Hepatitis
	Poliovirus	Poliomyelitis – often asymptomatic, fever, nausea, vomiting, headache, paralysis
	Rotavirus	Enteritis

Paraasitic Protozoa	*Cryptosporidium parvum*	Cryptosporidiosis – watery diarrhoea, abdominal cramps and pain
	Cyclospora histolytica	Often asymptomatic; diarrhoea; abdominal pain
	Entamoeba histolytica	Amoebiasis – often asymptomatic, dysentery, abdominal discomfort, fever, chills
	Giardia intestinalis	Giardiasis – diarrhoea, abdominal cramps, malaise, weight loss
Helminths	*Ascaris lumbricoides*	Generally no or few symptoms; wheezing; coughing; fever; enteritis; pulmonary eosinophilia
	Taenia solium/saginata	Taeniasis
	Trichuris trichura	Trichuriasis - Unapparent through to vague digestive tract distress to emaciation with dry skin and diarrhoea
	Hookworm	Itch; rash; cough; anaemia; protein deficiency
	Schistosoma Spp. (blood fluke)	Schistosomiasis, bilharzias

3. Analysis of pathogens present in liquid effluent and biosolids from FSTPs: indicator organisms[12]

Culture-based methods are traditionally used for detecting microorganisms. However, their usefulness is limited due to the occurrence and prevalence of pathogens, and because many are not easy to culture, cannot be cultured, or are otherwise expensive to isolate and enumerate. Since it is not practical to detect and monitor all known pathogens, indicator organisms are employed as surrogates for the presence of faecal contamination, hence detecting the possible presence of pathogens. A good indicator should be present in the pathogen source and absent from unpolluted areas. It should be present in abundance, be non-pathogenic and easy to culture, and exhibit behaviour that is similar to the pathogen. The most widely used indicator organisms are enteric bacteria, primarily due to the ease and low cost of the relevant culture detection methods. These enteric bacteria are also called coliform bacteria or coliforms. Faecal coliform, the coliform bacterial group specific to mammalian intestines, have been used as an indicator for assessing the pathogens present in discharge water from sewage treatment plants in India (MoEF&CC, 2017). *E. coli*, a predominant member of the faecal coliform, in particular, is considered a mandatory faecal indicator by the United States Environmental Protection Agency (USEPA) and European Union (EU) for monitoring recycled water and wastewater discharges.

However, faecal indicator organisms are only linked to the presence or absence of faecal contamination (and hence risk of pathogen presence), but they do not necessarily give any information about the movement, removal, or inactivation of pathogens. Bacterial faecal indicators have been shown to be poor surrogates for viruses and protozoans. Due to differences in size and structure, it is unlikely that all groups of pathogens (bacteria, viruses, protozoa, and helminths) will behave in the same way, therefore it is not ideal to have a single, universal microbial indicator. Therefore, there is a need for process indicators or model organisms, which are defined as groups of organisms that are indicative of pathogen behaviour in similar environments. The process indicators for different groups of pathogens present in faecal sludge are given in Table 2. Nevertheless, testing for all the process indicators is expensive and time-consuming and requires skilled personnel, resources, and sophisticated equipment. Hence, they can be tested on a case-by-case basis, and are particularly necessary during periods of disease outbreaks.

Table 2: Process indicators for different groups of pathogens present in FS

Pathogen group	Examples of pathogen group	Process indicators
Bacteria	Enteric pathogenic bacteria (eg. *Shigella, Campylobacter, Salmonella*)	*E. coli*
Virus	Human enteric viruses (eg. adenoviruses, noroviruses)	Bacteriophage: somatic coliphage, F-RNA coliphage MS2
Protozoa	Pathogenic protozoa (eg. *Giardia, Cryptosporidium*)	Clostridium perfringens spores
Helminths	Parasitic helminths (eg. *Ascaris lumbricoides, Taenia solium*)	Ascaris ova

4. Technologies for pathogen reduction in liquid effluent from FSTPs and recommendations for effective pathogen management

Tertiary treatment and disinfection

The final and possibly the most important step in tertiary treatment (in terms of microbial safety, at least) is the disinfection of the effluent prior to reuse. It is the final polishing step required to achieve the desired quality of liquid effluent and is mediated by a variety of chemical, biological, and physical processes. The selection of treatment processes is dependent upon the desired end use. Removal of nutrients such as nitrogen and phosphorus is an essential step in the treatment process as they promote the growth of microorganisms. Therefore, appropriate treatment should be provided to reduce or remove these nutrients from the liquid effluent prior to tertiary treatment.[13]

The technologies used for the disinfection of FS effluents have been adapted from those used in wastewater/sewage treatment, which have advanced with time. However, only a few of them have been used for treating the FS liquid effluent, which is several times lower in quantity compared to sewage. Depending on the treatment process, the techniques used for disinfection can be classified into two types—chemical and physical methods. The methods commonly used for the treatment of FS liquid effluent are given in Table 3. Many parameters, including water, pH, temperature, type of microorganisms, type of disinfection, disinfectant dose, contact time, and inorganic and organic material in water, are known to influence disinfection.

Table 3: Technologies for pathogen inactivation of liquid effluent from FSTPs

Method of disinfection	Treatment technology
Chemical methods	• Chlorination • Ozonation

Physical methods	• UV radiation
	• Solar disinfection
	  ◦ Polishing pond
	  ◦ Maturation pond
	  ◦ Solar pond
	• Filtration
	  ◦ Membrane filter
	  ◦ Sand filter
	  ◦ Activated carbon filter

4.1 Chemical methods of disinfection

4.1.1 Chlorination[14]

Chlorination has been used for many decades and is the leading technology for disinfecting recycled water. Chlorine has high oxidizing capacity and is mostly used in high concentrations to kill pathogens, although high dosages can cause the formation of harmful by-products.

Mode of action: Chlorine reacts with the cell membrane and alters or damages vital cell functions. Exposure to chlorine causes stress to microorganisms via irreversible cell injuries and in some cases, it causes bacteria (e.g., *Salmonella typhimurium*) to enter a viable non-culturable state (VBNC) if the dose is not high enough to cause complete cell death.

Technology description: Chlorine is added to effluent water for predetermined periods of time and is designed to optimize microorganism exposure and inactivation following which any residual chlorine is neutralized prior to discharge into the environment or water body.

Pathogen removal efficiency: By convention, chlorine disinfection targets are set by contact time, or CT, which is measured as the product of the chlorine dose (in mg/L) and time (in minutes). It is therefore possible to achieve the same CT using a high dose/short time or low dose/long time. The chlorine CT is affected by the level of free available chlorine, which is determined by temperature, pH and formation of chlorine complexes with other compounds present in reused water which has been discussed below. The CTs for chlorine disinfection of drinking water or wastewater have been determined for the major enteric pathogens. These CT values, defined in many guidelines, are provided in Table 4 below.

Table 4: Chlorine CT values for major enteric pathogens for pathogen inactivation of liquid effluent from FSTPs

Pathogen group	Pathogen name	Chlorine CT	Inactivation achieved
Enteric bacterial pathogens	*Salmonella*	≤1 mg min/L	100%
	Campylobacter	≤1 mg min/L	100%
	E. coli	≤1 mg min/L	100%
Protozoan parasites	*Cryptosporidium*	15,300 mg min/L	3 $\log_{10}$ reduction
	Toxoplasma	>144,000 mg min/L	

Factors affecting pathogen removal efficiency:

High solids content: The presence of high amounts of organic and inorganic solids (particles) reduces the chlorine disinfection (therefore increases chlorine demand) due to the following:

i. Organic matter utilizes free residual chlorine and hence decreases its availability for disinfection,

ii. Organic matter stabilizes the bacterial cell membrane and makes them resistant to chlorine

iii. The solid particles embed the bacterial cells inside them, reducing access to disinfectants. Hence, high solids content demands a high initial chlorine concentration that is required for chlorine to penetrate/diffuse at a high rate through the particles to reach the embedded pathogens and inactivate them.

Bacteria associated with particles also results in a 'tailing' effect which is characterized by no further increase in the inactivation of microorganisms even after increased amounts of disinfectant are applied.

Temperature: Temperature is inversely proportional to CT. Hence, as the temperature decreases, especially in colder regions or during winters, much higher CTs are required for pathogen inactivation in cold water. For instance, a CT of 8 mg min/L is required for the inactivation of viruses at 5 °C, compared to a CT of 3 mg min/L at 20 °C.

High ammonia: Achieving the desired CT in treated sewage/FS effluent water can be more difficult compared to drinking water because of the higher chlorine demand in (ammonia-rich) effluent water. The presence of ammonia in the wastewater that has been treated with chlorine results in the formation of a compound called chloramine, which has several times lower oxidation potential than chlorine. This, not only makes CT calculation more complex, but also demands requirement of much higher CTs to achieve the same level of disinfection as chlorine.

Measures to be taken to increase the efficiency of disinfection:

- Solid-liquid separation technologies like settling-thickening tanks and stabilization reactors should be implemented with effective operation before the treatment of FS liquid effluent. This will enable the maximum removal of solids from the liquid effluent by stabilization and/or sedimentation. This will also aid in increasing the efficiency of secondary and tertiary treatment units due to the presence of less suspended solids for treatment. Installation of tertiary treatment units like ultrafiltration, sand filter (to reduce inorganic sand particles), and activated carbon filter (to remove organic compounds) before chlorination with proper operation and maintenance will further increase the efficiency of chlorine disinfection by removing particulate matter.

- Ammonia (nitrogen) should be removed/reduced prior to chlorine disinfection which prevents/reduces the formation of harmful by-products and poor oxidising agents like chloramine. This results in the decrease of overall treatment cost due to reduced chlorine demand as well as reduction in the high cost involved in the removal of harmful by-products like chloramine.

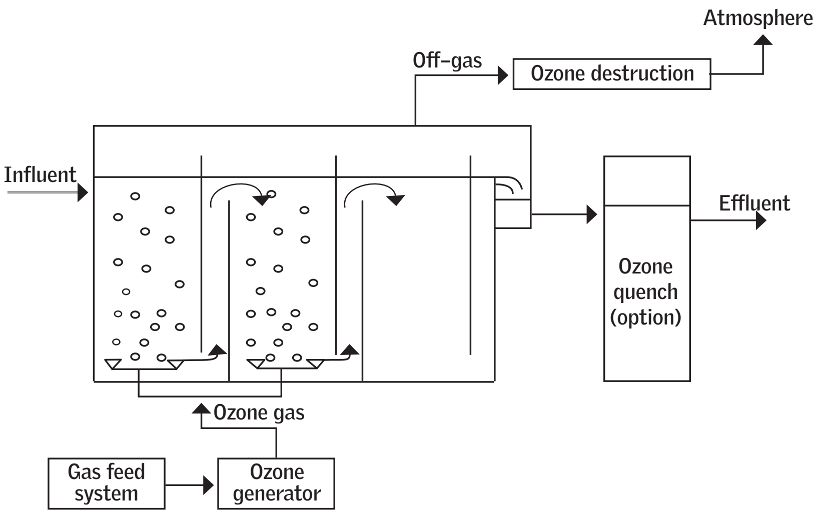
Advantages:
- Chlorine disinfection requires short to moderate contact time.
- Chlorine disinfection procedure is very old and well established, and its design and operating characteristics are also well understood. It is also cheap compared to alternatives such as ozone.

Disadvantages/limitations:
- A major disadvantage of chlorination is that the majority of protozoans with cyst forms (*Toxoplasma, C. parvum,* and *G. duodenalis*), helminths, and certain strains of bacteria are highly or moderately resistant to chlorine.
- After disinfection, dechlorination is generally carried out to remove residual chlorine, which increases the overall cost of the process. This step is critical to protect the environment that receives any wastewater discharges because chlorine and derivatives (e.g., chloramines) are toxic to many aquatic organisms.

4.1.2 Ozone[15]

Another chemical method of disinfection is ozonation which is done by using ozone gas, a potential disinfecting agent. Ozone has been proven to be effective against viruses, protozoan cysts, and helminth eggs. However, ozone has low efficiency of helminth inactivation at economical doses.

Figure 1: Schematic representation of ozone disinfection system



Mode of action: Ozone is a highly reactive molecule with an oxidation potential of 2.07 V. Moreover, under certain conditions, it can generate secondary oxidants such as hydroxyl radicals which have a reactivity that is even higher than ozone. Due to these characteristics, ozone has the capacity of reacting with several cellular constituents, such as the cell wall and DNA structures. These reactions damage the cell walls and DNA structures, thus killing or inhibiting the growth and multiplication of microorganisms.

Technology description: Ozone (O_3) is produced by the reaction between singlet oxygen (O) and oxygen molecule (O_2), and it is highly unstable because of which it is generated onsite.

Most wastewater treatment plants generate ozone using high electric discharge in ozone generators or ozonators using air or pure oxygen as feed-gas. The generated ozone gas, which is highly insoluble, is uniformly mixed in the water to be treated in contactors in optimum doses to minimize release of harmful unused gases (off-gases). The off-gases are either recycled or destroyed (see *Figure 1: Schematic representation of ozone disinfection system).*

Pathogen removal efficiency: Efficiency is high for disinfection of bacteria and some protozoa, and very high for disinfection of viruses. The optimal ozone dose for disinfection could range from 2–15 mg O_3/L, depending upon the effluent organic matter load.

Factors affecting pathogen removal efficiency and measures to be taken to increase the efficiency of disinfection

Dissolved organic matter and suspended solids also consume oxidant species of ozone and hence, reduce the disinfection ability. Therefore, the required ozone dose and contact time for efficient disinfection are highly dependent upon the effluent characteristics. The use of treatment units that remove particulate matter like sand and carbon filters before ozonation can improve treatment efficiency.

Generally, ozone systems are considered expensive mainly due to the low ozone usage efficiency. It was observed that energy consumption (while improving disinfection performance) could be reduced in a reactor with a baffle configuration by increasing the number of vertical baffles. Thus, proper design and control may lead to suitable ozone-based disinfection systems.

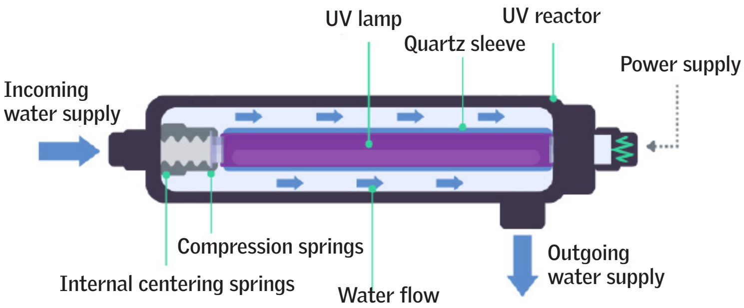
Advantages:

- Ozone is more effective than chlorine in destroying viruses and bacteria.
- The ozonation process utilizes a short contact time (approximately 10–30 minutes).
- Removal of harmful residuals is not required as ozone decomposes rapidly.
- As ozone is generated onsite, there are fewer safety problems associated with shipping and handling.
- Ozonation elevates the dissolved oxygen (DO) concentration of the effluent and hence, raises the DO level in the receiving waterbody.

Limitations:

- Higher cost and complexity than chlorination and needs to be generated on-site.

Figure 2: Closed pipe UV reactor



Source: waterfilterguru.com

- Needs to be applied to effluents with low organic matter and suspended solids contents.
- Leads to the production of hazardous products (off-gases) which must be destroyed to prevent worker exposure.

4.2 Physical methods of disinfection

4.2.1 Ultraviolet radiation[16]

An effective alternative to chemical disinfection is ultraviolet (UV) radiation, which is a physical process that involves exposing water to a UV (UV-C) light source, usually a UV lamp enclosed in a quartz sleeve within a stainless-steel pipe or suspended in a concrete channel, thereby getting disinfected. It is a widely used and well-characterized disinfection process.

Mode of action: The UV light spectrum can be split into UV-C (200–280 nm), UV-B (280–320 nm), and UV-A (320–400 nm), with only UV-C used for disinfection. The other components of UV (UV-B and UV-A) occur in natural sunlight. Key biological components required by microorganisms are DNA and RNA, these molecules absorb light at 260–280 nm and can be damaged by UV. The germicidal wavelength of UV light is 254 nm, which is the wavelength that causes maximum DNA damage by inducing DNA adducts called thymine dimers, which hinder normal transcriptional and DNA replication processes and prevent cell division. Other wavelengths of UV across the spectrum cause cell death by damaging critical proteins that are required for cell function. UV radiation provides effective inactivation of bacteria, protozoa, and some viruses.

Technology description: There are two types of UV lamps used for disinfection—low-pressure UV lamps, which produce UV light of around 254 nm, and medium-pressure lamps, which produce UV light of range 200–300 nm. There are two main formats for UV reactors, open channels, where UV lamps encased in quartz sleeves are suspended in the channel as water flows through it, and closed pipe systems, which are normally constructed from stainless steel with the lamps enclosed in a quartz sleeve and placed in the middle of the pipe, and the water flows through the stainless-steel pipe and gets disinfected as shown below (see *Figure 2: Closed pipe UV reactor*). Closed pipe systems are generally used in FSTPs as the volume of water generated is lesser.

Pathogen removal efficiency: UV is particularly effective against bacteria and some enteric protozoans (*Giardia* and *Cryptosporidium*) but some viruses, adenovirus in particular, have high UV resistance. In the case of adenovirus, medium pressure UV is more effective, with a lower wavelength of around 220 nm associated with the inactivation. UV has also been shown to cause a reduction of some helminths' eggs (*Ascaris lumbricoides*), which are one of the most resistant pathogens to other disinfection processes. However, the reduction is very less (see *Table 5: UV doses for inactivation of different pathogens*).

Table 5: UV doses for inactivation of different pathogens

Pathogen group	Pathogen	UV dose	Reduction observed
Protozoa	*Cryptosporidium parvum* oocysts	25 mJ/cm^2	3 $\log_{10}$
	Giardia duodenalis	40 mJ/cm^2	4 $\log_{10}$
Virus	Pathogenic viruses	30-40 mJ/cm^2 (Low pressure)	4 $\log_{10}$
	Adenoviruses	200 mJ/cm^2	4 $\log_{10}$
Helminths eggs	*Ascaris lumbricoides* eggs		0-1.5 $\log_{10}$

Factors affecting pathogen removal efficiency

High solids content: Turbidity, suspended solids and dissolved organic carbon affect the efficiency of UV. The presence of organics causes attenuation of the light. Solid particles can shield microorganisms in different ways by providing shading (≥10 mm) or partial absorption of the UV energy to reduce the effective dose, or by scattering the light (inorganic silica).

Bacterial flocs and biofilm: Bacteria, if present in high densities, can contribute to the formation of particles by forming aggregates, a natural phenomenon known as bioflocculation. This is often mediated by an exopolymeric substance (EPS) produced by microorganisms. This substance not only holds the bacterial floc together but also provides protection to the enmeshed bacteria by absorbing UV radiation. Consequently, bacterial flocs are also a cause of tailing. High densities of virus particles or protozoan (oo) cysts can also contribute to the formation of aggregates. This aggregation of microorganisms presents a challenge for measuring UV dose-responses.

UV Lamp: Lamp sleeve fouling, and lamp aging affect the efficiency of UV.

Measures to be taken to improve the efficiency of disinfection:

- Attenuation of the light caused by organics can be overcome by the use of sufficient lamp power. UV lamps should be regularly monitored for performance and should be replaced with a new lamp whenever there is a dip in performance which is caused due to a decrease in UV radiation due to an aging lamp. The sleeves of a UV lamp should be regularly cleaned to remove fouling which reduces the intensity of light.
- Tertiary treatment units like ultrafiltration, sand filter (to reduce inorganic sand particles), and activated carbon filter (to remove organic compounds) should be installed before UV treatment to reduce particulate matter, thereby increasing the efficiency of UV disinfection.
- The appropriate dose of UV for sufficient time should be provided to reduce the high densities of different groups of microorganisms (bacteria, protozoa and viruses) which can prevent the formation of microbial aggregates which are more resistant to disinfection.

Advantages:

- UV radiation is often preferred to chlorination because it requires fewer steps, and is safer compared with handling chlorine gas or other methods of generating chlorine.
- Avoids the production of disinfection by-products.

Limitations:

- UV disinfection tends to be more expensive than chlorination, especially for building the required infrastructure.
- It does not provide any residual disinfection, which means that any surviving microorganisms can regrow post disinfection and also that if there is any subsequent contamination of the water (e.g., due to a pipe break)

then there is no disinfectant to inactivate any introduced contaminants.

- Many microorganisms have systems for the repair of UV-induced DNA damage, which means that they can regain the capacity to grow or cause infection if the level of UV damage is not enough to overcome the capacity of these repair systems.

4.2.2 Solar disinfection[17]

Sunlight is known to be a pertinent factor governing the infectivity of waterborne pathogens in the environment. Sunlight is used as the final disinfection step to eliminate pathogens in various technologies, including Decentralized Wastewater Treatment Systems (DEWATS), waste stabilization ponds and constructed wetlands.

Mode of action: Sunlight inactivates pathogens (bacteria, viruses) via endogenous or exogenous inactivation. Endogenous (or direct) inactivation is promoted by internal chromophores, such as the nucleic acid or aromatic amino acids, which absorb light in the solar range (UV-B) and gets degraded, thereby inactivating the pathogen. In exogenous (or indirect) inactivation, reactive species are produced by pathogen-independent chromophores present in a solution, which then oxidise/degrades and inactivates the pathogens present in the solution.

Technology description

Polishing pond: The polishing ponds of DEWATS technology for FS treatment uses solar energy to remove pathogens. The polishing pond is the final step in the treatment in DEWATS. This follows processes that have already removed BOD and TSS. Its main purpose is to remove residual organics (by oxidation) and pathogens (by sunlight) which is carried out in an open pond that receives sufficient sunlight and oxygen. An installed aerator, and algal growth in the pond further increases dissolved oxygen content required for the oxidation of residual organics by bacteria.

Maturation ponds: Maturation ponds, deployed after facultative ponds and constructed wetlands, provide a simple pathogen reduction option using sunlight. Maturation ponds are designed for pathogen removal; their shallow depth, typically 1–1.5 m, allows sunlight to penetrate to the bottom of the pond and inactivate pathogens. Like the polishing pond of DEWATS, maturation ponds are also designed only to remove pathogens and hence, must follow processes that have already removed organics and suspended solids. Maturation ponds should have a length-to-width ratio of at least 2:1 and up to 10:1, with 2:1 ratio appropriate for two or more ponds in series. Since the solids content and sludge accumulation are both lesser in maturation ponds, the parallel arrangement of ponds is not essential for pathogen removal.

Solar ponds: Another method for water disinfection by means of solar energy is the use of solar ponds. Solar ponds are dug into the ground, filled with water and covered with glazing (sheets of plastic or glass). Due to the greenhouse effect of the glazing cover, the temperature reaches up to 65 °C within the solar pool, which is very close to the pasteurization temperature, thereby leading to pathogen inactivation.

Pathogen removal efficiency: With temperatures between 55–65 °C, it is possible to obtain inactivation yields of 90 per cent (1-$\log_{10}$) for protozoa (*Giardia, Cryptosporidium, Entamoeba*), bacteria (*V. cholerae, E. coli, Shigella, Salmonella typhi*) and viruses, with an exposure time of one minute. However, with an exposure time of five minutes, the inactivation yields can reach 99.99 per cent (3-$\log_{10}$).

Factors affecting pathogen removal efficiency and recommendations for effective treatment:

- The extent of sunlight inactivation is still difficult to predict, as it depends on multiple parameters including microbial characteristics, water composition, season and geographical location.

- Algal blooms, which masks sunlight penetration, is another problem associated with ponds using solar radiation for disinfection. Availability of sunlight and nutrients in the water favour luxuriant algal growth leading to the formation of algal blooms. So, appropriate nutrient removal is essential for the efficient working of these ponds.
- In case of solar pond, in order to obtain an effective bacterial inactivation, it is important to maintain an optimal saline gradient in all solar pond surface which is still being explored.
- If several ponds are provided in series, maximum pathogen removal is achieved in case of maturation ponds.

Advantages:

- Low cost compared to other technologies.
- Solar disinfection is based on the use of natural sunlight. Hence, cost and problems associated with production, transport and handling of chemical (chlorine, ozone) and physical disinfectants (UV) are eliminated.

Limitations:

- Large land intake is a drawback when it comes to maturation ponds.
- They need good management systems and a reliable supply chain.
- These ponds are only be effective for liquids with low suspended solids concentrations.

4.2.3 Filtration

Filtration techniques have been used since ancient times for the removal of contaminants from water and wastewater. Pathogens can be physically removed by filtration methods. Different types of methods have been designed for the removal of different types of compounds. These methods have been discussed below. Unless a high level of filtration is employed—as in the case of ultra or nanofiltration that removes the tiniest particulates, including viruses—complete pathogen elimination is not possible using the filtration method. The use of these ultra and nanofiltration technologies is not cost-effective either. However, filtration has the added benefit of removing particulates to improve downstream disinfection processes (chlorination, ozonation, UV etc.) that are required to inactivate remaining pathogens. Therefore, these filtration methods are usually used in conjunction with other disinfection processes for the complete elimination of pathogens.

Filtration is based on the use of filters. Two basic types of filters are available for water and wastewater treatment—particulate filters and adsorptive/reactive filters. Particulate filters, also called surface filters, include membrane filters that contain a membrane that acts as a sieve to exclude particles (by size). Adsorptive/reactive filters contain a material (medium) that either adsorbs or reacts with a contaminant present in the water. The medium is present over a depth, providing a large surface area for the contaminants to get trapped in. Hence, these are also called depth filters/media filters. Sand filter, dual media filter and activated carbon filter, all fall within this category.

A. Particulate/surface filters

These filters work on the principle of occlusion, which is the physical separation of particulates based on size over a membrane surface with pores, allowing the liquid to pass through it. As it occurs on the surface of a filter media, it is also called surface filtration.

Membrane filtration[18]:

The membrane filtration technique uses a membrane as a barrier to separate two phases from each other by restricting the movement of components through it in a selective way. This technique has been in use since ancient times. However, several improvements have now been made to make the membrane better suited for different applications. Depending on the material used, membranes are of two types—organic and

Table 6: UV doses for inactivation of different pathogens

Membrane Process	Molecular weight cut off (kilo Dalton)	Retained Diameters (µm)	Pressure Required (bar)	Membrane Type	Average Permeability ($L/m^2 h$ bar)	Solutes Retained
MF	100–500	10^{-1}–10	1–3	Porous, asymmetric or symmetric	500	Bacteria, fat, oil, grease, colloids, organics, micro-particles
UF	20–150	10^{-3}–1	2–5	Micro porous, asymmetric	150	Viruses, proteins, pigments, oils, sugar, organics, microplastics

inorganic. Organic membranes are made from synthetic organic polymers like polyethylene (PE), polytetrafluorethylene (PTFE), polypropylene, and cellulose acetate etc. that are used mostly in pressure driven membrane processes used widely in wastewater treatment. Inorganic membranes are made from materials like ceramics, metals, zeolites, or silica that are chemically and thermally stable and used widely in industrial applications.

Mode of action: Particulates in water are separated by occlusion. Movement of media through the membranes is based on different driving forces. Based on this, there are equilibrium based, non-equilibrium based, pressure driven and non-pressure driven processes. Non-equilibrium based, pressure driven membrane processes are the most widely applied membrane processes in wastewater treatment and are used for pre-treatment to post-treatment of wastewater. These processes rely on hydraulic pressure to achieve separation. There are four main types of these processes—microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The membranes used for these processes are mostly made up of synthetic organic polymers. The main difference exhibited by these processes, apart from their pressure requirements, is their membrane pore sizes. NF (0.001–0.01 µm pore size) and RO (0.0001–0.001 µm pore size) have very minute pore sizes and are used in drinking water treatment for softening water by removing ions. A summary of the main features of microfiltration (MF) and ultrafiltration (UF) that are used for the treatment of FS liquid effluent is given in Table 6.

Figure 3: Micron filtration/microfiltration unit

Source: https://constrofacilitator.com/

Microfiltration (MF) and ultrafiltration (UF) [19]: MF and UF are filtration processes using a porous/microporous media to retain the suspended solids, microorganisms and other contaminants of a fluid. Microfiltration differs from UF in that it does not require pressure and is driven by hydraulic pressure. Both MF and UF are often used as a pre-treatment for RO or as a stand-alone filtration process for water and wastewater/FS treatment. MF usually also serves as a post-treatment for granular media filtration. MF filters can be at atmospheric pressure or with a vessel at a certain pressure (maximum 25 psi), but they usually work at low pressures.

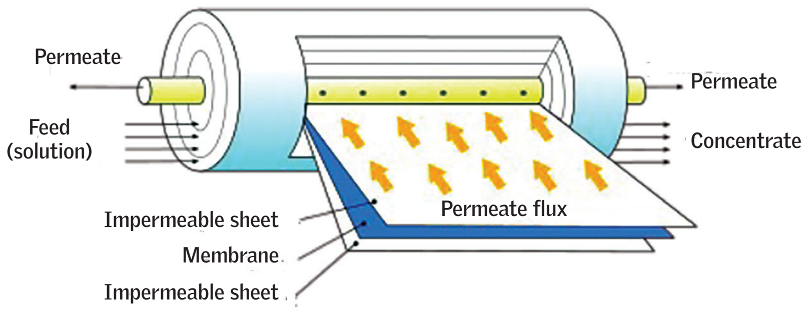
Technology description: The suspended liquid is passed through parallel/tangential to the semi-permeable membrane in a sheet or tubular form (see *Figure 3: Micron filtration/ microfiltration unit*). Membrane filtration processes can be distinguished by three major characteristics: driving force, retentate stream and permeate streams. The suspended particles and water that is retained on the surface of the membrane are treated as retentate, while the dissolved solutes and water that passes through the membrane constitute the permeate. In the pressure-driven MF and UF processes, hydraulic pressure acts as the driving force which accelerates the separation process by increasing the flow rate (flux) of the liquid stream. However, it does not affect the chemical composition of the species in the retentate and product streams. A pump is commonly fitted onto the processing equipment to allow the liquid to pass through the membrane filter. There are also two pump configurations, either pressure-driven or vacuum. A differential or regular pressure gauge is commonly attached to measure the pressure drop between the outlet and inlet streams.

Membrane arrangements[20,21]: Depending on the shape and material of the membrane, different modules can be used for MF and UF processes. Commercially available designs in MF and UF modules vary according to the required hydrodynamic and economic constraints, as well as the mechanical stability of the system under particular operating pressures. The main modules used in industry include:

- **Tubular modules:** The tubular module design uses polymeric membranes cast on the inside of plastic or porous

Figure 4: Hollow fibre module

Figure 5: Spiral-wound membrane module

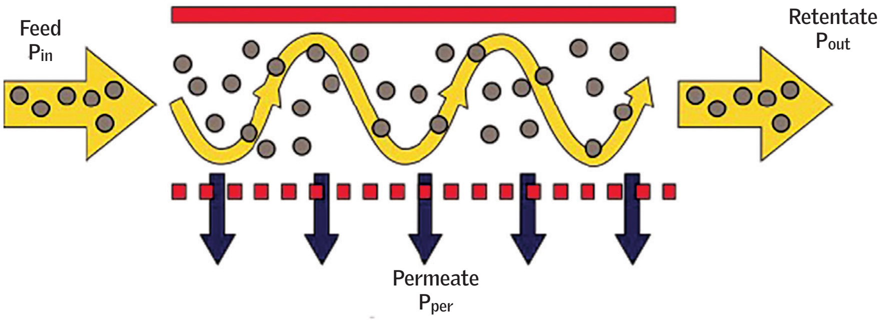


paper components with diameters typically in the range of 5–25 mm with lengths from 0.6–6.4 m. Multiple tubes are housed in a PVC or steel shell. The feed of the module is passed through the tubes, accommodating radial transfer of permeate to the shell side. This design allows for easy cleaning however the main drawback is its low permeability, high volume hold-up within the membrane and low packing density.

- **Hollow fibre:** This design is conceptually similar to the tubular module with a shell and tube arrangement. A single module can consist of 50 to thousands of hollow fibres and therefore are self-supporting unlike the tubular design. The diameter of each fibre ranges from 0.2–3 mm with the feed flowing in the tube and the product permeate collecting radially on the outside. The advantage of having self-supporting membranes is the ease with which it can be cleaned due to its ability to be back flushed. However, replacement costs are high as one faulty fibre will require the whole bundle to be replaced. Since the tubes have small diameters, using this design also makes the system prone to blockages (see *Figure 4: Hollow fibre module*).

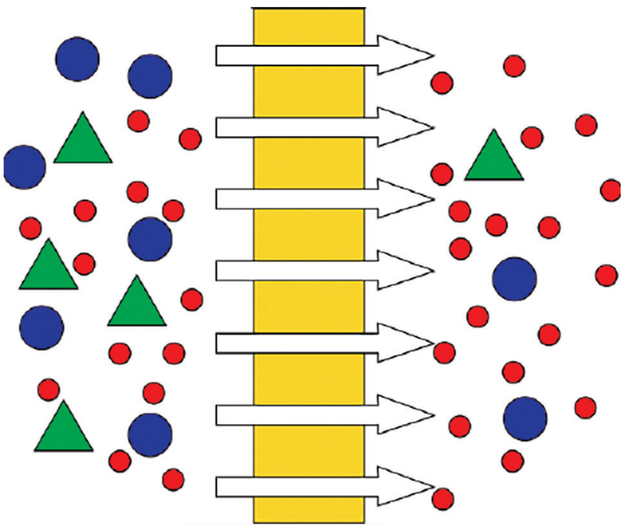
- **Spiral-wound membrane module:** They are composed of a combination of flat membrane sheets separated by a thin

Figure 6: Cross-flow filtration schematic



meshed spacer material which serves as a porous plastic screen support. These sheets are rolled around a central perforated tube and fitted into a tubular steel pressure vessel casing. The feed solution passes over the membrane surface and the permeate spirals into the central collection tube. Spiral-wound modules are a compact and cheap alternative in ultrafiltration design and offer a high volumetric throughput. They can also be easily cleaned. However, the design is limited by thin channels where feed solutions with suspended

Figure 7: Dead-end filtration schematic



solids can result in partial blockage of the membrane pores (see *Figure 5: Spiral-wound membrane module*).

Plate and frame: This uses a membrane placed on a flat plate separated by a mesh-like material. The feed is passed through the system from which permeate is separated and collected from the edge of the plate. The channel length can range from 10–60 cm and the channel height from 0.5–1.0 mm. This module provides low volume hold-up, relatively easy replacement of the membrane, and the ability to feed viscous solutions because of the low channel height— features that are unique to this particular design.

Membrane configurations:[22,23] MF and UF membranes generally operate in one of two configurations.

Cross-flow filtration: In this configuration, the fluid is passed through tangentially with respect to the membrane. Part of the feed stream containing the treated liquid is collected below the filter (permeate) while parts of the water are passed through the membrane untreated (retentate) (see *Figure 6: Cross-flow filtration schematic*).

Dead-end filtration: Here, all of the processed fluid flows through the membrane, and all the particles that are larger than the pore sizes of the membrane are stopped at its surface. All of the feed water is treated at once subject to cake formation. This process is mostly used for batch or semi-continuous filtration of solution with low concentrations (see *Figure 7: Dead-end filtration schematic*).

Pathogen removal efficiency: MF has excellent properties to eliminate suspended solids and is highly effective for the removal of pathogens, especially for larger organisms such as protozoa and bacteria. MF is an alternative to the classic sand filter. UF is efficient for virus removal. UF membranes have demonstrated greater than 6-Log removal of *Cryptosporidium* and *Giardia lamblia*.

Factors affecting pathogen removal efficiency and recommendations for effective treatment:

- Hard sharp materials can tear the porous cavities in the membrane filter, rendering it ineffective. Liquids must be subjected to pre-treatment before passage through the MF or UF filter. This may be achieved by a variation of macro separation processes such as screening, or granular media filtration.
- When undertaking cleaning regimes, the membrane must not dry out once it has been contacted by the process stream. Thorough water rinsing of the membrane modules, pipelines, pumps, and other unit connections should be carried out until the end water appears clean.
- When the membrane modules are being used for the first time, a slow-start is required when the feed is introduced into the modules to prevent irreversible fouling caused by even slight perturbations above the critical flux.

Like any other membranes, MF and UF membranes are prone to fouling. A major characteristic that limits the performance of any membrane technology is a process known as fouling. Fouling describes the deposition and accumulation of feed components such as suspended particles, impermeable dissolved solutes or even permeable solutes, on the membrane surface and or within the pores of the membrane. Fouling of the membrane during the filtration processes decreases the flux and thus overall efficiency of the operation. This is indicated when the pressure drop increases to a certain point. It occurs even when operating parameters are constant (pressure, flow rate, temperature and concentration) Fouling is mostly irreversible although a portion of the fouling layer can be reversed by cleaning for short periods of time. It is therefore necessary that regular maintenance through routine 'backwashing' be carried out to prolong the life of the membrane module. Depending on the specific application of the membrane, backwashing is carried out in short durations (typically 3 to 180 seconds) and in moderately frequent intervals (five minutes to several hours). ‘backflushing’, a more rigorous and thorough cleaning technique is commonly practiced in cases of particulate and colloidal fouling.

When major cleaning is needed to remove entrained particles cleaning agents/detergents, such as sodium hypochlorite, citric acid, caustic soda or even special enzymes are typically used for this purpose. The concentration of these chemicals is dependent on the type of the membrane (its sensitivity to strong chemicals), but also the type of matter to be removed.

Advantages[24]:

- MF methods are highly effective for the removal of pathogens, especially for larger organisms such as protozoa and bacteria
- UF is effective for virus removal
- Low operating pressure required for MF
- Low energy consumption in semi-inactive units compared to nanofiltration or reverse osmosis
- Virtually no manual operations are required
- It is relatively inexpensive
- It does not require energy-intensive phase transitions such as the evaporation technique

Disadvantages/Limitations[25]:

- Sensitivity to oxidizing chemicals (such as high concentrations of peroxides and nitric, sulfuric persulfates)
- Hard and sharp particles > 0.1 mm can cause damage and therefore require more open pore pre-filtration
- The diaphragm will fail if the diaphragm is flushed again with a pressure higher than 1 bar
- Fouling of the membrane leads to decreased performance and requires regular maintenance

B. Adsorptive/reactive filters or media filters[26]:

They work on the principle of adsorption, which is the attachment/adherence of a suspended particle to the surface of a filter media. These filtration systems remove particulate matter and, because of the large surface area of filter media present across a depth (depth filtration), they also can be used to drive chemical reactions that result in the removal of several contaminants. Media filters come in two configurations, vertical and horizontal. Horizontal filters are used when large flows are to be filtered. Depending upon the application, various filter media, namely, fine sand, anthracite, garnet or pumice are used. They are used either alone (sand filter) or in combinations as observed in dual and multimedia filters. These filters are used to remove suspended solids and turbidity from the water. If the turbidity of the water is greater than one NTU, a media filter is needed. The media filter is generally located at or near the upstream of the water treatment system, to protect downstream equipment from the suspended solids.

1. Sand filter

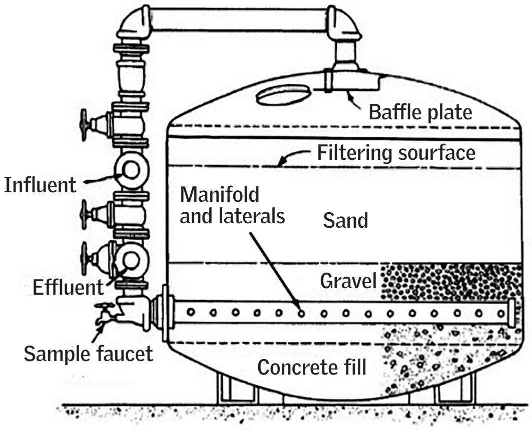
In a sand filter, sand is exclusively used as a filter media. There are three main types of sand filters—rapid sand filters (RSF), upward flow sand filters and slow sand filters (SSF). All three methods are used extensively in the water industry throughout the world. The first two require the use of flocculant chemicals to work effectively while SSF can produce very high-quality water with pathogens removal from 90 per cent to >99 per cent (depending on the strains), good taste and odour without the need for chemical aids. SSF technology is widely used for the treatment of municipal sewage water since many years. Although sand filters are efficient in removing pathogens, their use in FS treatment is limited as it requires a large area for operation.

Rapid sand filter[27, 28]: Rapid sand filters (RSF) provide rapid and efficient removal of relatively large suspended particles. RSF only involves the physical process for the removal of contaminants. Unlike SSF, it lacks the biological layer (biofilm) on filter media. Hence, it is less efficient in removing pathogens than SSF. The construction and operation of rapid sand filters is cost-intensive. It is a relatively sophisticated process that usually requires power-operated pumps, regular backwashing or cleaning, and flow control of the filter outlet. However, due to its low land requirement and compact design, it is now widely used for wastewater as well as FS effluent treatment with pre-(sedimentation and flocculation) and post-treatment (disinfection) steps to remove pathogens and prevent fouling. Two types of RSF are typically used—rapid gravity (GSF) and rapid pressure sand filters (PSF).

Mode of action: Coarse-grained sand and gravels efficiently remove suspended solids along with biological particles with the help of straining and adsorption. As coarse sand provides a larger space, a higher rate of filtration is achieved in RSF. This filtering process is determined by two basic physical principles. First, relatively large suspended particles get stuck between sand grains as they pass the filter medium (mechanical straining). Second, smaller particles adhere to the surface of the sand grains due to the effect of the van der Waals forces (physical adsorption). A chemical filter-aid (i.e. coagulant or flocculant) might be added to promote additional adhesion.

Technology description: RSF is constructed in a rectangular tank that is usually made of concrete. Three to five layers of graded gravel are installed at the bottom of the tank over a network of drainage pipes placed on the floor. The filter media, which is coarse sand with diameters ranging from 0.4–0.6 mm is filled over a gravel layer. Gravel and sand together reach up to a height of 1.5–2 metres. The gravel layer prevents the sand from draining out during the filtration process. Additionally, it facilitates the even distribution of water through the filtration media during backwash. The water is supplied to the top of the sand-bed and filtered as it flows through layers of graded sand and gravel. A system of perforated pipes at the bottom drains the chamber. The top of the RSF is either open for supernatant water (gravity filter) or closed (pressure filter). In GSF, water flows through the filter media with the help of gravity. In contrast, in PSF, the water is

Figure 8: Cross section of typical pressure sand filter (PSF)



Source: https://www.netsolwater.com/

Figure 9: Pressure sand filter (PSF)

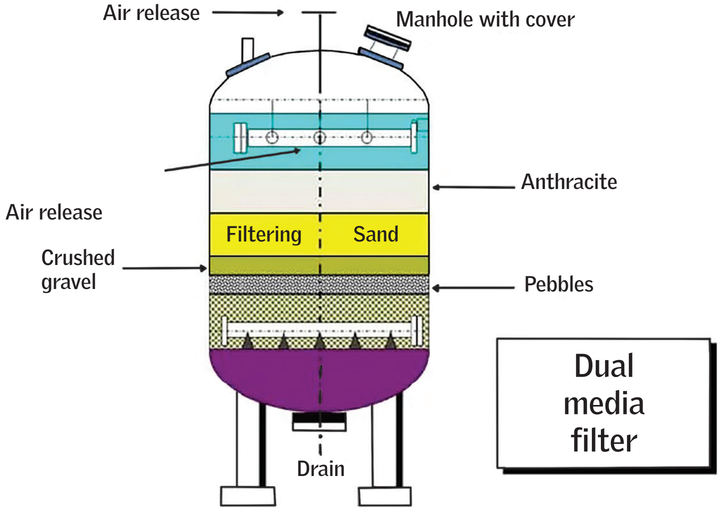
Source: https://www.roplant.net/pressure-sand-filter.html

injected into the filter media using a pump, and hence flows with a pressure.

Pressure sand filter (PSF): In addition to traditional technology described for PSF, it now comes with a compact design that is widely used in wastewater and industrial applications. Its design and technology consist of a closed structure made up of a cylindrical tank made of carbon steel with several brass strainers at the bottom. These are attached to a manifold that is set in concrete or fixed on a false bottom. The strainers have been sawed with thin slots. The top is covered with a layer of gravel that is fairly coarse. Sand is layered above this, serving as a filtration medium. To avoid disturbing the sand with a direct stream, baffles are placed at the feed inlet site. The filter collection is provided at the bottom (see *Figure 8: Cross section of typical pressure sand filter (PSF)* and *Figure 9: Pressure sand filter (PSF)*).

2. Dual media filter (DMF)[29]: It is a type of rapid pressure media filter, where, in addition to sand, a second filter media such as anthracite is present. DMF is used for the removal of turbidity and suspended solids from heavily contaminated

Figure 10: Design of a dual media filter



Source: https://www.membranechemicals.com/

water sources such as grey water and domestic sewage. It is also used as a roughening filter ahead of two-stage filtration systems (see *Figure 10: Design of a dual media filter*). Compared to the sand filter, dual media and multimedia filter are more efficient in filtering particulate matter due to the presence of two or more filter media with varying densities/pore spaces. They also require fewer back washes compared to PSF.

Pathogen removal efficiency: RSF is not as good for pathogen removal because of larger pore sizes of medium and lack of biofilm. However, RSF removes biological particles along with suspended solids. Prominent biological particles retained by RSF include algal microcolonies (5–20 mm), protozoan cysts (3–10 mm), bacterial cells (0.2–2 μm), and virus particles (0.01–0.1 μm).

Factors affecting pathogen removal efficiency:

- The deposition of microorganisms and other particles in filters depends on transportation efficiency and retention in surface pore of filter media.

- The removal mechanism for suspended bacterial cells involves diffusion, differential sedimentation, and interception. Effective grain size is an important factor for the collection of bacteria on media surface.
- The removal of nanoscale particles such as viruses is governed by diffusion. Smaller grain size of media is a major factor for the removal of freely suspended viruses and other nano sized particles.
- Protozoans are removed by the cumulative effect of sedimentation and interception. Lower hydraulic loading rates would be improving removal efficacy for protozoan pathogens. Removal of *Giardia* cysts and *Cryptosporidium* oocysts was shown to be affected by extent of filter maturation and application of coagulant chemicals.
- Removal of microbial aggregates is chiefly influenced by hydraulic loading rates.
- Other factors such as net surface charge on the filter media and microbial surfaces; media properties (type, size, and depth); hydraulic loading rates; upstream chemical use (oxidants and/or coagulants); water quality variables; flow control; and backwashing and post backwashing practices may also significantly influence pathogen removal efficiency of filter media. Backwashing of filter media in RSF may release pathogen from RSF granules.
- Additional factors such as pH, ionic strength, temperature of effluent; concentration, molecular size, and charge density of dissolved organics; and particle characteristics influence removal efficiency.

Recommendations for improved performance

Cleaning filters (backwash): Tertiary filters (RSF, DMF) need better backwashing techniques as the load on them is higher and also there is possibility of mudball formation. Mudballs are agglomerations of extraneous material that accumulate in the bed over extended periods of time due to improper backwashing. Consequently, the effectiveness of the filtration is greatly affected.

Cleaning filters is necessary to remove the solids collected by the media during the filtration run. There are three common methods of cleaning filters that are in use today—hydraulic backwash, hydraulic backwash plus sub-surface wash, and hydraulic backwash plus air scour.

Hydraulic backwash: The traditional method of cleaning a filter has been to reverse the flow and bring clean water up from beneath the bottom of the bed at a rate that is sufficient to fluidize the media and shear off the floc.

Limitation: Chemicals and trapped solids can adhere tightly to filter media grains to form crusts. Shearing action of backwash water alone is not sufficient to remove them. If the media is not completely cleaned each time, dirt (crusts) can accumulate causing mud balls. If mud balls are allowed to accumulate, they can sink to the bottom of the media and plug the gravel. The bed will then become upset, resulting in poor performance and loss of media.

Hydraulic backwash plus surface wash: As discussed above, mud ball formations, if not removed, can hinder the performance of the treatment process. As backwash alone cannot remove them, a common practice is to install a distributor to clean the media surface. This distributor, or "surface wash" mechanism, is situated just below—approximately four inches— from the media. Nozzles distribute high-pressure water to scour the media surface as well as provide motion to the distributor. The surface washer is normally turned on for one or two minutes to scour the surface. Then the backwash flow is begun, expanding the media up past the surface washer and allowing it to continue its scouring action deeper in the bed. Although sub-surface wash is a substantial improvement in cleaning a filter, it does not completely eliminate mud balls. Nor does it clean the entire bed. The circular agitator has difficulty cleaning the corners where mud balls can form.

Hydraulic backwash plus air scour: The current practice worldwide is to provide an air scour in place of the surface wash. Air scour in the range of 30–48 $m^3/m^2/hr$ provides much more violent agitation of the media than surface wash. In addition, air scour combined with a low rate backwash (concurrent air and water) is the most effective way to remove solids from a filter. The media grains have a greater potential to collide, increasing the scrubbing action during the air scour. Tests have shown that air scour is the most effective backwash method and uses the least amount of water.

Rinse: After the backwash cycle is complete, the vessel is rinsed and can then be returned to normal service. The rinse cycle is used to remove any residual backwash water in the media bed. The rinse mode is the same as the service mode, except the water drained instead of being sent for service.

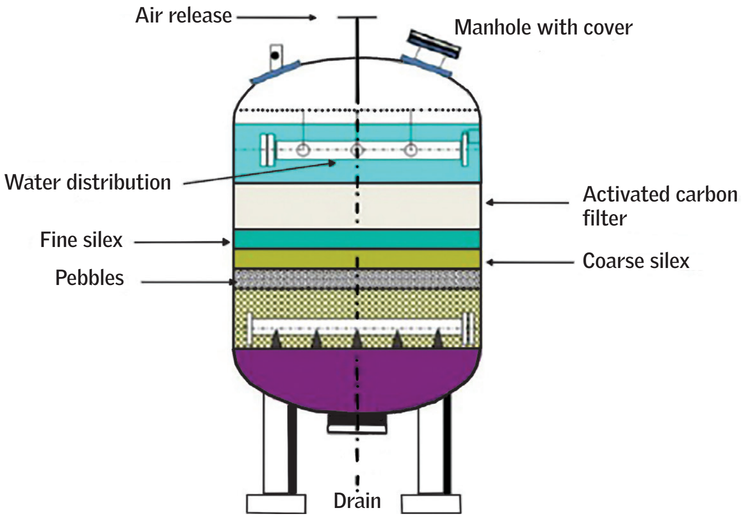
Advantages:

- RSF requires less facilities and lesser area for construction for the treatment of unit volume of water compared to SSF.
- The filters remove odours and chlorine.
- Removal of turbidity and suspended solids from lightly contaminated water sources such as deep wells and municipality water supplies. Used frequently upstream of reverse osmosis and demineralization systems.

Limitations:

- RSF must be aided with pre-treatment (sedimentation and flocculation) and post-treatment (disinfection) steps to remove pathogens and prevent fouling.
- In order to achieve efficient filtration, particles must slow down enough to be held on the surface of a substance. High flows can prevent adsorption due to a lack of surface interaction time. Secondly sufficiently high flow can shear adsorbed particles off the filtering media.

Figure 11: Schematic diagram of activated carbon filter



Source: https://www.membranechemicals.com/

3. Activated carbon filter[30]

Activated carbon filter (ACF) is an indirect method of removing pathogens. It removes organic compounds from water, and hence, also removes the pathogens associated with them. Activated carbon (AC) is a special form of carbon that is produced by heating organic material such as coconut shells, walnut shells, or coal in the absence of oxygen. The heat removes trapped moisture and gases and pyrolizes most of the organic material; it also leaves the remaining material with a slightly positive surface charge. Due to its high degree of micro-porosity, just one gram of activated carbon has a surface area in excess of 500 m^2. Large surface area and high adsorption properties makes AC a highly effective media to absorb contaminants from wastewater.

Mode of action: AC works on the principle of adsorption. Adsorption is the adhesion of atoms, ions, or molecules from a gas, liquid, or solid to a surface. The impurity molecules are held within the carbon's internal pore structure by electrostatic attraction (van der Waals forces), also known as chemisorption.

It is activated using thermal or chemical processes to extend its adsorption capacity. A filter with granular activated carbon (GAC) is a proven option to remove certain chemicals, particularly organic chemicals, from water.

Technology description: ACF also comes in a similar compact design as DMF, with anthracite and sand replaced with activated carbon and silex respectively (see *Figure 11: Schematic diagram of activated carbon filter).* Granular activated carbon (GAC) is mostly used in fixed filter beds.

Carbon regeneration: Once activated, and after repeated use for removal of contaminants, carbon becomes saturated and turns into spent carbon, having lost its adsorption characteristics. Once this happens, it can't be used in the filtration system. In order to bring it back to its original form and reactivating it for reuse, a process called carbon regeneration is employed. Several methods have been developed for this purpose, the most common method of which is thermal activation. This is performed in three major steps, starting with drying, then heating, and finally residual organic gasification by oxidizing gas (steam or carbon dioxide). Replacing the carbon bed is an option, if regeneration is cost intensive.

Pathogen removal efficiency: Activated carbon (AC) is not effective in the direct removal of pathogenic bacteria and viruses from water. However, a laboratory study showed that activated charcoal could be a good adsorbent system for the removal of verotoxin-producing *Escherichia coli* (VTEC) and verotoxin (VT).

Factors affecting removal of contaminants and measures to be taken to improve performance

- **Pore size of activated carbon:** Accumulation of molecules within the internal pores of activated carbon occurs in pores slightly larger than the molecules that are being adsorbed.

Hence, it is very important to match the pore size of activated carbon media with the particulate molecules of concern that has to be removed. Activated carbon media with varying pore sizes are commercially available that can be used, after knowing the average size of the particulate molecules that has to be removed. The desired pore structure of an activated carbon product is attained by combining the right raw material and activation conditions. In applications where there are a wide variety of impurities to be removed, the best type of activated carbon is not so easily determined. When impurities range from very small to very large in size, the large molecules often clog up small pores, making them inaccessible to other molecules. In this case, performance testing (isotherm and pilot column) to identify the best activated carbon for a specific application should be performed.

- **Regeneration:** Activated carbon has a certain life after which it cannot remove impurities and hence needs to be removed or replaced. Simple backwash cannot regenerate activated carbon, it only removes the trapped material and reclassifies the filter bed. The regeneration procedure described above has to be followed to reactivate the carbon media.

- **Properties of AC:** A proper activated carbon has a number of unique characteristics such as a large internal surface area, dedicated (surface) chemical properties and good accessibility of internal pores. The pore size distribution is highly important for the practical application; the best fit depends on the molecules to be trapped, the phase (gas, liquid) and treatment conditions. The characteristics of the carbon material (particle and pore size, surface area, surface chemistry, etc.) influence the efficiency of adsorption.

- The amount of activated carbon present and retention time of the treated water in the filter media can decide the effectiveness of filtration. The effectiveness of the carbon filter media decreases if water does not stay in contact with the filter long enough.

Advantages/applications:

- AC can efficiently remove free chlorine. It is also a better removal of free chlorine compared to sodium bisulphite (SBS), as SBS increases bacterial growth.
- AC can remove minute suspended particles, colloidal particles and dissolved organics/ organic matter
- Removes smell and odour from lightly contaminated water supplies.
- Bromate Removal (after ozonation of SWRO permeate)
- GAC filters also can be used to remove chemicals that give objectionable odors or tastes to water such as hydrogen sulfide or chlorine.

Limitations:

- These types of filters are not effective when eliminating non-carbon chemicals (e.g. heavy metals, nitrates, fluoride, sodium, etc.).
- They have a limited-service life. If contaminants are filled at the location of the connection (those responsible for 'trapping' contaminants), AC filters will stop operating and must therefore be replaced.
- These filters may not be efficient for removing any pathogenic bacteria or viruses and can harbor bacteria that may result in bacterial growth; however, some filters have been able to prevent this by adding traces of silver to prevent the growth of the bacteria (these filters are known as silver-impregnated activated carbon filters).

4.3 Other disinfection methods[31]

Improved disinfection technologies such as advanced oxidation processes (AOPs) have been developed and used in recent years as an effective alternative to traditional chemical disinfection processes for wastewater treatment. Unlike chemical disinfection processes, AOPs do not produce harmful by-products which require removal before discharge. AOPs are redox technologies that involve various oxidation processes, including ozonation, ozonation coupled with hydrogen peroxide (H_2O_2) and/or UV radiation, photocatalysis activated by semiconductors such as TiO_2, and electrochemical oxidation among others. Their mechanism of action is by the formation of very effective non-target-specific reactive oxygen species (ROS) that can be utilized as a pre-or post-treatment to a biological procedure. However, these technologies remain unexplored in the disinfection of FS products.

Measures to be taken for the safety of treatment plant operators while handling hazardous disinfectants

The safety of treatment plant operators should be considered whenever disinfectants are used because some of the disinfectants are harmful. Hence, compliance with safety precautions by the operators handling the disinfectants is important. The harmful effects of three disinfectants UV, ozone and chlorine are given below.

- **UV radiation:** UV radiation is considered a “complete carcinogen” because it is both a mutagen and a nonspecific damaging agent. Additionally, it can initiate and promote tumor formation.

- **Ozone:** Ozone can harm the lungs when inhaled. In relatively lesser doses, chest pain, coughing, shortness of breath, and throat irritation can occur. Additionally, ozone may weaken the body’s defences against respiratory infections and aggravate chronic respiratory conditions like asthma.

- **Chlorine:** Chlorine is a greenish-yellow gas with a pungent, irritating odour. Exposure to low levels of chlorine can result in nose, throat, and eye irritation. In higher doses, breathing chlorine gas may result in changes in breathing rate and coughing, and damage to the lungs.

Therefore, appropriate personal protective equipment (PPE), such as goggles, gloves, long-sleeved shirts, long pants, and masks should be worn while applying disinfectants. Using a suitable mask for a given purpose is preferable to using any non-specific mask.

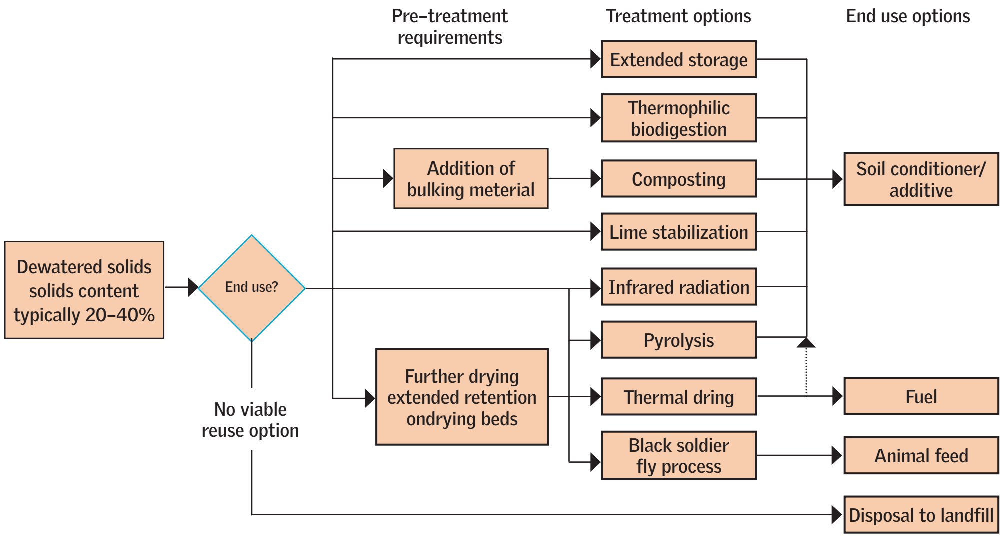
5. Technologies for pathogen reduction in biosolids from FSTPs and recommendations for effective pathogen management[32]

Separated faecal sludge solids, referred to as biosolids, may be used in place of conventional resources, including energy, nutrients, and water. In doing so, they will contribute to the Sustainable Development Goals (SDGs) on combating climate change, providing affordable energy, and reducing the use of natural resources. It has been suggested that treated FS might be used as a soil conditioner, building material, biofuel or in the production of animal feed. Dewatered FS typically has a solids content in the range of 15–40 per cent and contains large number of pathogens. Further treatment would be/is required to ensure that separated solids are suitable and safe for the end uses identified above. Figure 12 shows possible treatment options for each of these end uses, together with the option of disposal into landfills without further treatment. Additionally, options for achieving high solids content required for some of the processes are also given (see *Figure 12: Overview of end-use and treatment options for dewatered faecal sludge*).

Guidelines for reuse of FS biosolids

Acceptable pathogen levels in relation to the intended end-use of treated biosolids were recommended in the USA's Part 503

Figure 12: Overview of end-use and treatment options for dewatered faecal sludge



Source: Kevin Taylor, 2018

Biosolids Rule (EPA, 1994). Whenever it is difficult to achieve stringent Class A biosolids status, because of the difficulty involved in controlling and monitoring a process or due to high operational costs, the objective will be to achieve the much lower standards required for Class B biosolids. WHO and USEPA recommendations and options for biosolids reuse are provided in Table 7.

Safety recommendations for workers having direct contact with FS biosolids

People working with FS biosolids often come in direct contact with them. This is particularly important for workers dealing with FS biosolids used for animal feed and solid fuel, because less attention is given to pathogen reduction in these reuse options compared to those intended for agricultural use. The best way to deal with this health risk is to ensure that workers follow practices designed to protect their health. These include wearing protective clothing, particularly gloves, when handling potentially hazardous materials and washing hands with soap every time a worker

Table 7: Recommended pathogen requirements and suitable options for biosolids reuse given by WHO and US EPA

Agency	Type of biosolid	Recommended pathogen requirements for biosolids reuse	Biosolids are suitable for
World Health Organization	Not applicable	• Helminth egg count: ≤1 egg per gram of total solids • E. coli: ≤1 000 count per gram of total solids	
US Environmental Protection Agency (Part 503 biosolids rule)	Class A biosolids	• ·Faecal coliform density ≤1,000 per gram of total dry solids, or • Salmonella spp density ≤3 per 4 grams of total dry solids	Unrestricted use
	Class B biosolids	• Faecal coliform density ≤2,000,000 per gram of total dry solids	• Use on arable land used to grow crops that are not to be consumed raw and to which there will be no public access for more than a year after application. • Use on forest land and spreading on woodlots (these may be good options for the relatively small volumes of biosolids produced by many faecal sludge and septage treatment plants)

comes into contact with these materials. Where direct contact with biosolids cannot be avoided, it is advisable to ensure that the biosolids meet the less stringent USEPA Class B requirements given in *Table 7*.

Technologies for pathogen reduction in biosolids from FSTPs[33]

The primary function of five of the technologies namely, storage for an extended period, composting, lime stabilization, infrared radiation and thermophilic biodigestion shown in Figure 1, is to reduce pathogen concentrations. Thermal drying and pyrolysis are very effective at killing pathogens, but their main use to date has been to prepare biosolids for use as a fuel. Thermophilic biodigestion is a form of anaerobic fermentation process which leads to the production of biogas. The biogas can be used as a fuel. Since high temperatures are reached, it also results in the destruction of pathogens.

5.1 Storage for an extended period

The simplest option for reducing pathogen concentration is to store dried sludge for a long period. This can be considered in areas with a dry climate where the space to accommodate stored sludge is available. However, the challenge with this option is to determine the storage period that is necessary. This option is simple but is difficult to control and monitor. As a result, its effect on pathogen concentrations is also difficult to predict.

Mode of action: Sunlight (UV radiation), and a reduction in nutrients and moisture content are responsible for pathogen reduction or die-off in FS biosolids during extended storage.

Pathogen removal efficiency: In a study conducted in Cameroon, it was concluded that the health risks associated with handling sludge from planted drying beds would be minimal if there is a gap of at least six months between the application of wet sludge to the drying bed and removal of the dried solids.

Factors affecting pathogen removal efficiency and recommendations for improved pathogen reduction

Given the difficulty of managing the conditions under which sludge is stored, it will normally be appropriate to allow a large margin of safety when assessing storage requirements.

- The die-off rate of pathogens is affected by temperature, moisture content and the size and shape of the storage heap.
- If the sludge is covered in a way that it remains dry, the storage period should not be less than 18 months.
- Where sludge may be subject to periods of wet weather, during which its moisture content rises, the storage period should be at least three years.

Note: The figures mentioned above are provisional and may be amended if testing shows good pathogen reduction in a shorter period.

Recommendations for sludge storage to reduce the risk of contamination caused by watered sludge due to stormwater and rain water:

- To reduce the risk of surface water pollution, sludge should not be stored in sites where the slope exceeds the ground by two per cent or in locations that are subject to occasional flooding.
- To reduce the possibility of groundwater pollution, sites for extended storage should be located in areas where the water table is well below the surface—preferably at least 3–4 m—throughout the year. Even so, for all but the most impermeable soils, the provision of an impermeable 'pad' is desirable. Concrete and asphalt are commonly used for composting pads but they are relatively expensive. Other options include clay and filter fabric overlaid with gravel. Where a risk of groundwater pollution cannot be avoided, groundwater monitoring wells or lysimeters should be installed. The challenge will then be to ensure that samples are regularly taken and analyzed.
- Drainage should be provided to direct leachate from sludge subjected to flooding or rain towards simple treatment facilities such as ponds and constructed wetlands.
- Ridges should be provided to divert stormwater run-off around the drying area and provision should be made for collecting and safely disposing of any contaminated water that escapes from the drying sludge.
- Pathogens will die off more rapidly if the storage area is covered to keep off rain. However, the cost of roofing over the large area required must be taken into account when assessing this option.

Limitations:

- Pathogen regrowth may occur during storage depending on temperature and moisture conditions.
- In view of the uncertainties associated with extended storage, sludge that has been stored for an extended period should

be assumed to meet only the requirements for a Class B biosolid and used accordingly.

5.2 Solar drying

Solar drying is an option for increasing the solids content of sludge to the levels required for some of the treatment options identified in Figure 12. However, as pathogen reduction also occurs along with drying of sludge, this method is considered here as an option for pathogen reduction. Most of our understanding of performance of solar drying is based on studies and operational data from wastewater treatment plants. Since the basic mechanisms are the same, information obtained from assessing solar drying performance at wastewater treatment plants should be generally applicable to septage and faecal sludge treatment plants.

Mode of action:

- Solar drying relies entirely on evaporation to remove moisture. The transparent covering 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.

Technology description: It can also be used as a stand-alone sludge drying technology. It differs from simple unplanted drying beds in the following respects:

- The beds are housed within greenhouse-type structures that are typically made with translucent polyethylene mounted on

a metal frame.
- Commercially available solar dryers may operate in either batch or continuous mode. Sludge is turned by a series of combs and paddles which cut the surface of the sludge and allow aeration of the lower layers. In systems that operate in continuous mode, this 'tilling' mechanism also moves the sludge slowly along the length of the bed. The bed may be flat or may be provided with a gentle slope away from the end at which the sludge is delivered.

Pathogen removal efficiency: Solar drying reduces pathogen numbers but varying conclusions are reported by different studies about the extent of this reduction. Taking into consideration the uncertainty about the degree of pathogen reduction achieved, the solids produced by solar drying should at best be considered as Class B biosolids, to be applied to fields that are not used to grow vegetables that are eaten raw.

Factors affecting drying performance:
- The amount of solar radiation, air temperature, relative humidity, and the depth of sludge are the main factors influencing the rate at which sludge will dewater on a solar drying bed.
- Relative humidity is strongly influenced by the ventilation flux, the rate at which saturated air is removed from the greenhouse and replaced by relatively drier air.
- There is some evidence that the initial total solids content also influences performance. It was observed that sludge with approximately 15–20 per cent initial solids content improves the drying rate.

Recommendations and operational guidelines for improving performance:
- Solar drying requires mechanical equipment and a reliable electricity supply. Maintenance systems, supported by reliable supply chains for spare parts, must be in place to ensure the

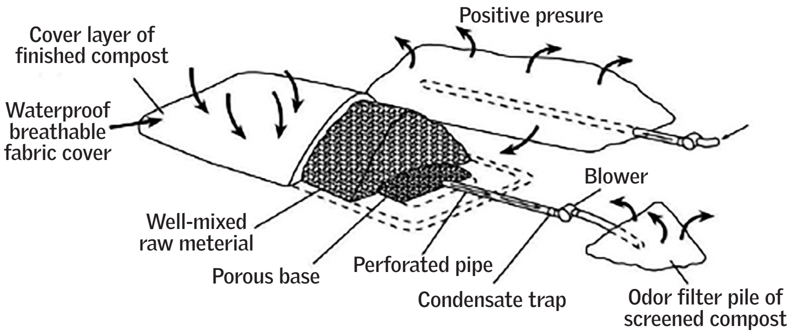
continued functioning of all mechanical equipment. A reliable electricity supply must be available to provide power for ventilation fans and tilling devices.

- Manual operation of solar drying facilities is labour intensive, requiring the manual conveyance of dewatered sludge to the solar drying area, and regular manual mixing and turning of the sludge. For all but the smallest facilities, mechanical tilling devices will be required to turn the sludge. Mechanical tilling devices can be automated to ensure optimum drying performance. Automated systems can provide effective and efficient performance, but have additional operational requirements, and require trained operators with a good understanding of the monitoring instruments and the automation system.
- Multiple beds, laid parallel to each other, should be provided so that they can be loaded sequentially. At least one additional bed should be provided in addition to the number required for continuous operation to allow beds to be taken out of commission for maintenance and repair.
- The greenhouse covering should be cleaned regularly to ensure that a build-up of dust and dirt does not block solar radiation and reduce drying performance.

5.3 Composting

Composting uses aerobic decomposition to break down organic material under controlled conditions and produces stabilized products. Aerobic microorganisms use oxygen to convert carbon to carbon dioxide, generating heat and raising the temperature of the compost. Pathogens in the composting material are inactivated if the compost temperature can be maintained in the thermophilic range (40–70°C) over a sufficient time period. FS is a suitable source for composting as it is rich in organic content. However, it needs the addition of a suitable 'bulking agent' with high carbon (co-composting) to improve the composting process. If properly performed, composting not only reduces pathogen content to safe levels for reuse, but also produces a product that

Figure 13: Schematic of aerated static pile composting[34]



can be used as fertilizer. However, several factors govern the property of the finished compost; they have been discussed in detail below. The stabilized product is a dark, humus-like material that can be added to the soil to increase its organic content and improve water retention in the soil.

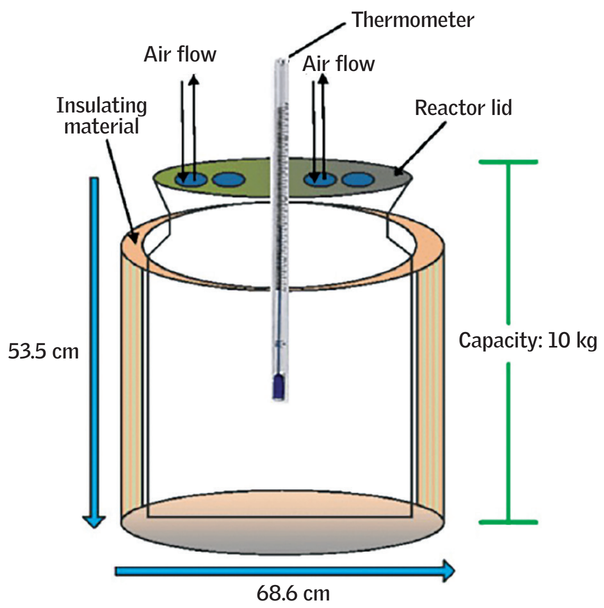
Technology description: Several methods are available for composting; the options that are suitable and commonly used for FS co-composting include the following:

Windrow composting: This is the most common method used so far for co-composting of FS. The material to be composted is formed into long piles, which are typically triangular or trapezoidal in shape and 1.25–2.5 m in height, with a width to height ratio of roughly 2:1. The piles must be large enough to retain heat and ensure that thermophilic conditions are reached but porous enough to allow oxygen flow to its core. Windrows must be turned at regular intervals to maintain porosity and allow oxygen into the core of the windrow.

Aerated static-pile composting: The material to be composted is placed in piles, typically around two metres deep, and covered with 150–300 mm of a finished compost or another suitable material to reduce heat loss. Blowers are used to pump air into the piles through pipes laid under the piles. The use of aeration removes the need for labour to turn the compost. Additionally, the forced aeration better controls the process and the time needed is generally lower than for turned windrow composting. However, these systems are more expensive than turned windrow systems and require good maintenance systems and a reliable power source (see *Figure 13: Schematic of aerated static pile composting*).

In-vessel composting: The material to be composted is placed in enclosed reactors with systems to control temperature,

Figure 14: Schematic representation of in-vessel composting



Source: Waqas et al, 2017[35]

moisture, and odours. Commercial in-vessel composters are expensive and relatively complex to perform (see *Figure 14: Schematic representation of in-vessel composting*).

The viability of composting depends on the availability of:

- Land to accommodate the composting process;
- Either labour or mechanical equipment to carry out the tasks associated with composting, particularly the turning of windrow piles;
- A reliable and inexpensive source of carbon-rich waste for use as a bulking agent;
- Operational capability and management support systems to monitor the composting process; and,
- A market for soil-conditioning material produced from composted material.

Factors affecting composting/pathogen reduction and operational guidelines for improving pathogen reduction: Achieving the required temperature for pathogen inactivation requires three parameters that should be maintained within optimum range in the composting material—moisture, carbon to nitrogen (C: N) ratio and oxygen.

Moisture content: Moisture content within or close to 55–60 per cent is required for optimal microbial activity and rise in temperature. This will result in the production of a good quality compost with low pathogen content. It may also be necessary to add water to maintain the moisture content within the optimum range. To maintain moisture within the optimal range, regular monitoring of moisture content in the compost pile is required which can be done in different ways. The manual method is a simple qualitative method and can be done as follows. The feel of a 'wrung out' sponge or the production of a drop of water after squeezing a handful of compost indicates that moisture is within the optimum range. Quantitative assessment includes gravimetric method which is accurate but requires drying and weighing facilities. Commercially produced moisture sensors provide another moisture content assessment option.

C:N ratio: Composting is most effective when the C:N ratio is in the range 25–35 to 1. At C:N ratios lower than 25, the temperature will not increase to sufficient levels for pathogen inactivation and ammonia gas is likely to form, producing an odour. Conversely, C:N ratios greater than 35 lead to reduced microbiological activity and lower temperatures in the compost.

The C:N ratio of dewatered FS is much lower than the optimum range required for effective composting. C:N ratios as low as 5.5:1 and 11:1 were reported for dewatered FS respectively from Ghana and Crete in Africa. To increase the C:N ratio, material with a high carbon content must be mixed with FS. These materials are called 'bulking agents' which usually has a high carbon content and a low water content. Materials commonly used as bulking agents include municipal solid waste, agricultural waste, and sawdust. The volume of bulking agent required is typically 2–5 times the volume of FS, the ratio depending on the C:N ratio and the water content of the sludge and bulking agent.

Oxygen: Effective composting is only possible if the compost remains aerobic, providing sufficient oxygen for aerobic microorganisms to thrive. Free air space must be available in the compost pile to allow the circulation of air. The addition of a bulking agent helps to increase the free air space, facilitating aeration. Forced aeration and turning the compost increase the air supply and improve air circulation.

Other factors affecting pathogen reduction

Active and passive composting: An effective composting process includes an active phase, during which compost is regularly turned, followed by a passive phase during which compost is left in piles without turning. The inclusion of a passive composting phase during which the temperature remains high for extended time periods in the composting pile, increases the chances of achieving pathogen concentrations to acceptable levels in the finished compost. However, this increases the area required for composting, typically by a factor of about two.

Windrow size and turning: Compared to smaller windrows, larger windrows achieve the temperature required for pathogen inactivation more quickly as they hold more compost mixture. However, they require a greater level of effort for turning. Manual turning of windrows is labour intensive and mechanical equipment, in the form of front-end loaders, will be required at larger facilities.

Rainwater exclusion and roofing: Windrows should be properly covered to protect from rainwater which increases the water content and reduces composting performance, including pathogen reduction. However, the sides of the covering structure should be open to allow cross-ventilation. If the cost of roofing is a problem, it may be appropriate to provide a cover over the active composting area but leave the area required for subsequent passive composting open.

Recommendations for effective composting/pathogen reduction—testing and monitoring requirements:

- The C:N ratio and water content of composite samples of both the sludge to be composted and one or more potential bulking materials should be tested at the planning stage and the information obtained from testing should then be used to determine an appropriate ratio of sludge to bulking material.
- Once the composting process is operational, the temperature of the sludge should be regularly monitored to ensure that the requirements for inactivation of pathogens are met. Temperatures should be recorded at several points in the compost pile, including points close to the surface. This can be done using a long-stem compost thermometer.
- If the compost heap is correctly sized, failure to achieve the

temperature required for pathogen reduction is an indication that the water content, the C:N ratio, or both are outside the range required for effective composting.

Temperature and time requirements during composting to reduce pathogens (US EPA): The overall objective of composting is to reduce pathogens to safe levels. However, testing for pathogens requires specialist equipment and skills that can be expensive. Keeping this in mind, the normal practice is to monitor temperature during the composting process and adjust process parameters to ensure that minimum temperature and time criteria are met. The temperature and time requirements given by US EPA (Part 503) to be maintained during composting to achieve Class A and Class B biosolids are given in Table 8.

Table 8: US EPA Part 503 temperature and time criteria for composting

Class	Requirement
Class A (unrestricted use)	Windrow composting: Temperature must be >55°C for at least 15 days and windrows must be turned at least five times Aerated static pile or vessel composting: Temperature must be >55°C for at least 3 days
Class B (restricted use)	Temperature must be >40°C for at least 5 days and >55°C for at least 4 hours within the 5-day period

5.4 Lime stabilization

Lime stabilization involves the addition of either quicklime (CaO) or hydrated lime ($Ca(OH)_2$), also known as calcium hydroxide or slaked lime, to the sludge. Both increase the pH of the sludge

Table 9: US EPA Part 503 lime stabilization requirements

Class of biosolids	pH and contact time	Temperature	Additional requirements
Class A	>12 for 72 hours	52°C for >12 hours or 70°C for >30 minutes	Air dry to >50% dry solids
Class B	>12 for 2 hours	No requirement	None

and quicklime also reacts with the water in the sludge to raise its temperature. To ensure pathogen inactivation, the lime must be evenly mixed through the sludge. Lime-stabilized biosolids can be added to the soil, increasing the pH, and are particularly beneficial for acidic soils. To date, all lime stabilization initiatives in lower-income countries have used hydrated lime.

Technology description: Lime can be applied to faecal sludge or septage prior to solid-liquid separation and dewatering, when the relatively high-water content facilitates mixing. Adding lime to septage or faecal sludge at the start of the treatment process reduces odours but increases the volume of sludge to be dealt with at a later time in the treatment process. If lime is added at the end of the treatment process, the higher solids content of the dewatered sludge will make mixing more difficult. Specialized mechanical equipment, including pugmills, paddle mixers, and screw conveyors, are available to ensure effective mixing of lime with thicker, dewatered solids.

Pathogen removal efficiency: The inactivation of pathogens by lime stabilization is dependent upon the addition of sufficient lime to achieve a minimum pH and temperature for a minimum contact time. Table 9 sets out the US EPA guidelines for the results to be achieved for lime stabilization to produce Class A and Class B biosolids.

Factors affecting pathogen removal efficiency and operational guidelines for improved performance:

- Hydrated lime is available in the form of a powder. It is difficult to make a good mixture of dry lime and sludge, and the normal procedure is to mix the dry lime with water to form a slurry, which is then mixed with the sludge. The mixing ratio is typically one 20 kg bag of lime to 60–80 litres of water.
- Complete pathogen inactivation is only possible if the lime is thoroughly mixed into the sludge. When mixing by hand,

it is difficult to ensure that the lime will completely mix with the sludge, and the sludge may not reach a pH of 11 or greater that is required for the elimination of pathogens. Mechanical mixing will therefore be required for all but the smallest of facilities. Overdosing with lime does not compensate for poor lime mixing. The long-term viability of mechanical mixing is dependent on a reliable source of power, adequately skilled operators, and a good supply chain for spare and replacement parts.

- The pH of the mixture must be monitored at regular intervals to verify that it is held at the required level for the required time.

Health and safety issues: Hydrated lime can irritate the skin, eyes, lungs, and digestive system. It is therefore important that workers who handle lime, or work in close proximity to it, wear appropriate personal protective equipment. Workers should have access to an appropriately stocked first-aid box and guidance on the procedures to be followed in the event of eye and skin irritation.

Limitations:

- Regardless of the mixing method adopted, the use of lime as a long-term response to sludge stabilization and pathogen reduction needs will only be viable if hydrated lime is available at an affordable price.
- Lime-stabilized biosolids are alkaline, so, they are beneficial only for acidic soils. They should not be added to alkaline soils.
- Lime-stabilized biosolids are generally lower in nitrogen than other biosolid products as nitrogen is converted to ammonia during processing.
- Quicklime reacts violently with water and its use is potentially hazardous.
- The findings on helminth egg ova reduction show that lime stabilization does not reliably remove helminth ova.
- When using hydrated lime, an external heat source will be required to meet the temperature conditions required to

produce Class A biosolids. For this reason, lime stabilization with hydrated lime should normally be considered only as an option for achieving the less onerous Class B biosolids requirements.

5.5 Infrared radiation

Medium-wave infrared is an invisible form of electromagnetic radiation that is emitted by objects at high temperatures. It heats objects more rapidly than conventional heating and is used, for example, in the food industry to increase the surface temperature of food sufficiently to kill microorganisms without causing any substantial increase in the interior temperature. Because of its low penetration, it will only be appropriate for pathogen inactivation in FS if the sludge has first been processed to be broken up into small particles.

Mode of action: Infrared radiation increases the temperature, thereby killing pathogens.

Technology description: Latrine sludge dehydration and pasteurization (LaDePa), is a technology developed by eThekwini Water and Sanitation, a unit of eThekwini Municipality in South Africa, in association with Particle Separation Solutions (Pty) Ltd (PSS) that uses medium-wave infrared irradiation to convert pit latrine sludge into a soil conditioner. A case study of LaDePa has been discussed in this report for technology description. This technology is also referred to as infrared pasteurization.

The process is powered by a diesel generator and is designed to deal with sludge containing a high percentage of garbage and other detritus. The feed sludge must have a solids content of 25–30 per cent, which is typical for faecal sludge removed from pit latrines in South Africa. It has a treatment capacity of 1.5 m3/h (or 12 m3/day) and was designed to treat the waste from 35,000 ventilated improved pit (VIP) latrines, which eThekwini Water and Sanitation is responsible for emptying every five years. The stages in the process are as follows:

- Sludge and detritus taken from pits are compressed in a screw compactor that has lateral ports through which compressed sludge is ejected. Detritus is ejected through the end of the screw compactor.
- The separated sludge falls onto a porous steel conveyor belt, on which it forms a layer, typically 25–40 mm thick. The belt carries the sludge through a pre-dryer, heated by the exhaust gases from the diesel generator.
- The sludge then passes through a machine, patented by PSS, which subjects it to medium-wave infrared radiation. Power is provided by electricity produced by the diesel generator while a vacuum draws air through the sludge as it passes along the belt, extracting more water.
- The temperature of the sludge is raised by the combined effects of the infrared radiation and the exhaust gases from the diesel generator.
- The dried and pasteurized sludge falls off the far end of the moving belt and is then collected and bagged.
- During the process, the sludge is heated to temperatures above 100°C for about eight minutes. This, together with the exposure to infrared radiation, kills pathogens, including helminth eggs, and makes the bagged sludge safe for reuse as an agricultural conditioner.

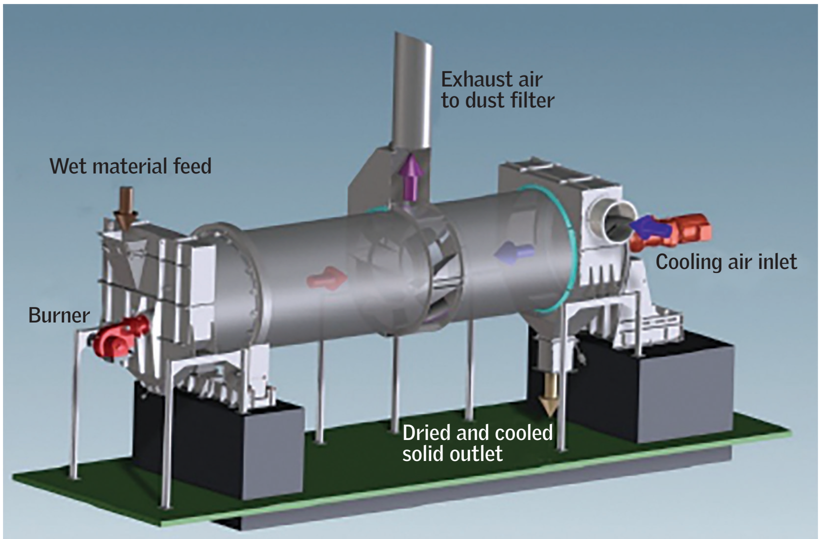
Advantages: The LaDePa system requires minimal labour, has a low footprint, and is housed in two standard shipping containers, allowing the plant to be moved to other locations as necessary.

Limitations: Its main disadvantages are its power dependency and its reliance on mechanical equipment.

5.6 Thermal drying

Thermal drying involves heating dewatered biosolids to evaporate water and hence reduce their water content. It serves to reduce the sludge volume, as a result reducing any onward

Figure 15: Schematic representation of rotary dryer



Source: https://www.victoriartilloedm.com/, https://www.at-minerals.com/

transportation costs for the treated product. It raises temperature levels sufficiently to kill pathogens and increases the specific (per unit volume) calorific value of the biosolids, an important consideration if the intention is to use dried solids as a fuel.

Technology description: Thermal dryers fall into two basic categories—direct thermal dryers, in which hot air is directly blown over the sludge, and indirect thermal dryers, in which heat is transferred to the sludge from a heat transfer medium, such as oil, by conduction through the metal wall of the vessel holding the sludge. The heat transfer medium has no direct contact with the solids. Thermal dryers have a high energy requirement. Both direct and indirect dryers require an outside energy source to provide the heat that is needed for drying. An electricity supply is typically also required to turn the dryer and to power a blower or pump to move the heating medium around the material to be dried.

Direct thermal dryers: The most commonly used types of direct thermal dryers are rotary and belt dryers.

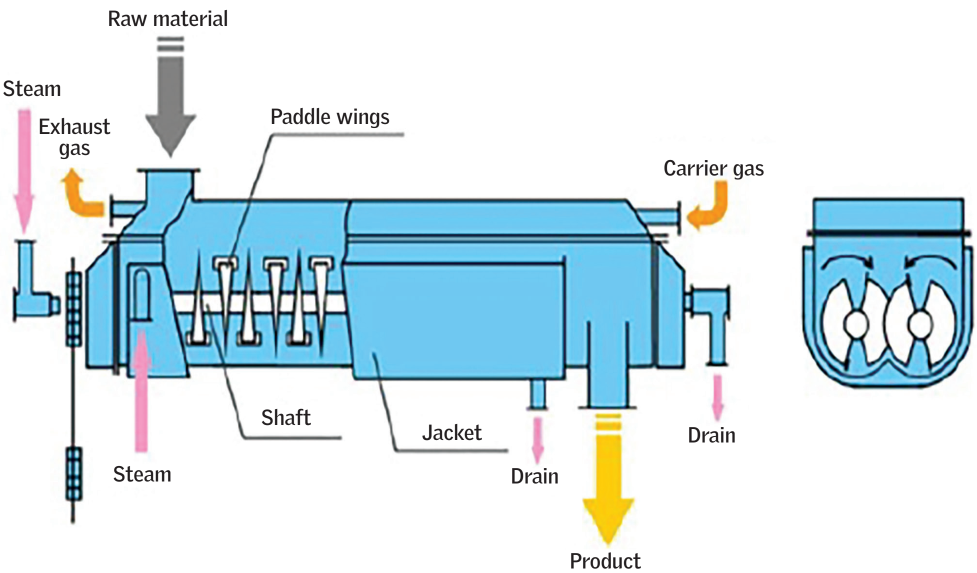
Rotary dryer: The simplest form of dryer is the direct rotary dryer. This consists of a cylindrical steel shell that rotates on bearings and which is mounted horizontally, with a slight slope down from the feed end to the discharge end. The feed sludge is mixed with hot gases produced in a furnace and is fed through the dryer. As it passes through the dryer, flights (fin-like attachments to the wall of the cylinder) pick up and drop the sludge, causing it to cascade through the gas stream. Moisture in the sludge evaporates, leaving a much dryer material at the discharge end of the dryer. The dried sludge is separated from the warm exhaust gas, part of which is recycled to the dryer while the remainder is treated to remove pollutants and is then vented to the atmosphere (see *Figure 15: Schematic representation of rotary dryer*).

Belt dryer: Belt dryers operate at lower temperatures than rotary drum dryers. The heat from the furnace is transferred to a thermal fluid, which heats the air in the dryer. The dewatered cake that is to be dried is distributed onto a slow-moving belt, which exposes a high surface area to the hot air.

Indirect thermal dryers: Indirect drying options include paddle dryers, vertical tray dryers, and an indirect type of fluidized-bed dryer. Flash dryers, installed to dry municipal wastewater sludge also fall in this category. Fluidized-bed dryers have been used to produce a pelletized product from sewage works sludge. They are more complex and require more energy than rotary dryers.

Paddle dryer[36]: In the jacket shell body of paddle dryers there are two parallel shafts which 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

Figure 16: Schematic structure of paddle dryer



Source: https://chemsept.in/

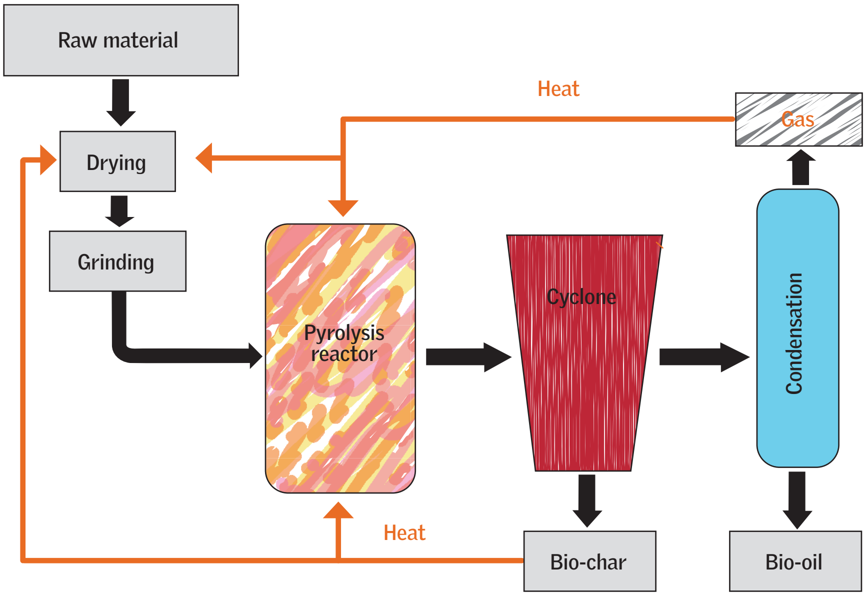
discharged through the revolving joint. The material is continuously fed into the equipment, next it is agitated and mixed near the paddles. At the same time, the material is gradually dried by the heat conduction of paddle and jacket. The height of overflow weir can be changed to adjust residence time. In addition to this, the steam produced in the drying process is discharged through the escape hole with trace amounts of air. This technology has been used in two FSTPs in India to treat FS biosolids *(see Fig. 16)*.

Pathogen removal efficiency: The solids content of the dried sludge produced by rotary 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.

Factors/recommendations for improving performance:

- A sludge feed with a water content of around 60–65 per cent is required in rotary dryers to allow the sludge to move through the dryer without sticking.

Figure 17: An overview of pyrolysis process



Source: Khitab et. al., 2021[37]

- To reduce energy requirements, solar drying can be used to reduce the water content of the sludge prior to thermal drying.

Limitations:

- Thermal drying systems produce dust, particularly when the solids content exceeds 95 per cent. Dust removal, often using baghouse filters, is required for direct dryers. The system must be designed in a way that ensures that the equipment does not pulverize the product and produce more dust.
- Thermal drying equipment requires skilled operators who have been trained to operate the equipment correctly and safely, are able to troubleshoot problems, and who can repair simple equipment faults.

5.7 Pyrolysis

Pyrolysis is the thermal decomposition of material at high temperatures in the absence of oxygen. It may be classified as fast, intermediate, or slow. Fast and intermediate pyrolysis requires that the material undergoing decomposition remains in the reactor for seconds or minutes. Slow pyrolysis requires a retention time measured in hours and a temperature of at least 200°C and typically more, up to around 700°C. Pyrolysis differs from combustion in that little or no carbon dioxide is released during the process. Instead, organic material undergoes carbonization, or conversion into carbon in the form of hard, porous charcoal. This material, which is called biochar, can be used as a soil amendment or as a fuel source. Pyrolysis produces a mixture of gases that are used as fuel to power the process *(see Fig. 17)*.

Pathogen removal efficiency: The high temperatures reached during pyrolysis completely remove pathogens, ensuring that the biochar produced is safe to use.

Factors affecting the efficiency of pathogen removal:

- Solids content of the sludge affects the temperature required for pyrolysis, and it is even possible to achieve an energy-neutral process by optimizing solids content and temperature.
- From the studies conducted, it was found that a dry solids content of at least 60–70 per cent is required for pyrolysis to be self-sufficient in energy.
- Most pyrolysis plants operating in low-income countries operate in a batch mode. This simplifies their operational requirements but increases the need for an external fuel source to heat the reactor contents to the required reaction temperature.

Challenges/limitations:

- Potential challenges include the difficulty of controlling emissions and the maintenance challenges arising from the nature of the liquid produced during pyrolysis. This is normally referred to as tar and consists of a mixture of complex hydrocarbons and water.

6. Summary and conclusions

- With the initiation of Swachh Bharat Mission by the Government of India—whose major focus has been on the sanitation sector—several toilets and subsequently several FSTPs have been built across the country for the safe management of excreta to protect public health and the environment.
- In a recent study conducted by the Centre for Science and Environment (CSE) on the performance evaluation of FSTPs in India, it was observed that both liquid effluent and solids derived from several FSTPs are high in pathogen levels which may harm the public and the environment if they are reused. Hence, a study has been undertaken to investigate the issue of pathogen management in FSTPs and provide guidelines for pathogen reduction.
- In FSTPs, the liquid and solid streams, referred to as faecal sludge (FS) leachate/effluent and FS biosolid respectively, are separated and each component is separately treated for effective treatment. For the treatment of FS liquid effluent, the pathogen disinfection technologies employed in majority of the FSTPs in India are sunlight and UV, while chlorination and membrane filtration are used in a few FSTPs.
- Sunlight is a natural disinfection agent that can destroy pathogens with exposure over an adequate period of time. As it is the cheapest method of disinfection, it is widely used in FSTPs that have been studied. However, the major problem associated with sunlight is the prediction of the extent of inactivation achieved. This can be overcome by regular monitoring of pathogen content in the sunlight treated effluent water.
- The next widely used disinfection method for liquid treatment in FSTPs is UV. UV is undoubtedly one of the best options and is a well-characterized method for the treatment of liquid effluents. In addition to being cost-effective compared to

treatment by sunlight, it has certain limitations, such as high solids content, lamp fouling, and aging, all of which should be taken care for efficient performance.

- Chlorination is one of the oldest and most well-characterized water disinfection technologies available to date. The optimal chlorine doses (chlorine contact time, CT) for the inactivation of some of the major enteric pathogens are also well-established. However, large eukaryotes like protozoan parasites and their cysts are resistant to chlorine. Other treatment technologies like UV/ozonation/microfiltration, that can remove protozoan parasites, can be used in this case. Chlorination has a few additional concerns compared to UV. Some of them are residual chlorine, disinfection by-products and 'tailing effect' due to high solids content. Hence, as discussed in more detail in the chlorine disinfection section above, optimizing chlorine dosing to minimize chlorine usage, removal of ammonia, and reduction of high solids content must definitely be executed for chlorine disinfection to be safe and effective. Free residual chlorine can be removed by using activated carbon.
- Membrane filtration is the physical separation of particulates (including pathogens) using membranes of specific pore sizes. If properly performed, membrane filtration techniques will aid in 100 per cent elimination of pathogens, including viruses. However, these are cost-effective and sensitive to highly turbid or heavily contaminated waters, hence requires pre-treatment steps and proper maintenance procedures for optimum performance.
- Media filtration techniques like rapid sand filter (RSF), dual media filter (DMF) and activated carbon filter (ACF) are installed in most of the FSTPs prior to all other disinfection steps discussed above. The main function of RSF and DMF are removal/reduction of suspended solids, odours, turbidity, and chlorine (if present). In addition, they also remove pathogens, but not as effectively as other disinfection methods. ACF's function is to remove organic matter, colour,

odour and chlorine. However, though these techniques are less efficient in removing pathogens, they are essential for improving the performance of subsequent disinfection steps. However, the operation and maintenance procedures discussed in detail in the respective sections should be accurately followed for proper maintenance and performance of these units.

- In contrast to the FS liquid effluent treatment, the technologies used for the treatment of FS biosolids in the FSTPs is very inadequate. Except for two plants that use IR radiation, all other plants store the dewatered and partially dried faecal sludge in a storage shed for sun drying without proper monitoring. This may be the reason for high pathogen content observed in many of the FSTPs. Three of the FSTPs practice co-composting. However, various sludge/ biosolid treatment/reuse options available for pathogen reduction, and their best practices for optimum performance are discussed in the current report to provide recommendations to the FSTP operators/ managers for better pathogen management of biosolids in the FSTPs to promote their reuse.
- Pyrolysis and thermal drying technologies operating at high temperatures can provide a100 per cent removal of pathogens. However, they require a high energy input and hence, are cost-effective, and require skilled personnel for operation and maintenance. In addition to this, the pyrolysis process essentially used to produce biochar, a material better used as a fuel than an organic fertilizer/soil conditioner.
- Co-composting FS biosolids with municipal solid waste/ other wastes is another good option for reusing FS biosolids as an organic fertilizer to promote plant growth. The composting process, due to reaching high temperatures during the process, is also capable of complete elimination of pathogenic organisms if optimally performed. However, several factors are responsible for optimal performance that have been discussed in the composting section above. Critical factors that are responsible for obtaining a best

quality compost include maintenance of optimum moisture content (25–35 per cent), C:N ratio (between 25:1 to 35:1) and adequate aeration in the composting material.

- IR radiation is the only treatment option available for treating FS biosolids, other than cost-intensive thermal drying. Due to low penetrating ability of IR radiation, IR treatment is best performed when the sludge undergoing treatment is made into fine particles before treatment. However, in the two FSTPs using IR treatment, a paddle dryer and a thermal drying process is employed prior to the IR treatment.
- Lime stabilization is a good option for FS biosolids treatment. However, it is not being used in any FSTPs studied (by CSE) in India. Lime treatment is very effective in removing pathogens. Nevertheless, it has limitations, including its hazardous nature and hence the requirement for safe handling procedures; as the pH rises. This method is only suitable for applying the treated sludge to acidic soils; skilled personnel are required for complete mixing of lime with FS biosolids for the treatment to be effective.
- Though extended storage in drying beds and solar drying are the easiest and cost-effective ways to reduce pathogens, proper maintenance is required to prevent regrowth of pathogens due to increase in moisture content due to rains. As discussed earlier, prediction of the extent of inactivation achieved is a concern associated with sunlight inactivation and this further requires frequent monitoring of pathogen content in sludge.
- It can be concluded that, though adequate pathogen treatment technologies are employed in FSTPs in India for the treatment of mainly FS liquid effluent and also biosolid, following appropriate procedures of operation and maintenance of the technologies can significantly improve the pathogen management in FSTPs that will promote

the safe reuse of FS products. However, pathogen reduction in FSTPs is not only dependent on tertiary treatment or post treatment technologies alone; the characteristics and quantity of FS received, various technologies adopted for FS treatment including different steps involved in treatment starting from stabilization and solid-liquid separation of FS (primary treatment), followed by secondary treatment modules like ABR, AF, PGF etc., all play role for effective pathogen removal from FSTPs.

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