A SCOPING STUDY

EVALUATION OF BIOCHAR FROM FSTPS (RAJASTHAN)

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ABBREVIATIONS AND ACRONYMS

AAETI	Anil Agarwal Environment Training Institute
ACF	Activated carbon filter
ADB	Asian Development Bank
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
AN	Ammoniacal Nitrogen
APHA	American Public Health Association
As	Arsenic
BMGF	Bill & Melinda Gates Foundation
BOD	Biological Oxygen Demand
BS	Biosolid
C	Carbon
C:N ratio	Carbon–to–Nitrogen ratio
Ca	Calcium
CapEx	Capital expenditure
Cd	Cadmium
COD	Chemical Oxygen Demand
COP	Combustion-based omni-processor
Cr	Chromium
CSE	Centre for Science and Environment
Cu	Copper
CU	Capacity Utilization
DO	Dissolved oxygen
E. coli	*Escherichia coli*
EC	Electrical conductivity
EML	Environment Monitoring Laboratory
FC	Faecal coliform
FCO	Fertilizer Control Order
FS	Faecal sludge
FSS	Faecal sludge and septage
FSSM	Faecal sludge and septage management
FSTP	Faecal sludge treatment plant
GoR	Government of Rajasthan
Gy	Gray
Hg	Mercury
HRT	Hydraulic retention time
ICP-OES	Inductively Coupled Plasma Optical Emission spectroscopy
K	Potassium
KL	Kilolitre
KLD	Kilolitres per day
kW	Kilowatt
MBBR	Moving Bed Biofilm Reactor
MeOH	Methanol

Mg	Magnesium
MLD	Million litres per day
MLG	Microbiology Laboratory Guidebook
Mn	Manganese
MoEF&CC	Ministry of Environment, Forest and Climate Change
MPN	Most probable number
N	Nitrogen
Na	Sodium
NGT	National Green Tribunal
NH3-N	ammoniacal nitrogen
NH4+N	ammonium nitrogen
Ni	Nickel
NPK	Nitrogen, phosphorus and potassium
OD	Open Defecation
ODF	Open Defecation Free
O&M	Operation and maintenance
OP	Omni-processor
OpEx	Operational expenditure
OSS	On-site sanitation systems
P	Phosphorus
PAOs	Phosphorus-accumulating organisms
Pb	Lead
pH	Potential of hydrogen
PHA	Polyhydroxyalkanoates
POP	Pyrolysis based omni-processor
PPE	Personal protective equipment
PSF	Pressure sand filter
PU	Polyurethane
RUIDSCO	Rajasthan Urban Drinking Water, Sewerage and Infrastructure Corporation
SBM	Swachh Bharat Mission
SCWO OP	Supercritical water oxidation omni-processor
SND	Simultaneous Nitrification and Denitrification
SR	Stabilization reactor
SRT	Solids retention time
TDS	Total Dissolved Solids
TKN	Total Kjeldahl nitrogen
TP	Total Phosphate
TS	Total solids
TSS	Total Suspended Solids
ULB	urban local body
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VFAs	Volatile fatty acids
Zn	Zinc

Executive summary

The safe and sustainable management of faecal sludge (FS) has become a critical priority for urban sanitation in India. Recognizing non-sewered sanitation as a critical solution for small and medium towns, the sector is piloting innovative treatment technologies to boost resource recovery and environmental protection. Pyrolysis-based omni-processor (POP) systems are particularly promising, converting FS into valuable resources like biochar and treated effluent. The term 'omni-processor', coined by the Gates Foundation, refers to a suite of self-sustaining technologies designed to treat human FS safely and profitably where modern sewer systems are absent.

This report, conducted by the CSE's Environment Monitoring Laboratory is a scoping study which evaluates the performance of two faecal sludge treatment plants (FSTPs) in Rajasthan—Khairthal and Kishangarh Bas—that utilize POP technology. The study focused on three primary objectives: firstly, treatment efficiency by evaluating whether the POP-based FSTPs effectively treat FS and if the generated effluent meets discharge standards set by the Ministry of Environment, Forest & Climate Change (MoEF&CC) and the National Green Tribunal (NGT); resource recovery potential by assessing the suitability of biosolids and biochar for agricultural use by analysing carbon, nutrient content and pathogen levels. Thirdly, oil impact by quantitatively comparing the effects of biochar versus untreated FS on local soil quality.

Field evaluations were conducted between April and July 2025 at the two selected FSTPs. Samples of raw faecal sludge, leachate after solid-liquid separation and treated effluent were collected and evaluated for critical parameters such as pH, solids content (total solids [TS], total suspended solids [TSS] and total dissolved solids [TDS]), organic content (BOD and COD), nutrients (total Kjeldahl nitrogen [TKN], ammoniacal nitrogen [AN] and total phosphorus [TP]) and pathogen levels (faecal coliform [FC]) to assess the efficacy of the treatment plants and the quality of the generated effluent. The solid by-products such as biosolids and biochar along with soil and soil mixtures of FS and biochar in nearby agricultural fields were collected and parameters such as pH, electrical conductivity [EC], moisture, carbon, nutrients such as nitrogen, phosphorus and potassium (NPK), heavy metals, and pathogens (FC, *E. coli*, *Salmonella* and helminth eggs) were evaluated to assess their quality and suitability for agriculture.

Khairthal and Kishangarh Bas FSTPs are equipped with a screw press, which is a mechanical solid-liquid separation technology; they have moving bed biofilm reactor (MBBR) technology for liquid treatment, and POP, for biosolids treatment. The treatment plants are moderate to good in the removal of solids content (50-94 per cent) and highly effective in the removal of organic content (90-98 per cent for BOD and 98-99 per cent for COD) in the effluent. Nutrient removal (TKN, AN) was slightly higher in Khairthal (92 per cent) than in Kishangarh Bas FSTP (73-78 per cent). Corresponding to the high efficiency of the plants for the removal of various contaminants, the effluent has pH, solids (TSS) and organic content (BOD and COD) within the safe limits of the MoEF&CC and the NGT. However, in spite of good per cent removal, nutrients (TKN, AN and TP) exceeded the NGT limit in Kishangarh Bas. With installed UV disinfection, both the plants are effective in removing pathogen load as observed from the low and safe levels (30-230 MPN/100 mL) of FC in the treated effluent.

PH and EC of biosolids and biochar were within the FCO standard limits of 6.0-8.5 and 4 dS/m respectively in the treatment plants. The moisture content in the biosolids ranged from 29.96-83.93 per cent, while that in biochar from 7.28-10.75 per cent, which is within the FCO standard of < 25 per cent for organic manure. The carbon and nitrogen content in the biosolids ranged from 32.4-37.8 per cent and 1.94-3.88 per cent respectively, while that in biochar, they ranged from 22.25-34.8 per cent to 0.57-1.93 per cent respectively, both of which complied with FCO standards of carbon (≥ 14 per cent) and nitrogen (≥ 0.5 per cent). C:N ratio in the biosolids and biochar ranged from 8.5-19.5 per cent and 11.6-61.0. A C:N ratio of 10:1 (or 15:1) to 20:1 in soil is considered optimal for plant and microbial growth. Hence, the higher value of 61.0 which was observed in Kishangarh Bas should be reduced to below 20 when considering for using it for agricultural purposes. The total of NPK content in the biosolids from the two FSTPs ranged from 5.88-7.63 per cent, while in biochar it ranged from 5.76-9.95 per cent, both of which are compliant with the FCO standard of ≥ 3 per cent and also represent a good nutrient (NPK) source for agricultural purposes. The study found that volatile heavy metals like Mercury (Hg) and Zinc (Zn) were largely removed/vaporized during high-temperature pyrolysis (>650°C), but other metals like Copper (Cu), Nickel (Ni), and Chromium (Cr) concentrated in the ash/char residue. Consequently, levels of Hg, Zn, Cr, Ni, and Cu in the biochar exceeded Fertilizer Control Order (FCO) limits.

The pyrolysis process proved highly efficient in pathogen reduction. While untreated FS poses significant health risks, the biochar produced was sterile immediately after production, though proper handling is required to prevent recontamination.

It was observed that, production of pathogen-free biochar is enhanced when steam drying adopted in POP to reduce moisture content in biosolids is effectively performed. However, helminth egg counts in both biosolids (213–2969 eggs/4g dry solids) and biochar (10–83 eggs/4g dry solids) exceeded USEPA Class A limits (<1 egg/4g), indicating they are not yet suitable for unrestricted agricultural use without further control measures.

Field analyses confirmed that biochar is a superior soil amendment compared to untreated FS. Its application improved soil water retention and nutrient balance (phosphorus and potassium). Unlike untreated FS, which carries pathogen risks, biochar offers a safer alternative for closing the sanitation-agriculture loop. The report validates POP technology as a robust solution for sustainable sanitation and resource recovery. While it effectively mitigates public health risks by stabilizing raw waste, challenges remain regarding heavy metal concentration and meeting strict pathogen limits for unrestricted use. The report's findings suggest the potential for the adoption of pyrolysis in municipal infrastructure for septage management. It emphasizes the need for standardised biochar production quality and better-post-processing handling to ensure safety of reuse in order to make most effective use of this technology.

1. Introduction

Rajasthan is the largest Indian state by area, occupying 10.4 per cent of India's total geographical area. It is the seventh largest state by population with a total population of nearly 68.5 million. The climate of Rajasthan is largely arid or semi-arid, and characterised by high temperatures throughout the year, with sharp extremes in both summer and winter, and generally moderate rainfall. The state's sanitation situation has improved considerably in recent years, driven largely by the Swachh Bharat Mission (SBM). However, significant challenges remain, especially in managing waste beyond the construction of toilets.

Although the state declared itself open defecation free (ODF) in both rural and urban areas under SBM, independent surveys around 2018 indicated that a portion of the population, particularly in rural areas, was still practicing open defecation (OD) despite having access to a toilet, highlighting the challenge of sustaining behavioural change. Following the large-scale toilet construction drive under SBM, Rajasthan had built 2.73 million toilets by 2018. However, only 30 per cent of these were connected to a sewer network, and these were concentrated in 27 of the state's 191 urban local bodies (about 14 per cent of ULBs). The remaining 70 per cent of urban households continued to rely on underground containment or on-site sanitation systems such as kuis, pits and septic tanks.[1]

To tackle the increasing amount of faecal sludge that is being accumulated due to the increase in the number of toilets, the Government of Rajasthan (GoR), with the grants support from Bill & Melinda Gates Foundation (BMGF) through Asian Development Bank (ADB), developed Faecal Sludge Treatment Plants (FSTPs) as a pilot in towns of Phulera, Lalsot, and Khandela. The state also formulated a State FSSM Policy to provide a holistic approach to safe collection, conveyance, treatment, and disposal/reuse of faecal sludge and septage.[2] However, while the policy is in place, there is a huge lag in infrastructure (FSTPs) leaving behind a massive amount of faecal sludge and septage (FSS) untreated. The state's total FSTP capacity is reported as 2,363 kilolitres per day (KLD). About 38.7 lakh litres (=3870 KLD) of FSS is generated in a day from septic tanks, public latrines and pit latrines, while around 3.3 lakh litres (=330 KLD) of human waste is generated daily from open defecation; hence still about 1,837 KL of FSS per day requires treatment.[3]

Expansion of sewerage networks that can treat 1,260 MLD by the year 2021 was proposed in the State's Sewerage and Waste Water Policy, 2016. Nevertheless, considering various on-going and proposed programmes of the GoR, through Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and Rajasthan Urban Drinking Water, Sewerage and Infrastructure Corporation (RUIDSCO), this would still cover only 84 out of the 191 ULBs (44 per cent), the remaining 107 ULBs (56 per cent) still need to depend on OSS, and hence on decentralized non-sewered sanitation systems such as FSTPs for treatment of FSS.[4]

In recent years, the safe and sustainable management of faecal sludge (FS) has emerged as a critical priority for urban sanitation systems in India. With the growing recognition of non-sewered sanitation as a viable solution for small and medium towns, innovative treatment technologies are being piloted to enhance resource recovery and environmental protection. Among these, pyrolysis-based omni-processor (POP) systems offer a promising pathway for converting FS into valuable byproducts such as biochar and treated effluent.

Omni-processor (OP) is a term coined by the BMGF to describe a range of self-sustaining technologies designed to safely and profitably treat human FS, particularly in areas without modern sewer systems. It tackles the severe global problem of inadequate sanitation, which is a major cause of disease. The proof-of-concept model was funded and spearheaded by BMGF which was designed to improve sanitation in poor and developing nations. OP is a self-sustaining community-scale sanitation system that turns human waste into a valuable commodity such as electricity/potable water/biochar etc. while also removing pathogens. It is a portfolio of technologies that is capable of processing FS from various sources, hence the use of the word *omni*. Instead of a single trademarked technology, the idea is to use different approaches for community specific needs, such as pyrolysis, supercritical water oxidation, electro-catalytic oxidation, double membrane treatment, combustion, among others. By generating its own power and creating commercially valuable products (water, electricity, fertilizer), OP acts as a self-sustaining model and offers a business case for local entrepreneurs to operate the system.[5]

OPs primarily rely on thermal treatment technologies, with three main types of OPs currently being developed and deployed. First is the combustion-based OP (COP) (the Janicki Model). This is the original and most well-known OP, primarily developed by Sedron Technologies (formerly Janicki Bioenergy). This highly sustaining model operates on boiling/thermal drying (of wet FS) and incineration (of dried biosolids) to generate potable water, electricity and ash containing valuable nutrients such as phosphorus, potassium, etc. The energy released by burning the dried sludge is more than enough to power the entire drying and water purification process. The Sedron Technologies (Janicki) S100 prototype was installed in Dakar, Senegal in 2015 to process the waste of 50,000 to 100,000 people. Generally designed for larger community-scale sanitation (e.g., 50,000+ people).[6]

Second is the pyrolysis-based OP (POP) (The Biogenic Refinery Model). This approach focuses on maximizing the recovery of carbon and nutrients in the form of biochar, primarily championed by companies like Biomass Controls PBC. In pyrolysis, dried FS (dried biosolids) is heated to high temperatures (e.g. 350–800°C) in a low-oxygen or zero-oxygen environment. Biochar, a stable, carbon-rich, pathogen-free solid residue that retains most of the beneficial nutrients (like phosphorus and potassium) is generated and can be used as a soil enhancer. Apart from biochar, gaseous and liquid fuels (syngas/bio-oil) are also produced; the syngas is often burned to provide the process heat, making the system self-sufficient. Treated water is also recovered from the sludge drying process. As high temperatures are achieved during the pyrolysis process, it ensures 100 per cent destruction of all pathogens and harmful chemical compounds, rendering the waste completely safe. Biomass Controls PBC deployed one of its first Biogenic Refinery prototype to process non-sewered sanitation waste in New Delhi in 2014. Typically designed for smaller, decentralized, community-scale use (e.g., 100 to 10,000 people). The other companies/pilot projects which focus in POP are Climate Foundation, Unilever and Ankur Scientific/Indo-German 'Pyrasol' Project.[7]

Third is supercritical water oxidation (SCWO) OP. This is an advanced chemical treatment method that leverages the unique properties of water under extreme conditions, with prototypes developed by institutions like Duke University and companies like 374Water. Faecal sludge (even wet sludge) is subjected to supercritical water oxidation which is a set of conditions above the critical point of water. Under these conditions, organic matter is rapidly and completely oxidized. The products obtained are clean water which can be further purified for drinking, inert salts/minerals which contain valuable nutrients (like phosphorus) that can be recovered for fertilizer, and heat/electricity. The process is generally energy-efficient. Prototypes have been successfully tested in labs and pilot units (often containerized) for rapid, complete destruction of pathogens and organics. Highly compact and scalable, often fitting within a standard shipping container, making it ideal for smaller communities or rapid deployment. While all OPs aim to safely treat FS and recover value, the best choice depends on the desired output.[8]

This report is a scoping study which presents an evaluation of two POP-based FSTPs located in Khairthal and Kishangarh Bas, Rajasthan. Commissioned in 2023 and operated by MVR Technology, these decentralized facilities represent a new generation of treatment systems designed to recover biosolids, biochar and treated water from FS. The study was conducted by the Environment Monitoring Laboratory (EML) of Centre for Science and Environment (CSE). It aims to assess the treatment efficiency of the selected FSTPs, evaluate the quality of biosolids and biochar for agricultural use, and benchmark the performance of POP technology against environmental and public health standards. The research quantitatively compares the impact of applying the resulting biochar on local soil quality against the impact of using untreated fecal sludge, thereby addressing data gaps related to the safety and efficacy of this resource recovery approach in a real-world setting. Through rigorous sampling, laboratory analysis, and field observations, the report provides insights into the operational strengths and challenges of POP-based FSTPs and their potential role in advancing sustainable sanitation and circular economy goals in India. The subsequent sections detail the specific objectives, the selection criteria for the FSTP sites, the analytical methodology, and the key findings from the field and laboratory analyses.

2. Objectives of the study

1. To evaluate the treatment efficiency of two POP-based FSTPs in Rajasthan
2. To check whether the quality of treated effluent generated by the FSTPs is meeting the effluent discharge standard limits set by the Ministry of Environment, Forest & Climate Change (MoEF&CC) and the National Green Tribunal (NGT)
3. To determine the potential of biosolids and biochar generated in the FSTPs for their use in agriculture

3. Selection criteria of FSTPs

The FSTPs evaluated in this study were commissioned during 2024. Hence, their capacity utilization is low to moderate.

In this study:

- The selection of the FSTPs for evaluation has been done on the basis of technology
- FSTPs with pyrolysis-based omniprocessor generating biochar were selected.
- Two FSTPs at Khairthal and Kishangarh Bas located in eastern Rajasthan were selected for the study

4. Significance of the study; parameters monitored

This study is critical for its focus on three outcomes–first, it has assessed the performance of POP-based FSTPs in the state; second, it has assessed the biosolid resource recovery potential of the FSTPs; and third, it has assessed the potential of biochar for agriculture.

4.1 Assessment of performance of FSTPs

Faecal Sludge Treatment Plants (FSTPs) are critical for removing contaminants from faecal sludge (FS), thereby safeguarding the environment and public health. Performance is assessed by monitoring key indicators like Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and nutrients (nitrogen and phosphorus). This evaluation allows operators to identify areas for improvement, optimize processes, reduce costs, and ensure regulatory compliance, ultimately leading to efficient and effective treatment that protects ecosystems and human health.

The most commonly adopted parameters for FSTP monitoring include:

4.1.1 Potential of hydrogen (pH): pH measures the acidity (<7) or alkalinity (>7) of the faecal sludge/wastewater based on the chemical activity of hydrogen ions in a solution. pH significantly influences the chemical and biological processes in treatment plants, such as neutralization, biological stabilization, precipitation, coagulation, and disinfection.

4.1.2 Total solids (TS), total suspended solids (TSS) and total dissolved solids (TDS): Total solids (TS) represents all matter (suspended or dissolved) that is left behind after a sample has evaporated and dried. TS comprises total suspended solids (TSS) (retained by a filter) as well as total dissolved solids (TDS) (passed through a filter). Total solids in wastewater are environmentally significant as they pose a threat to water quality, aquatic life, and human health. Elevated levels of these solids (both suspended and dissolved) can cause several negative effects: they reduce light penetration, decrease dissolved oxygen, increase water temperature, and may also transport harmful pathogens and pollutants.

4.1.3 Chemical oxygen demand (COD): COD measures the oxygen equivalent of all compounds that can be chemically degraded. It is a vital metric for quantifying pollutants in wastewater and for accurately modelling biotransformation in treatment processes.

4.1.4 Biochemical oxygen demand (BOD): BOD quantifies the oxygen consumed by microorganisms while degrading organic matter, hence indicating the amount of biodegradable organic matter present in a sample. Monitoring BOD is essential because high-oxygen-demand discharge can deplete oxygen in water bodies, potentially harming aquatic life. Stabilization via aerobic or anaerobic treatment reduces this oxygen demand.

4.1.5 Total Kjeldahl nitrogen (TKN) and ammoniacal nitrogen (AN): TKN is an important measure of total nitrogen, especially as FS typically has high concentrations. TKN is the sum of organic nitrogen and ammoniacal nitrogen [(NH_3-N)/ammonium (NH_4^+N)]. Excess nitrogen in effluent can cause eutrophication, promoting algal blooms and excessive plant growth. The subsequent microbial degradation of this biomass reduces oxygen levels and increases toxic substances, necessitating a reduction in effluent nitrogen content.

4.1.6 Total phosphate (TP): TP is measured to ensure effective FS treatment. Like nitrogen, excess phosphates in discharge are a significant concern as they stimulate unwanted algal growth, depleting oxygen and disrupting the aquatic ecosystem's ecological balance.

4.1.7 Faecal coliforms (FC): FC are indicator organisms used worldwide to test the sanitary quality of water and wastewater. FS contains numerous microorganisms, many of which are pathogenic, posing a significant health risk. Coliforms are bacteria predominantly found in the gastrointestinal tracts of warm-blooded animals, making FC and *Escherichia coli* (*E. coli*) excellent indicators of sewage/ faecal contamination.

4.2 Assessment of soil, biosolids and biochar

Faecal sludge-derived biosolids are valuable, nutrient-rich organic materials suitable for resource recovery as a soil conditioner and a solid fuel source. They can improve the physical, chemical, and biological properties of degraded soils by serving as a food source for microorganisms and acting as binding agents for aggregate stabilization. Biochar is a carbon-rich material produced by heating biomass (like biosolids, wood, manure, or crop waste) in a low-oxygen environment through a process called pyrolysis. Its main purposes are carbon sequestration by creating a stable form of carbon in the soil, improving soil health by enhancing water and nutrient retention, and acting as a soil amendment to increase fertility. The process can also produce clean energy as a byproduct.

According to United States Environmental Protection Agency (USEPA) guidelines, biosolids offer advantages over inorganic fertilizers because their nutrients are in organic forms that are released slowly through microbial decomposition over multiple growing seasons. This slow release increases nutrient use efficiency, reduces the likelihood of groundwater pollution (when application rates are appropriate), and minimizes the volume of waste that would need to be disposed in a landfill. This process promotes a closed-loop system and ecological balance.

The following parameters must be analyzed to confirm the usability of biosolids and biochar as an alternative to chemical fertilizers:

4.2.1 Potential of hydrogen (pH): The pH of biosolids varies based on their origin (sewage/FS), treatment processes, and amendments. Primary biosolids are typically neutral to slightly alkaline (pH), while secondary biosolids have varying pH depending on the biological treatment method used.

4.2.2 Electrical conductivity (EC): EC measures dissolved salts in the biosolids, soil, or fertilizer, typically in deciSiemens per meter (dS/m). High EC indicates elevated levels of dissolved salts (e.g., sodium, calcium, magnesium), which can negatively impact soil structure, fertility, and plant growth. Understanding EC is crucial for optimizing application rates.

4.2.3 Moisture content: Moisture is the quantity of water present in the material. It is one of the essential parameters as it governs the microbial activity of soil. High moisture content is a concern because it can promote microbial growth, including that of pathogens. Lack of moisture can slow down the breakdown of organic material in soil because it hinders microbial growth.

4.2.4 Carbon–to–nitrogen (C:N) Ratio: C:N ratio is a critical factor in soil science that determines nutrient availability for plants and microbes. An optimal ratio of 15:1 to 20:1 allows for efficient organic matter decomposition by bacteria and fungi, which require carbon as an energy source and structural component, and nitrogen for synthesizing biological compounds (amino acids, proteins). If C:N ratio is >20 in biosolids, it may result in reduced nitrogen availability for the plants, leading to immobilization of nitrogen. Conversely, a lower C:N ratio leads to higher mineralization of nitrogen uptake for the plants, which may result in loss of nitrogen. Therefore, a balanced C:N ratio between 15:1 to 20:1 ensures optimal decomposition.

4.2.5 Heavy metals: Heavy metals are elements with high atomic weights that can accumulate in biosolids from industrial, wastewater, agricultural activities or natural sources. They are non-biodegradable and can persist in the environment. If biosolids with high heavy metal levels are land-applied, there is a risk of leaching into groundwater or adversely affecting plants, potentially contaminating crops and ecosystems.

4.2.6 Nitrogen, phosphorus and potassium (NPK): NPK are essential macronutrients that play unique and vital roles in crop health, growth, and maximum yield. Nitrogen is primarily responsible for vigorous vegetative growth and is a key component of the machinery that powers the plant. Phosphorus is critical for energy transfer, root establishment, and reproductive success. Potassium, often called the 'quality nutrient,' is involved in numerous regulatory processes that enhance overall plant health and stress tolerance. The proper balance of NPK is crucial, as too much of one nutrient (e.g., excess nitrogen causing lush leaf growth at the expense of fruit) or a deficiency in any one can negatively impact crop growth and yield. The ideal NPK ratio in fertilizers varies depending on the specific crop and its stage of growth.

4.2.7 Faecal coliform (FC) and *E.coli*: FC/*E.coli* are specific indicators of faecal contamination as they predominate in faeces of warm-blooded animals including humans. Testing for these bacteria is necessary because raw FS and its derivatives contain a diverse range of pathogens (bacteria, viruses, protozoa, helminths) that pose a global public health risk (e.g., diarrhoea, fever) if humans are exposed to improperly treated materials.

4.2.8 *Salmonella*: *Salmonella* is a ubiquitous and hardy bacterium found frequently in sewage. *Salmonella* spp. are highly resistant to environmental stresses and can survive for extended periods, even regrowing in the soil.[9] Due to its resistance and association with foodborne outbreaks, it is a key indicator of pathogen reduction effectiveness in biosolids, making its monitoring essential for public health safety in agricultural reuse.

4.2.9 Helminth eggs: Helminth eggs are microscopic eggs (20–80 µm in size) of intestinal worms (e.g., hookworm, roundworm) that are the infectious agents for helminthiases, a group of parasitic diseases. Found in wastewater and sludge, these eggs pose an infection risk if ingested. Proper treatment of FS and biosolids is crucial to prevent the spread of these diseases, such as ascariasis and schistosomiasis.

5. Sample collection and testing parameters

Environment Monitoring Laboratory (EML) scientists visited each site and collected, properly preserved and transported the samples at the earliest to the lab by adopting standard protocols for sampling, preservation and transportation.[10] Personal protective equipment (PPE) like overalls, gloves, face masks, protective eyewear, and hand sanitizers were included in the sampling kit and used accordingly during the sampling process. The sampling bottles were properly cleaned and sterilized; the bottles and plastic bags were attached with appropriate labelling stickers. The sampling location, along with date and time, was accurately stated on each bottle and plastic bag after sampling. The samples were preserved with frozen ice-gel packs and transported in leak-proof ice-boxes.

5.1 Sampling interval and duration of the visit

Two to three lots of samples were collected from each location with an interval of 35–50 days between collections. The sampling process from each location was carried out for a duration of four months, i.e., April–July 2025.

5.2 FS, inlet and outlet collection

1. Raw faecal sludge samples were collected from the tanker when the tanker unloads the faecal sludge into the receiving chamber of FSTPs.

2. Around one litre of the inlet and outlet of FSTPs was collected to assess the performance of individual FSTPs. Inlet refers to the leachate entering the treatment modules after the solid–liquid separation process, and outlet refers to the final discharge water emerging from the final stage of treatment process in the FSTPs. Liquid samples were collected in sterile polypropylene bottles, capped and preserved with ice packs. They were transported to the laboratory thereafter in the shortest possible time for further analysis.

Desludging truck discharging faecal sludge at Khairthal FSTP
Source: EML, CSE

Collection of treated water from Kishangar Bas FSTP
Source: EML, CSE

5.3 Testing parameters and methods for the analysis of FS, inlet and outlet

Physico-chemical parameters such as potential of hydrogen (pH), total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), Total Kjeldahl Nitrogen (TKN), ammoniacal nitrogen (AN) and total phosphate (TP) and, microbial parameter Faecal Coliform (FC) were analyzed for the collected samples using standard methods (see *Table 1: Testing parameters and standard methods used for the analysis of FS, inlet and outlet*).

Table 1: Testing parameters and standard methods used for the analysis of FS, inlet and outlet[11]

Parameters	Standard methods
pH	APHA 4500-H+B, 24th ed., 2023[12]
Total solids (TS)	APHA 2540-B, 24th ed., 2023
Total suspended solids (TSS)	APHA 2540-D, 24th ed., 2023
Total dissolved solids (TDS)	APHA 2540-C, 24th ed., 2023
Chemical oxygen demand (COD)	APHA 5220-D, 24th ed., 2023
Biological oxygen demand (BOD)	Automated BOD Analyzer (Lovibond, BD 600) & APHA 5210-B, 24th ed., 2023
Total Kjeldahl nitrogen (TKN)	APHA 4500-Norg C, 24th ed., 2023
Ammoniacal nitrogen (AN)	APHA 4500-NH_3 C, 24th ed., 2023
Total phosphate (TP)	APHA 4500-P E, 24th ed., 2023
Faecal coliform (FC)	APHA 9221 E, 24th ed., 2023; USDA-FSIS, MLG Appendix 2.05, 2014[13]

Source: EML, CSE

5.4 Collection of soil, biosolids and biochar

Soil, biosolids and biochar were collected from both the locations. Two biosolid samples were collected from each FSTP after screw press and steam/belt drying. along with biochar. Three soil samples were collected from agricultural fields in each location—soil, soil mixed with FS 2–3 days ago, soil mixed with FS 3–4 weeks ago. Soil mixed with biochar was also collected at Kishangarh Bas. Around one kilogram (kg) of sample was collected in plastic bags, sealed properly and transported to the lab, and stored in a refrigerator at 4°C until analysis.

Collection of biosolids after screw press

Source: CSE

Collection of biosolids after steam drying

Source: CSE

Collection of biochar from pyrolyzer

Source: CSE

Collection of soil from agricultural field at Khairthal

Source: CSE

Collection of soil with FS added 2–3 days ago from agricultural field at Khairthal.

Source: CSE

Collection of soil with FS added 3–4 weeks ago from agricultural field at Khairthal.

Source: CSE

5.5 Testing parameters and methods used for the analysis of soil, biosolids and biochar

Physico-chemical parameters such as pH, electrical conductivity, moisture content, bulk density, carbon and nitrogen content, heavy metals and nutrients were determined along with microbiological parameters such as faecal coliform, *E. coli*, *Salmonella* and helminth eggs using standard methods. (see *Table 2: Testing parameters and standard methods / equipment used for the analysis of soil, biosolids and biochar*).

Table 2: Testing parameters and standard methods / equipment used for the analysis of soil, biosolids and biochar[14]

Parameters	Standard methods / Equipment used
pH	FCO, 2023 (pH meter, Eutech, pH 700)
Electrical conductivity	FCO, 2023 (Conductivity meter, Cyberscan 200)
Moisture content	FCO, 2023
Bulk density	FCO, 2023
Carbon and nitrogen content	CHN elemental analyser (LECO, USA, 828 series)
Heavy metals (Cu, Zn, Hg, As, Cd, Cr, Pb, Ni) and nutrients (Ca, Mg, Mn, Na, P, K)	ICP-OES (Perkin Elmer, Avio 200)
Faecal coliform and *E. coli*	APHA 9221 B, 9221 F, 24th ed., 2023; USDA-FSIS, MLG Appendix 2.05, 2014
Salmonella	USEPA, Method 1682, 2006; USDA-FSIS, MLG Appendix 2.05, 2014
Helminth eggs	Ambic-ZnSO4 method (Merlien Reddy, 2013)[15]

Source: EML, CSE

6. FSTPs evaluated in this study

In this study, two FSTPs with pyrolysis-based omniprocessor (POP) technology located at Khairthal and Kishangarh Bas in Rajasthan were evaluated. The consolidated details of the two FSTPs including their year of commissioning, treatment capacity, capacity utilization and treatment technology (modules) are provided in Table 3 below. The detailed technology specifications and other relevant information of the FSTPs observed during sample collection visit are provided in this section.

Table 3: FSTPs evaluated in this study

Sl. No.	Location	Year of commi-ssioning	Operator	Treat-ment capa-city	Capacity utilization	Solid-liquid sepa-ration	Treatment technology			Reuse of treated products	
							FS Leachate		Biosolids	Treated water	Biochar
							Secondary Treatment	Tertiary treat-ment			
1	Khairthal	2023	MVR Technology	35 KLD	4%	Screw press	MBBR	UV	Steam drying, Pyrolysis	Gardening within FSTP premises	None
2	Kishangarh Bas	2023	MVR Technology	10 KLD	6%	Screw press	MBBR	UV	Steam drying, Pyrolysis	Gardening within FSTP premises	None

Source: EML, CSE

Map 1: Locations of two FSTPs evaluated in this study

Source: EML, CSE

6.1 Khairthal FSTP

The 35–kilolitres per day (KLD) FSTP have been set up by Khairthal Municipality/ Nagar Palika with funding from the Housing and Urban Development Corporation (HUDCO), a Navratna Central Public Sector Enterprise (CPSE) under the Ministry of Housing and Urban Affairs (MoHUA) in collaboration with MVR Technology in Khairthal town which is the administrative headquarters of Khairthal-Tijara district of Rajasthan. The Khairthal Municipality has a population of 38,298 as per report released by Census India 2011 with a projected population of 53,000 by 2025. The FSTP was commissioned in 2023 and operated by MVR Technology. During the study period, the FSTP operated at only four per cent of its designed capacity, receiving just one 4,500-litre truck every three days.

The faecal sludge (FS) is received mainly from household septic tanks mostly connected to a soak pit. The FSTP is located near agricultural fields and is operated by five resource persons. Lack of awareness about the FSTP among public in the surrounding areas is one of the reasons for receiving less sludge. In addition, lack of awareness about the availability of FSTP-owned vehicle for desludging increases the desludging expense of households as they depend on private desludgers at increased cost (Rs 1500–2000 per trip) for desludging. The FSTP is a solar plant generating and operating on solar power, contributing to the reduction of O&M cost. Capex of the FSTP is 12.35 crores.

Following dewatering (using a screw press), the effluent water undergoes biological treatment via a moving bed biofilm reactor (MBBR). This is succeeded by tertiary treatment consisting of activated carbon filtration (ACF) and pressure sand filtration (PSF). The fully treated water is then subjected to UV disinfection before collection in a final tank. The dewatered sludge resulting from the screw press is managed separately by the pyrolysis process.

FS from various containments in the nearby areas is collected by vacuum trucks, and is discharged at the sludge receiving unit of the plant which is fitted with a screen (two in number arranged parallelly) to remove solid waste, floatable material and grit from FS. The FS gets collected in a stabilization reaction chamber (SRC-1) from which it is periodically transferred to SRC-2. Stabilization/ partial degradation of FS occurs in the SRCs-1 and 2 from where it is pumped periodically into a dewatering unit fitted with a mechanical screw press for solid-liquid separation. FS is mixed with polymer in the dewatering unit to flocculate solids in it for improved dewaterability. Overflow from dewatering unit enters into SRC-2. Leachate from screw press enters into MBBR unit which contains a filtrate tank followed by aeration, settling and filter feed tanks where degradation of organic matter and nutrients (nitrogen and phosphorus) takes place. In Khairthal, single-chambered MBBR technology is present. In a single-chambered MBBR, organic and nutrient removal occurs in different micro-environments (aerobic and anaerobic zones) within the biofilm present on (plastic) carriers present in the single aerated chamber/reactor. The digested sludge from aeration tank enters into a settling tank where digested matter/solids get settled and the liquid flows into filter feed tank. The effluent from filter feed tank of MBBR unit is periodically pumped into activated carbon and pressure sand filters for further treatment where removal of left over organics, suspended and dissolved solids takes place. Finally, the effluent passes through UV chamber for disinfection and gets collected in a collection tank. The water generated in the FSTP is used for gardening purpose within the premises of the FSTP.

The dewatered sludge from the dewatering unit is collected in a conveyor (Conveyor-1) from where it enters into the heat-pump based sludge dryer (operated at 60-75 °C), equipped with a horizontal belt dryer for drying. The sludge undergoes drying as it passes through the belt dryer. The dried sludge from the belt dryer is collected in a conveyor (Conveyor-2) from where it enters into the pyrolyzer. The pyrolyzer is equipped with a boiler where wood chips are used as a fuel. The sludge undergoes pyrolysis at a temperature of > 170°C (up to a maximum of 750 °C) under oxygen-limited conditions in the pyrolyzer and gets converted into biochar which gets collected in the collection unit. Around three to five kg of biochar is generated per day which is packed in plastic bags and stored in a storage room in the FSTP. The biochar has not been reused till date (see *Figure 1: Process flow in Khairthal FSTP*).

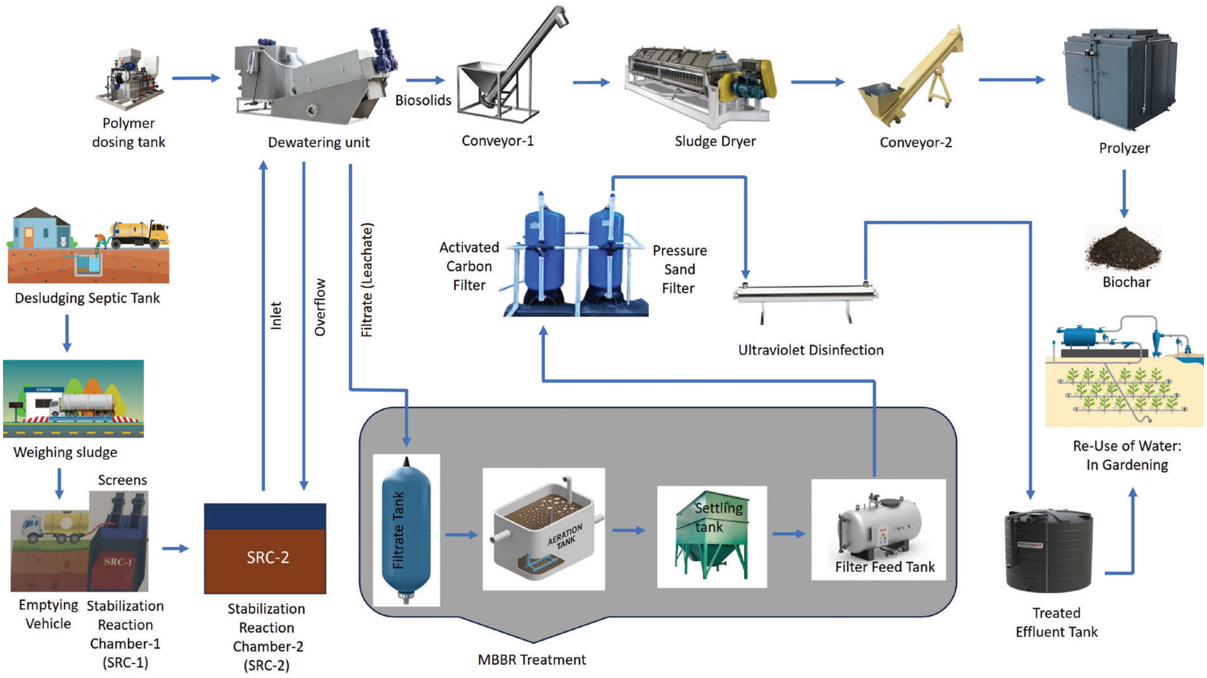
Pyrolysis-based omniprocessor (POP) at Khairthal FSTP showing conveyers, belt dryer and pyrolyzer

Source: EML, CSE

Wood chips at Khairthal FSTP; Source: EML,

CSE

Figure 1: Process flow in Khairthal, FSTP



Source: EML, CSE

6.2 Kishangarh Bas FSTP

The 10–kilolitres per day (KLD) FSTP have been set up by Kishangarh Bas Nagar Palika with funding from the HUDCO, MoHUA in collaboration with MVR Technology in Kishangarh Bas town, a census town in Alwar district of Rajasthan. The population of the Kishangarh Bas Community Development block (CD) is 316,832 as of a recent estimate. The population for the Tehsil (sub-district) was 201,279 according to the 2011 Census. The FSTP was commissioned in 2023 and operated by MVR Technology. During the study period, the FSTP was running at only six per cent capacity by receiving only one to two trucks of 4,000 litres capacity in 10–15 days. The faecal sludge (FS) is received mainly from household septic tanks mostly connected to a soak pit. The FSTP is located near agricultural fields and is operated by five resource persons. Narrow road near households which is unapproachable by cesspool trucks is one of the reasons for getting less FS in the plant. The FSTP is a solar plant generating and operating on solar power, contributing to the reduction of operation and maintenance cost. Capex of the FSTP is seven crores.

Post dewatering (screw press) the effluent water is treated by the adoption of MBBR, and finally thorough ACF, PSF and UV disinfection the treated water is collected in a tank. Pyrolysis process is used for dewatered sludge treatment.

FS from various containments in the nearby areas is collected by vacuum trucks, and is discharged at the sludge receiving unit of the plant which is fitted with a screen (two in number arranged parallelly) to remove solid waste, floatable material and grit from FS. The FS gets collected in a stabilization reaction chamber (SRC-1) from which it is periodically transferred to SRC-2. Stabilization/partial degradation of FS occurs in the SRCs-1 and 2 from where it is pumped periodically into a dewatering unit fitted with a mechanical screw press for solid-liquid separation. FS is mixed with polymer in the dewatering unit to flocculate solids in it for improved dewaterability. Overflow from dewatering unit enters into SRC-2. Leachate from screw press enters into MBBR unit which contains a filtrate tank followed by aeration, settling and filter feed tanks where degradation of organic matter and nutrients (nitrogen and phosphorus) takes place. Kishangarh Bas, like Khairthal, uses single-chamber MBBR technology. The digested sludge from aeration tank enters into a settling tank where digested matter/solids get settled and the liquid flows into filter feed tank. The effluent from filter feed tank of MBBR unit is periodically pumped into activated carbon and pressure sand filters for further treatment where removal of left over organics, suspended and dissolved solids takes place. Finally, the effluent passes through UV chamber for disinfection and gets collected in a collection tank. The water generated in the FSTP is used for gardening purpose within the premises of the FSTP.

The dewatered sludge from the dewatering unit is collected in a conveyor (Conveyor-1), and mixed with wood chips before it enters into the heat-pump based sludge dryer (operated at 60–75 °C), equipped with a horizontal belt dryer for drying.

Kishangarh Bas FSTP

Source: CSE

FS receiving unit with screens and effluent treatment modules at Kishangarh Bas FSTP;

Source: EML, CSE

The sludge undergoes drying as it passes through the belt dryer. The dried sludge from the belt dryer is collected in a conveyor (Conveyor-2) from where it enters into the pyrolyzer. The pyrolyzer is equipped with a boiler where wood chips are used as a fuel. The sludge undergoes pyrolysis at a temperature ranging from 350–750 °C under oxygen-limited conditions in the pyrolyzer and gets converted into biochar which gets collected in the collection unit. Around seven to eight kilograms of biochar is generated per day which is packed in plastic bags and stored in a storage room in the FSTP. The biochar has not been reused till date (see *Figure 2: Process flow in Kishangarh Bas FSTP*).

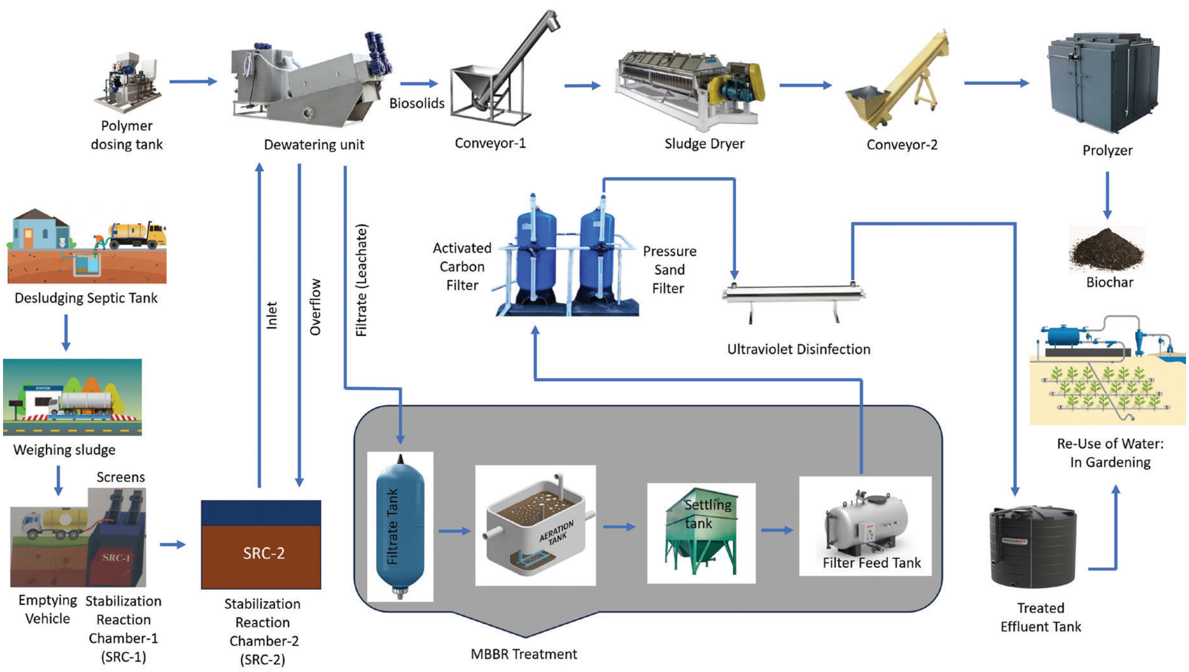
Pyrolysis-based omniprocessor (POP) at Kishangarh Bas FSTP;

Source: EML, CSE

Dewatered biosolids mixed with wood chips at Kishangarh Bas FSTP;

Source: EML, CSE

Figure 2: Process flow in Kishangarh Bas FSTP



Source: EML, CSE

7. The results of the study

The faecal sludge (FS), inlet and outlet samples collected from Khairthal and Kishangarh Bas FSTPs were characterized for 10 parameters (as mentioned in section 5.3). The term 'per cent removal' in this section implies 'removal that has occurred from inlet to final outlet'. Soil, soil mixtures with untreated FS/biochar, biosolids and biochar samples collected from Khairthal and Kishangarh Bas/ FSTPs have been analyzed for nine parameters (as mentioned in section 5.5). The graphs provided in this section depict the average data of two to three months.

The regulatory standards set by National Green Tribunal (NGT) 2019 and Ministry of Environment, Forest and Climate Change (MoEF&CC) 2017 for the discharge of STP effluent has been followed to assess the performance of the two FSTPs (see *Annexure 1 Tables 1-2*). The physico-chemical parameters in soil, soil mixtures with untreated FS/biochar, biosolids and biochar are compared with the Fertilizer Control Order (FCO) 2023 to evaluate the nutrient value of biosolids/biochar for agricultural applications (see *Annexure 1 Table 3*). To assess the pathogen level in soil, soil mixtures with untreated FS/biochar, biosolids and biochar, this study follows the regulatory limit set by WHO in 2006, and the US Environment Protection Agency (EPA) for class A biosolids (see *Annexure 1 Table 4*). The consolidated data of all the results is tabulated and depicted in *Annexure 2 Tables 1–3*.

7.1 Characterization of faecal sludge from Khairthal and Kishangarh Bas FSTPs

The FS samples collected from the desludging vehicle at the FSTPs were analyzed for the aforementioned ten parameters that are depicted in the table below (see *Table 4: Characterization of faecal sludge from Khairthal and Kishangarh Bas FSTPs*). The data presented here is the average value of the FS samples collected in two months—June and July 2025. The pH of FS ranges from 7.24 to 7.66. solids content (TS, TSS and TDS) were found to be higher in Kishangarh Bas (981–24,258 mg/L) compared to Khairthal (287–7641 mg/L). As anticipated due to high solids content, BOD and COD were also higher in the FS of Kishangarh Bas FSTP (1,605 to 51,500 mg/L) compared to Khairthal FSTP (465–18,260 mg/L). In the nutrients, while AN (626.66 to 697.71 mg/L) was almost similar in both FSTPs, TKN was higher in Khairthal FSTP, whereas TP was higher in Kishangarh Bas FSTP. FC are in the range of 5.34 to 6.06 $\log_{10}$ in the FSTPs.

Table 4: Characterization of faecal sludge from Khairthal and Kishangarh Bas FSTPs

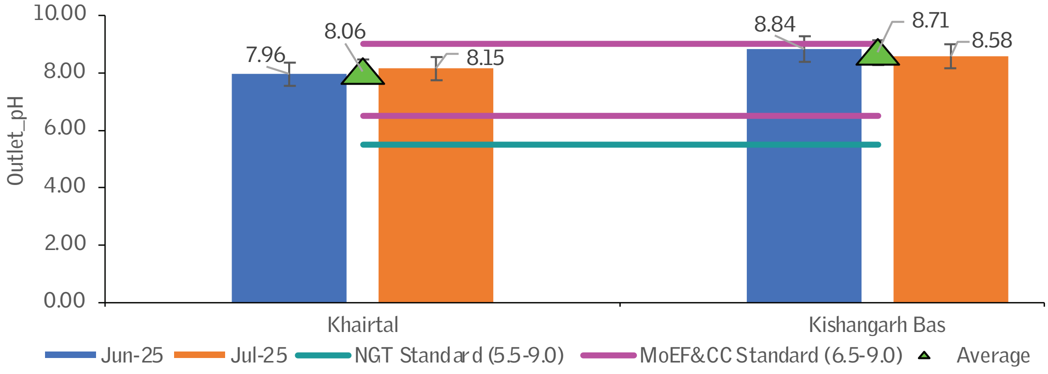
Location	pH	TS (mg/L)	TSS (mg/L)	TDS (mg/L)	TKN (mg/L)	AN (mg/L)	COD (mg/L)	BOD (mg/L)	TP (mg/L)	FC (MPN/ 100 mL)	FC Log_{10} value (MPN/ 100 mL)
Khairthal FSTP	7.24	7,641	287	7354	1,624.35	697.71	18260	465	61.0	21,7150	5.34
Kishangarh Bas FSTP	7.66	24,258	981	23,277	883.47	626.66	51,500	1,605	185.0	1,15,4650	6.06

7.2 Performance evaluation of FSTPs for effluent treatment and quality

Ten different parameters were selected for the evaluation of physico-chemical and microbiological characteristics of FSTP inlet and outlet samples namely pH, solids content such as total solids (TS), total dissolved solids (TDS) and total suspended solids (TSS), organic content based on chemical oxygen demand (COD) and biochemical oxygen demand (BOD), nutrient content such as Total Kjeldahl Nitrogen (TKN), ammoniacal nitrogen (AN) and total phosphate (TP) and pathogen content such as faecal coliform (FC). All the parameters are represented here to evaluate the performance of FSTPs.

7.2.1 pH: The standard limit of the MoEF&CC for the pH of treated effluent discharged from STPs ranges at 6.5–9 while the NGT ranges at 5.5–9. In this study, the pH of the outlet/treated effluent is slightly alkaline which ranged from 8.06 (Khairthal) to 8.71 (Kishangarh Bas). The pH is within the standard limits of both the MoEF&CC and the NGT (see *Graph 1: pH in the outlet of Khairthal and Kishangarh Bas FSTPs*).

Graph 1: pH in the outlet of Khairthal and Kishangarh Bas FSTPs



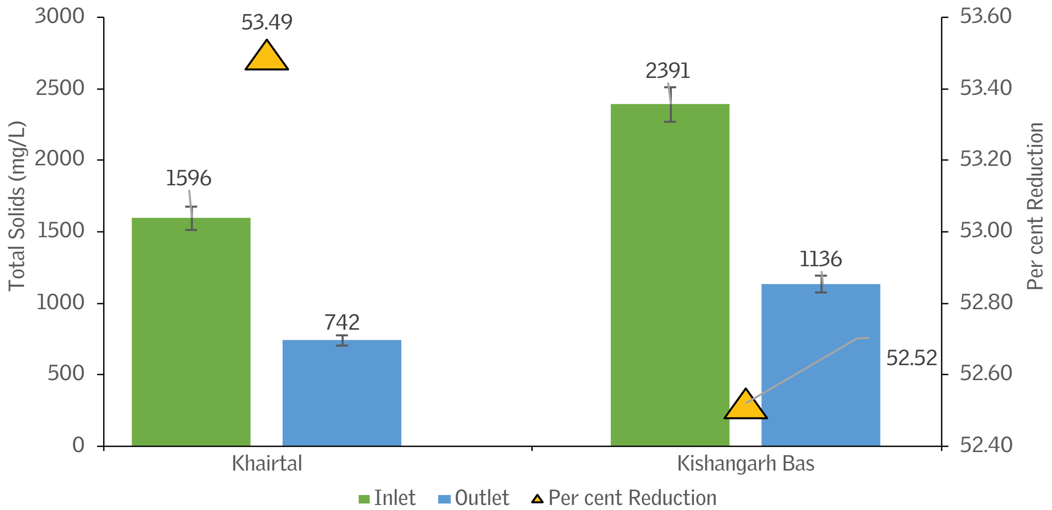
Source: CSE

7.2.2 Solids content (TS, TSS and TDS): The inlet TS, outlet TS and the 'per cent removal' of TS from Khairthal and Kishangarh Bas FSTPs are shown in Graph 2 (*see Graph 2: Total Solids (TS) in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet*)*;* the inlet TSS, outlet TSS and the 'per cent removal' of TSS from Khairthal and Kishangarh Bas FSTPs are shown in Graph 3 (*see Graph 3: Total Suspended Solids (TSS) in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet*). The inlet TS was found to be in the range of 1,596 mg/L (Khairthal) to 2,391 mg/L (Kishangarh Bas) whereas in the outlet, TS ranged from 742 mg/L (Khairthal) to 1136 mg/L (Kishangarh Bas) in the two FSTPs. The inlet TSS was found to be in the range of 39 mg/L (Khairthal) to 94.03 mg/L (Kishangarh Bas) whereas in the outlet, TSS ranged from 9 mg/L (Khairthal) to 13 (Kishangarh Bas) in the two FSTPs. While the 'per cent removal' of TS and TDS is around 50 per cent in both the FSTPs, 'per cent removal' of TSS varied from 75.32 per cent to 94.03 per cent in Khairthal and Kishangarh Bas FSTPs respectively.

The solids content such as TS, TSS and TDS in the outlet of Khairthal and Kishangarh Bas FSTPs is shown in Graph 4 (*see Graph 4: Solids content (TS, TSS and TDS) in the outlet of Khairthal and Kishangarh Bas FSTPs).* While TSS is quite low (9–13 mg/L) in both the FSTPs, the TDS and TS ranged from 733–742 mg/L and 1,123–1,136 mg/L in Khairthal and Kishangarh Bas FSTPs respectively (see *Graph 4: Solids content (TS, TSS and TDS) in the outlet of Khairthal and Kishangarh Bas FSTPs*). While no regulatory limits are available in India for TS and TDS, two regulatory limits are set by the MoEF&CC for the TSS of treated effluent discharged from STPs in various cities/towns (see *Annexure 1 Table 2*). The MoEF&CC limits are set at 50 mg/L for metro cities and other cities with over 10 lakh population (referred to as 'Category 1 cities/towns'), and 100 mg/L for other cities with a population below 10 lakh (referred to as 'Category 2 cities/towns'). In line with MoEF&CC norms, the NGT has prescribed three separate regulatory limits: one for 'Mega and Metropolitan Cities' with populations above one crore and ten lakh respectively; another for 'Class I cities' with populations between ten lakh and one lakh; and a third for 'Other' areas with populations below one lakh (*see Annexure 1, Table 1*).

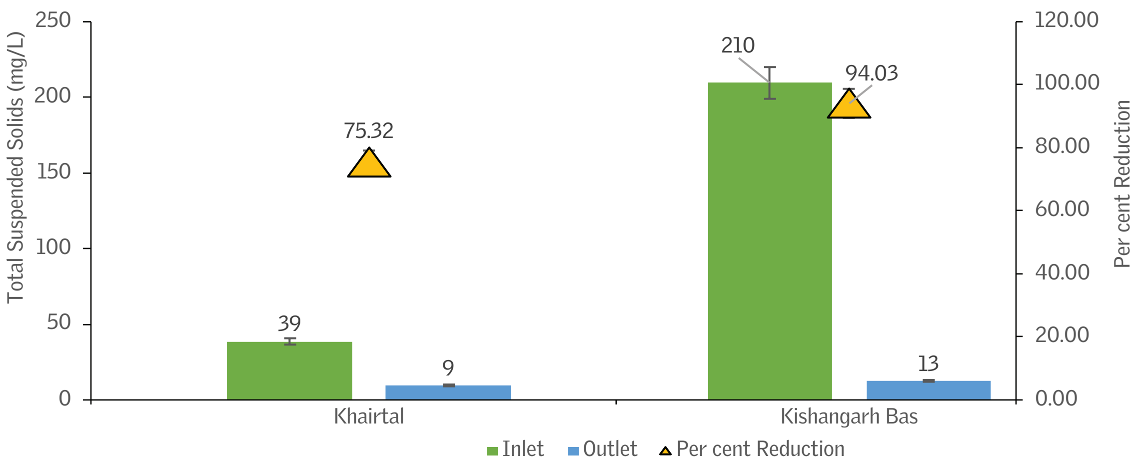
Both Khairthal and Kishangarh Bas with population less than ten lakh fall under the MoEF&CC's 'Category 2 cities/towns'; while Kishangarh Bas with a population between ten to one lakh falls under NGT's 'Class I cities', Khairthal with a population below one lakh falls under NGT's 'others' category of cities/towns; hence the two FSTPs were compared with the MoEF&CC and NGT limits accordingly. The National Green Tribunal (NGT) prescribes TSS limits of 30 mg/L for treated effluent from STPs in 'Class I cities' and 50 mg/L for those in the 'Others' category (*see Annexure 1, Table 1*). Both Kishangarh Bas and Khairthal showed an outlet TSS (9–13 mg/L) within the MoEF&CC limit of 100 mg/L. Kishangarh Bas and Khairthal FSTPs also showed an outlet TSS within the respective NGT limits of 30 mg/L and 50 mg/L (see *Graph 4: Solids content (TS, TSS and TDS) in the outlet of Khairthal and Kishangarh Bas FSTPs*).

Graph 2: Total Solids (TS) in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet



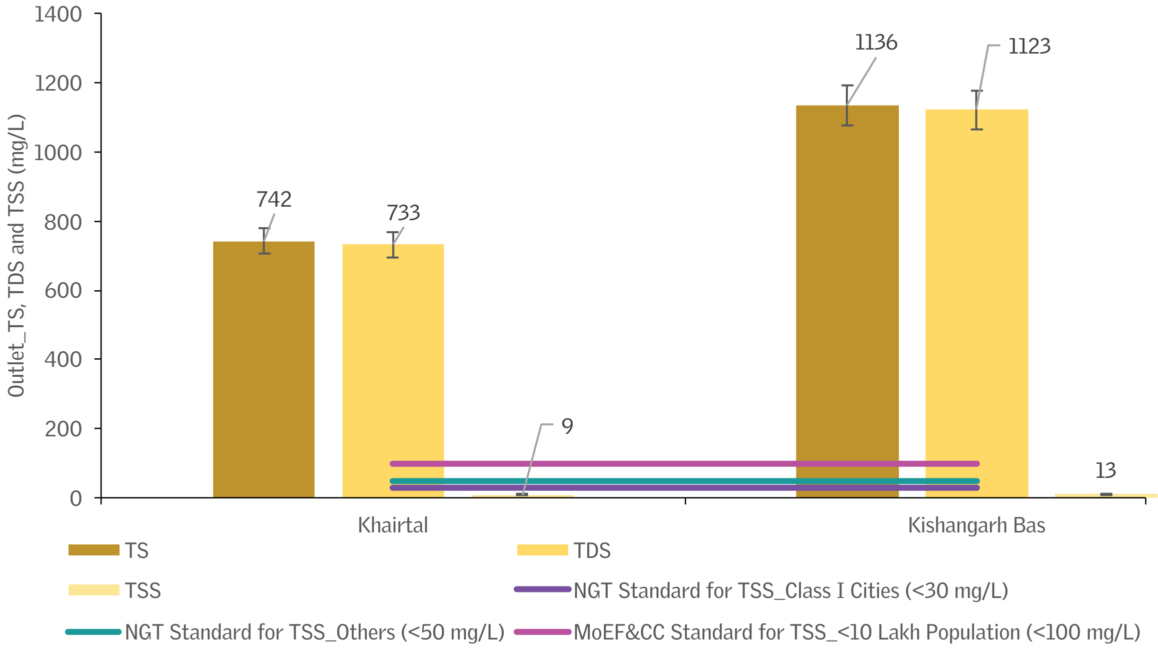
Source: CSE

Graph 3: Total Suspended Solids (TSS) in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet



Source: CSE

Graph 4: Solids content (TS, TSS and TDS) in the outlet of Khairthal and Kishangarh Bas FSTPs



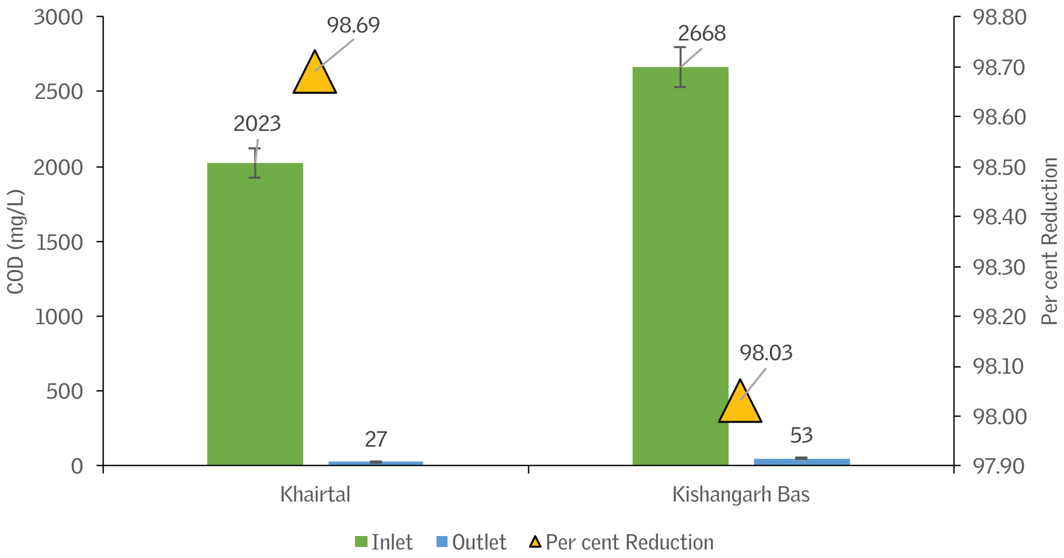
Source: CSE

7.2.3 Chemical oxygen demand (COD): The inlet COD, outlet COD and 'per cent removal' of COD from Khairthal and Kishangarh Bas FSTPs are shown in Graph 5 (*see Graph 5: COD in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet*). COD in the inlet of FSTPs ranged from 2,023 mg/L (Khairthal) to 2,668 mg/L (Kishangarh Bas) whereas in the outlet, COD ranged from 27 mg/L (Khairthal) to 53 mg/L (Kishangarh Bas). The 'per cent removal' of COD varied from 98.03–98.69 per cent in the two FSTPs.

No regulatory limit was given by the MoEF&CC for COD of the treated effluent discharged from STPs. Three regulatory limits are given by NGT for various cities/towns depending on their population as described above in Section 7.2.2 (see *Annexure 1 Table 1*). Both Kishangarh Bas (53 mg/L) and Khairthal (27 mg/L) FSTPs showed an outlet COD within the respective NGT limits of 100 mg/L for 'Class I cities' and 150 mg/L for 'Others' category of NGT cities/towns (see *Graph 6: COD in the outlet of Khairthal and Kishangarh Bas FSTPs*).

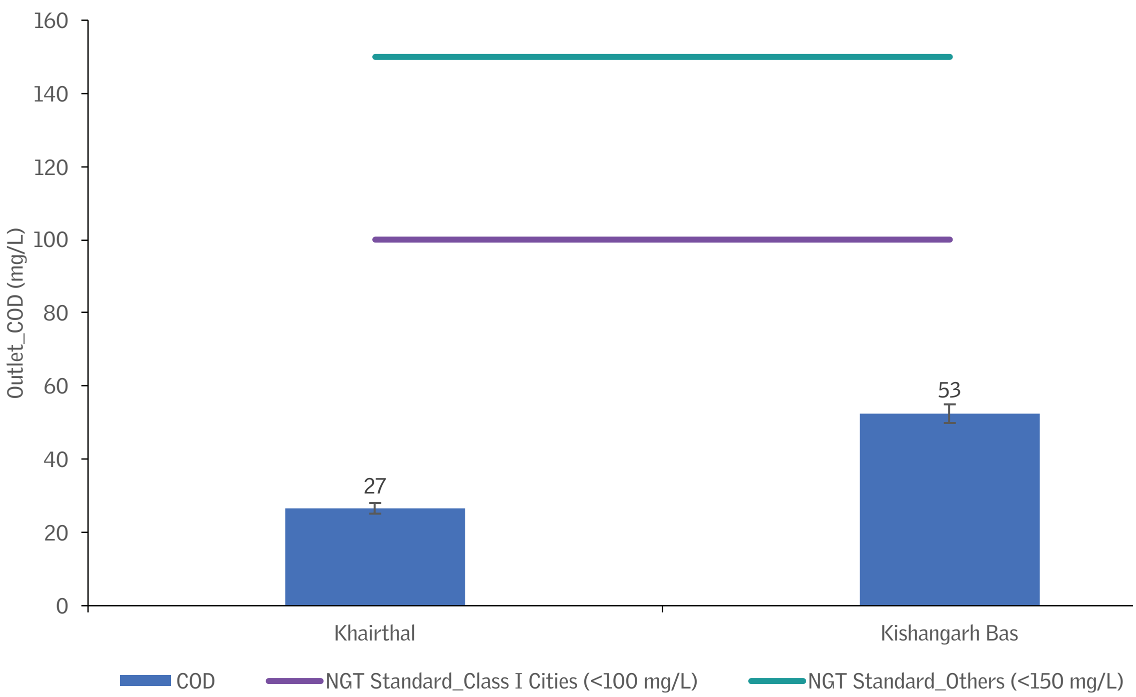
7.2.4 Biochemical oxygen demand (COD): The inlet BOD, outlet BOD and 'per cent removal' of COD from Khairthal and Kishangarh Bas FSTPs are shown in

Graph 5: COD in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet



Source: CSE

Graph 6: COD in the outlet of Khairthal and Kishangarh Bas FSTPs

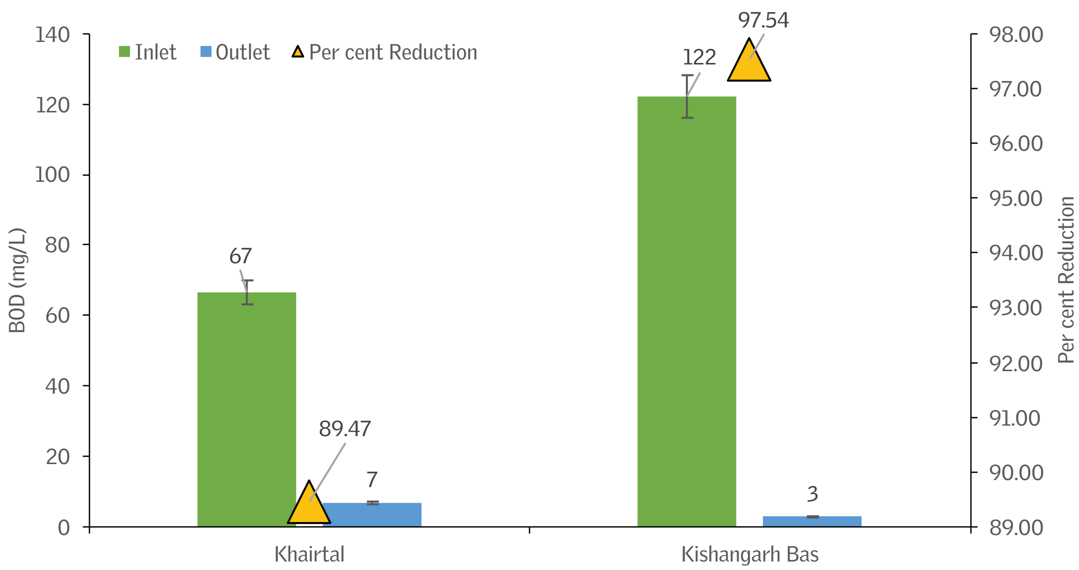


Source: CSE

Graph 7 (*see Graph 7: BOD in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet*). BOD in the inlet of FSTPs ranged from 67 mg/L (Khairthal) to 122 mg/L (Kishangarh Bas) whereas in the outlet, BOD ranged from 3 mg/L (Kishangarh Bas) to 7 mg/L (Khairthal). The 'per cent removal' of BOD varied from 89.47–97.54 per cent in the two FSTPs, with Kishangarh Bas showing a high removal than Khairthal.

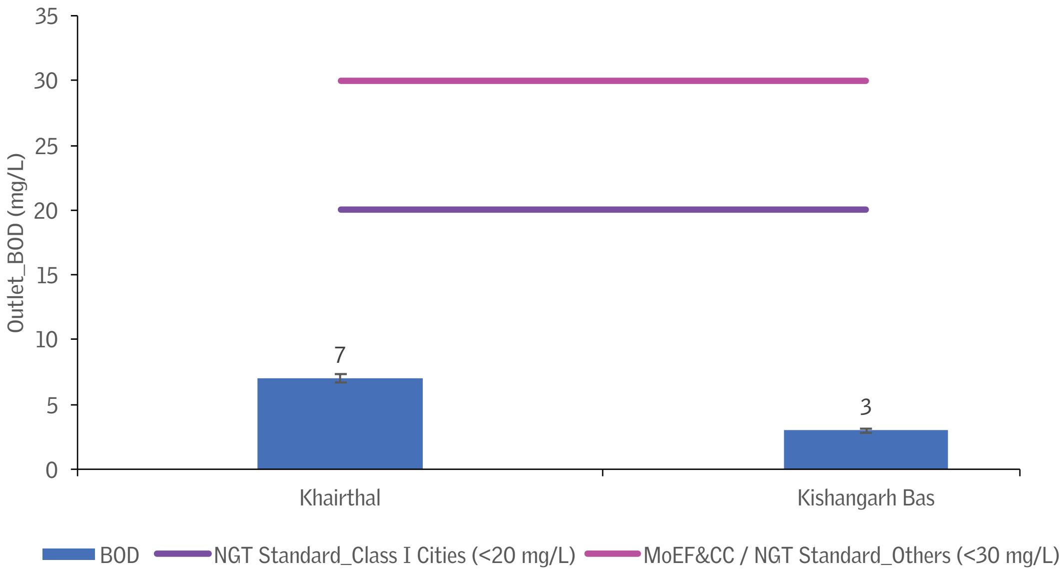
Two regulatory limits are given by the MoEF&CC for BOD of the treated effluent discharged from STPs of various cities/towns depending on their population (see *Annexure 1 Table 2*). The MoEF&CC limits are set at 30 mg/L for 'Category 2' cities/towns under which both Khairthal and Kishangarh Bas fall as described earlier in Section 7.2.2. Similarly, three regulatory limits are given by NGT for BOD for various cities/towns (see *Annexure 1 Table 1*). The NGT limits are set at 20 mg/L for 'Class I cities' under which Kishangarh Bas falls, and at 30 mg/L for 'others' category of cities/towns under which Khairthal falls; hence the two FSTPs were compared with the MoEF&CC and NGT limits accordingly. Both Kishangarh Bas and Khairthal showed an outlet BOD of 3–7 mg/L, which is within the MoEF&CC limit of 30 mg/L. Kishangarh Bas and Khairthal FSTPs also showed an outlet BOD within the respective NGT limits of 20 mg/L and 30 mg/L (see *Graph 8: BOD in the outlet of Khairthal and Kishangarh Bas FSTPs*).

Graph 7: BOD in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet



Source: CSE

Graph 8: BOD in the outlet of Khairthal and Kishangarh Bas FSTPs



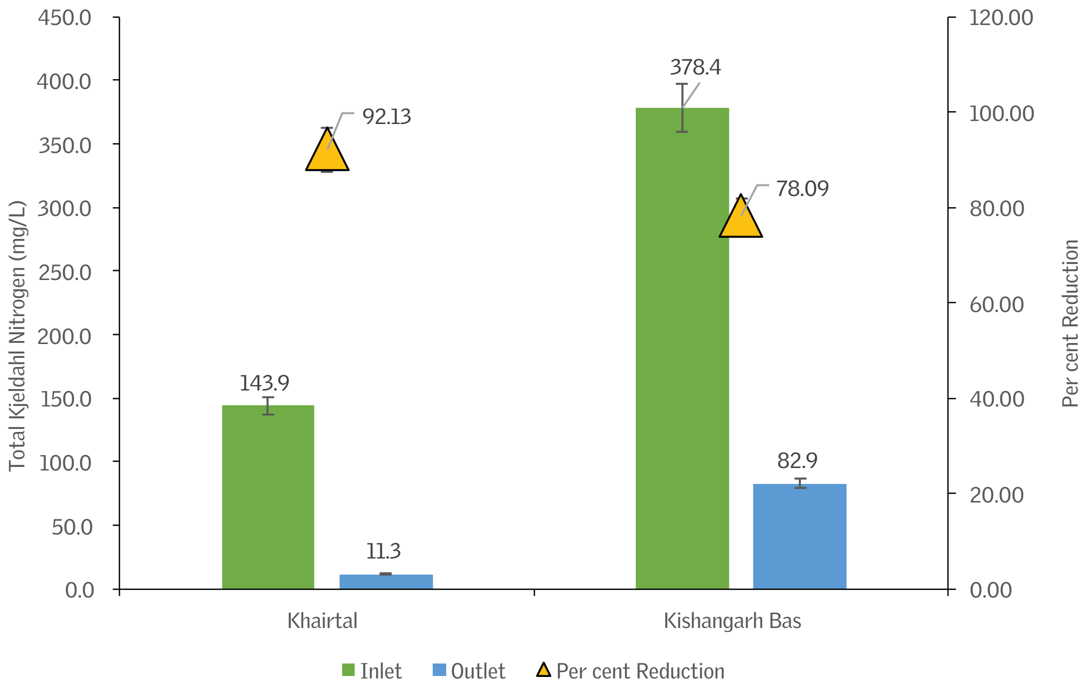
Source: CSE

7.2.5 Nutrients (TKN, AN, TP): The inlet TKN, outlet TKN and 'per cent removal' of TKN from Khairthal and Kishangarh Bas FSTPs are shown in Graph 9 (*see Graph 9: TKN in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet*). TKN present in the inlet of FSTPs ranged from 143.9 mg/L (Khairthal) to 378.4 mg/L (Kishangarh Bas) whereas in the outlet, TKN ranged from 11.3 mg/L (Khairthal) to 82.9 mg/L (Kishangarh Bas). The 'per cent removal' of TKN varied from 78.09 per cent (in Kishangarh Bas) to 92.13 per cent (in Khairthal). Similar per cent removal was observed for AN (72.78 per cent in Kishangarh Bas; 91.57 per cent in Khairthal) indicating higher per cent removal of nitrogen in Khairthal compared to Kishangarh Bas FSTP.

No regulatory limits for TKN or AN in treated effluent from STPs are specified under MoEF&CC guidelines. The NGT, however, prescribes total nitrogen (TN) limits of 10 mg/L for 'mega and metropolitan cities' and 15 mg/L for 'Class I cities' (*see Annexure 1, Table 1*). Kishangarh Bas showed an outlet TKN (82.9 mg/L) and outlet AN (63.9 mg/L) above the TN NGT limit of 15 mg/L for 'Class I cities' under which it falls. No regulatory limit was given by NGT for TN for 'others' category of cities/towns under which Khairthal falls (see *Graph 10: TKN and AN in the outlet of Khairthal and Kishangarh Bas FSTPs*).

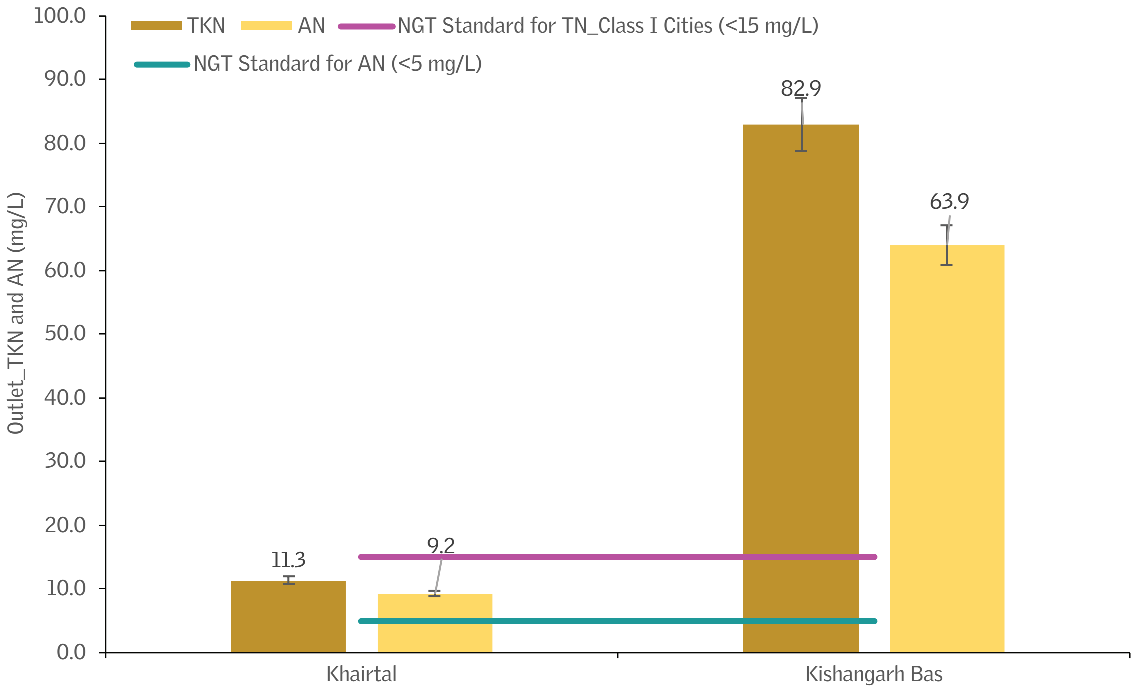
TP in the outlet ranged from 1.0 mg/L (Khairthal) to 1.5 mg/L (Kishangarh Bas). No regulatory limit was given by the MoEF&CC for TP of the treated effluent discharged from STPs. Three regulatory limits all set at 1.0 mg/L are given by NGT for total phosphorus (TP) of the treated effluent from STPs for discharge into ponds, lakes for 'mega and metropolitan cities', 'Class I cities' and 'others' category of cities/towns (see *Annexure 1 Table 1*). While Khairthal showed an outlet TP (1.0 mg/L) equal to the NGT limit of 1.0 mg/L, Kishangarh Bas (1.5 mg/L) showed above the limit (see *Graph 11: TP in the outlet of Khairthal and Kishangarh Bas FSTPs*).

Graph 9: TKN in the inlet and outlet of Khairthal and Kishangarh Bas FSTPs and 'per cent removal' from inlet to outlet



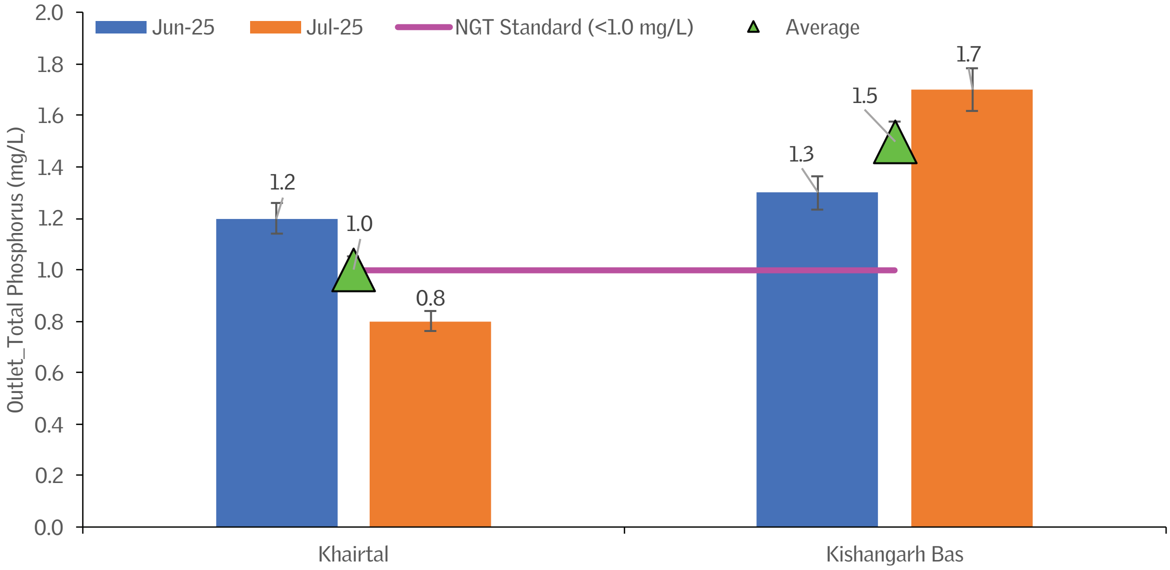
Source: CSE

Graph 10: TKN and AN in the outlet of Khairthal and Kishangarh Bas FSTPs



Source: CSE

Graph 11: TP in the outlet of Khairthal and Kishangarh Bas FSTPs



Source: CSE

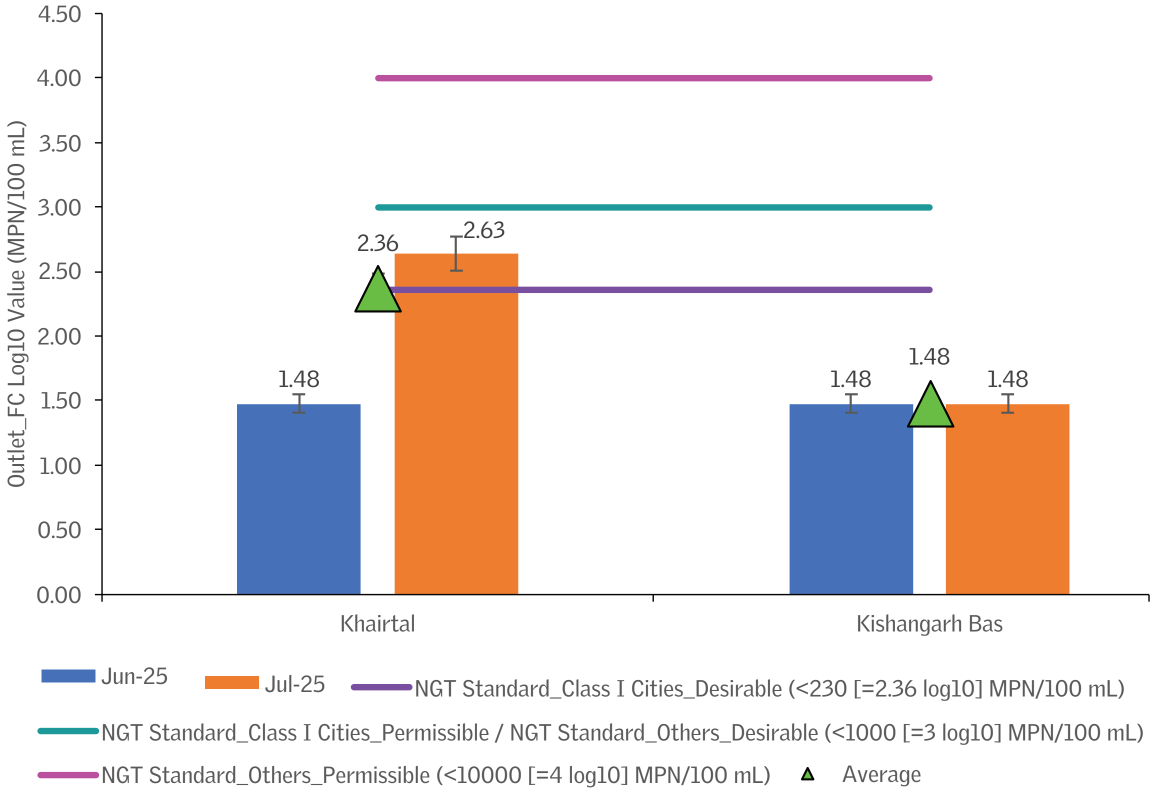
7.2.6 Faecal coliform (FC): The faecal coliform (FC) content in the outlet of Khairthal and Kishangarh Bas FSTPs is shown in Graph 12. (*see Graph 12: Faecal coliform (FC) in the outlet of Khairthal and Kishangarh Bas FSTPs)*. As the microbial populations (FC, *E. coli*, *Salmonella* etc.) show several-fold variations in their numbers across the samples, their estimates which are expressed in most probable numbers (MPN) or colony forming units (CFU) are represented in logarithmic (log_{10}) values (see *Graph 12: Faecal coliform (FC) in the outlet of Khairthal and Kishangarh Bas FSTPs*). This representation of MPN/CFU in logarithmic (log_{10}) values is followed throughout the report for the indicator/ pathogenic micro-organisms (FC, *E. coli* and *Salmonella*) to get better visualization of the results.

The regulatory limit given by the MoEF&CC for FC in the treated effluent discharged from STPs is 1,000 MPN/100 mL (log_{10} 1000 = 3) for both the MoEF&CC categories of cities/towns (see *Annexure 1 Table 2*). Six regulatory limits are provided by the NGT for various classes of cities/towns for FC in the treated effluent discharged from STPs (see *Annexure 1 Table 1*). While it limits about 230 MPN/100 mL (log_{10} 230 = 2.36) as the desirable limit and 1,000 MPN/100 mL as the permissible limit for Class I cities (under which Kishangarh falls), it limits about 1000 MPN/100 mL as the desirable limit and 10000 MPN/100 mL (log_{10} 10000 = 4) as the permissible limit for 'Others' category of cities/towns under which Khairthal falls. Hence the two FSTPs were compared with the MoEF&CC and NGT limits accordingly.

Faecal coliform (FC) in the outlet of the two FSTPs ranged from 30 MPN/100 mL (log_{10} 30 = 1.48) in Kishangarh Bas, to 230 MPN/100 mL (log_{10} 230 = 2.36) in Khairthal. When compared to the respective MoEF&CC and NGT standards described above, both the FSTPs showed FC within the limit in the outlet (see *Graph 12: Faecal coliform (FC) in the outlet of Khairthal and Kishangarh Bas FSTPs*).

In both Khairthal and Kishangarh Bas FSTPs, tertiary treatment through UV radiation, which is one of the disinfection methods to effectively kill the pathogens in the outlet water, is available. Presence of low amount of FC (30-230 MPN/100 mL) in the outlet within the regulatory limits of both MoEF&CC and NGT indicates the effective functioning of UV disinfection in the plants.

Graph 12: Faecal coliform (FC) in the outlet of Khairthal and Kishangarh Bas FSTPs



Source: CSE

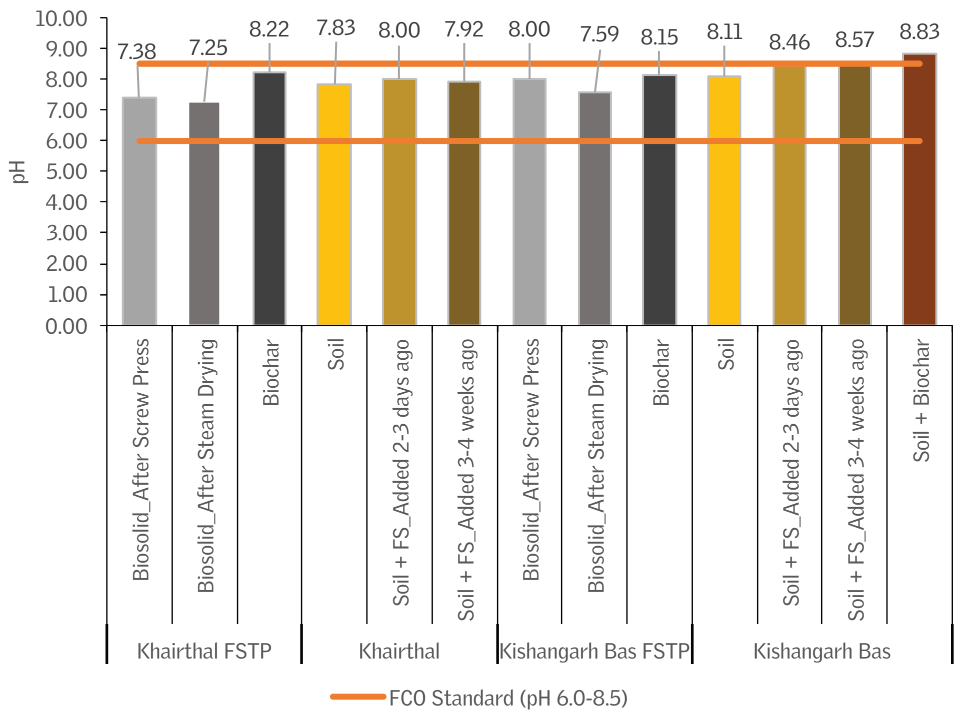
7.3 Evaluation of biosolids and biochar quality from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS / biochar

Organic manure, a rich source of nutrients, is used in agricultural fields to improve crop yield. However, the physical properties and chemical composition of organic manure must be maintained at optimum levels to prevent the adverse effects on soil, plants and environment. The Fertilizer Control Order (FCO) 2023 provides specifications to monitor the quality of various kinds of fertilizers. To evaluate the reuse potential of biosolids and biochar generated from Khairthal and Kishangarh Bas FSTPs for agricultural purposes, samples were tested for the various parameters set by the FCO 2023 for organic manure. For comparison and to know the effect of untreated FS on soil quality, soil, soil recently mixed with untreated FS (two to three days ago), soil mixed with untreated FS a few days ago (three to four weeks ago) were also collected from nearby agricultural fields in Khairthal and Kishangarh Bas. Soil mixed with biochar was also collected from

Kishangarh Bas. The results obtained were compared with the respective organic manure standards given in FCO 2023. The parameters and their specifications given in FCO 2023 for organic manure are provided in *Annexure 1 Table 3*.

7.3.1 pH: The pH of the biosolids, biochar, soil and soil mixtures of untreated FS/ biochar from Khairthal and Kishangarh Bas is shown in Graph 13. (*see Graph 13: pH of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar*). The standard for pH of the organic manure in FCO 2023 is at 6.0–8.5. The pH in the biosolids from Kishangarh Bas FSTP (7.59-8.0) is slightly higher than the biosolids from Khairthal FSTP (7.25-7.38). Biochar had a slightly alkaline pH (8.15-8.22) in the FSTPs. The pH of soil and soil mixtures of untreated FS from Kishangarh Bas (7.83-8.0) is higher than that of Khairthal (8.11-8.57). Highest pH (8.83) was observed in the soil mixed with biochar from Kishangarh Bas. Except Kishangarh Bas soil mixture of biochar and FS added three to four weeks ago, pH of all other samples is within the FCO limit of 6.0-8.5.

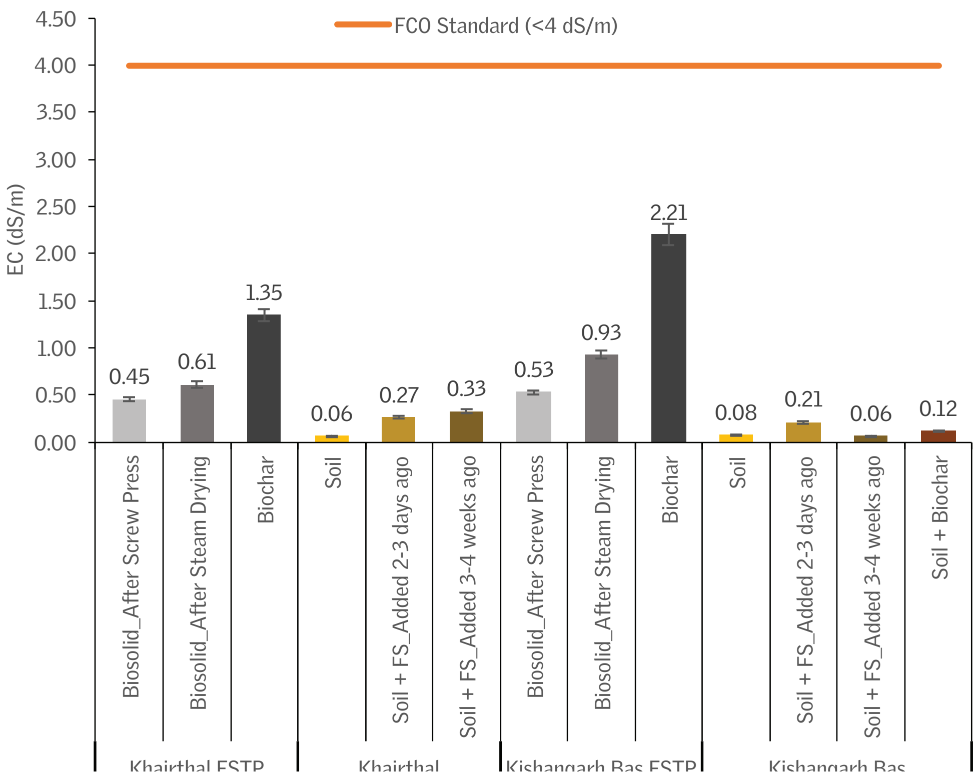
Graph 13: pH of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

7.3.2 Electrical conductivity (EC): The electrical conductivity (EC) of the biosolids, biochar, soil and soil mixtures of untreated FS/biochar from Khairthal and Kishangarh Bas is shown in Graph 14 *(see Graph 14: Electrical conductivity (EC) of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar)*. The standard for EC of the organic manure in FCO is <4 dS/m. The EC in the biosolids from Kishangarh Bas FSTP (0.53-0.93 dS/m) is slightly higher than the biosolids from Khairthal FSTP (0.45-0.61 dS/m). Soil EC is from 0.06–0.08 dS/m in the studied locations. The EC of soil mixtures of untreated FS from Khairthal (0.27-0.33 dS/m) is slightly higher than that of Kishangarh Bas (0.06-0.21 dS/m). Highest EC (2.21 dS/m) was observed in the biochar from Kishangarh Bas, while Khairthal Biochar had an EC of 1.35 dS/m. EC of all samples in both the locations is within the FCO limit.

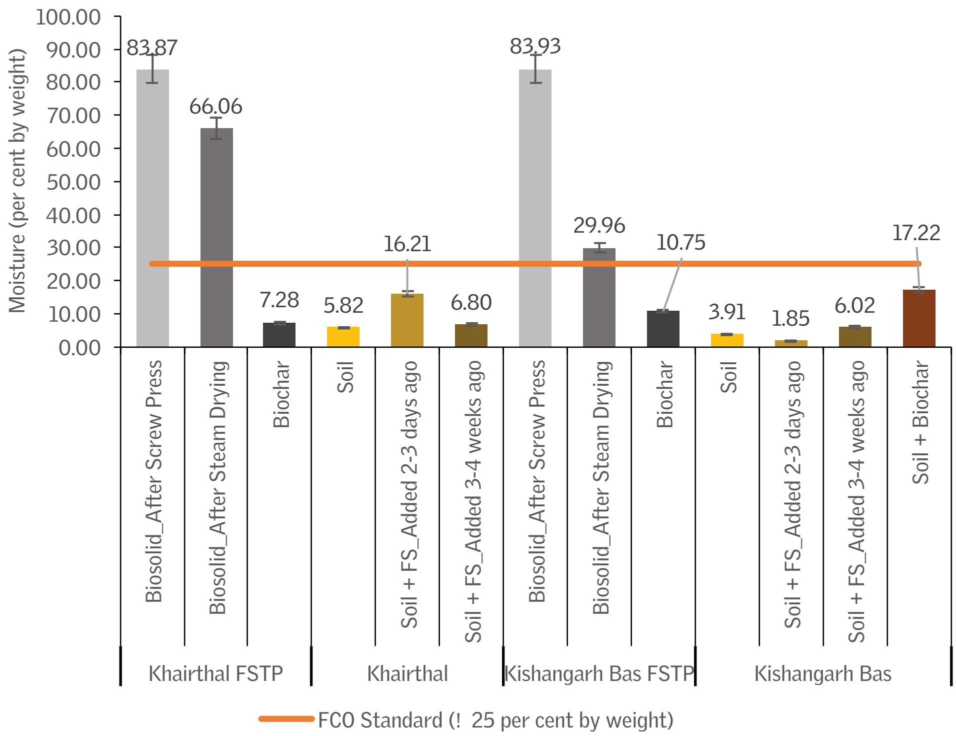
Graph 14: Electrical conductivity (EC) of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

7.3.3 Moisture content: The moisture content of the biosolids, biochar, soil and soil mixtures of untreated FS/biochar from Khairthal and Kishangarh Bas is shown in Graph 15 (*see Graph 15: Moisture content of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar)*. The standard for moisture content of the organic manure in FCO is <25 per cent (by weight). The moisture content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 29.96–83.93 per cent. The reduction in moisture content of biosolids after steam drying is higher in Kishangarh Bas FSTP (from 83.93 to 29.96 per cent) compared to Khairthal FSTP (from 83.37 to 66.06 per cent) indicating better (heat) treatment in Kishangarh Bas FSTP. Biochar had a moisture content of 7.28–10.75 per cent, soil from 3.91-5.82 per cent, while that of soil mixtures of FS is from 1.85-16.21 per cent in the studied locations. Soil with biochar had a moisture content of 17.22 per cent. Biochar, the final product of FSTPs and soil mixtures of FS/biochar had moisture content within the FCO limit.

Graph 15: Moisture content of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

7.3.4 Carbon (C) and nitrogen (N) content and carbon–to–nitrogen (C:N) ratio: The organic matter (carbon content) of biosolids/biochar is an important parameter that must be considered when applied to soil for agricultural purposes. Organic content influences the diversity of soil biota and can affect crop yield. The carbon (C), nitrogen (N) and carbon–to–nitrogen ratio (C:N ratio) of the biosolids, biochar, soil and soil mixtures of untreated FS/biochar from Khairthal and Kishangarh Bas is shown in Graph 16 (*see Graph 16: Carbon (C), nitrogen (N) and C:N ratio of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar)*. The standard given for total organic carbon content of the organic manure in FCO 2023 is ≥ 14 per cent by weight, whereas for total nitrogen (as N), the standard is ≥ 0.5 per cent by weight. The standard set for C:N ratio of the organic manure in FCO 2023 is <20.

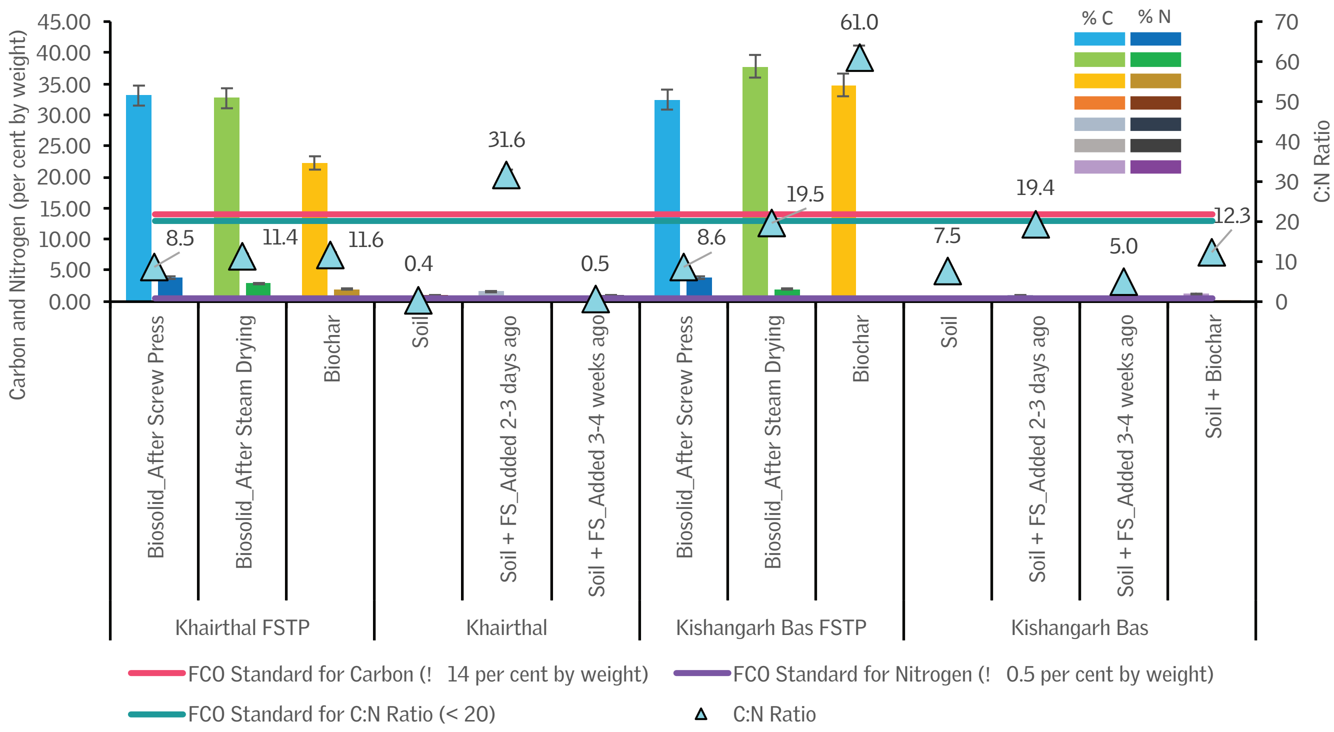
The total carbon content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 32.4–37.8 per cent. Biochar had a carbon content of 22.25–34.8 per cent, soil from 0.27–0.39 per cent, while that of soil mixtures of FS is from 0.29–1.58 per cent in the studied locations. Soil with biochar had a carbon content of 1.28 per cent. Organic carbon in biosolids and biochar from both the FSTPs is compliant with the FCO standard.

The total nitrogen content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 1.94–3.88 per cent. Nitrogen content in biosolids decreased slightly on heat treatment. Biochar had a nitrogen content of 0.57–1.93 per cent, soil from 0.04–1.04 per cent, while that of soil mixtures of FS is from 0.05–0.95 per cent in the studied locations. Soil with biochar had a nitrogen content of 0.1 per cent. Organic nitrogen in biosolids and biochar from both the FSTPs is compliant with the FCO standard, with biochar having lower nitrogen than biosolids, which is due to loss of nitrogen during pyrolysis.

However, when the carbon (C) and nitrogen (N) content of soil is considered, the proportion of carbon and nitrogen to each other, known as the C:N ratio is more important than individual carbon and nitrogen contents as a balanced C:N ratio (of 15:1 to 20:1) is essential to provide optimal nutrient (C, N) availability to both plants and soil microbes. This is because a higher C:N ratio of >20 reduces nitrogen utilization by plants by promoting nitrogen immobilization, whereas a low C:N ratio indicates higher mineralization of nitrogen for plant uptake, which results in the loss of nitrogen. Hence, an equilibrium is required between mineralization and immobilization for proper utilization of carbon and nitrogen by plants and soil microbes—by maintaining the C:N ratio between 15:1 and 20:1.[16]

In this study, the C:N ratio in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 8.5–19.5 per cent. Better C:N ratio (19.5) is achieved in the biosolids from Kishangarh Bas FSTP after heat treatment (steam drying). While biochar at Khairthal FSTP had a C:N ratio of 11.6, biochar from Kishangarh Bas FSTP had a very high C:N ratio of 61.0, which needs to be reduced before using it for agricultural purposes. The C:N ratio of soil from this study is 0.4 at Khairthal and 7.5 at Kishangarh Bas. The C:N ratio in the soil with recently added FS is higher (19.4–31.6) compared to soil with FS added few weeks ago (0.5–5.0). Soil with biochar had a C:N ratio of 12.3. Except in biochar from Khairthal, C:N ratio in all samples from both FSTPs is within FCO limit of 20. However, it is recommended that a C:N ratio of 15:1 to 20:1 be maintained in biosolids and biochar to provide optimal growth of the plants.

Graph 16: Carbon (C), nitrogen (N) and C:N ratio of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

7.3.5 Heavy metals: Faecal sludge (FS) can contain various heavy metals that get accumulated in biosolids. Biosolids or their products such as biochar, when used for agricultural purposes, can transfer these heavy metals to soil and contaminate the groundwater. Exposure to high levels of heavy metals can be harmful to humans and environmental health. The FCO 2023 has provided specifications for certain heavy metals such as arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc in the organic manure, which in higher quantities can be a public health concern. The concentrations of these heavy metals are evaluated in biosolids and biochar from the two studied FSTPs. Heavy metal concentration was also evaluated in soil and soil mixtures of FS/biochar from the two studied locations for comparison (see *Table 5: Heavy metal content in biosolids, biochar, soil, soil mixtures of FS/biochar from Khairthal and Kishangarh Bas FSTPs*). The standards set by the FCO for each heavy metal are also provided in Table 5 *(see Table 5: Heavy metal content in biosolids, biochar, soil, soil mixtures of FS/ biochar from Khairthal and Kishangarh Bas FSTPs).*

Table 5: Heavy metal content in biosolids, biochar, soil, soil mixtures of FS/biochar from Khairthal and Kishangarh Bas FSTPs

Location	Sample type	Arsenic (mg/kg) max. 10.00	Mercury (mg/kg) max 0.15	Cadmium (mg/kg) max. 5	Chromium (mg/kg) max. 50	Lead (mg/kg) max. 100	Zinc (mg/kg) max. 1000	Copper (mg/kg) max. 300	Nickel (mg/kg) max. 50
Khairtal FSTP	Biosolid after screw press	0.91	4.64	1.86	175.05	20.55	1255.00	227.50	52.75
	Biosolid after steam drying	0.14	3.60	1.20	44.35	14.05	864.00	165.00	29.95
	Biochar	0.15	0.32	1.52	117.25	19.75	1115.00	339.50	140.15
Khairtal	Soil	1.45	0.01	0.23	23.03	11.97	58.13	14.70	22.56
	Soil + FS added 2–3 days ago	2.52	1.11	0.44	24.10	17.45	210.00	40.00	27.10
	Soil + FS added 3–4 weeks ago	1.29	0.00	0.16	16.73	9.44	42.80	11.39	16.10
Kishangarh Bas FSTP	Biosolid after screw press	0.16	6.73	0.89	19.05	12.95	781.00	128.80	12.05
	Biosolid after steam drying	0.68	4.40	1.41	30.15	19.92	1221.50	198.00	18.42
	Biochar	0.05	3.79	1.37	71.35	19.27	1075.00	193.20	45.65
Kishangarh Bas	Soil	1.21	0.08	0.12	22.88	9.27	41.00	11.41	21.77
	Soil + FS added 2–3 days ago	2.01	1.02	0.21	17.03	10.70	105.70	16.42	19.00
	Soil + FS added 3–4 weeks ago	0.53	0.02	0.02	10.85	4.28	17.65	5.19	11.10
	Soil + Biochar	0.62	0.31	0.20	22.65	10.34	111.05	22.95	23.55

Source: CSE

In this study, the heavy metals arsenic (0.05-2.52 mg/kg), cadmium (0.02-1.86 mg/kg) and lead (4.28-20.55 mg/kg) were found to be within the FCO limit in all the samples. Nickel, copper (in Khairthal), chromium, zinc, and mercury (in both the FSTPs) were found to be above the FCO limit in biochar samples. High levels (above FCO limit) of chromium, zinc and nickel was also observed in biosolids from Khairthal. Except in soil and soil mixed with FS few weeks ago samples in both locations, mercury was found to be above the FCO limit. Mercury above the FCO limit in soil with recently added FS (1.02-1.11 mg/kg) and below the FCO limit in soil mixed with FS few weeks ago (0.0–0.02 mg/kg) indicates the reduction in mercury to safe levels which may have been achieved due to ploughing/thorough mixing of the untreated FS with soil.

7.3.6 Nitrogen, phosphorus and potassium (NPK) content: Nitrogen, phosphorus and potassium known as NPK nutrients are an important parameter that must be considered when biosolids/biochar is applied to soil for agricultural purposes. NPK are three essential macronutrients required by plants that are involved in several physiological functions of plant growth and development (N for leafy, green growth, P for root, flower and fruit development and K for overall plant health, vigor and disease resistance). The Nitrogen, phosphorus and potassium (NPK) content of the biosolids, biochar, soil and soil mixtures of untreated FS/biochar from Khairthal and Kishangarh Bas is shown in Graph 17 *(see Graph 17: Nitrogen, phosphorus and potassium (NPK) content of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar).* The standard given for NPK content of the organic manure in FCO 2023 is ≥ 0.5 per cent by weight, whereas for total of NPK, the standard is ≥ 3 per cent by weight.

The nitrogen content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 1.94–3.88 per cent, which reduced to 0.57–1.93 per cent in biochar due to pyrolysis. Soil had nitrogen content of 0.04–1.04 per cent, while that of soil mixtures of FS is from 0.05–0.95 per cent in the studied locations. Soil with biochar had a nitrogen content of 0.1 per cent. Nitrogen in biosolids and biochar from both the FSTPs is compliant with the FCO standard, with high nitrogen (1.93 per cent) in the biochar of Khairthal FSTP compared to Kishangarh Bas FSTP (0.57).

The phosphorus content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 2.32–4.64 per cent, while in biochar it ranged from 4.04–5.55 per cent. Soil had a phosphorus content of 0.23 per cent, while that of soil mixtures of FS it is from 0.08–0.58 per cent in the studied locations. Soil with biochar had a phosphorus content of 0.35 per cent. Phosphorus in biosolids and biochar from

Graph 17: Nitrogen, phosphorus and potassium (NPK) content of biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar

Source: CSE

both the FSTPs is compliant with the FCO standard, with high phosphorus (5.55 per cent) in the biochar of Khairthal FSTP compared to Kishangarh Bas FSTP (4.04 per cent).

The potassium content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 0.09–0.39 per cent, while in biochar it ranged from 1.15–2.47 per cent. Soil had a potassium content of 0.18–0.28 per cent, while that of soil mixtures of FS it is from 0.08–0.45 per cent in the studied locations. Soil with biochar had a potassium content of 0.26 per cent. While potassium in biochar is compliant with FCO standard, potassium in biosolids is non-compliant in both the FSTPs.

The total of NPK content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 5.88–7.63 per cent, while in biochar it ranged from 5.76–9.95 per cent, with highest in Khairthal biochar. Soil had a NPK content of 0.45-1.55 per cent, while that of soil mixtures of FS it is from 0.22–1.32 per cent in the studied locations. Soil with biochar had a total NPK content of 0.72 per cent. Soil and soil mixtures of FS/biochar in Khairthal and Kishangarh Bas had low total NPK content which is non-compliant with FCO standard indicating requirement of NPK. Both biosolids and biochar in both the FSTPs had a total NPK content within the FCO standard of ≥ 3 per cent, with biochar from Khairthal having highest content (9.95 per cent). Hence the biosolids and biochar from the two studied FSTPs with high total NPK content are a good source of NPK for application in agricultural fields.

7.3.7 Faecal coliform and *E. coli*: The faecal coliform (FC) and *E. coli*, which are used as a proxy indicator to assess the pathogen content in the biosolids/biochar samples collected from the FSTPs is shown in Graph 17 *(see Graph 17: Faecal coliform (FC) and E. coli in the biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar).* FC and *E. coli* were also tested in soil and soil mixtures of FS/biochar for comparison. The regulatory limit given for pathogen content of the organic manure in the FCO 2023 is *nil*. No biosolid/biochar sample from the two locations evaluated in this study is free from the indicator organisms FC and *E. coli*. The presence and extent of FC and *E. coli* in the biosolids/biochar samples and their suitability for agricultural purposes, are compared with the respective limits set by the USEPA and the WHO (2006). The USEPA (Class A biosolids) and WHO (2006) standards for FC and *E. coli* in biosolids to be used for the above-mentioned applications are set at 1,000/g total dry solids ($\log_{10}$ 1000 = 3), which are provided in *Annexure 1 Table 4*.

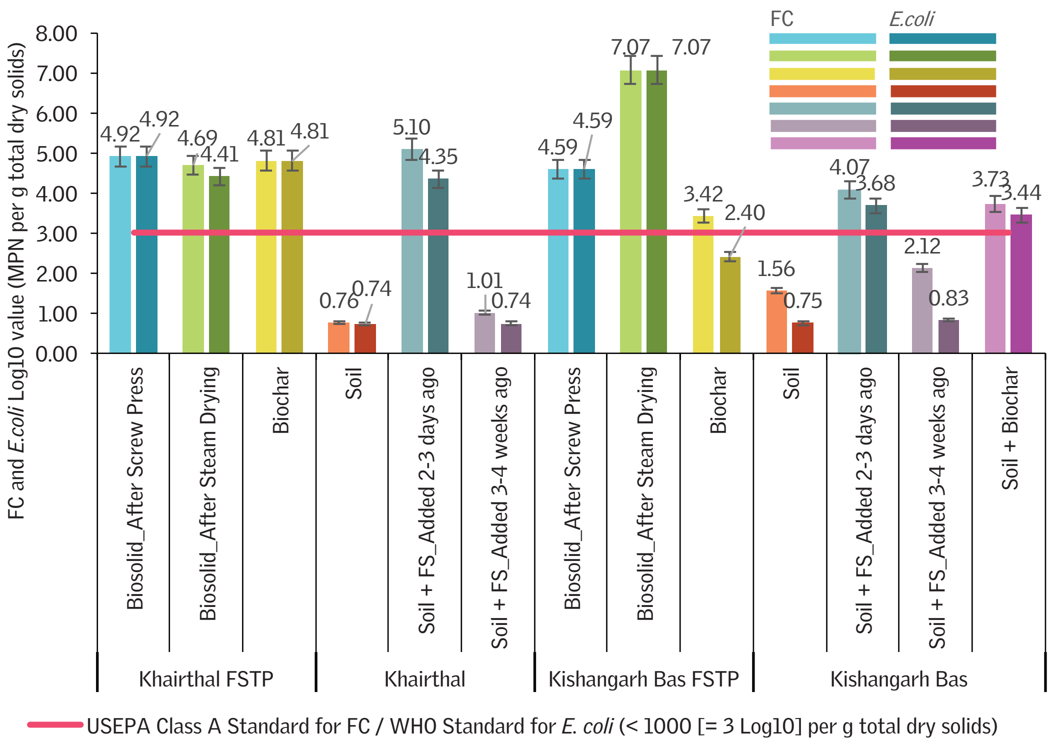
In this study, the FC in the biosolids samples from Khairthal FSTP ranged from 4.69–4.92 $\log_{10}$ MPN/g total dry solids (=48580-82978 MPN/g total dry solids) whereas *E. coli* was recorded to be in the range of 4.4–4.92 $\log_{10}$ MPN/g total dry solids (=25809-82766 MPN/g total dry solids). In Kishangarh Bas FSTP, both FC and *E. coli* in the biosolids ranged from 4.59–7.07 $\log_{10}$ MPN/g total dry solids (=38704-11782336 MPN/g total dry solids). After steam drying, only a slight reduction in FC and *E. coli* was observed in Khairthal FSTP, whereas an increase was observed in these two indicator organisms in Kishangarh Bas FSTP. Increase in FC and *E. coli* in the biosolids after steam drying might be due to the following: limited disinfection achieved in this process which operates at 60–75 °C might have retained the bacterial load (including coliforms) in the biosolids. If drying temperatures might have reached only up to 45°C, this will promote the growth of thermotolerant coliforms including *E. coli*, thereby increasing their population.

FC and *E. coli* in the biochar were found to be above the USEPA/WHO limits in Khairthal FSTP, whereas FC exceeded the limit while *E. coli* was within the limits in Kishangarh Bas biochar. While pyrolysis is an efficient process that can eliminate pathogens due to the high temperatures in the process, presence of high levels of FC and *E. coli* in the biochar indicates that all steps in the POP including steam drying and pyrolysis process have to be very optimally performed (with precise maintenance of time and temperature etc.) to reduce the pathogen/ indicator bacterial load. Reduction of FC and *E. coli* in biochar from both the FSTPs to safe levels (3-10 MPN/g total dry solids) that are compliant with the USEPA/WHO standards, which was observed in first set of samples collected in June 2025, reiterates the optimization of pyrolysis process of POP for efficient disinfection of pathogens (see *Annexure 2 Table 2*). Presence of constantly high population of these bacteria in biosolid samples from both the locations (4.41–7.07 $\log_{10}$ MPN/g total dry solids; =25809-11782336 MPN/g total dry solids) after steam drying indicates that the steam drying process in POP will only reduce moisture content in the biosolids which is required for downstream pyrolysis process to produce biochar, but not reduce the pathogen content to safe levels specifying the requirement for further treatment.

FC and *E. coli* in soil and soil mixed with FS few weeks ago from the two studied locations are in the range of 0.74–1.56 $\log_{10}$ MPN/g total dry solids (=5–36 MPN/g total dry solids) and 0.74–2.12 $\log_{10}$ MPN/g total dry solids (=6-132 MPN/g total dry solids) respectively, which are within the USEPA/WHO limits. Presence of indicator organisms such as FC and *E. coli* within USEPA/WHO limits in soil mixed with FS few weeks ago indicates the reduction of pathogen load after few weeks of FS inoculation in soil. However, both FC and *E. coli* in the soil mixed with freshly added FS is very high (3.68–5.10 $\log_{10}$ MPN/g total dry solids; =4808–124861 MPN/g total dry solids) warranting risk to public health and the environment through discharge of untreated FS in agricultural fields. Soil with biochar has FC and *E. coli* from 3.44–3.73 $\log_{10}$ MPN/g total dry solids (=2784–5379 MPN/g total dry solids); this indicates the addition of improperly treated biochar to soil. It can be concluded from this study that POP must be optimally performed to reduce pathogens to safe levels in the biochar; adding of untreated FS to agricultural fields may pose risk of contamination from pathogens to public and the environment.

7.3.8 *Salmonella*: *Salmonella* is an enteric and food/water-borne pathogenic bacterium that causes typhoid fever and salmonellosis, through infection from (faecal) contaminated food/water. It is found in the faeces of infected humans and animals, and hence, also present in FS biosolids. *Salmonella* found in the biosolids, biochar, soil and soil mixtures of FS/biochar from Khairthal and Kishangarh Bas is

Graph 18: Faecal coliform (FC) and *E. coli* in the biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

depicted in Graph 18 *(see Graph 18: Salmonella in the biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar)*. The regulatory limit of *nil* given in the Fertilizer Control Order 2023 (FCO 2023) for pathogen content of the organic manure is also applicable to *Salmonella*. Like FC and *E. coli*, *Salmonella* was present across all biosolid, biochar and soil samples. Further, the *Salmonella* concentration in the samples is compared with the standards set by the USEPA for class A biosolids (=3 MPN / 4 g total dry solids [$\log_{10} 3 = 0.48$]) which includes all types of biosolids that can be applied to all land types, to assess the biosolids' suitability for agricultural applications (see *Annexure 1 Table 4*).

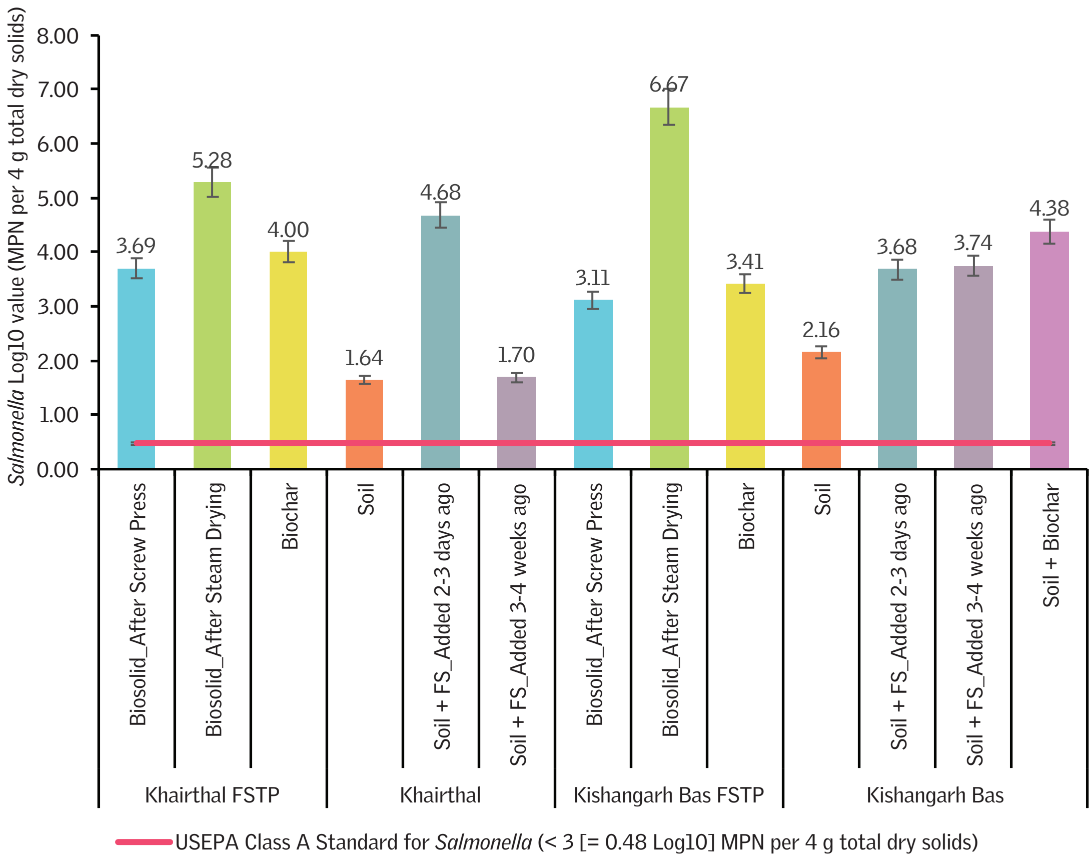
In this study, *Salmonella* in the biosolids from Khairthal FSTP ranged from 3.69–5.28 $\log_{10}$ MPN/4 g total dry solids (=4,942–192,564 MPN/4 g total dry solids), while in Kishangarh Bas FSTP, they ranged from 3.11–6.67 $\log_{10}$ MPN/4 g total dry solids (=1292–4703996 MPN/4 g total dry solids). After steam drying, an increase in *Salmonella* was observed in the biosolids in both the FSTPs, as was observed with FC and *E. coli*. Increase in *Salmonella* in the biosolids after steam drying might be due to the following: limited disinfection achieved in this process which operates at 60–75°C might have retained the bacterial load (including *Salmonella*) in the biosolids.

Salmonella in the biochar was found to be in the range of 3.41–4.00 log_{10} MPN/4 g total dry solids (=2559–10026 MPN/4 g total dry solids) in the two FSTPs. While pyrolysis is an efficient process that can eliminate pathogens due to the presence of high temperatures in the process, presence of high levels of *Salmonella* in the biochar indicates that all steps in the POP including steam drying and pyrolysis process have to be very optimally performed (with precise maintenance of time and temperature etc.) to reduce the pathogen load. Reduction of *Salmonella* in biochar from both the FSTPs to minimal levels (12–101 MPN/4 g total dry solids), which was observed in first set of samples collected in June 2025, reiterates the optimization of pyrolysis process of POP for efficient disinfection of pathogens (see *Annexure 2 Table 2*).

In soil, *Salmonella* in the two studied locations ranged from 1.64–2.16 log_{10} MPN/4 g total dry solids (=44-145 MPN/4 g total dry solids). While in soil with recently mixed FS, they ranged from 3.68–4.68 log_{10} MPN/4 g total dry solids (=4750-47868 MPN/4 g total dry solids), in soil mixed with FS few weeks ago, *Salmonella* ranged from 1.70–3.74 log_{10} MPN/4 g total dry solids (=50-5525 MPN/4 g total dry solids) in the two locations. As reduction in *Salmonella* was not observed even after few weeks in the soil mixed with untreated FS (as in the case of Kishangarh Bas), hence discharging of untreated FS into agricultural fields will not only pose public health risk but also causes environment/ground water contamination, if leaching occurs. This also indicates the resistant nature of *Salmonella* which can survive for longer periods of time in soil or environment. *Salmonella* in soil mixed with biochar was found to be 4.38 log_{10} MPN/4 g total dry solids (=24149 MPN/4 g total dry solids), indicating the mixing of improperly treated biochar with soil. *Salmonella* is above the USEPA class A biosolids limit in all the samples tested indicating the non-suitability of biosolids/biochar for unrestricted agricultural use.

7.3.9 Helminth eggs: FS biosolids contain helminth eggs upto10^4 per 4 g (dry weight) depending on the rate of infection in the community. Helminth eggs found in the biosolids, biochar, soil and soil mixtures of FS/biochar from Khairthal and Kishangarh Bas is shown in Graph 19 *(see Graph 19: Helminth eggs in the biosolids*

Graph 19: *Salmonella* in the biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar



Source: CSE

and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS/biochar). The regulatory limit of *nil* set by the FCO for pathogen content of the organic manure is also applicable to helminth eggs that are used as an indicator to estimate the concentration of parasitic worms (a type of pathogen) present in biosolids. Helminth eggs are also detected in all biosolids and biochar samples evaluated in this study. The USEPA class A standard of <1 helminth egg/4 g total dry solids of biosolids for unrestricted use in agriculture, is used to assess the suitability of biosolids and biochar for agricultural purposes (see *Annexure 1 Table 4*).

In this study, helminth eggs in the biosolids from Khairthal FSTP ranged from 2579–2969 eggs/4 g total dry solids which is much higher than those observed in

Kishangarh Bas FSTP (213-368 eggs/4 g total dry solids). Only a slight reduction in helminth eggs (from 2969 to 2579 eggs/4 g total dry solids) was observed after steam drying in Khairthal FSTP. Failure to eliminate helminth eggs during steam drying in both the FSTPs indicates the non-suitability of this step for helminth eggs removal. Helminth eggs in the biochar were found to be in the range of 10-83 eggs/4 g total dry solids in the two FSTPs. Presence of a smaller number of helminth eggs in biochar (in Kishangarh Bas FSTP) indicates that removal of helminth eggs is possible in POP especially during the pyrolysis step. Optimization of time and temperature during pyrolysis might help to completely eliminate helminth eggs from biochar.

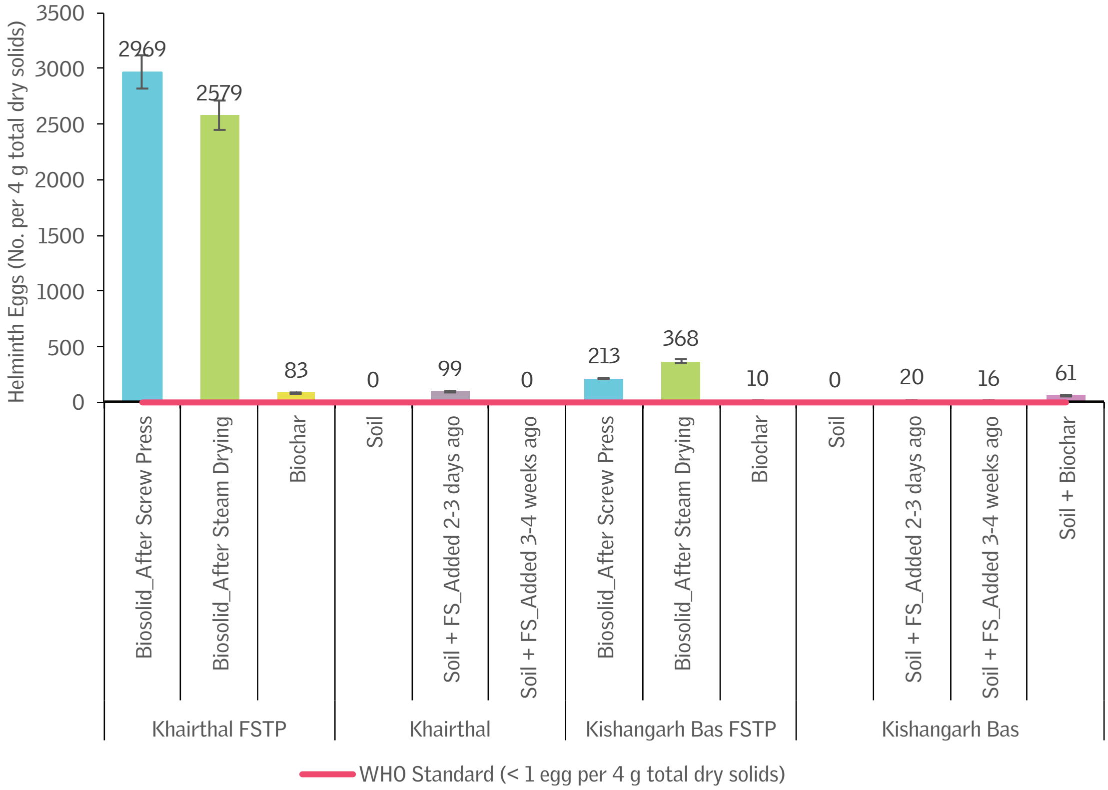
Helminth eggs are not detected in soil samples from both the study locations. In soil that had recently been mixed with FS, counts ranged from 20–99 eggs per 4 g of total dry solids. In soil mixed with FS a few weeks earlier, they ranged from 0–16 eggs per 4 g of total dry solids in both locations. While complete removal of helminth eggs was observed in Khairthal after few weeks of untreated FS addition in soil, only partial reduction was observed in Kishangarh Bas (from 20–16 eggs/ 4 g total dry solids). This again indicates the risk of discharging untreated FS into agricultural fields/environment. Sixty-one helminth eggs/4 g total dry solids were detected in soil mixed with biochar in Kishangarh Bas indicating the mixing of improperly treated biochar with soil. Helminth eggs are above the USEPA Class A biosolids limit in the biochar and biosolids in both the locations indicating the non-suitability for agricultural use. However, proper treatment during pyrolysis can make the biochar free from helminth eggs and their suitability for unrestricted agricultural use.

7.4 The findings: A summary

7.4.1 Treatment technologies: Khairthal and Kishangarh Bas FSTPs are equipped with a screw press, which is a mechanical solid-liquid separation technology; they have MBBR technology for liquid treatment, and pyrolysis-based omniprocessor (POP), for biosolids treatment. The end products generated are treated effluent and biochar, the latter being a good organic and nutrient source for agricultural purposes.

7.4.2 Faecal sludge characteristics: The faecal sludge collected from desludging vehicles at Khairthal and Kishangarh Bas FSTPs showed the following

Graph 20: Helminth eggs in the biosolids and biochar from Khairthal and Kishangarh Bas FSTPs in comparison with soil and soil mixtures of untreated FS



Source: CSE

characteristics: The pH was found to be in the range of 7.24 to 7.66. Solids content (TS, TSS and TDS) were found to be in the range of 287–24258 mg/L with highest recorded in Kishangarh Bas. BOD and COD were in the range of 465–1605 mg/L and 18260-51500 mg/L respectively with highest recorded in Kishangarh Bas. The nutrients TKN, AN and TP were in the range of 883.47–1624.35 mg/L, 626.66-697.71 mg/L and 61–185 mg/L respectively. FC ranged from 5.34–6.06 $\log_{10}$ MPN/100 mL (=217150 to 1154650 MPN/100 mL).

7.4.3 Treatment efficiency and effluent quality

- pH of the outlet water from the two FSTPs ranged from 8.06 in Khairthal to 8.71 in Kishangarh Bas which is within the 5.5–9.0 standard limits of the MoEF&CC and the NGT.
- The per cent removal of TS is 52.52–53.49 per cent in the FSTPs while that of TDS is around 50 per cent in both the FSTPs; per cent removal of TSS varied

from 75.32 per cent in Khairthal to 94.03 per cent in Kishangarh Bas. TS in the outlet ranged from 742–1136 mg/L; TDS varied from 733-1123 mg/L in the FSTPs. The outlet TSS varied from 9–13 mg/L in the two FSTPs which is within the respective standard limits of the MoEF&CC (100 mg/L) and the NGT (30/50 mg/L).

- The per cent removal of COD varied from 98.03–98.69 per cent in the two FSTPs. The outlet COD ranged from 27–53 mg/L in the FSTPs which is within the respective MoEF&CC and NGT standard limits.

- The per cent removal of BOD varied from 89.47–97.54 per cent in the two FSTPs. The outlet BOD ranged from 3–7 mg/L, which is within the respective MoEF&CC and NGT standard limits.

- The per cent removal of TKN varied from 78.09 per cent in Kishangarh Bas to 92.13 per cent in Khairthal, while that of AN varied from 72.78 per cent in Kishangarh Bas to 91.57 per cent in Khairthal. Higher per cent removal of nitrogen was observed in Khairthal FSTP. Outlet TKN and AN ranged from 11.3–82.9 mg/L and 9.2-63.0 mg/L respectively in the FSTPs, with lowest recorded in Khairthal FSTP which is correlating with the high per cent removal observed in Khairthal FSTP for these two parameters. The outlet TKN and AN in Kishangarh Bas FSTP are above the TN NGT limit of 15 mg/L.

- TP in the outlet ranged from 1.0 mg/L in Khairthal to 1.5 mg/L in Kishangarh Bas. The outlet TP exceeded the NGT limit of 1.0 mg/L in Kishangarh Bas.

- FC in the outlet of the two FSTPs ranged from 30 MPN/100 mL ($\log_{10} 30 = 1.48$) in Kishangarh Bas, to 230 MPN/100 mL ($\log_{10} 230 = 2.36$) in Khairthal, which are well within the respective MoEF&CC and NGT standards limits.

- The two pyrolysis-MBBR based FSTPs in Khairthal and Kishangarh Bas are efficient in removing solids (TSS), organic (BOD, COD), nutrient (TKN, AN, TP) and pathogen content in FS to safe levels; however, a decreased efficiency for nutrient removal (nitrogen and phosphorus) was observed in Kishangarh Bas FSTP.

7.4.4 Quality of biosolids and biochar

- The pH of biosolids from Khairthal and Kishangarh Bas FSTPs varied from

7.25–8.0 while that of biochar varied from 8.15–8.22. The pH of both biosolids and biochar complied with the FCO standard of 6.0–8.5 for organic manure.

- EC of biosolids from Khairthal and Kishangarh Bas FSTPs varied from 0.45–0.93 dS/m while that of biochar varied from 1.35–2.21 dS/m which are within the FCO standard of 4 dS/m for organic manure.

- The moisture content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 29.96–83.93 per cent, while that in biochar ranged from 7.28–10.75 per cent. While moisture content of biochar complied with the FCO standard of < 25 per cent for organic manure in both the FSTPs, (steam) dried biosolids did not comply.

- The total carbon content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 32.4–37.8 per cent, while that in biochar, it ranged from 22.25–34.8 per cent. Organic carbon in both biosolids and biochar from both the FSTPs is compliant with the FCO standard of ≥ 14 per cent. The total nitrogen content in the biosolids from the two FSTPs ranged from 1.94–3.88 per cent, while that in biochar, it ranged from 0.57–1.93 per cent. Organic nitrogen in both biosolids and biochar from both the FSTPs is compliant with the FCO standard of ≥ 0.5 per cent. C:N ratio in the biosolids from the two FSTPs ranged from 8.5–19.5 per cent, while that in biochar it ranged from 11.6–61.0, higher value of 61.0 being observed in Kishangarh Bas which needs to be reduced before using it for agricultural purposes. Except the biochar from Khairthal, C:N ratio of all biosolids and Kishangarh Bas biochar is within FCO limit of 20. However, a C:N ratio between 15–20 would be optimum for a biosolid/biochar sample to be used as organic manure for agricultural purposes.

- The heavy metals arsenic, cadmium and lead were found to be within the FCO limit in both biochar and biosolids from both Khairthal and Kishangarh Bas FSTPs. The heavy metals mercury, and zinc exceeded the FCO limit in both biosolids and biochar in both the FSTPs. While chromium and nickel exceeded the FCO limit in both biosolids and biochar in Khairthal FSTP, chromium exceeded in only biochar in Kishangarh Bas FSTP. Copper exceeded the FCO limit in Khairthal biochar.

- The nitrogen content in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 1.94–3.88 per cent, which reduced to 0.57–1.93 per cent in biochar after pyrolysis. The phosphorus content in the biosolids from the two FSTPs ranged from 2.32–4.64 per cent, while in biochar it ranged from 4.04–5.55 per cent. The potassium content in the biosolids from the two FSTPs ranged from 0.09–0.39 per cent, while in biochar it ranged from 1.15–2.47 per cent. Nitrogen and phosphorus in biosolids and biochar from both the FSTPs is compliant with the FCO standard of ≥ 0.5 per cent. While potassium in biochar is compliant with FCO standard of ≥ 0.5 per cent, potassium in biosolids is non-compliant in both the FSTPs. The total of NPK content in the biosolids from the two FSTPs ranged from 5.88–7.63 per cent, while in biochar it ranged from 5.76–9.95 per cent, both of which are compliant with the FCO standard of ≥ 3 per cent and also represent a good nutrient (NPK) source for agricultural purposes.

- FC in the biosolid samples from Khairthal and Kishangarh Bas FSTPs ranged from 38,704-11,782,336 MPN/g total dry solids, whereas *E. coli* ranged from 38,485-11,765,725 MPN/g total dry solids. FC in the biochar samples from the two FSTPs ranged from 2,627-64,085 MPN/g total dry solids, whereas *E. coli* ranged from 250-64,085 MPN/g total dry solids, with lowest recorded in Kishangarh Bas for both FC and *E. coli*. Except *E. coli in* Kishangarh Bas biochar, FC and *E. coli* in all other biosolid and biochar samples from both the FSTPs exceeded the USEPA/WHO limit of 1,000 MPN/g total dry solids.

- *Salmonella* in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 1,292–4,703,996 MPN/4 g total dry solids, while that in biochar, they ranged from 2,559–10,026 MPN/4 g total dry solids. *Salmonella* is above the USEPA Class A biosolids limit in all the biochar and biosolid samples indicating the non-suitability of biosolids/biochar for unrestricted agricultural use.

- Helminth eggs in the biosolids from Khairthal and Kishangarh Bas FSTPs ranged from 213–2,969 eggs/4 g total dry solids, while that in biochar, they ranged from 10–83 eggs/4 g total dry solids. Helminth eggs are above the USEPA Class A biosolids limit of <1 helminth egg/4 g total dry solids in all the biochar and biosolid samples indicating their non-suitability for unrestricted agricultural use.

- From this study, it was observed that pyrolysis, a thermal decomposition process performed at elevated temperatures in an oxygen-free/oxygen-limited atmosphere is an efficient process in removing pathogens from FS biosolids. However, for efficient removal of pathogens to safer levels in biosolids and biochar, drying of dewatered biosolids and pyrolysis should be optimally performed with precise maintenance of time and temperature. It was also observed that steam drying adopted in POP to reduce moisture content in biosolids for effective pyrolysis is inefficient in removing pathogens, if not performed optimally.

7.5 Recommendations

7.5.1 Measures to improve the treatment efficiency and effluent quality: As nutrients such as TKN, AN and TP are found to be in high amounts (i.e., above the respective MoEF&CC/NGT standard limits) in Kishangarh Bas FSTP in this study, we have provided several approaches to reduce these parameters in the pyrolysis-MBBR based technology present in the FSTP.

7.5.1.1 Reduce nitrogen content[17]: Nitrogen is primarily removed from wastewater by the processes of nitrification and denitrification which are biological processes. In nitrification, ammonia is oxidized into nitrite and then into nitrate by autotrophic bacteria (bacteria that use ammonia as an energy source; also called as nitrifying bacteria) under aerobic (oxygen-rich) conditions, whereas denitrification involves the conversion of nitrate into nitrogen gas by denitrifying bacteria under anoxic (low or no oxygen) conditions. The nitrogen gas escapes into atmosphere.

In the MBBR technology, nitrogen removal takes place through the same processes described above. MBBR can be of two types: two-chambered or single-chambered. In a two-chambered MBBR, nitrification and denitrification occur in two separate chambers viz. aerobic and anoxic chambers respectively with the help of nitrifying and denitrifying bacteria on the biofilm carriers in their respective chambers. In a single-chambered MBBR, both nitrification and denitrification occur in a single chamber, but in two distinct zones—aerobic and anoxic—within the biofilm. This process is called as simultaneous nitrification and denitrification (SND). Aeration is provided in the single chamber due to which upper layers of biofilm exposed to high levels of oxygen become aerobic and promote the growth of nitrifying bacteria which convert ammonia to nitrate, whereas in the deeper layers of biofilm due to non-availability of oxygen (as it is already consumed by surface bacteria, and due to non-penetration to deeper layers), it becomes anoxic and denitrification takes place here with the dominant denitrifiers present.

In the single-chambered MBBR system present in the two FSTPs (Khairthal and Kishangarh Bas), the following can be done to improve nitrogen removal efficiency.

Maintaining an optimal, low DO level is crucial. If the DO is too high, it will penetrate the entire biofilm and inhibit the anoxic zone needed for denitrification. If it is too low, it will limit the nitrification in the outer layer. Many studies find an optimal DO range below 2 mg/L for efficient SND. Denitrifying bacteria require an organic carbon source to reduce nitrate. A balanced C/N ratio in the wastewater is necessary to provide enough carbon for denitrification without inhibiting the nitrifying bacteria. Temperature and pH affect the activity and growth rates of both nitrifying and denitrifying bacteria. Optimal performance is typically achieved within a favourable range for both types of microbes. Increasing HRT can improve the overall nitrogen removal efficiency. Other methods include use of advanced biofilm carriers with high specific surface areas, such as polyurethane (PU) sponges, that can enhance microbial growth and treatment performance. When the natural C/N ratio is insufficient, adding external carbon sources like methanol (MeOH) can significantly improve denitrification rates. Introducing specific zooplankton like rotifers can help control biofilm overgrowth and improve the activity of the microbial community.

7.5.1.2 Reduce phosphorus content[18]: Phosphorus removal from wastewater can be achieved by two processes—biological and chemical. Biological phosphorus removal is carried out by a specialized group of bacteria called as phosphorus-accumulating organisms (PAOs). In the single-chambered MBBR, biological phosphorus removal occurs through the activities of PAOs in the anaerobic and aerobic zones within the biofilm of carriers. PAOs gets stressed in the anaerobic zone (inner layers) of biofilm and respond by releasing phosphorus into the wastewater through energy from breakdown of stored glycogen. They also absorb simple organic carbon compounds (like volatile fatty acids, or VFAs) as energy source from the wastewater for speeding this process, and store the excess VFAs as polyhydroxyalkanoates (PHAs). As the biofilm carriers containing PAOs move into the oxygen-rich aerobic outer regions of the reactor/chamber, PAOs multiply and absorb phosphorus from the wastewater by utilizing stored PHAs for energy, and store them as polyphosphates. The PAOs rich in stored polyphosphate gets detached from the biofilm and gets accumulated in the waste sludge as biomass which is periodically removed.

Several operational factors are critical for effective phosphorus removal in a single-chamber MBBR. The dynamic DO concentration within the reactor is essential for creating the alternating anaerobic and aerobic conditions needed to select for PAOs. The availability of sufficient organic carbon (VFAs) is vital for the PAOs in the anaerobic zone to release phosphorus and store carbon. Low temperatures can suppress PAO performance, potentially leading to lower phosphorus removal efficiency. For higher removal efficiency of phosphorus or as a polishing step, chemical precipitation is often used alongside the biological process, either continuously or intermittently. Chemical coagulants, typically metal salts like aluminum sulfate (alum) or ferric chloride (iron salts), are added to the reactor. These chemicals react with the soluble phosphorus in the wastewater to form insoluble precipitates which are then removed from the reactor as part of the waste sludge. This method can provide robust, reliable phosphorus removal and help achieve low effluent concentrations, especially when biological methods alone are insufficient.

7.5.2 Measures to improve biosolids quality: Some measures to reduce moisture and pathogens that are present in high levels in the evaluated biosolids are provided below.

7.5.2.1 Measures to reduce moisture content: FS biosolids generated in the FSTPs contain a high amount of pathogens and hence to be treated effectively to reduce them to safe levels before reuse. Adequate drying of biosolids is essential as high moisture content promotes microbial growth; water in biosolids will promote the growth and multiplication of micro-organisms, including pathogens by making the nutrients in a readily utilizable (dissolved) form compared to dry biosolids. Sun drying of FS is the most common method used in many FSTPs which can be applied. However, spreading the biosolids on a surface in thin layer is essential for effective drying throughout the biosolids. Optimization of time and temperature in belt dryer of POP can reduce moisture to desired levels. Pulverization, a process of breaking down the larger solid material into smaller pieces (powder form) by using mechanical equipment, can be applied to the larger biosolids flakes to ensure adequate drying throughout (including the inside portion of) the biosolids. Pulverization, followed by drying or heat treatment, is one of the best methods to reduce pathogen content including helminth eggs in biosolids. As pulverization increases the OpEx of the FSTP, it can only be used in locations where it is highly essential—regions receiving frequent rain and coastal regions.

7.5.2.2 Measures to prevent pathogen regrowth: Biosolids are a rich source of nutrients that can promote luxuriant growth of microbes, including pathogens, when they are exposed to moisture and subjected to contamination. Hence, appropriate storage of dried biosolids—specifically from contamination through storm water run-off and exposure to animal faeces—is crucial to prevent pathogen regrowth. Microbial/pathogen regrowth is reported in several studies especially for FC, *E. coli* and *Salmonella*. From the studies, it was found that while the regrowth of FC and *E. coli* mainly occurs from indigenous sources, the regrowth of *Salmonella* is expected to occur exclusively from external sources such as contamination with animal faeces.[19] Hence, the use of a closed storage room to preserve biosolids is highly recommended in the FSTPs to prevent from pathogen re-inoculation and multiplication. It was also noted that long term storage (>one year) of biosolids also reduces pathogens such as *Salmonella* and helminth eggs.

7.5.2.3 Measures to reduce pathogen content: Solar drying can cause maximum reduction of pathogen content, if ideally performed. However, due to the practical difficulty for optimally providing solar drying for all the FS received, a complete pathogen removal cannot be ensured. Treatments involving use of certain chemicals or thermal treatment might be required for a complete removal. Chemicals like lime and acids are commonly employed for this purpose. Lime doses of 20–40 per cent dry weight basis can inactivate 6–8 log_{10} faecal coliforms, 5–7 log_{10} *Salmonella* and 4–5 log bacteriophages in post-stabilized and dewatered sludge by increasing pH to >12. Using 550 ppm of peracetic acid in sludge with high pathogen content has shown an inactivation of 5–6 log_{10} faecal coliform and 4–5$_{10}$ log *Salmonella* in just 10 minutes. Unlike bacterial pathogens that are effectively inactivated using chemical treatments described above, helminth eggs are highly resistant to treatment as they have hard envelopes. Hence, their inactivation levels are decreased; the same doses/duration of lime and peracetic acid described above can cause inactivation of only 0.5–2 log_{10} and 2–3 log_{10} helminth ova, respectively. Thermal treatment at 108°C, irradiation at 3500 Gy and pasteurization at 70°C are some of the most effective technologies for inactivating helminth eggs in sewage sludge and can also be applied to FS biosolids. Additionally, solar drying can remove a considerable amount of helminth eggs.[20]

7.5.3 Measures to improve biochar quality: Some measures to reduce pathogens and heavy metals (in POP) that are present in high levels in the evaluated biochar are provided below. Measures to reduce heavy metals in biochar provided in this section are also applicable to biosolids.

7.5.3.1. Measures to reduce pathogen content[21]: The pyrolysis-based omni-processor (POP) system treats FS biosolids through two primary stages: initial drying (steam drying) and final thermal treatment (pyrolysis). To reduce pathogen content in dewatered FS biosolids using a POP, the key is to optimize pyrolysis temperature, residence time, and pre-treatment steps to ensure complete thermal inactivation of pathogens.

7.5.3.1.1 Drying: Steam drying or belt drying before pyrolysis reduces moisture content, improving thermal efficiency and pathogen kill rate in the biochar.

7.5.3.1.2 Optimization of pyrolysis temperature: Pathogen inactivation typically requires pyrolysis temperatures above 500°C. The POP must be operated to ensure the minimum temperature within the reactor reaches at least 300°C–400°C and is often run higher, up to 600°C or more. At this heat level (600–700°C), thermal destruction of all pathogens (bacteria such as *E.coli*, *Salmonella*, viruses, eggs, cysts) is rapid and complete. Higher temperatures also reduce the risk of pathogen regrowth by altering the chemical structure of biosolids. However, if nutrients (C, N, P) have to be retained in the biochar, then pathogen reduction has to be compromised. At high temperatures (>500 °C), C, N and P are largely decreased in their compostion in the biochar; nevertheless, other nutrients such as K, Ca, Na and Mg are retained and concentrated. While lower temperatures best preserve the overall mass of nutrients (especially N and P), higher temperatures (up to 700° C or more) are often chosen to create biochar with other beneficial properties, such as greater carbon stability (higher aromaticity) for long-term carbon sequestration, increased surface area and porosity (for better water retention and contaminant adsorption) and higher pH (which is more effective for amending acidic soils). Therefore, the optimal temperature is a trade-off based on the primary goal.

7.5.3.1.3 Optimization of pyrolysis residence time: Biosolids must remain in the pyrolysis chamber long enough to achieve uniform heating. The design of the POP must ensure uniform heat distribution throughout the entire feedstock mass. A minimum residence time of 30–60 minutes is recommended depending on moisture content and feedstock density. Shorter times may leave cold spots, allowing pathogens to survive. Modern omniprocessors use mechanisms like internal agitation or specific reactor geometries (e.g., rotary kilns) to ensure all material is fully pyrolyzed. Polymer addition during dewatering enhances solid separation and reduces microbial load prior to pyrolysis.

7.5.3.1.4 Low moisture content of feed stock: The feedstock (dewatered sludge) must have a very low moisture content. High moisture consumes a massive amount of energy to vaporize, which lowers the reactor temperature and makes it harder to achieve the necessary thermal destruction efficiency. The POP often uses waste heat from the pyrolysis unit itself to achieve optimal pre-drying.

7.5.3.1.5 Homogeneity of feed stock: The dewatered sludge should be relatively uniform in size and composition before being fed into the reactor. Large, dense clumps may take longer to heat through, increasing the risk of incomplete pyrolysis in the core of the clump.

7.5.3.1.6 Post-processing and handling: Pathogen risk can be reintroduced if the sterile biochar is improperly handled after production:

7.5.3.1.7 Immediate cooling and sealing: Once discharged from the pyrolysis unit, the hot biochar is sterile. It should be rapidly cooled and stored in sealed containers to prevent recontamination from the environment (e.g., dust, insects, or moisture containing environmental bacteria).

7.5.3.1.8 Monitoring and quality control: Regular testing of the final biochar product for indicator organisms (e.g., *E. coli* or *Salmonella*) is mandatory. This quality control check validates that the POP is operating correctly and producing a consistently safe product that meets the required agricultural or environmental standards.

7.5.3.2 Keep heavy metals in safe limits[22]: Biosolids/biochar are rich in organic matter and nutrients required for plant growth. They also contain heavy metals. To ensure that the biosolids/biochar are safe as an organic fertilizer or soil conditioner, it is important to comply with the FCO standards for organic manure. Heavy metals are essential, however, when present in excessive amounts, they can be highly toxic to plants, animals, and humans. Several methods are available to remove heavy metals from biosolids/biochar including chemical precipitation, adsorption, ion exchange, membrane filtration, electrodialysis, biosorption, bioremediation, and electrochemical treatment. The most suitable method depends on the type and amount of heavy metals present, the desired level of removal, cost and operational feasibility and its environmental impact.

In this study, the heavy metals mercury (Hg), zinc (Zn), chromium (Cr), nickel (Ni) and copper (Cu) exceeded the respective FCO limits in biosolids/biochar. During pyrolysis/incineration, especially when high temperatures are used (>650° C), Hg and Zn, being relatively volatile, are easily vaporized and removed from the solid residue (biochar). Other metals like Cu, Ni, and Cr are generally not removed and instead become concentrated in the ash/char residue. They may then be recovered from the ash. During pyrolysis, which is performed at high temperatures, under low or no oxygen, chemical structure of carbon compounds changes in a such a way that the heavy metals get trapped inside the complex structure and will not easily leach out (sequestered).

Other methods which are known to be efficient for removing these heavy metals in biosolids/biochar include acid leaching which can achieve high removal rates for divalent metals like Zn, Ni, and to a large extent, Cu and Hg. However, Cr (especially in the trivalent form), can be more difficult to remove and may require additional oxidative steps. Bioleaching is another method which uses acid-producing microorganisms, such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*, to generate acid and oxidize metal-bearing compounds, facilitating metal solubilization. This method has shown good efficiency for Zn, Cu, and Ni. It is often preferred over chemical leaching due to lower reagent costs and simpler operation, but it requires longer reaction times (several days). An advanced method includes electrokinetic treatment (electro-remediation) which involves applying a low-level electric current to the biosolids, which mobilizes metal ions toward electrodes for collection.

Ensure biochar has high carbon and nutrient content, stable pH (neutral to slightly alkaline), low electrical conductivity (to avoid salt stress in soil), less heavy metals and absence of viable pathogens to qualify it as a good quality biochar. Mix with soil at recommended ratios (e.g., 5–10 per cent by weight) to improve fertility and carbon sequestration.

In conclusion, this scoping study conducted in two locations of Rajasthan successfully validated the efficacy and environmental safety of utilizing pyrolysis-based omniprocessor (POP) technology for resource recovery within FSTPs across Rajasthan. The primary objective—to assess the quality of the resulting biochar and its impact on soil—was comprehensively achieved, providing clear evidence that this technology is a viable and critical component of a sustainable sanitation economy. The most compelling outcome of this evaluation is the confirmation of the biochar's superior safety profile. By stabilizing the raw FS, the pyrolysis process effectively mitigated public health risks associated with untreated waste, demonstrating a significant reduction in pathogen loads and the effective immobilization of heavy metals below permissible limits. This transformation converts a hazardous disposal challenge into a safe, usable resource. Furthermore, the comparative field analyses decisively proved the agricultural benefits. Unlike the application of untreated FS, which carries inherent risks, the biochar consistently functioned as an effective soil amendment. Its use resulted in measurable improvements in soil quality indicators, specifically enhanced water retention capacity and better nutrient balance (P and K), confirming its value as a product that can genuinely close the sanitation-agriculture resource loop. In summary, the POP technology is not just a treatment option but a robust, resource-generating solution. The findings strongly suggest for the accelerated integration of pyrolysis into municipal sanitation infrastructure. Future efforts should focus on standardizing biochar production quality and developing clear market mechanisms to scale this circular economy approach across wider geographic regions.

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Annexures

Annexure 1

Table 1. National Green tribunal (NGT) standards 2019 for effluent discharge from STPs

Sl. No.	Parameters	Standards (Applicable to all mode of disposal)			
		Mega and Metropolitan Cities	Class I Cities	Others	Deep Marine Outfall
1	pH	5.5-9.0	5.5-9.0	5.5-9.0	5.5-9.0
2	Bio Chemical Oxygen Demand (BOD) (mg/L)	10	20	30	30
3	Total Suspended Solids (TSS) (mg/L)	20	30	50	50
4	Chemical Oxygen Demand (COD) (mg/L)	50	100	150	150
5	Total – Nitrogen (mg/L)	10	15	-	-
6	Phosphorus - Total (For Discharge into Ponds, Lakes) (mg/L)	1.0	1.0	1.0	
7	Faecal Coliform (FC) (Most Probable Number per 100 mililitre, MPN/100 mL)	Desirable - 100 Permissible-230	Desirable - 230 Permissible - 1000	Desirable - 1000 Permissible - 10,000	Desirable - 1000 Permissible - 10,000

Notes:

(i) Mega-Metropolitan Cities have population more than 1 crore, Metropolitan Cities– Population more than 10 Lakh and Class-1 Population more than 1 Lakh.

(ii) All value in mg/l except for pH and Faecal Coliform.

(iii) These standards will be applicable for discharge into water bodies as well as for land disposal/applications.

(iv) These Standards shall apply to all new STPs for which construction is yet to be initiated.

(v) The existing/under construction STPs shall achieve these standards within 7 years from the date of notification.

(vi) In case where the marine outfall provides a minimum initial dilution of 150 times at the point of discharge and a minimum dilution of 1500 times at a point 100 m away from discharge point, then norms for deep sea marine discharge shall be applied.

(vii) Reuse/recycling of treated effluent shall be encouraged.

(viii) State Pollution Control Boards/Pollution Control Committees may make these norms more stringent taking into account the local conditions.

Annexure 1

Table 2. Ministry of Environment, Forest and Climate Change (MoEF&CC) standards 2017 for effluent discharge from STPs

Sl. No.	Parameters	Standards	
		Effluent discharge standards (applicable to all mode of disposal)	
		Location	**Concentration not to exceed**
		(a)	**(b)**
1	pH	Anywhere in the country	6.5-9.0
2	Bio Chemical Oxygen Demand (BOD) (mg/L)	Cities (with more than 10 lakh population): Metro Cities*, all State Capitals except in the State of Arunachal Pradesh, Assam, Manipur, Meghalaya Mizoram, Nagaland, Tripura Sikkim, Himachal Pradesh, Uttarakhand, Jammu and Kashmir, and Union territory of Andaman and Nicobar Islands, Dadar and Nagar Haveli Daman and Diu and Lakshadweep	20
		Areas/regions other than mentioned above	30
3	Total Suspended Solids (TSS) (mg/L)	Cities (with more than 10 lakh population): Metro Cities*, all State Capitals except in the State of Arunachal Pradesh, Assam, Manipur, Meghalaya Mizoram, Nagaland, Tripura Sikkim, Himachal Pradesh, Uttarakhand, Jammu and Kashmir and Union territory of Andaman and Nicobar Islands, Dadar and Nagar Haveli Daman and Diu and Lakshadweep	<50
		Areas/regions other than mentioned above	<100
4	Fecal Coliform (FC) (MPN/100 mL)	Anywhere in the country	<1000

*Metro Cities are Mumbai, Delhi, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad and Pune.

Notes:

(i) All values in mg/l except for pH and Fecal Coliform.

(ii) These standards shall be applicable for discharge into water bodies as well as for land disposal/applications.

(iii) The standards for Fecal Coliform shall not apply in respect of use of treated effluent for industrial purposes.

(iv) These Standards shall apply to all STPs to be commissioned on or after the 1st June, 2019 and the old/existing STPs shall achieve these standards within a period of five years from date of publication of this notification in the Official Gazette.

(v) In case of discharge of treated effluent into sea, it shall be through proper marine outfall and the existing shore discharge shall be converted to marine outfalls, and in cases where the marine outfall provides a minimum initial dilution of 150 times at the point of discharge and a minimum dilution of 1500 times at a point 100 meters away from discharge point, then, the existing norms shall apply as specified in the general discharge standards.

(vi) Reuse/Recycling of treated effluent shall be encouraged and in cases where part of the treated effluent is reused and recycled involving possibility of human contact, standards as specified above shall apply.

(vii) Central Pollution Control Board/State Pollution Control Boards/Pollution Control Committees may issue more stringent norms taking account to local condition under section 5 of the Environment (Protection) Act, 1986".

Annexure 1

Table 3. Fertilizer Control Order standards for organic manure 2023*

Sl. No.	Parameters	Standard
1	Moisture per cent by weight, maximum	25
2	Particle size	Minimum 90% material should pass through 4.0 mm IS sieve
3	Bulk density (g/cm^3)	<1.0
4	Total organic carbon per cent by weight, minimum	14
5	Total nitrogen (as N) per cent by weight, minimum	0.5
6	Total phosphates (as P_2O_5) per cent by weight, minimum	0.5
7	Total potash (as K_2O) per cent by weight, minimum	0.5
8	NPK nutrients – Total N, P_2O_5 and K_2O nutrient should not be less than 3%	
9	C:N ratio	<20
10	pH	6.0-8.5
11	Pathogen	Nil
12	Heavy metal content, (as mg/kg), maximum	
	Arsenic (as As_2O_3)	10
	Cadmium (as Cd)	5
	Chromium (as Cr)	50
	Copper (as Cu)	300
	Mercury (as Hg)	0.15
	Nickel (as Ni)	50
	Lead (as Pb)	100
	Zinc (as Zn)	1000

*Electrical conductivity (EC) and its limit is not mentioned in FCO 2023 for organic manure; however, it is mentioned in FCO 2013 for organic manure with limit as <4 dS/m, which is used for evaluating EC in this report.

Annexure 1

Table 4. Global standards for pathogens in biosolids

Sl. No.	Type of organism	Standard	Regulatory body	Remarks
1.	Faecal coliform	1000 MPN per gram total dry solids	USEPA	Pathogen Class A category concentration limits for biosolids applied to all land types: agricultural land, forests, reclamation sites, and lawns and home gardens
2.	*E. coli*	1000 per gram total dry solids	WHO (2006)	Faecal sludge reuse in agriculture
3.	*Salmonella*	3 MPN per 4 grams of total dry solids	USEPA	Pathogen Class A category concentration limits for biosolids applied to all land types: agricultural land, forests, reclamation sites, and lawns and home gardens
4.	Helminth eggs	< 1 egg per 4 grams of total dry solids	USEPA	Pathogen Class A category concentration limits for biosolids applied to all land types: agricultural land, forests, reclamation sites, and lawns and home gardens
		< 1 egg per gram of total dry solids	WHO	Faecal sludge reuse in agriculture

Annexure 2

Table 1: Consolidated data of physico-chemical parameters and pathogen content in FS, inlet and outlet from Khairthal and Kishangarh Bas FSTPs

FSTP location	Month	Type of sample	Physico-chemical parameters									Pathogen content	
			pH	TS (mg/L)	TSS (mg/L)	TDS (mg/L)	COD (mg/L)	BOD (mg/L)	TKN (mg/L)	AN (mg/L)	TP (mg/L)	FC (MPN/100 mL)	FC Log_{10} value (MPN/100 mL)
Khairthal	June 2025	FS	7.3	12877	540	12337	34500	750	1675.80	821.34	69.0	4300	3.63
		Inlet	7.9	1486	45	1441	356	50	157.00	103.56	22.7	230	2.36
		Outlet	8	1036	4	1032	44	9	7.35	8.92	1.2	30	1.48
	July 2025	FS	7.1	2405	34	2371	2020	180	1572.90	574.08	53.0	430000	5.63
		Inlet	7.6	1705	32	1673	3690	83	130.83	114.82	33.4	9300	3.97
		Outlet	8.2	448	15	433	9	5	15.29	9.49	0.8	430	2.63
	Mean	Mean FS	7.24	7641	287	7354	18260.0	465.0	1624.35	697.71	61.0	217150	5.34
		Mean Inlet	7.73	1596	39	1557	2023.0	66.5	143.91	109.19	28.1	4765	3.68
		Mean Outlet	8.06	742	9	733	26.5	7.0	11.32	9.21	1.0	230	2.36
Kishangarh Bas	June 2025	FS	7.6	29499	1900	27599	59500	2230	517.44	517.24	87.0	2300000	6.36
		Inlet	8.2	2121	380	1741	830	115	333.40	262.60	31.6	460000	5.66
		Outlet	8.8	1315	20	1295	75	3	136.42	96.12	1.3	30	1.48
	July 2025	FS	7.7	19016	62	18954	43500	980	1249.50	736.08	283.0	9300	3.97
		Inlet	8	2662	39	2623	4505	129	423.36	207.18	36.4	6400	3.81
		Outlet	8.6	956	5	951	30	3	29.40	31.77	1.7	30	1.48
	Mean	Mean FS	7.66	24258	981	23277	51500.0	1605.0	883.47	626.66	185.0	1154650	6.06
		Mean Inlet	8.08	2391	210	2182	2667.5	122.0	378.38	234.89	34.0	233200	5.37
		Mean Outlet	8.71	1136	13	1123	52.5	3.0	82.91	63.95	1.5	30	1.48

Annexure 2

Table 2: Consolidated data of physico-chemical parameters and pathogen content in soil, biosolids and biochar from Khairthal and Kishangarh Bas

Location	Sample Type	Month	Physico-chemical Parameters					Pathogen content						
			pH	EC (dS/m)	Mois-ture (%)	Organic Carbon (% by weight)	Total Nitrogen (% by weight)	Helminth Eggs (Eggs/4 g total dry solids)	FC (MPN/g total dry solids)	FC Log_{10} value (MPN/ g total dry solids)	*E. coli* (MPN/g total dry solids)	*E. coli* Log_{10} value (MPN/g total dry solids)	*Salmonella* (MPN/4 g total dry solids)	*Salmonella* Log_{10} value (MPN/4 g total dry solids)
Khairtal FSTP	Biosolid_ After Screw Press	June 2025	7.12	0.47	81.66	34.70	2.74	2372	659	2.82	236	2.37	3271	3.51
		July 2025	7.63	0.44	86.09	31.50	5.01	3565	165297	5.22	165297	5.22	6612	3.82
		Mean	7.38	0.45	83.87	33.10	3.88	2969	82978	4.92	82766	4.92	4942	3.69
	Biosolid_ After Steam Drying	June 2025	7.66	1.09	54.87	33.80	0.65	833	95271	4.98	50959	4.71	381084	5.58
		July 2025	6.84	0.14	77.25	31.60	5.08	4325	1890	3.28	659	2.82	4043	3.61
		Mean	7.25	0.61	66.06	32.70	2.86	2579	48580	4.69	25809	4.41	192564	5.28
	Biochar	June 2025	9.39	1.22	0.38	25.00	0.00	16	3	0.48	3	0.48	12	1.08
		July 2025	7.05	1.48	14.17	19.50	3.85	149	128166	5.11	128166	5.11	20041	4.30
		Mean	8.22	1.35	7.28	22.25	1.93	83	64085	4.81	64085	4.81	10026	4.00
Khairtal	Soil	April 2025	7.94	0.09	2.22	0.44	0.10	0	3	0.49	3	0.49	15	1.17
		June 2025	8.34	0.05	5.01	0.42	0.00	0	4	0.58	3	0.50	15	1.18
		July 2025	7.22	0.04	10.22	0.310	3.02	0	10	1.01	10	1.01	102	2.01
		Mean	7.83	0.06	5.82	0.39	1.04	0	6	0.76	5	0.74	44	1.64
	Soil + FS_ Added 2-3 days ago	April 2025	7.92	0.27	3.66	0.87	0.10	75	249118	5.40	44634	4.65	95495	4.98
		June 2025	8.08	0.26	28.76	2.29	0.00	124	604	2.78	51	1.70	241	2.38
		Mean	8.00	0.27	16.21	1.58	0.05	99	124861	5.10	22342	4.35	47868	4.68
	Soil + FS_ Added 3-4 weeks ago	April 2025	8.01	0.09	0.78	0.48	0.10	0	23	1.37	9	0.97	93	1.97
		June 2025	8.34	0.07	4.17	0.40	0.00	0	3	0.50	3	0.50	13	1.10
		July 2025	7.41	0.82	15.46	0.516	2.76	0	4	0.63	4	0.63	44	1.64
		Mean	7.92	0.33	6.80	0.47	0.95	0	10	1.01	6	0.74	50	1.70

Location	Sample Type	Month	Physico-chemical Parameters					Pathogen content						
			pH	EC (dS/m)	Moisture (%)	Organic Carbon (% by weight)	Total Nitrogen (% by weight)	Helminth Eggs (Eggs/4 g total dry solids)	FC (MPN/g total dry solids)	FC Log_{10} value (MPN/ g total dry solids)	*E. coli* (MPN/g total dry solids)	*E. coli* Log_{10} value (MPN/g total dry solids)	*Salmonella* (MPN/4 g total dry solids)	*Salmonella* Log_{10} value (MPN/4 g total dry solids)
Kishangarh Bas FSTP	Biosolid_ After Screw Press	June 2025	8.12	0.59	85.69	35.90	2.66	336	76886	4.89	76886	4.89	2069	3.32
		July 2025	7.87	0.47	82.17	28.90	4.90	90	522	2.72	84	1.92	516	2.71
		Mean	8.00	0.53	83.93	32.40	3.78	213	38704	4.59	38485	4.59	1292	3.11
	Biosolid_ After Steam Drying	June 2025	7.90	1.05	6.69	37.40	2.86	86	49299	4.69	16076	4.21	1843	3.27
		July 2025	7.28	0.81	53.22	38.20	1.02	650	23515372	7.37	23515372	7.37	9406149	6.97
		Mean	7.59	0.93	29.96	37.80	1.94	368	11782336	7.07	11765724	7.07	4703996	6.67
	Biochar	June 2025	8.33	2.49	9.23	33.80	0.32	11	10	1.01	10	1.01	101	2.01
		July 2025	7.97	1.92	12.28	35.80	0.82	9	5244	3.72	490	2.69	5016	3.70
		Mean	8.15	2.21	10.75	34.80	0.57	10	2627	3.42	250	2.40	2559	3.41
Kishangarh Bas	Soil	April 2025	7.26	0.10	0.75	0.41	0.10	0	3	0.48	3	0.48	12	1.08
		June 2025	8.44	0.07	1.80	0.21	0.00	0	4	0.56	4	0.56	12	1.09
		July 2025	8.63	0.05	9.17	0.209	0.01	0	102	2.01	10	1.01	410	2.61
		Mean	8.11	0.08	3.91	0.27	0.04	0	36	1.56	6	0.75	145	2.16
	Soil + FS_ Added 2-3 days ago	April 2025	8.93	0.29	2.84	0.99	0.10	25	23673	4.37	9572	3.98	9469	3.98
		June 2025	7.98	0.14	0.87	0.96	0.00	16	43	1.64	43	1.64	30	1.48
		Mean	8.46	0.21	1.85	0.97	0.05	20	11858	4.07	4808	3.68	4750	3.68
	Soil + FS_ Added 3-4 weeks ago	April 2025	8.96	0.09	0.07	0.36	0.10	32	3	0.48	3	0.48	600	2.78
		July 2025	8.17	0.03	11.96	0.226	0.02	0	261	2.42	10	1.02	10450	4.02
		Mean	8.57	0.06	6.02	0.29	0.06	16	132	2.12	7	0.83	5525	3.74
	Soil + Biochar	April 2025	9.35	0.18	13.18	0.50	0.10	0	5298	3.72	107	2.03	1060	3.03
		July 2025	8.31	0.07	21.25	2.06	0.11	122	5460	3.74	5460	3.74	47238	4.67
		Mean	8.83	0.12	17.22	1.28	0.10	61	5379	3.73	2784	3.44	24149	4.38

Annexure 2

Table 3: Consolidated data of heavy metals and nutrients in soil, biosolids and biochar from Khairthal and Kishangarh Bas

Location	Sample Type	Month	Heavy metals								Nutrients					
			As (mg/kg) max. 10.0 as As_2O_3	Hg (mg/kg) max. 0.15	Cd (mg/kg) max. 5.0	Cr (mg/kg) max. 50.0	Pb (mg/kg) max. 100.0	Zn (mg/kg) max. 1000.0	Cu (mg/kg) max. 300.0	Ni (mg/kg) max. 50.0	Total Phosphates (asP_2O_5), per cent by weight, min. 0.5	Total Potash (as K_2O), per cent by weight, min. 0.5	Ca per cent by weight	Mg per cent by weight	Mn per cent by weight	Na per cent by weight
Khairtal FSTP	Biosolid_After Screw Press	June 2025	1.45	7.30	1.64	20.10	19.30	1190.00	218.00	16.20	2.73	0.18	3.60	0.58	0.04	0.27
		July 2025	0.38	1.98	2.07	330.00	21.80	1320.00	237.00	89.30	4.37	0.23	4.99	0.71	0.07	0.32
		Mean	0.91	4.64	1.86	175.05	20.55	1255.00	227.50	52.75	3.55	0.21	4.30	0.65	0.05	0.30
	Biosolid_After Steam Drying	June 2025	0.00	5.61	1.13	57.10	13.80	879.00	161.00	42.60	2.47	0.63	4.05	0.56	0.05	0.34
		July 2025	0.29	1.59	1.26	31.60	14.30	849.00	169.00	17.30	2.79	0.14	3.32	0.50	0.03	0.20
		Mean	0.14	3.60	1.20	44.35	14.05	864.00	165.00	29.95	2.63	0.39	3.69	0.53	0.04	0.27
	Biochar	June 2025	0.00	0.00	1.45	136.00	20.50	1180.00	346.00	220.00	5.93	3.32	13.00	1.40	0.20	0.96
		July 2025	0.30	0.64	1.59	98.50	19.00	1050.00	333.00	60.30	5.18	1.62	7.34	1.25	0.12	0.54
		Mean	0.15	0.32	1.52	117.25	19.75	1115.00	339.50	140.15	5.55	2.47	10.17	1.33	0.16	0.75
Khairtal	Soil	April 2025	1.50	0.04	0.22	38.00	12.70	107.00	20.00	35.20	0.29	0.47	0.71	0.92	0.06	0.02
		June 2025	2.33	0.00	0.26	8.60	12.30	29.00	10.10	8.38	0.23	0.17	0.71	0.23	0.04	0.01
		July 2025	0.53	0.00	0.21	22.50	10.90	38.40	14.00	24.10	0.18	0.20	0.40	0.47	0.04	0.01
		Mean	1.45	0.01	0.23	23.03	11.97	58.13	14.70	22.56	0.23	0.28	0.61	0.54	0.05	0.01
	Soil + FS_Added 2-3 days ago	April 2025	1.12	0.13	0.20	27.90	15.60	136.00	23.00	32.00	0.31	0.54	5.13	0.88	0.08	0.05
		June 2025	3.93	2.09	0.69	20.30	19.30	284.00	57.00	22.20	0.85	0.35	2.00	0.61	0.07	0.19
		Mean	2.52	1.11	0.44	24.10	17.45	210.00	40.00	27.10	0.58	0.45	3.57	0.75	0.07	0.12
	Soil + FS_Added 3-4 weeks ago	April 2025	0.72	0	0.09	18.40	8.53	60.30	12.80	20.00	0.20	0.25	0.92	0.45	0.03	0.02
		June 2025	2.74	0.00	0.25	16.60	12.00	28.80	11.40	12.40	0.27	0.15	0.99	0.18	0.04	0.02
		July 2025	0.41	0.00	0.14	15.20	7.79	39.30	9.98	15.90	0.11	0.13	0.54	0.34	0.03	0.01
		Mean	1.29	0.00	0.16	16.73	9.44	42.80	11.39	16.10	0.20	0.17	0.82	0.32	0.03	0.01

Location	Sample Type	Month	Heavy metals								Nutrients					
			As (mg/kg) max. 10.0 as As_2O_3	Hg (mg/kg) max. 0.15	Cd (mg/kg) max. 5.0	Cr (mg/kg) max. 50.0	Pb (mg/kg) max. 100.0	Zn (mg/kg) max. 1000.0	Cu (mg/kg) max. 300.0	Ni (mg/kg) max. 50.0	Total Phosphates (asP_2O_5), per cent by weight, min. 0.5	Total Potash (as K_2O), per cent by weight, min. 0.5	Ca per cent by weight	Mg per cent by weight	Mn per cent by weight	Na per cent by weight
Kishangarh Bas FSTP	Biosolid_ After Screw Press	June 2025	0.00	10.30	0.69	17.50	10.50	643.00	94.60	10.30	2.31	0.08	1.92	0.40	0.02	0.15
		July 2025	0.32	3.15	1.09	20.60	15.40	919.00	163.00	13.80	2.34	0.11	2.51	0.42	0.03	0.15
		Mean	0.16	6.73	0.89	19.05	12.95	781.00	128.80	12.05	2.32	0.09	2.22	0.41	0.02	0.15
	Biosolid_ After Steam Drying	June 2025	1.26	8.05	2.50	49.00	34.70	2160.00	349.00	31.00	8.54	0.23	7.11	1.29	0.06	0.36
		July 2025	0.09	0.74	0.31	11.30	5.14	283.00	47.00	5.84	0.74	0.26	1.22	0.17	0.02	0.06
		Mean	0.68	4.40	1.41	30.15	19.92	1221.50	198.00	18.42	4.64	0.25	4.17	0.73	0.04	0.21
	Biochar	June 2025	0.00	7.03	2.20	120.00	32.60	1760.00	310.00	78.50	6.73	1.62	9.08	1.11	0.11	0.51
		July 2025	0.10	0.55	0.53	22.70	5.93	390.00	76.40	12.80	1.34	0.68	2.75	0.33	0.04	0.14
		Mean	0.05	3.79	1.37	71.35	19.27	1075.00	193.20	45.65	4.04	1.15	5.92	0.72	0.08	0.33
Kishangarh Bas	Soil	April 2025	0.68	0.25	0.09	22.40	8.90	69.10	15.00	27.50	0.27	0.26	0.72	0.55	0.04	0.04
		June 2025	2.55	0.00	0.21	9.64	11.10	31.80	8.94	11.30	0.30	0.15	0.90	0.19	0.04	0.03
		July 2025	0.41	0.00	0.07	36.60	7.81	22.10	10.30	26.50	0.12	0.14	0.69	0.34	0.03	0.01
		Mean	1.21	0.08	0.12	22.88	9.27	41.00	11.41	21.77	0.23	0.18	0.77	0.36	0.04	0.03
	Soil + FS_Added 2-3 days ago	April 2025	0.88	1.90	0.26	24.80	12.00	165.00	23.80	27.90	0.70	0.65	1.88	0.81	0.06	0.09
		June 2025	3.15	0.13	0.16	9.25	9.40	46.40	9.04	10.10	0.40	0.15	0.81	0.18	0.04	0.03
		Mean	2.01	1.02	0.21	17.03	10.70	105.70	16.42	19.00	0.55	0.40	1.34	0.49	0.05	0.06
	Soil + FS_Added 3-4 weeks ago	April 2025	0.74	0.05	0.00	10.90	3.31	20.90	4.37	10.10	0.08	0.10	0.24	0.18	0.01	0.01
		July 2025	0.33	0.00	0.04	10.80	5.25	14.40	6.01	12.10	0.08	0.07	0.21	0.20	0.02	0.01
		Mean	0.53	0.02	0.02	10.85	4.28	17.65	5.19	11.10	0.08	0.08	0.22	0.19	0.02	0.01
	Soil + Biochar	April 2025	0.82	0	0.14	25.20	11.30	72.10	14.40	27.70	0.25	0.38	0.78	0.73	0.05	0.07
		July 2025	0.42	0.61	0.25	20.10	9.38	150.00	31.50	19.40	0.46	0.15	1.67	0.40	0.03	0.04
		Mean	0.62	0.31	0.20	22.65	10.34	111.05	22.95	23.55	0.35	0.26	1.22	0.56	0.04	0.05

In an attempt to understand the scope and advancement of circular economy within urban sanitation, Environment Monitoring Laboratory of Centre for Science and Environment (CSE) has done a scoping study on one of the key technologies such as Pyrolysis-based Omni-Processor (POP) that could transform faecal sludge into valuable biochar in two locations of Rajasthan, Khairthal and Kishangarh Bas. The study investigated whether turning human waste into biochar is a safe and viable alternative to traditional disposal methods.

An in-depth look at how POP systems process faecal sludge to generate energy, treated water, and nutrient-rich biochar was made. The report quantitatively compares the use of POP-generated biochar against untreated faecal sludge, revealing significant benefits in pathogen reduction and soil health improvement. While the technology effectively stabilizes waste and improves soil water retention, the study frankly addresses remaining challenges, including heavy metal concentrations and strict regulatory compliance for unrestricted agricultural use.

This study validates POP technology as a promising tool for closing the sanitation loop, converting a hazardous waste challenge into a sustainable resource opportunity for India's growing towns. It serves as a vital resource for policymakers, sanitation experts, and environmentalists who would consider POP and similar technologies as a valuable option to enhance circular economy.

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