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FOREWORD

India is in the midst of an urban sanitation evolution, where conventional systems of water-based sewerage, designed to transport faecal material from homes through pipes to sewage treatment plants, is being replaced. The paradigm shift is towards non-sewered sanitation, where household faecal material is transported to treatment facilities — where this human waste is treated in either designed faecal sludge treatment plants (FSTPs) or in the conventional sewage treatment plants, through co-treatment.

The treatment plants are designed in the first stage to do solid-liquid separation; then the liquid used water is treated to meet discharge standards, while the solid portion of the faecal sludge is dried, either in sunlight or mechanically.

The challenge now is to ensure resource recovery from the faecal sludge or biosolids in the treatment plants. If this is not done, the quantity of biosolids will grow exponentially and will add to problems of contamination and management in the plants.

Centre for Science and Environment's (CSE) Environment Monitoring Laboratory (EML) has undertaken this first study on the quality of biosolids from faecal/sewage treatment plants.

For this study, my colleagues collected samples from FSTPs and co-treatment STPs in seven states — Telangana, Tamil Nadu, Odisha, Rajasthan, Uttar Pradesh, Uttarakhand, and Madhya Pradesh. In this study, 47 FSTPs were visited; samples were collected three times from each plant, and in addition, 14 co-treatment sludge samples were analysed in triplicate.

In most of the plants visited it was found that the biosolid was dried in sunlight for 30 to 45 days or by mechanical drying, harvested, and stored in a storage room/shed. In a few cases, it was then used for gardening or co-composted.

It is important to note that India does not have standards for the quality of biosolids, other than for compost, which has been issued under the Fertilizer Control Order (2009 and then 2013).

The results of this study are encouraging as they point to the opportunity for resource recovery.

The issues that arise are:
1. The biosolids from FSTPs are high on nitrogen but low on carbon. The question is, what then is the way ahead? Should there be separate standards for nitrogen-rich organic fertilizers? Or should plants be required to do co-composting with vegetation and with organic material from households? Should there be a variation of fertilizer standards, designed for biosolids, to meet different nutrient inputs for soil?

2. In many cases, the samples are high on microbial load and this, if not handled, will lead to increased load from pathogens and disease burden. But the fact is that the study found that this micro-bacterial contamination is technology neutral; it has much more to do with the deliberate actions taken by plant operators to ensure that the biosolid is fully dried.

The study points to a direct co-relation with moisture content and bacterial load. In some plants visited, there are no sufficient sludge drying beds; and even if these are present, the management is under pressure to over-use these beds. The biosolid, even before it dries, is removed and kept for storage. The best practice noted in the study comes from sites in Telangana, where plant operators crushed the sludge and then dried it so that there was less moisture and less pathogens.

The study also notes that pathogen level is high in sludge of co-treatment plants as STPs are dumping this without any drying beds/or mechanical treatment. This suggests the need for ensuring systems for drying and standard operating procedures (SOPs) for plant operators to ensure that the samples are pathogen-free.

3. The study has found the samples were detected with heavy metals; namely mercury, chromium and zinc. But this also requires that FCO standards be reviewed for heavy metals in biosolids, given the final resource recovery method. For instance, zinc is not harmful *per se* for application on land, and global standards (USEPA) have higher zinc limits for land applications.

The question now is if the country needs quality standards for nitrogen-rich biosolids; what are the other opportunities for reuse and resource recovery? And what must be done in each treatment plant to ensure that the sludge is pathogen-free?

We hope that this study will stimulate discussion and regulatory action so that the sanitation evolution in the country can close the circle; the nutrient-rich human waste is reused to enrich the land and or is used for energy or other resource recovery. It is not a waste but a resource.

Sunita Narain

Introduction

Inadequate waste management has increased the interest in finding sustainable ways to safely empty, transport and dispose of faecal sludge. Numerous research efforts have been carried out to dispose of the generated faecal sludge, especially from urban centres. Stabilisation, drying and pathogen reduction form the three main components in faecal sludge (FS) treatment which can be achieved with different treatment technologies, and by a combination of various technologies.

Each FS treatment technology results in end products which need to be further treated, disposed of, or utilised for some type of resource recovery. For example, dried or partially dried sludge, compost, leachate and biogas are some of the end-products produced from FS treatment, each of which have an inherent value, which can turn treatment from simply a method for environmental and public health protection to resource recovery and value creation. The various types of end products produced from different FS treatment technologies, potential difficulties and restrictions associated with their end use, and additional steps that can or should be applied to turn them into a valuable asset are discussed below.

The most common resource recovery from FS from ancient times has been its use as a soil conditioner and organic fertiliser. This is due to the presence of essential plant nutrients and organic matter in FS that increases the fertility and water retaining capacity of soils. However, there are several other treatment options that allow for resource recovery. For example, biogas can be produced during anaerobic digestion of FS, with the remaining sludge also being used as a soil conditioner. Novel developments are underway to recover end products as a biofuel, for example pyrolysis, gasification, incineration and co-combustion or as resource recovery of organic matter through the growth of Black Soldier flies for protein production.

However, raw faecal sludge cannot be directly applied to soils, as it contains pathogenic microorganisms that create a health risk to farmers and other people who depend on the crops grown in the soil supplemented with faecal sludge. In order to reduce the microbial content, a post-treatment step for deactivating the microbes is essential. Co-composting with carbon-rich materials such as agricultural wastes, food waste is one of the approaches to reduce the microbes as it provides two benefits: enables thermophilic temperature required for pathogen destruction and prevents nitrogen volatilisation.

Treatment objectives and processes

Many FS treatment technologies are based on those developed for wastewater and wastewater sludge treatment, but it is important to remember that these technologies cannot be directly transferred. FS characteristics differ greatly from wastewater, and have a direct impact on the efficiency of treatment mechanisms. Important properties of the sludge to consider include stabilisation, organic load, particle size and density, dissolved oxygen, temperature, pH, water content and viscosity. Environmental and public health treatment objectives are achieved through pathogen reduction, stabilisation of organic matter and nutrients, and the safe end-use or disposal of treatment end products.

Thickening and dewatering

Dewatering (or thickening) of FS is an important treatment objective — FS contains a high proportion of liquid and the reduction in this volume greatly reduces the cost of transporting water weight and simplify subsequent treatment steps. It dewaters sludge which reduces the sludge volume and increase the concentration of total solids. FS has different dewatering characteristics compared to wastewater sludge, in that it tends to foam upon agitation, and resist settling and dewatering. The duration of onsite storage and the age of FS also affects the ability to dewater the sludge. Empirical evidence shows that 'fresh' or 'raw' FS is more difficult to dewater than older, more stabilised FS.

Thickening is performed prior to stabilization, while dewatering is the final method of volume reduction before the ultimate disposal of stabilized sludge (drying beds and mechanical processes). Common methods for dewatering of FS include gravity settling, filter drying beds, and evaporation/evapotranspiration. Other methods include Mechanical belt presses, Centrifugation, Reed beds and Lagoons.

Pathogens

FS contains large amounts of microorganisms, mainly originating from the faeces. These microorganisms can be pathogenic, and exposure to untreated FS constitutes a significant health risk to humans, either through direct contact or indirect exposure. FS needs to be treated to an adequate hygienic level based on the end-use or disposal option. For instance, exposure pathways are very different for treated sludge discharged to the environment, used in agriculture, or combusted as fuel. Mechanisms for pathogen reduction and/or inactivation include starvation, predation, exclusion, desiccation, partitioning, and temperature

Nutrients

FS contains significant concentrations of nutrients, which can be harnessed for beneficial resource recovery, but if not properly managed can result in environmental contamination. The nutrients in FS can supplement synthetic nitrogen based fertilizers that are heavily dependent on fossil fuels and phosphorus, which is a mined resource of which finite supplies are estimated to reach their peak availability within 100 years. Environmental impacts from nutrients include eutrophication and algal blooms in surface waters, and contamination of drinking water (e.g. nitrates leading to methemoglobinemia).

Stabilisation

Untreated FS has a high oxygen demand due to the presence of readily degradable organic matter that consumes significant amounts of oxygen during aerobic respiration. If FS is discharged into the environment, it can result in the depletion of oxygen in surface waters. The process of stabilization results in a FS containing organic, carbon-based molecules that are not readily degradable, and which consists of more stable, complex molecules (e.g. cellulose and lignin). Stabilisation is achieved through the biodegradation of the more readily degradable molecules, resulting in a FS with a lower oxygen demand.

Common indicators of stabilisation include measurement of Volatile Suspended Solids (VSS), BOD, and COD. In addition, stabilisation ensures that organic forms of nutrients present in treatment end-products are stable, and can be more predictably and reliably used. Stabilisation also reduces foaming of FS, leading to better dewatering. It reduces problems associated with sludge odor and putrescence and the presence of pathogenic organisms. It uses biological, chemical, and/or thermal processes to reduce organic matter, water content and odors and also provides some pathogen reduction like biological digestion (aerobic or anaerobic) and chemical (e.g., alkaline (lime)) stabilization.

Other methods

Other methods are used to dewater sludge that can reduce the sludge volume and increase the concentration of total solids — these include composting, heat drying and combustion.

Table 1: Treatment technologies and products generated from treatment of faecal sludge

Treatment process	Treatment technology	Inputs	Description	Potential products
Physical	Storage	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Prolonged storage, open or enclosed, results in degradation of material and gives a stabilised sludge. Pathogen reduction is a function of time, temperature, moisture, competition etc	Stabilised sludge
	Desiccation	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Treatment should be given for decreasing water content to an extent that the product becomes pseudo-stable. Pathogen reduction is a function of low moisture content. Moisture content below 5 per cent is required for inactivation of persistent pathogens.	Pseudo-stabilised sludge
Biological	Aerobic treatment	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Collective name for a number of treatments using aerobic microorganisms to break down biodegradable matter — can be a part of wastewater treatment. For composting processes, see below.	Stabilised sludge
	Composting	Faecal sludge, dewatered faecal sludge	Aerobic, auto thermal process in which biodegradable matter is decomposed by microorganisms, fungi, and invertebrates. Pathogen inactivation will depend on thermophilic temperatures.	Stabilised compost
	Vermicomposting	Faecal sludge, dewatered faecal sludge	Aerobic process in which earthworms and microorganisms degrade the organic matter. Worms may be harvested as animal feed. Requires dewatering of sludge or addition of co-substrates.	Stabilised compost, worms
	Fly larvae composting	Faecal sludge, dewatered faecal sludge	Aerobic process in which fly larvae and microorganisms degrade the organic matter. Larvae may be harvested as animal feed. Requires dewatering of sludge or addition of organic matter.	Active compost, larvae
	Anaerobic treatment	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Collective name to a number of processes in which microorganisms break down biodegradable matter in the absence of oxygen while producing biogas. Pathogen inactivation depends on process temperature dependent on heating.	Stabilised sludge, biogas
	Lactic acid fermentation	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Biological, anaerobic process in which the sludge is inoculated with lactic acid bacteria and commonly also a co-substrate. Preserves a majority of the material in a pseudo-stable form. Low pH and carboxylic acids are involved in pathogen inactivation.	Pseudo- stabilised sludge

Treatment process	Treatment technology	Inputs	Description	Potential products
	Productive wetland	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	An artificial wetland or planted drying bed used to treat wastewater, and sludge and produce biomass. Biochemical processes at the plant interface remove pollutants.	Stabilised sludge, biomass (plants)
	Aquaculture	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Rearing of fish in ponds that are fertilised by effluent or sludge. The fish feed on algae and other small aquatic organisms that grow in the nutrient-enriched water.	Stabilised sludge, fish
	Microbial fuel cells	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	A bio-electrochemical device that uses microorganisms to convert chemical energy into electrical energy using oxidation-reduction reactions.	Sludge, nutrient solution
Chemical	Precipitation	Faecal sludge and the supernatant from the dewatering process	Nutrient extraction from liquids by converting the substance into an insoluble form or by changing the composition of the solvent to diminish its solubility.	Inorganic precipitate
	Elution	Faecal sludge, dewatered faecal sludge	Extraction of nutrients from solid material by washing with an alkaline or acid solvent, e.g., extraction of P from ash. Elution is often followed by membrane separation, sorption or solvent extraction.	Nutrient solution
	Ammonia treatment	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Addition of ammonia, often as urea. Pathogen inactivation is due to ammonia (NH3) and carbonates. Shall be a closed treatment to minimise ammonia losses.	Pseudo- stabilised sludge
	Alkaline stabilisation	Faecal sludge, dewatered faecal sludge and the supernatant from the dewatering process	Highly alkaline chemicals, e.g., lime, caustic soda or ash are added to increase the pH. Pathogen inactivation depends on a pH over 12 or when using CaO, a combination of alkaline pH and heat from the exothermic reaction.	Stabilised sludge

Treatment process	Treatment technology	Inputs	Description	Potential products
Thermal	Carbonisation	Faecal sludge, dewatered faecal sludge	Carbonisation of organic solids at elevated temperatures in the absence of oxygen. Heat energy may be captured. Non-volatile nutrients remain in the biochar.	Biochar
	Incineration	Dewatered faecal sludge	Combustion of organic substances in the presence of oxygen. Heat energy may be captured while non-volatile nutrients remain in the ash.	Ash
	Pasteurisation	Faecal sludge, dewatered faecal sludge	Heating of sludge to 65-75°C in order to inactivate pathogens. Often used as a pre-treatment to anaerobic treatment for biogas production.	Pseudo- stabilised sludge
	Solar drying	Faecal sludge, adewatered faecal sludge	Use of solar radiation to dry and sanitise sludge. Can be done in open or closed beds. Closed beds have been shown to have a higher drying efficiency. Temperature, reduced moisture content and partially UV contribute to pathogen inactivation.	Pseudo- stabilised sludge
Physiochemical	Sorption	Faecal sludge	Process in which one substance becomes attracted to another, e.g., the capture of nutrients in filter material (zeopeats, P-filters, etc).	Nutrient-enriched sorbent material

Pathogen removal from faecal sludge

The potential use of end products should be considered from the initial design phase of any complete FS management (FSM) system, as the treatment technologies used are intrinsically linked to the quality of end products generated. FS contains large amounts of microorganisms, mainly originating from the faeces. The microorganisms can be pathogenic, and exposure to untreated FS constitutes a significant health risk to humans, either through direct contact, or indirect exposure. Hence, FS needs to be treated to an adequate hygienic level which again depends on the end-use or disposal option as exposure pathways differ widely for different end-uses or disposal options like environmental discharge or agricultural use or incineration. For example, if treated FS is reused in agriculture crops with human exposure, pathogens are a major concern and hence, in this case, FS has to be treated to an extent that completely eliminates pathogens or reduces their content to safe levels.

Pathogen reduction in FS takes place at various stages of treatment. Several processes can decrease pathogen concentrations in sludge including stabilisation, thickening and dewatering which are discussed above — but here the pathogens are only partially removed. Other processes are required to completely eliminate the pathogens which include incineration, chemical treatment, co-composting, etc. But several factors influence these processes in pathogen removal which are discussed below.

Factors and mechanisms for pathogen reduction in sludge

The mechanisms that result in inactivation of pathogens from physical, biological, and chemical mechanisms are described below. It is important to have an understanding of all of these interrelated mechanisms, to ensure that pathogen reduction is achieved during FS treatment. They affect all biological processes, which need to be considered to ensure that treatment processes function as designed.

Physical parameters

Temperature: Most pathogens are inactivated above temperatures of 60˚C when cell proteins and nucleic acids are denatured. This is achieved in processes such as thermophilic co-composting as well as lime treatment. As the temperature increases, less time is needed for pathogen inactivation. Examples of sludge management technologies that can achieve temperatures greater than 45ºC if properly designed and operated are: (1) composting, (2) thermal treatment, and (3) thermophilic digestion. For lower temperature treatments, pathogen concentrations are reduced but still routinely identified in treated sludge.

Time: The duration of treatment (e.g. planted drying beds) or the storage of treated sludge can result in pathogen reduction, as they have a limited survival time in adverse conditions. In faeces, most bacteria can only survive between one week and two months. For example, *Salmonella* spp. survives on an average for 30 days and faecal coliforms for 50 days. Helminth eggs however are very persistent, and can maintain viability for several months to years. The required storage duration for pathogen reduction also depends on the ambient temperature. Storage time of FS for up to one year at an ambient temperature of 35˚C, and two years at 20˚C are recommended for pathogen reduction. Storage at temperatures less than 10°C does not result in adequate inactivation.

Desiccation: Evaporation resulting in desiccation or dehydration reduces active pathogens as microorganisms need water for survival. Water activity is represented by the ratio of water vapour pressure of the sludge to the water vapour pressure of pure water under the same conditions. Pure water has a water activity of 1, and most pathogens cannot survive under a water activity of 0.9, while some yeast and eggs survive in much drier conditions. All dewatering technologies therefore contribute to the die-off of pathogens (e.g. drying beds) if the water content gets below a certain point where desiccation has an effect. Further storage also contributes to disinfection due to the reduction of the available water.

Other ways to improve pathogen destruction by reducing moisture content are drying through evaporation by sunlight or solar radiation, transpiration by use of deep rooted plants, and drainage of water vertically from a drying bed.

Temperature/Time/Moisture: The inactivation of pathogens in sludge is a function of temperature, time, and moisture content. The rate of inactivation increases with increasing temperature and decreasing moisture content. For instance, treatment at lower temperatures requires more time at the same moisture content to achieve the same level of pathogen reduction.

Evidence of pathogen vulnerability: Long-term storage of dewatered sludge can inactivate all pathogens at the following temperatures:

- 2 to 20°C: 1.5 to 2 years: - Reduces all pathogens to low levels
- 20 to 35°C: > 1 year - Substantial to total inactivation of viruses, bacteria, and protozoa.
- More or less complete inactivation of helminths after 1 year.

Viruses: Poliovirus has been inactivated 3.0 log in laboratory thermophilic digesters (49 to 55 °C).

Protozoa: High temperatures cause more rapid inactivation of *Cryptosporidium* (oo) cysts.

Helminths: Temperature is the most important factor for the inactivation of helminth eggs in thermophilic anaerobic digesters. A 3.0 log removal of *Ascaris* was documented at temperatures of 53 and 55°C. *Ascaris* in composted excreta has been inactivated in a solar thermal post-treatment unit at the following levels:

- 2.0 log10: 2 hours at 50°C and 50% moisture
- 3.0 log10: 3 hours at 60°C and 50% moisture

Helminth eggs are particularly resistant to treatment, including thermal and chemical treatment. Therefore, in regions where helminth infections regularly occur, it is recommended to first provide treatment in sludge-drying beds, and then to bury the dried sludge to minimise exposure. The World Health Organization also provides recommendations for storage and treatment of dried excreta and faecal sludge. WHO further recommends an additional barrier of safety by waiting for one month between the time, stored excreta is applied to a crop and the time the crop is harvested.

Sorption: Helminth eggs tend to sorb or settle, and hence separate with the solids fraction in FS systems. In settling and thickening tanks, about 50 per cent of the helminth eggs are separated from the liquid fraction due to settling. In filtration that occurs with drying beds, a majority of Helminth eggs remain with the solid fraction, as does 90 per cent of indicator bacteria. Although the majority of Helminth eggs partition with the solids fraction, the fate of all pathogens must be considered.

UV radiation: Solar/UV radiation in the range of 300-400 nm effectively inactivates pathogens by denaturing DNA molecules via photochemical reactions. UV light has been shown to effectively inactivate *E coli* in waste stabilisation ponds. However, it is important to remember that for this mechanism to be effective, the light rays must be able to penetrate the FS during treatment. This mechanism is therefore most likely only occurring at the surface, as the high organic matter and turbidity prevents penetration of UV radiation.

Biological parameters

Digestion and composting can reduce the volatile organic fraction of sludge; thus, reducing disease vector attraction.

Chemical parameters

pH: Most microorganisms can only survive and grow within a range of 2-3 pH units, and very few can survive below pH 3 and above pH 10. In this way, chemical addition for pH control can result in pathogen reduction. However, the pH can also upset composting and anaerobic digestion processes, and it is therefore important to consider downstream treatment steps when employing pH control for pathogen reduction. Application of CaO to dewatered sludge to raise the pH >12 causes an exothermic reaction with temperatures exceeding 50°C. Alkaline stabilization, if properly engineered and operated, can inactivate viral, bacterial, protozoan and helminthic pathogens.

Resource recovery from faecal sludge

The potential use of end products should be considered from the initial design phase of any complete FS management (FSM) system, as the treatment technologies used are intrinsically linked to the quality of end products generated. Potential resource recovery options from faecal sludge can be as follows:

Soil conditioner

The use of FS as a soil conditioner can range from deep row entrenchment of untreated FS, to packed compost that is sold as a commercial product for household level use in horticulture. Using FS as a soil conditioner has several benefits over using chemical fertilisers alone. Organic matter in FS can increase soil water holding capacity, build structure, reduce soil erosion and provide a source of slowly released nutrients. However, when using FS as a soil conditioner, the factors like the fate of and exposure to pathogens, heavy metals, and social acceptance should be considered. Following are the technologies through which untreated and treated faecal sludge can be used as a soil conditioner:

Untreated faecal sludge: Untreated faecal sludge can be used in deep row entrenchment and landfilling as described below:

Deep row entrenchment: Raw FS can be used in deep row entrenchments in forestry applications. In this method, the FS is buried in deep ditches which helps in the removal of odours and also reduces the risk of exposure to pathogens. Later, high-nitrogen utilizing trees are planted on top of it. This method has an advantage of applying larger volume of FS at one time compared to conventional methods such as spraying on trees or spreading on the soil surface. However, the effect on groundwater needs to be thoroughly studied, and should be considered on a case-by-case basis (restricted and unrestricted crops) to ensure environmental protection when using this method.

Land application: The direct use of untreated FS in land application has been in practice for a long time in parts of China, South-East Asia and Africa. This method has the highest level of risk for human health, and, therefore, it is generally not recommended and hence requires the availability of adequate barriers and sufficient land area for its use. This practice is best applied in arid to semi-arid regions where raw sludge is spread out on farm fields during the dry season, and then incorporated into fields when crops are planted during the rainy season.

Treated faecal sludge: Treated faecal sludge can be used as soil conditioner directly from drying beds, co-composting, vermicomposting and pellets as described below:

Sludge from drying beds: Planted and unplanted sludge drying beds are two different treatment methods used for the treatment of FS that partially treat the sludge that can be used in land applications. Major concern with these two methods is with regard to the presence of pathogens, especially helminth eggs which are more resistant to treatment and thus have longer survival times. In addition, the majority of helminth eggs are retained in the sludge layer. The short retention time of sludge on unplanted drying beds (i.e., weeks) means that further sludge treatment or storage is required if pathogen reduction is to be achieved. The longer retention time of planted drying beds (i.e., years) means that significant pathogen reduction can be achieved, but this needs to be evaluated on a case-by-case basis as the presence of viable Helminth eggs varied in different studies irrespective of retention time. In addition, due to the long retention time on planted drying beds, the treated sludge has properties and nutrient content similar to mature compost.

Co-composting: Co-composting refers to composting of FS together with other waste streams such as municipal solid waste. Time and temperature are two main factors which aid in pathogen reduction during composting. Temperature increases during the composting process which causes pathogen reduction. The properly treated end product is a stabilised organic product which is safe to handle and can be stored or applied to land without associated concerns of pathogen transmission.

Vermicomposting: Vermicomposting is another method of composting where earthworms are used to enhance the quality of the final end product. During this process, worms breakdown larger organic particles, stimulate microbial activity, and increase the rate of mineralisation, thereby converting FS into humic-like substance with a finer structure than normal compost. However, during vermicomposting, sufficient pathogen reduction may not be achieved as the operating maximum temperature is only 35˚C which is required to maintain the viability of worms. Hence, if complete inactivation of pathogens is required, storage period has to be increased after vermicomposting or the process should be combined with thermophilic composting.

Pellets: Dried pellets are another good option of FS resource recovery. During this process, FS is dried, and the dried sludge after necessary pathogen inactivation is converted into pellets using a binder. The pellets have reliable characteristics for end use and are also safe to handle and have the advantage of easy transportation. Resource recovery options from pellets include use as a soil amendment, or for combustion as a bio-fuel. LaDePa (latrine dehydration and pasteurisation) process, which produces pellets from mostly dried FS, has been developed in South Africa and is currently operating on a pilot-scale. Another pellet process being developed in Ghana produces dried pellets which are enriched with urea, so the end product has similar fertilising properties as poultry manure.

Additional forms of resource recovery

In addition to using end products from FS management as soil amendments and for water reclamation, there are many other opportunities for resource recovery depending on the type of treatment and processing technologies. Possibilities include food and agricultural uses (ex. protein, fodder, fish), or energy reclamation (ex. biofuels).

Protein: The larvae of Black Soldier Fly (BSF) *Hermetiaillucens* can be used as a conventional protein and fat source for poultry and fish feed, and could readily replace fish meal as a key component of animal feed. Organic matter present in FS and other organic wastes is the feeding source for the BSF larvae. The last larval non-flying pre-pupa stage which is rich in protein and fat content is the desired end product for fish feed. Additionally there is low risk of BSF being a vector for disease transmission. BSF larvae have the potential of reducing the volume of organic waste by about 55 per cent and the residue remaining after digestion can be composted or anaerobically digested to produce a soil conditioner. It will, however, be lower in nitrogen and phosphorus than raw organic wastes.

Fodder and plants: The plants grown in drying beds can be harvested and used for resource recovery as fodder for livestock. In a case study conducted in Cameroon, *Echinochloapyramidalis* grown in drying beds was used by breeders to feed horses, goats, sheep, dairy cows, rabbits, greater cane rats and guinea pigs.

Fish and plants: The nutrients present in FS can be utilised in aquaculture by growing fish in stabilisation ponds receiving effluents from FSTPs. The nutrients in the pond also increase the growth of plankton, and aquatic plants like duckweed, water spinach or water mimosa which can be harvested for use as fish feed, and for animal feed or human consumption respectively. Fish grown in these ponds can be used as animal feed or sometimes directly for human consumption. Nevertheless, when used for direct human consumption, care should be taken to prevent transmission of pathogens and adverse health effects, as fish, though not susceptible themselves, can act as carriers of human pathogens. Therefore, thorough cooking, growing fish for two-three weeks in clean water ponds before consumption, or maintaining a faecal coliform count of <1,000/100mL in ponds receiving effluent from FSTPs are some of the protective barriers which can prevent pathogen transfer to humans.

Apart from this, fish can also act as intermediate hosts to helminths, which is a concern with FS. Another major concern is the existence of poor knowledge of the technical aspects of using FS or wastewater in aquaculture which may lead to some major potential problems such as the rapid eutrophication of ponds due to loading of excess nutrients.

Building materials: Dried FS can be used in the manufacturing of cement and bricks, and in the production of clay-based products. This resource recovery option captures the material and chemical properties of FS, but the nutrient value is not utilized and hence compromised. As human contact is reduced, pathogen presence is not a major problem here. In addition, the high temperatures used in manufacturing will result in complete destruction of pathogens. Dried FS has been shown to have similar properties to limestone and clay which are the commonly used raw materials for building purposes. In Japan, FS is commonly used in the cement industry. It is used as an alternative fuel in the kiln, and/or the ash resulting from FS incineration is also combined with cement.

Another method of using FS in the cement industry is through treatment with lime for stabilization and drying of FS, resulting in a fine powder-like structure that can replace limestone in cement manufacturing. Other than this, FS can also be used in the manufacture of ceramics. In this process, 1–10 wt % of dried sludge is used in making clay and addition of sludge increases the permeability and reduces the bending strength of clay.

Energy recovery options from faecal sludge

Energy can be produced from faecal sludge by different biological and thermal methods. An increasing interest in these technologies have been found by the researchers due to the demand for sustainable biofuels. One of the biological methods is anaerobic digestion, which produces biogas, heat and digestate. Thermal technologies include pyrolysis, gasification, hydrothermal carbonization which produces biochar, biooil and biogas. Biodiesel can be produced through fermentation or chemical reactions and incineration or co-combustion of dried FS. Energy recovery harnesses the energy potential of organic matter in FS, but frequently at a trade-off of nutrient recovery.

Biogas: Biogas is obtained from the anaerobic digestion of faecal sludge. The nature of gaseous compounds in the mixture and the amount gas produced depends on the operating parameters including temperature, stability and COD of the sludge. The major component in the gaseous mixture is methane and has high calorific value which is the main reason of high energy content in biogas. Hence, biogas obtained from faecal sludge can be used directly as fuel for cooking or in engines, provided hydrogen sulphide is removed from the mixture to avoid corrosion. Electricity generation from biogas on a small scale is not a feasible option.

Pathogen inactivation during anaerobic process depends on the operating temperature where higher temperature (>50°C) favour significant reduction and lower temperature (30-38°C) do not guarantee pathogen inactivation. Maintaining a well-mixed reactor also increases the degree of pathogen deactivation as it prevents the formation of dead zones in the reactor.

Incineration/co-combustion: Incineration is one of the thermal techniques for resource recovery in the form of electricity or heat. The process generates ash, which can be used as a raw material for construction. FS has a calorific value of 17 MJ/kg solids which is more or less equal to that of wastewater sludge (10–29 MJ/kg) (coal calorific value is 26 MJ/kg) which is commonly used for incineration in Europe and US. Hence, the energy generated by FS incineration can be harnessed for energy recovery like in coal-fired power plants by co-combustion with coal, or in other industrial applications such as cement kilns. Even though FS is rich in nitrogen content, the nitrous oxide emissions from FS incineration are lower compared to coal incineration. Emissions of dioxins and furans are also lower from sludge incinerators than from waste incinerators.

The direct addition of dewatered FS to a cement kiln can reduce NOx and CO_2 emissions by 40 per cent and 30 per cent, respectively, compared to when the sludge is incinerated.

Pyrolysis/gasification: Pyrolysis is the thermochemical conversion of feedstock in an oxygen-depleted environment at temperatures between 350-800°C, which generates biochar, oil and gases with more compounds such as CO_2 and CH_4. Gasification occurs at a much higher temperature where more amounts of syngas — H_2 and CO — and very low amounts of char is generated. Both end products can be used as fuels, and the gases produced can also be recovered.

Biochar: (Bio)char produced by pyrolysis/gasification of sludge can be used as a fuel or soil conditioner. Trials with char have shown both plant yield suppression and plant yield increases. However, as char is a highly porous material, it is thought that this will increase the surface area in soils, and hence improve water retention and aeration capacity. Till date, information is only available based on wastewater sludge (biosolids) and not with FS, although research is currently being conducted as part of the Reinventing the Toilet Challenge (RTTC) programme of BMGF.

Hydrochar: Pyrolysis carried out with wet biomass in the presence of subcritical water is referred to as hydrous pyrolysis or hydrothermal carbonisation (HTC) and the end product produced during this process is referred to as hydrochar to distinguish it from char obtained from dry pyrolysis. Hydrochar is reported to have a highly porous nanostructure, which can be utilised for ion binding, pollutant or water absorption, or as a scaffold for particle binding of catalysts.

Gasification: Gasification is made up of a series of chemical and thermal steps: drying, pyrolysis, oxidation and reduction. This process mainly produces a synthetic gas, or syngas, which is made up of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2) and other trace elements. Syngas has a high energy content and can be either directly used for electricity generation in gas engines and turbines, or it can be further processed to obtain liquid fuel.

Hydrogen gas is potentially a valuable renewable fuel which has the potential to power hydrogen fuel cells or hydrogen engines without greenhouse gas emissions. Under the right operating conditions, hydrogen can make up a substantial portion of the syngas that is produced, and research efforts are focused on optimising processing conditions to maximise hydrogen gas yield.

Biodiesel: As FS contains oils and fats (lipids), they can be extracted and used to produce biodiesel. Maximising the extraction of lipids from FS is a difficult and cost-intensive process which limits the use of FS in producing biodiesel. Once lipids are extracted, through base- or acid-catalysed trans-esterification process using alcohol, they are converted to fatty acid alkyl esters (i.e., methyl, propyl or ethyl) which make up the biodiesel. The biodiesel produced from FS can be used in similar applications as conventional fossil fuel-based diesel and it has certain advantages over fossil fuel-based diesel. Due to the lower heat of combustion for biodiesel, it results in an overall reduction of power usage by 10 per cent compared to petroleum-based diesel. It also increases engine life and produces less exhaust gas emissions compared to conventional diesel.

Methodology

Sampling locations

Biosolid samples were collected from FSTPs in six states — Telangana, Tamil Nadu, Odisha, Rajasthan, Uttar Pradesh, and Madhya Pradesh. After the solid-liquid separation in the first stage of the treatment process, the solid portion of FS is dried in sunlight for 30 to 45 days or by mechanical drying, harvested, and stored in a storage room/shed.

Sample collection

Samples were collected by visiting the individual FSTPs, using a soil sampler. Approximately 1 kg of each sample was collected in plastic bags, sealed properly, transported to the lab, and stored in the refrigerator until analysis.

Storage of biosolids in the FSTP sites

Table 2: List of samples collected from the respective FSTP locations

S No	Location	Treatment technology	Capacity	Technology for solid-liquid separation process	Treatment process	Reuse practice
Telangana						
1	Boduppal	Geotube technology	15 KLD	Geotube dewatering system	Sun drying	Gardening
2	Uppal	MBBR with solar sludge drying	40 KLD	Dewatering unit	Sludge dried by paddle dryer followed by IR decontamination	Gardening
3	Siddipet	DEWATS	20 KLD	Sludge drying bed	Sun drying	Gardening
4	Sircilla	DEWATS	18 KLD	unplanted sludge drying bed	Sun drying	Gardening
5	Nirmal	Moving bed bioreactor	30 KLD	Settling tank	Heat treatment by screw press	Gardening
6	Kamareddy	Moving bed bioreactor	30 KLD	Solid-liquid separator	Sludge dried by paddle dryer followed by IR decontamination	Gardening
7	Nalgonda	Electrocoagulation	75 KLD	Screw press	Sun drying chamber	Gardening
8	Bongir	Geotube technology	15 KLD	Geotube dewatering system	Sun drying	Gardening
Tamil Nadu						
9	Periyanaickenpalayam	MBBR	30 KLD	Screw press	Sun drying	Co-composting
10	Thirumangalam	DEWATS	40 KLD	Gravity-based settling on drying beds	Sun drying	Gardening and selling to farmers
11	Thuraiyar	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	Given for co-composting
12	VK Puram	DEWATS	30 KLD	Gravity-based settling on drying beds	Sun drying	Co-composting
13	Shenkottai	DEWATS	20 KLD	Gravity-based settling on drying beds	Sun drying	No Reuse practice
Uttar Pradesh						
14	Jhansi	DEWATS	6 KLD, 12 KLD	Planted sludge drying bed	Sun drying	No Reuse practice
15	Loni	MBBR	32 KLD	Screw press technology	Sun drying	No Reuse practice
16	Chunar	DEWATS	10 KLD	Planted sludge drying bed	Sun drying	Gardening

S No	Location	Treatment technology	Capacity	Technology for solid-liquid separation process	Treatment process	Reuse practice
17	Unnao	DEWATS	32 KLD	Screw press technology	Sun drying	No Reuse practice
Rajasthan						
18	Lalsot	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	Gardening
19	Phulera	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
20	Khandela	DEWATS	10 KLD	Planted sludge drying bed	Sun drying	No Reuse practice
Odisha						
21	Puri	STP co-treatment: waste stabilisation pond	50 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
22	Balasore	DEWATS	60 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
23	Baripada	DEWATS	50 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
24	Bhubaneswar	DEWATS	75 KLD	, Unplanted sludge drying bed	Sun drying	No Reuse practice
25	Dhenkanal	DEWATS	27 KLD	Unplanted sludge drying bed	Sun drying	Co-composting
26	Berhampur	DEWATS	40 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
27	Angul	DEWATS	18 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
28	Sambalpur	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
29	Rourkela	DEWATS	40 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
30	Asika	DEWATS	10 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
31	Bhadrak	DEWATS	30 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
32	Choudwar	DEWATS	12 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
33	Jagatsinghpur	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
34	Jatni	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice

S No	Location	Treatment technology	Capacity	Technology for solid-liquid separation process	Treatment process	Reuse practice
35	Khordha	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
36	Nimapada	DEWATS	10 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
37	Paralakhemundi	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
38	Surada	DEWATS	10 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
39	Kashinagar	DEWATS	10 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
40	Hinjilicut	DEWATS	10 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
41	Talcher	DEWATS	20 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
42	Cuttack	STP co-treatment	60 KLD	Unplanted sludge drying bed	Sun drying	No Reuse practice
Madhya Pradesh						
43	Indore	DEWATS	3 KLD	Planted sludge drying bed	Sun drying	No Reuse practice
44	Ojus, Jabalpur	MIZUCHI	100 KLD	MIZUCHI	Vermicomposting and sun drying	No Reuse practice
45	St.Alosius Jabalpur	MIZUCHI	100 KLD	MIZUCHI	Vermicomposting and sun drying	No Reuse practice
46	Elanza Jabalpur	MIZUCHI and TERRA	50 KLD	MIZUCHI	Vermicomposting and sun drying	No Reuse practice

Testing methods

The dried sludge (biosolids), co-compost and biochar samples were evaluated for various parameters, including physical properties (pH, electrical conductivity and moisture). Elemental analysis was done of total carbon (TC), total nitrogen, sulfur and heavy metals. The parasites/microbiological parameters included helminths eggs, faecal coliform and *E coli*.

The samples were mixed with distilled water in 1:5 ratio (w/v) for one hour. After decantation, when the supernatant was separated from the settled material, the pH and the EC were measured using a pH/conductivity meter (Biofertilizers and Organic Fertilizers in Fertilizer (Control) Order, 1985: Part-D Methods of Analysis of Organic Fertilizers).

Collection of samples from the storage site

CHNS analysis

The CHNS elemental analyzer (LECO, USA, CHN828, and S832 series) is used for the determination of carbon, hydrogen, nitrogen, and sulfur in organic materials or other substrates such as soil, compost, fertilizer, etc. The instrument works on the principle of the classical Pregl-Dumas method where the sample undergoes high-temperature combustion in an oxygen-rich environment. During combustion, carbon is converted to carbon dioxide; hydrogen to water; nitrogen to nitrogen gas/oxides of nitrogen, and sulfur to sulfur dioxide. The combustion products are swept out of the combustion chamber by an inert carrier gas such as helium and passed over heated (about 600°C) high-purity copper. The function of this copper is to remove any oxygen not consumed in the initial combustion and to convert any oxides of nitrogen-to-nitrogen gas. The gases are then passed through the absorbent traps in order to leave only carbon dioxide, water, nitrogen, and sulfur dioxide. Detection of the gases is carried out in a series of separate infra-red and thermal conductivity cells for the detection of individual compounds. Quantification of the elements requires calibration for each element by using high-purity 'micro-analytical standard' compounds such as acetanilide and benzoic acid.

Method: Samples are weighed in tin capsules. The amount of sample required is in the range of 0.09- 0.12 g and after taking the sample in the capsule, it has to be wrapped and introduced into the auto sampler. The sample enclosed in the capsule falls into the reactor chamber (temperature >900 °C), where excess oxygen is introduced which facilitates the sample combustion.

ICP OES: The PerkinElmer Avio® 200 ICP-OES instrument is used to analysis the heavy metals in the bio-solids and composts. PerkinElmer NIST® traceable quality control standards for ICP were used as the stock standards for preparing working standards. For the heavy metal analysis acid digestion (HNO_3) of dried sludge/ co-compost samples was carried out in a microwave digester (Milestone, USA) and filtered samples were further analysed in ICP-OES.

Helminth eggs: Merlien Reddy, (2013), Standard Methods for the recovery and enumeration of Helminthes ova in wastewater, sludge, compost and urine-diversion waste in South Africa. Standard Operation Procedures, University of KwaZulu-Natal.

Faecal coliform: USEPA, Method 1680, 2014; USDA, MLG Appendix 2.05, 2014

E coli: APHA 9221 B, 9221 F, 20th Ed., 1998; USDA, MLG Appendix 2.05, 2014

Results

Multiple parameters were analysed in this study (*see Annexure 3*). The results obtained for some highly significant parameters have been discussed and represented here:

pH

The average pH of the biosolid collected from the FSTPs was analyzed, which ranging from 5.0 to 8.4. The Fertilizer Control Order (FCO) 2009 suggested the pH should be in the range of 6.5 to 7.5. Low pH values were observed in the Odisha FSTPs and the dried sludge collected from Cuttack showed the lowest pH (5.0). PNP and Bongir locations sludge showed higher pH scale.

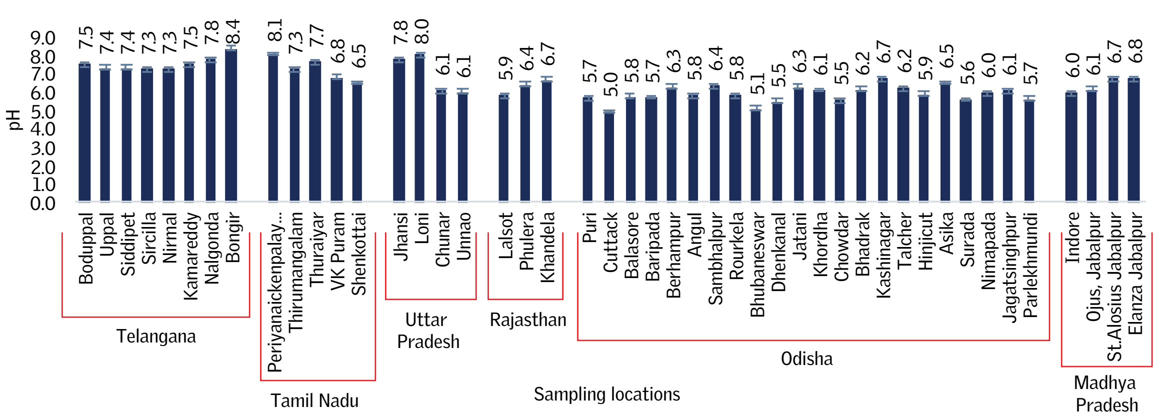
Electrical conductivity (EC)

The electrical conductivity of biosolid is shown in Graph 2. The EC for the sludge ranges from 0.35 dS/m to 5.06 dS/m. As per FCO standard recommendation, the EC value should be less than 4dS/m for biosolids. However, Thuraiyur, Rourkela, Paralakhemundi, and Uppal FSTP biosolid showed high EC values than the standard which could be mostly due to the elevated level of sodium or other salts found in the biosolid.

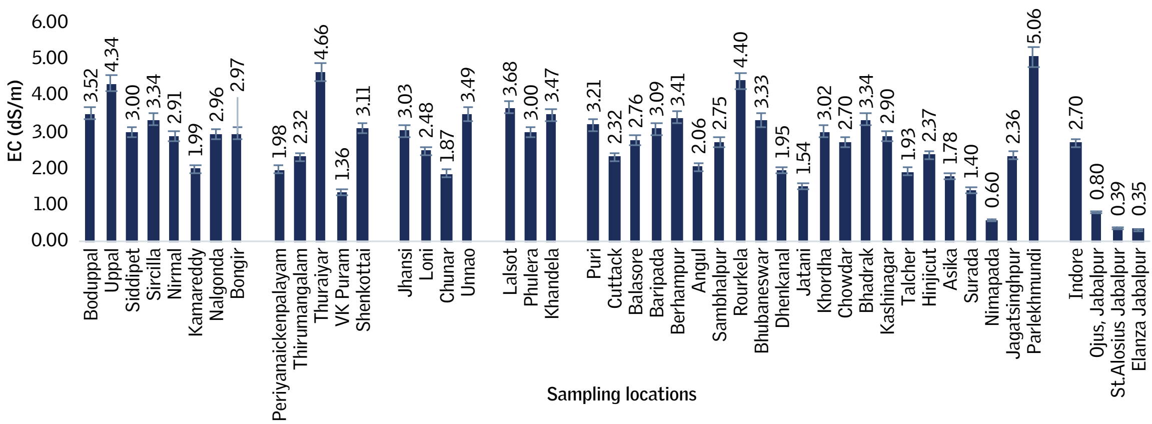
Moisture content

The moisture in FS can be as high as 99 per cent (wet basis) and drying can reduce moisture to below 5 per cent. Drying FS at a temperature r80°C stabilises the material and also inactivates pathogens. Drying process concentrates the energy

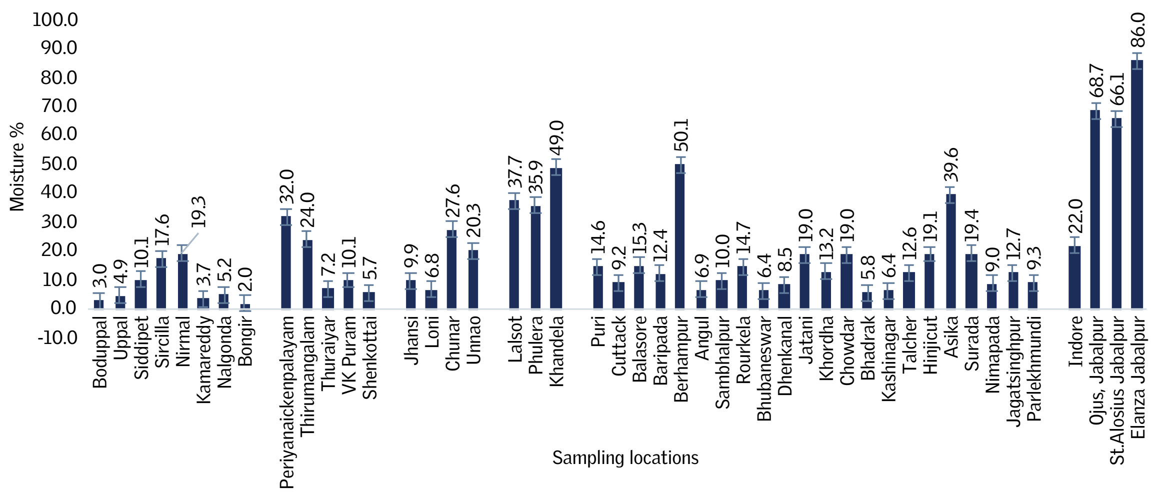
Graph 1: pH of the biosolids collected



Graph 2: EC of the biosolids collected



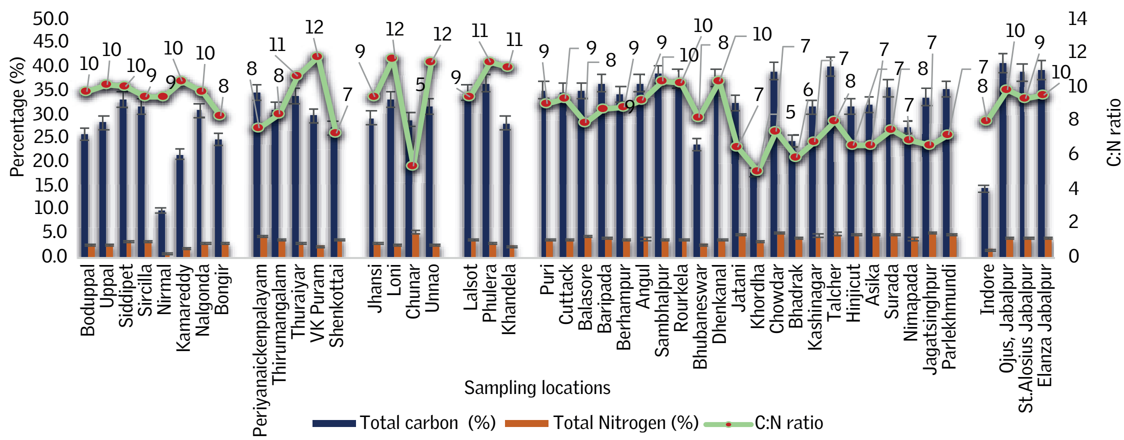
Graph 3: Moisture content of the biosolids collected



in the sludge by removing water and increasing the calorific value, consequently transforming the sludge into an acceptable combustible material.

The moisture content of the dried biosolid collected from the FSTPs is between 2.0 to 85.9 per cent. On average, the biosolid collected from Telangana state showed comparatively less moisture content (<20%) than other states whereas Rajasthan and Madhya Pradesh showed high moisture content (>35%). The highest moisture content was observed for the biosolid collected from Jabalpur and the lowest from Bongir. Sludge of ~10% or less moisture content is stabilized, easily conveyed, and generally suitable for end use as a soil conditioner, or processing by thermochemical methods such as incineration, pyrolysis, or gasification.

Graph 4: Carbon and nitrogen content (C/N ratio) of the biosolids collected



Carbon-nitrogen content (C/N ratio)

Any type of organic waste with a sufficient carbon-to-nitrogen ratio can be degraded through composting. Organic matter of biosolid is one of the key component for successful usage as an organic amendment. It has an important role in the soil such as increasing the stability of the formed aggregate, reducing the bulk density, and upholding better infiltrations of water. In addition, organic matter positively influences the storage and yield of nutrients, activity, and diversity of soil biota.

The total carbon content of the biosolids ranges from 9.9 per cent to 40.9 per cent and the total nitrogen content is in the range of 1.1 per cent to 5.4 per cent. The C/N ratio of the collected biosolids is within the range of 5:1 to 12:1. An ideal C/N ratio for composting process and maturation of organic material, would be between 20:1 and 30:1. So in the composting process, there is a need to increase the carbon concentration of biosolid by adding organic waste containing more carbon such as bark, dried leaves, paper, etc. Additionally, a lower C/N ratio increases the leaching and consequently loss of nitrogen and volatilization of ammonia resulting in a foul smell.

Heavy metal analysis

The application of sewage sludge or biosolids on soils has been widespread in agricultural areas. However, depending on characteristics, biosolids may cause an increase in the heavy metal concentration of agricultural soils. Generally, domestic biosolids have lower heavy metal contents than industrial sludge. The range of heavy metal concentrations found in the dried biosolids from the FSTPs varied depending on the locations and is represented in the Table 3.

Table 3: Heavy metal concentration in the biosolids collected from the different FSTPs in India

		Heavy metals (mg/Kg)							
Sl No	FSTP Locations	Hg (0.15 mg/ Kg)max	As (10.001 mg/Kg)max	Cd(5.0 mg/Kg) max	Cr (0.15 mg/ Kg)max	Cu (300 mg/ Kg)max	Ni(50 mg/Kg) max	Pb (100 mg/Kg) max	Zn(1000 mg/Kg) max
	Telangana								
1	Boduppal	1.38	0.38	3.06	845.77	197.10	25.15	51.18	3607.33
2	Uppal	0.83	0.36	3.32	974.90	213.90	32.90	43.34	5658.67
3	Siddipet	1.94	0.30	2.48	39.35	211.10	25.88	25.95	1037.50
4	Sircilla	1.76	0.31	2.72	25.21	196.83	18.81	26.25	897.10
5	Nirmal	0.84	0.99	4.45	79.60	547.05	52.82	68.15	2316.50
6	Kamareddy	1.30	0.29	1.75	26.75	164.21	18.37	36.98	808.80
7	Nalgonda	0.49	0.04	0.59	12.61	47.66	7.56	9.09	192.73
8	Bongir	0.99	0.21	1.75	524.10	114.50	12.96	24.36	3737.00
	Tamil Nadu								
9	Periyanaickenpalayam	0.29	0.10	0.67	30.65	105.90	17.20	12.78	336.70
10	Thirumangalam	1.13	1.62	1.89	29.86	169.43	19.71	28.43	760.70
11	Thuraiyar	1.04	0.11	2.64	33.92	160.15	21.16	33.14	902.50
12	VK Puram	5.85	2.33	4.81	48.03	214.14	34.57	37.69	944.93
13	Shenkottai	3.06	0.91	3.07	36.22	144.20	25.96	23.97	561.30
	Uttar Pradesh								
14	Jhansi	1.67	0.19	5.02	74.26	386.60	40.23	104.90	2891.00
15	Loni	4.48	0.02	5.44	39.01	119.70	25.45	31.12	659.40
16	Chunar	0.80	4.67	2.72	29.25	280.80	20.26	98.53	1231.00
20	Unnao	NA	NA	NA	NA	NA	NA	NA	NA
	Rajasthan								
17	Lalsot	NA	NA	NA	NA	NA	NA	NA	NA
18	Phulera	NA	NA	NA	NA	NA	NA	NA	NA
19	Khandela	NA	NA	NA	NA	NA	NA	NA	NA
	Odisha								
21	Puri	NA	NA	NA	NA	NA	NA	NA	NA
22	Cuttack	NA	NA	NA	NA	NA	NA	NA	NA
23	Balasore	NA	NA	NA	NA	NA	NA	NA	NA
24	Baripada	NA	NA	NA	NA	NA	NA	NA	NA
25	Berhampur	NA	NA	NA	NA	NA	NA	NA	NA
26	Angul	NA	NA	NA	NA	NA	NA	NA	NA
27	Sambhalpur	NA	NA	NA	NA	NA	NA	NA	NA
28	Rourkela	NA	NA	NA	NA	NA	NA	NA	NA
29	Bhubaneswar	NA	NA	NA	NA	NA	NA	NA	NA
30	Dhenkanal	NA	NA	NA	NA	NA	NA	NA	NA
31	Jatani	2.04	2.13	3.55	54.04	315.97	50.72	71.20	1268.97
32	Khordha	2.34	0.91	2.71	73.38	209.56	37.23	39.56	984.60
33	Chowdar	1.41	1.05	3.81	378.67	411.40	59.22	34.86	1969.00
34	Bhadrak	1.32	1.34	2.83	77.49	236.60	42.16	20.24	1131.00
35	Kashinagar	0.56	1.68	3.90	40.77	347.60	37.97	31.67	1508.67
36	Talcher	1.15	1.39	3.93	45.32	393.75	43.82	41.27	1849.50
37	Hinjicut	0.49	2.13	2.44	144.59	264.23	31.66	43.96	1109.77
38	Asika	1.49	1.22	3.36	136.49	300.93	38.26	49.19	1114.03
39	Surada	1.32	1.15	2.87	124.78	406.57	41.45	32.31	1442.27
40	Nimapada	1.68	1.15	2.38	51.21	231.90	34.31	20.43	1115.90
41	Jagatsinghpur	1.37	0.95	3.24	45.43	312.53	38.37	30.13	1546.67
42	Parlekhmundi	3.33	1.11	3.97	44.85	377.23	41.24	33.47	1748.33
	Madhya Pradesh								
43	Indore	0.25	2.42	3.61	443.35	410.05	68.82	49.91	1409.00
44	Ojus, Jabalpur	0.02	0.37	0.12	10.42	23.99	8.32	5.20	60.90
45	St.Alosius Jabalpur	0.00	0.41	0.11	10.89	23.06	8.25	4.61	75.19
46	Elanza Jabalpur	0.00	0.04	0.14	10.78	25.38	8.05	4.93	48.64
	Mean	1.46	1.01	2.79	141.94	236.38	30.90	36.52	1403.92
	Max	5.85	4.67	5.44	974.90	547.05	68.82	104.90	5658.67
	Min	0.00	0.02	0.11	10.42	23.06	7.56	4.61	48.64
								NA- Not analysed	

Mercury was observed to be higher than the standard limit for all the FSTP sites. This may be due to contaminated water, unusual disposal of paints, domestic waste inputs in toilets, groundwater infiltration, and stormwater drainage. Chromium and zinc were found to be higher than the standard in some of the FSTPs as given in Table 3. All other heavy metals were found to be within the standard range.

Microbial (indicator pathogens) analysis in dried biosolids

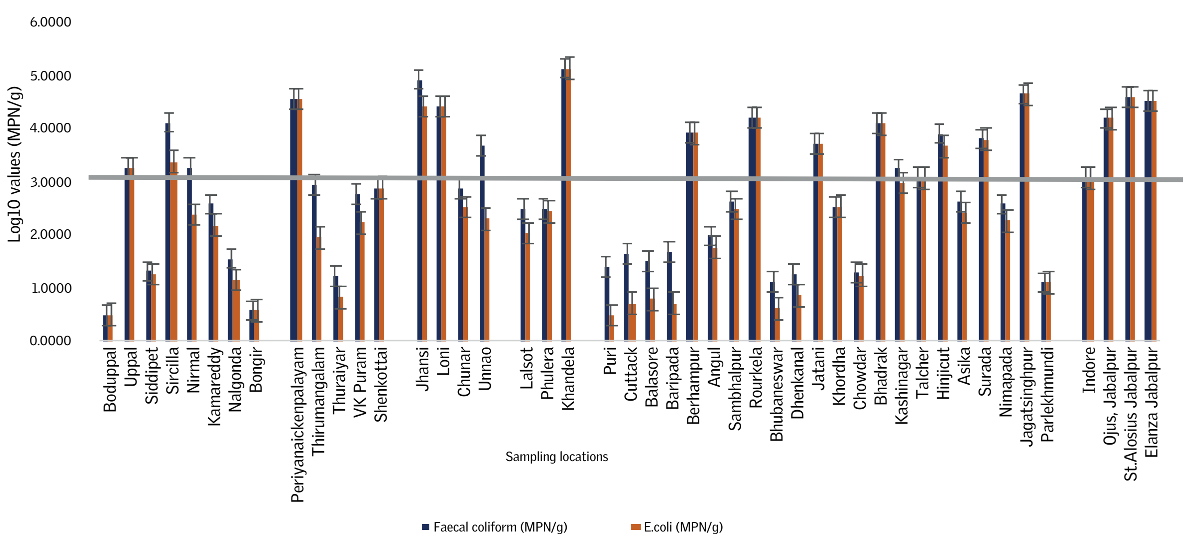
To assess the microbial safety of biosolids, we examined the inactivation of microbial indicators for potential bacterial and Helminth pathogens. Indicator microorganisms are used as a simple and reliable measure of the potential risk to human health.

Faecal coliform and *E coli*

The presence of faecal coliform and *E coli* in the biosolids varied in the evaluated FSTP locations. In two locations in Telangana — Uppal and Sircilla; one location in Tamil Nadu (PNP); two sites in Uttar Pradesh (Jhansi and Loni); one in Rajasthan (Khandela); seven locations in Odisha (Berhampur Rourkela, Jatani, Bhadrak, Hinjilicut, Surada, and Jagatsinghpur); and all the four locations in Madhya Pradesh, the microbial count is higher and above the standard limit recommended by USEPA/WHO for biosolids (<1000 MPN/g).

In the present study, mostly the microbial count and the moisture content of the biosolids are observed to be directly correlated. To reduce the risk of biological

Graph 5: Faecal coliform and E coli in the biosolids



contamination, various processes with variable degrees of pathogen reduction can be implemented according to sludge disposal and reuse option. Composting is the easiest procedure as stable humus can be produced under aerobic thermophilic conditions for more than 30 days at 55-65°C.

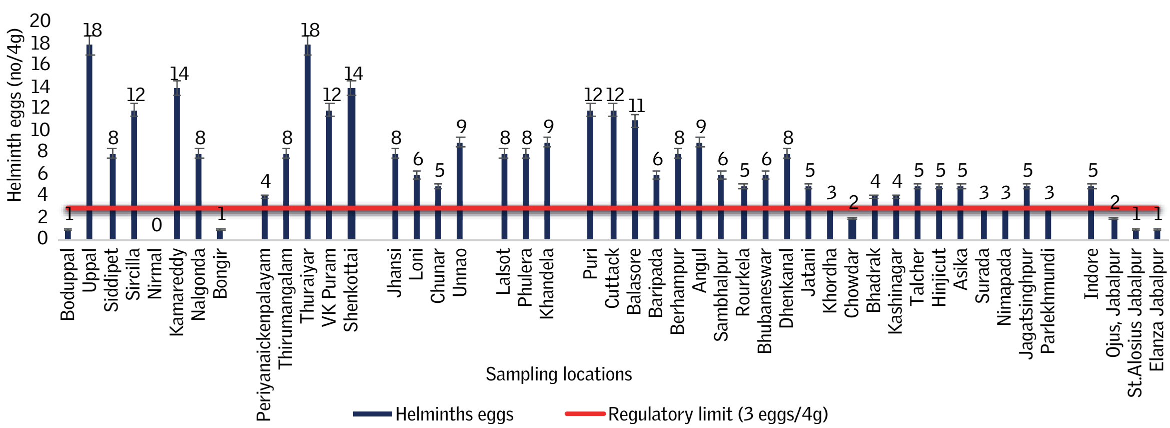
Helminth eggs

The concentration of helminth ova in raw septage (1 L) and sludge (4 gm dry weight) can be as high as 10^3-10^4 depending upon the rate of infection in the community. Due to the high settling velocity of helminth ova, their concentration in sludge should be higher than in wastewater. Helminth eggs were detected in most of the dried biosolid samples from FSTPs and represented in the fig 6 which is above the regulatory limit of USEPA/WHO limit for biosolids (3 eggs/4g of dry weight). Helminth eggs are resistant to many of the post-treatment methods to remove pathogens like UV, IR radiation or even in sunlight.

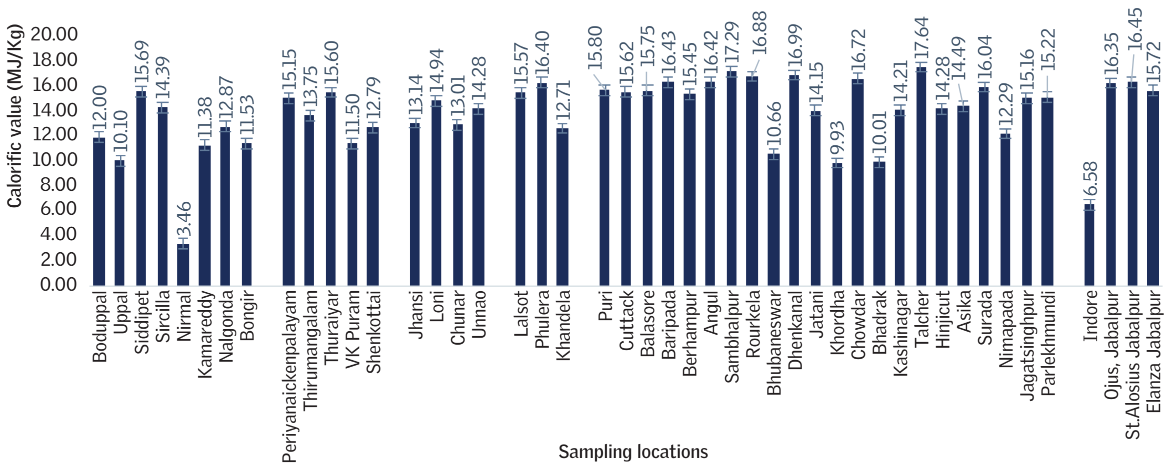
Calorific value (energy potential)

Fully dried biosolid has a calorific value comparable to that of lignite and can help substitute primary energy sources such as gas, oil, and coal. The dry substance-based calorific value of sludge depends, among other factors, on the degree of stabilization. The calorific value of the biosolids ranged from 3.5 -17.6 MJ/Kg with an overall mean value of 14 MJ/kg. The lower value in Nirmal FSTP sludge is due to the pretreatment of the biosolids, where the sludge is heated up to 500-600°C, which removed organic constituents thus reducing calorific value. The presence of non-combustible materials like sand is also a reason for less calorific values in some samples. The calorific value is an indication of the extent of digestion of the sludge under treatment. More digested sludge showed a less calorific value.

Graph 6: Helminth eggs content of the biosolids



Graph 7: Calorific value of the biosolids



Characterisation of biosolids (dry sludge) from STP co-treatment system

Multiple parameters were analysed and presented (see Annexure 1, Table 3). The result obtained for some highly significant parameters is discussed and represented as follows:

pH

The average pH of the biosolid collected from the STP co-treatment systems was analyzed, and the pH is ranging from 5.2 to 8.7. The higher pH value was

Graph 8: pH of dry sludge from STPs

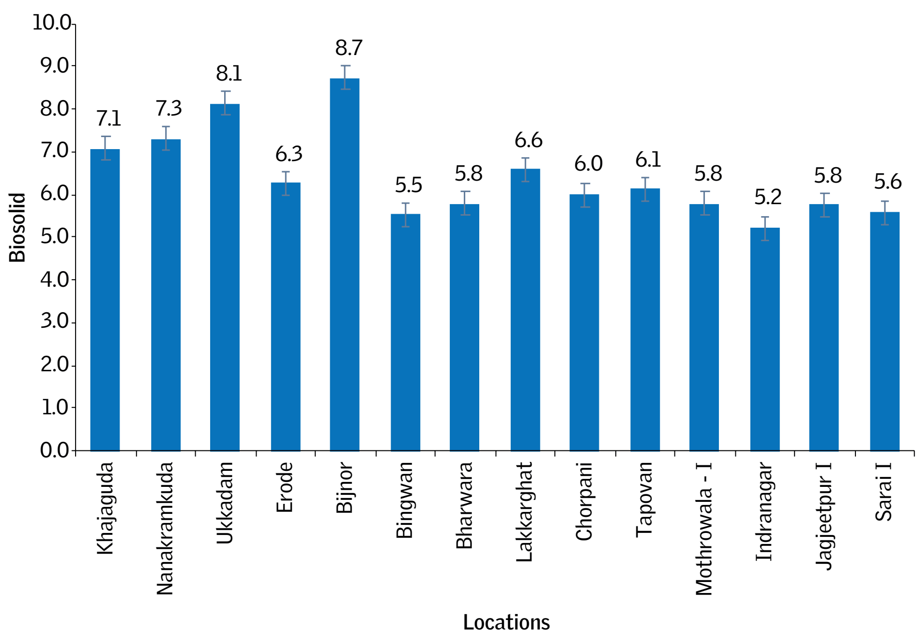


Table 4: Samples collected from respective STP co-treatment locations

STP location	Capacity	Technology	Technology for solid-liquid separation process	Treatment process	Reuse practice
Khajaguda	7 MLD	MBBR	Centrifugal separation of solids	No treatment	No reuse practice
Nanakramguda	4.5 MLD	MBBR	Centrifugal separation of solids	No treatment	No reuse practice
Ukkadam, Coimbatore	70 MLD	SBR	Screening, grit chamber	No treatment	No reuse practice
Erode	50 MLD	MBBR	Grit chamber	No treatment	No reuse practice
Bijnor	24MLD (20KLD FST)	UASB	Sludge drying bed	Sun drying	No reuse practice
Bharwara, Lucknow	345 MLD	UASB	Filter press and finally to the sludge drying bed	No treatment	No reuse practice
Bingawan, Kanpur	210 MLD	UASB	Filter press and finally to the sludge drying bed	No treatment	No reuse practice
Lakkarghat, Rishikesh	26 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Chorpani, Rishikesh	5 MLD	MBBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Tapovan, Rishikesh	3.5 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Mothrowala-I, Dehradun	20 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Indira Nagar, Dehradun	5 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Jagjeetpur, Haridwar	68 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice
Sarai, Haridwar	18 MLD	SBR	Centrifugation of sediment to separate solid sludge	No treatment	No reuse practice

observed in the Bijnor STP and the dried sludge collected from Indiranagar STP in Uttarakhand showed the lowest pH (5.2).

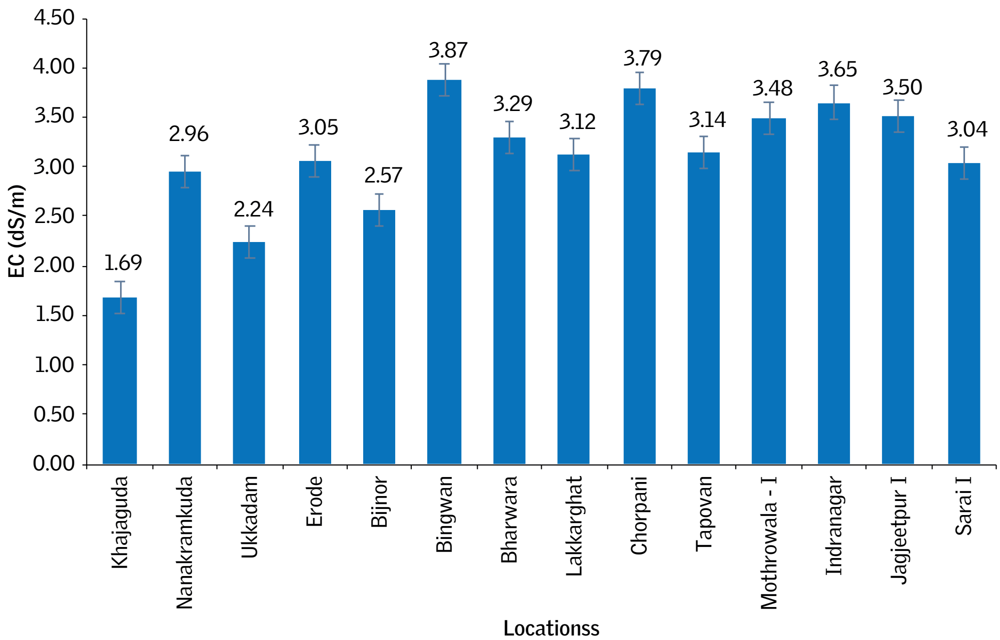
Electrical conductivity

The electrical conductivity of the biosolid is shown in Graph 9. The EC for all the STP co-treated sludge is above 1.0 and ranges from 1.69dS/m to 3.87dS/m, which is higher than the soil EC, whereas for non-saline soil, the EC value is less than one.

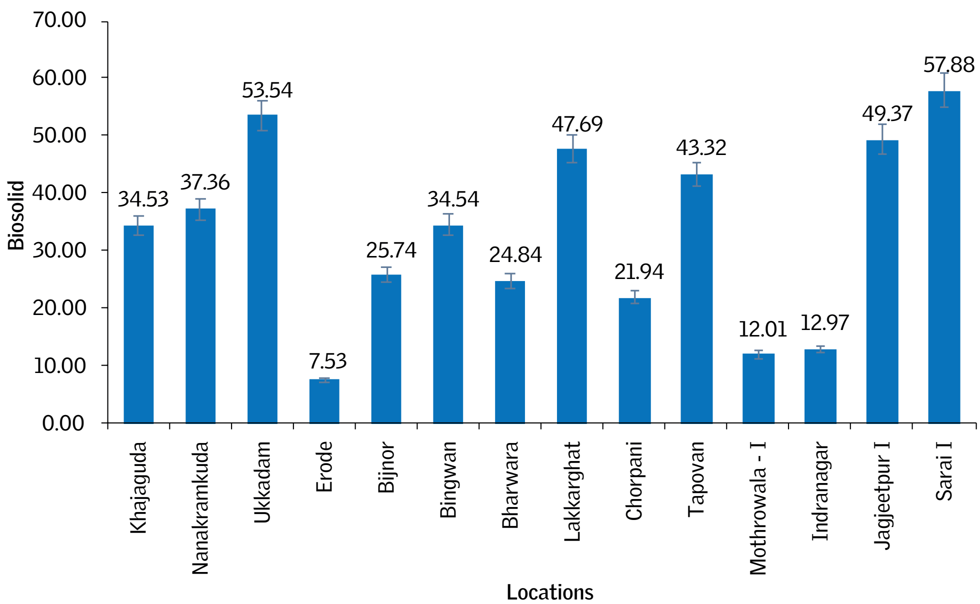
Moisture content

The average moisture content of the biosolid dumped in the STP ranged between 7.5 to 57.8 per cent. The biosolid collected from Erode STP showed less moisture content (7.5 per cent), while the Sarai-I STP sludge showed high moisture content (57.8 per cent). In STPs, there are no dedicated sludge drying facilities like those that are in place in FSTPs.

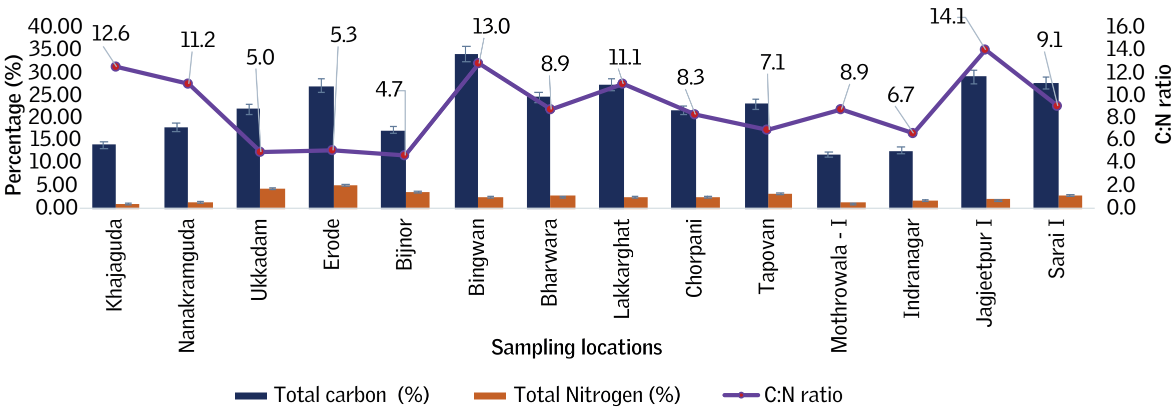
Graph 9: Electrical conductivity of the biosolid from STPs



Graph 10: Moisture content of dry sludge from STPs



Graph 11: Carbon-nitrogen content



C/N ratio

The total carbon content ranges from 12 to 34.5 per cent and the total nitrogen is 1.1 to 5.2 per cent. The sludge's organic matter is the key component for successful usage as an organic amendment. The C/N ratio of the evaluated biosolid is within the range of 3.1 to 12.4. An ideal C/N ratio, for the maturity of the organic material, would be between 20 and 30. A lower C/N ratio increases leaching and consequently loss of nitrogen and volatilization of ammonia. The STP sludge is mainly used for landfill application.

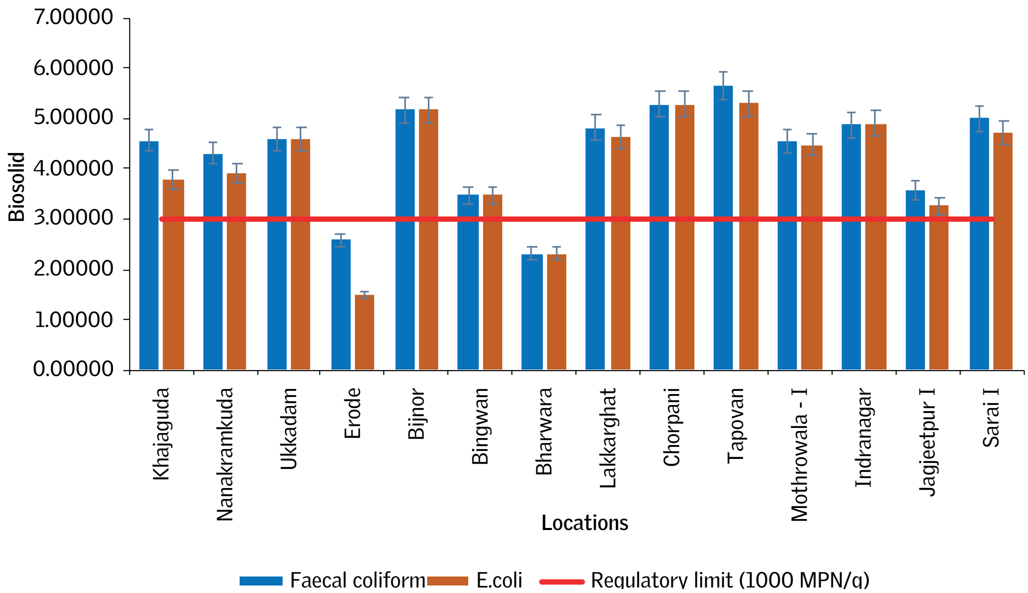
Heavy metals

The range of heavy metal concentrations found in the biosolid from the STPs varied depending on the locations (*see Table 5*).

Table 5: Heavy metal concentration in biosolids collected from STP co-treatment sites

	Heavy metals (mg/Kg)							
Locations	Hg (mg/kg) max 0.15	As (mg/kg) max. 10.001	Cd (mg/kg) max. 5	Cr (mg/kg) max. 50	Cu (mg/kg) max. 300	Ni (mg/kg) max. 50	Pb (mg/kg) max. 100	Zn (mg/kg) max. 1000
Khajaguda	1.43	0.19	1.37	44.86	63.35	21.86	49.10	223.20
Nanakramguda	0.49	0.34	2.74	51.29	106.10	31.29	100.73	507.85
Ukkadam	1.25	2.10	15.45	129.58	1052.45	51.91	49.35	611.85
Erode	2.72	3.50	2.29	113.20	254.00	102.00	45.81	604.60
Bijnor	2.20	0.13	7.07	51.63	156.70	32.66	40.11	867.60

Graph 12: Faecal coliform and E coli in dry sludge from STPs



Faecal coliform and E coli

The faecal coliform and *E.coli* in the dried sludge varied in the evaluated STP locations. All except in two locations namely, Erode and Bharwara STPs, the microbial count of the dried sludge is higher and above the standard limit recommended by USEPA/WHO for biosolids (<1000MPN/g). To overcome the risk of biological contamination, various processes with variable degrees of pathogen reduction can be implemented according to sludge disposal and reuse.

Composting is the easiest procedure as stable humus can be produced by maintaining aerobic thermophilic conditions for more than 30 days at 55-65 °C. Most of the STPs are employing landfilling only rather than treating it efficiently by compost or biochar process. Moreover, some STPs are giving the dried sludge to farmers to use directly in agricultural fields.

Current practices of resource recovery from faecal sludge-based biosolids in India

Periyanaickenpalayam (PNP) FSTP co-compost

The PNP FSTP site is producing 300-400 kg of sludge daily that is collected by a screw press dewatering machine. The collected sludge is dried and used for a co-composting process by mixing it with municipal solid waste that consists mostly of vegetable waste. Windrow composting method has been employed that takes 45-

60 days total for the completion of the composting process. Windrow composting is an aerobic composting method in which series of composting platforms (windrows) are constructed on plain cement concrete with a slope of about 1 per cent to drain the excess water (leachate).

Composting process starts by mixing the biosolid and vegetable waste followed by filling and arranging it into the piles of windrows. After that, the outer layers of windrow piles are moved to inner layers by turning the windrows once in every week for five weeks to ensure proper aeration. A turning should occur based on the rate of decomposition, moisture content, porosity of material and composting time. Each windrow stays on the compost platform for 35 days. After that, the compost is ready for sieving.

PNP FSTP: Composting sites and the finished produce

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

Sircilla FSTP co-compost

Co-composting is the process of controlled aerobic degradation of organic matter with more than one feedstock (faecal sludge and organic waste). Sircilla adopted co-composting technology to manage faecal sludge. Around one tonne of dried sludge is obtained every three days if the daily sludge received is equivalent to one-two trucks of 3 L capacity. Windrow composting method is adopted for the preparation of co-compost. Municipal organic solid waste (vegetable waste) and dried sludge mixed in the ratio of 3:2 is placed in windrows and turned at frequent intervals to ensure proper supply of oxygen. It takes approximately 30-45 days to obtain final co-compost. Further, it is stored in sludge storage room until usage.

Sircilla: The composting site...

...and the finished product

Warangal FSTP co-compost

Warangal FSTP receives faecal sludge on every five days in a week and the source of faecal sludge mainly being community toilets, household toilet, hospital sludge and public toilet. Every day, a maximum of three trucks with a capacity of 3 KL discharges faecal sludge in the FSTP site. The sludge separated from the dewatering

Open composting sites in Warangal

unit is conveyed to the pyrolysis unit for the preparation of biochar as well as to the composting unit. For the preparation of co-compost, the sludge and garden waste is arranged in layers and kept in piles for few days

Warangal FSTP biochar

Another approach is to thermo-chemically convert faecal sludge by various technologies such as gasification, combustion, hydrothermal carbonization and pyrolysis and use the transformed product for various applications like carbon sequestration, adsorbent for water, wastewater treatment and soil amendment. Among the mentioned technologies, pyrolysis has been the most adopted strategy for converting faecal sludge to biochar.

Pyrolysis is the process whereby a carbon-rich feedstock is heated in an oxygen deficit environment at temperatures in the range of 350-800°C. As the process involves high temperatures, a complete reduction of microbes occurs making the final product (biochar) free from pathogens. Pyrolyzing feedstock with high water content reduces the energy efficiency. Hence, to improve the energy efficiency, it is advisable to co-treat the faecal sludge with other organic materials like rice husk, leaves, sawdust etc. By co-pyrolysis method, the mobility of heavy metals can be greatly reduced.

Pyrolysis process for biochar production

Biochar production for FS management and reuse has been demonstrated at scale and is now being adopted by an increasing number of municipalities in India. For preparing biochar, the sludge separated from the dewatering unit is mixed with wood pellets for 40 mins in a mechanical drier, after which it is conveyed to pyrolysis unit. The dried sludge is thermo-chemically converted to biochar in the pyrolysis unit. The temperature maintained in the pyrolysis unit ranges from 500-800°C.

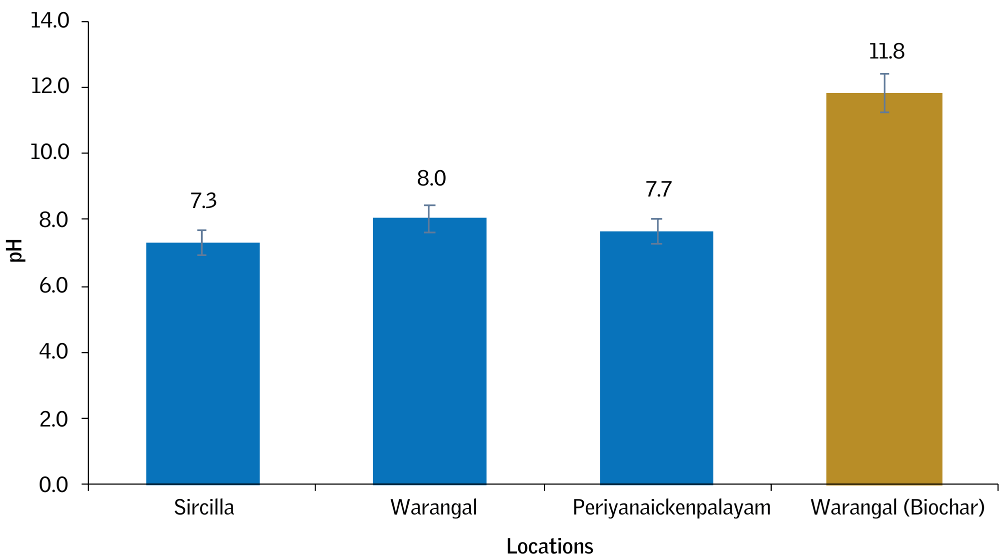
The potential benefits of pyrolyzing faecal waste with a limited oxygen supply are 1) it destroys all pathogens present in human waste; 2) provides fast volume and mass reduction; 3) provides a net energy output (heat and electricity); and 4) a usable end product — biochar, which is an excellent soil enricher when used with compost.

Characterisation of co-compost and biochar

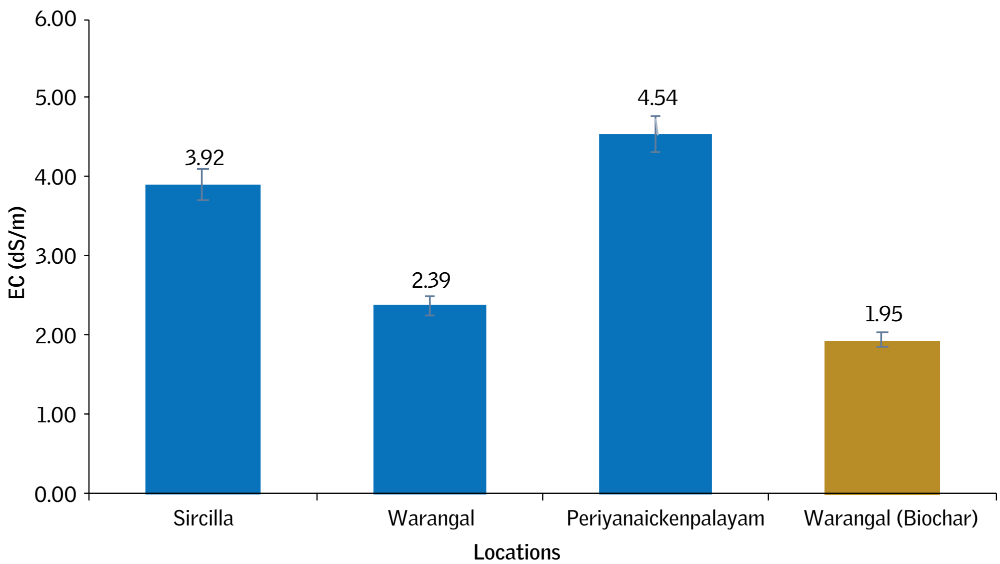
pH

The average pH of the co-compost collected from three FSTPs — Sircilla, Warangal and PNP — is 7.3, 8.0, and 7.7, respectively. The Fertilizer Control Order (FCO) 2009 suggested the pH should be in the range of 6.5 to 7.5. The average pH of biochar from Warangal is very high (11.8). It is reported that the pyrolysis process will increase the pH of the product and this highly alkaline biochar is suitable for acidic soil.

Graph 13: pH of the co-compost and biochar



Graph 14: EC of the co-compost and biochar



Electrical conductivity

The average electrical conductivity of the co-compost collected from the respective locations is shown in Graph 14. The EC of Sircilla, Warangal and PNP co-compost is above 2.0 and is 3.92dS/m, 2.39dS/m, and 4.54dS/m, respectively. The biochar showed 1.95 dS/m, which is higher than the soil EC, whereas, for non-saline soil, the EC value is less than one.

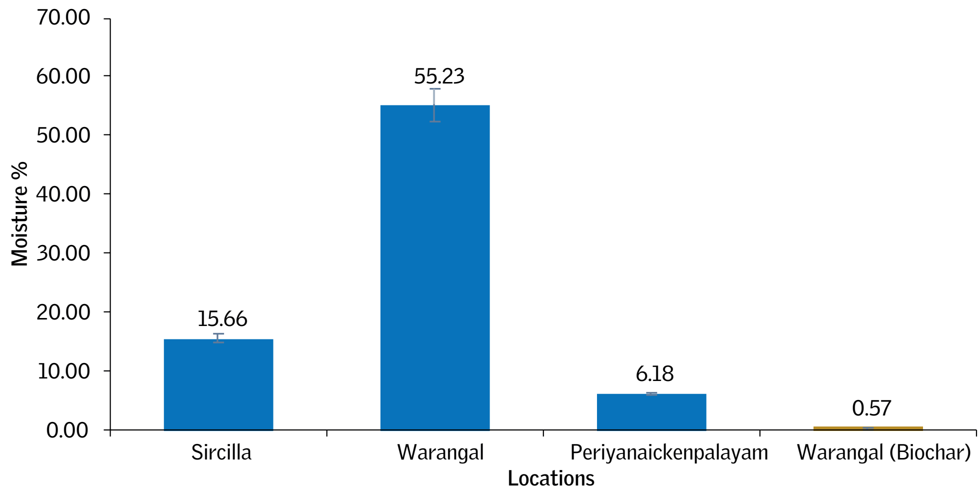
Moisture content

The average moisture content of the co-compost from the FSTP sites showed varying levels. The Sircilla compost contains 15.6 per cent moisture, whereas in PNP it is 6.1 per cent. The compost from the Warangal plant is very high in moisture (55 per cent) — here, the composting is done in an open space which increases the moisture content due to rain and other environmental factors. The biochar contains a negligible amount of moisture (0.57 per cent), because the process (pyrolysis) goes through very high temperatures.

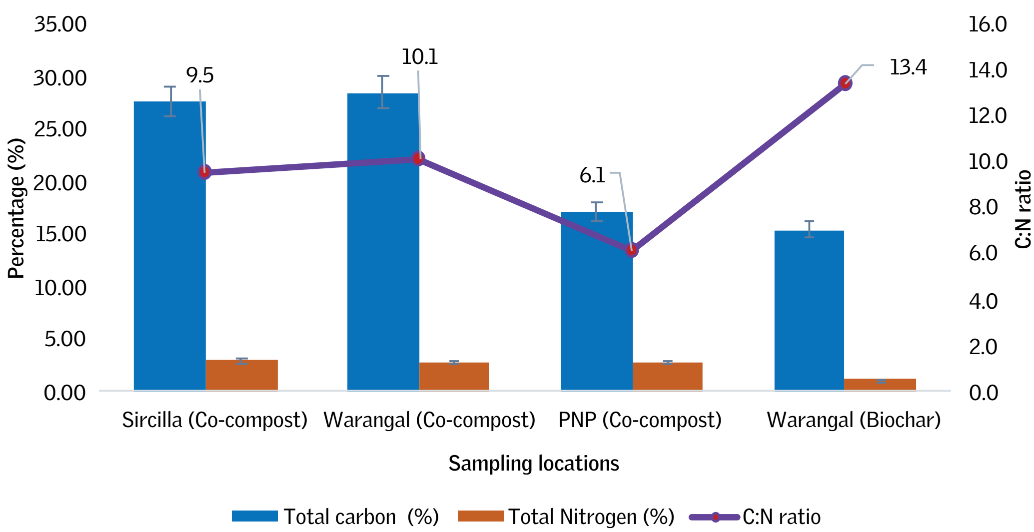
Carbon-nitrogen content

Composting is one of several methods for treating biosolids to create a marketable end product that is easy to handle, store, and use. The end product is usually a Class A, humus-like material without detectable levels of pathogens that can be applied as a soil conditioner and fertilizer to gardens, food and feed crops, and range lands. The obtained mean values of organic matter (carbon) were 16 per cent in Sircilla,

Graph 15: Moisture content of the co-compost and biochar

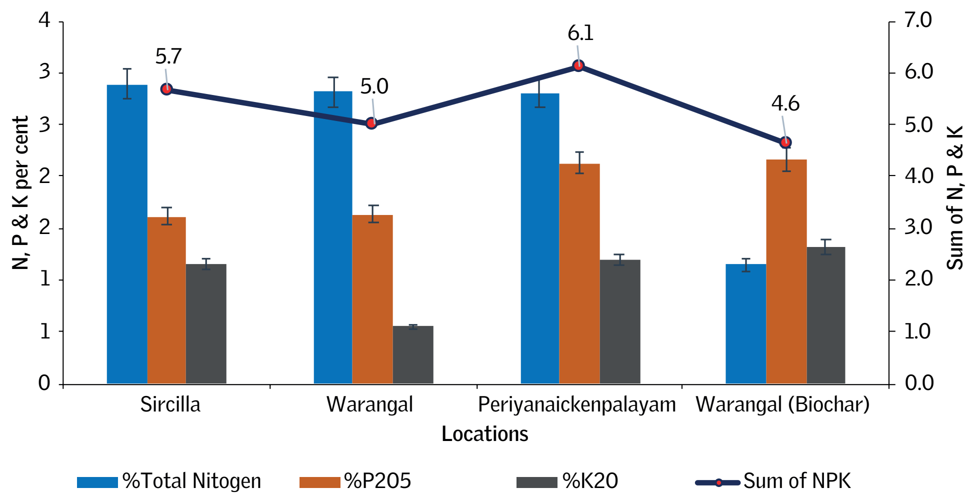


Graph 16: Carbon-nitrogen content



16.5 per cent in Warangal and 10 per cent in PNP compost. The biochar has less carbon content than the co-compost which is 8.9 per cent. The organic matter of the sludge is the key component to use successfully as organic amendment. The C/N ratio of the co-compost from Sircilla, Warangal and PNP is 5.7, 6.1 and 5.7, respectively whereas biochar C/N ratio is 7.9. The Fertilizer (Control) Order (FCO 2013) also suggested C/N ratio should be below 20. A lower C/N ratio increases leaching and results in nitrogen loss and ammonia volatilization.

Graph 17: NPK values of co-compost and biochar



NPK values

The NPK value indicates the amount of nitrogen, phosphorus and potassium in the compost or fertilizer. These three essential macronutrients are needed by all plants. The NPK value of the soil and fertilizer helps to determine the right amount of nutrients required for plants. There should be appropriate balance in the consumption of different fertilizer nutrients. The appropriate NPK ratio for fertilizer under Indian soil conditions is stated to be 4:2:1. The NPK ratio of the co-compost was observed to be approximately close (3:2:1) to the given standard ratio. However, NPK ratio of biochar was found to be 1:2:1 that is due to reduction in the amount of nitrogen during pyrolysis process. The sum of NPK values for the co-compost and biochar is considerably high which is well above the recommended value by FCO where it is stated that the sum of NPK should not be less than 1.5.

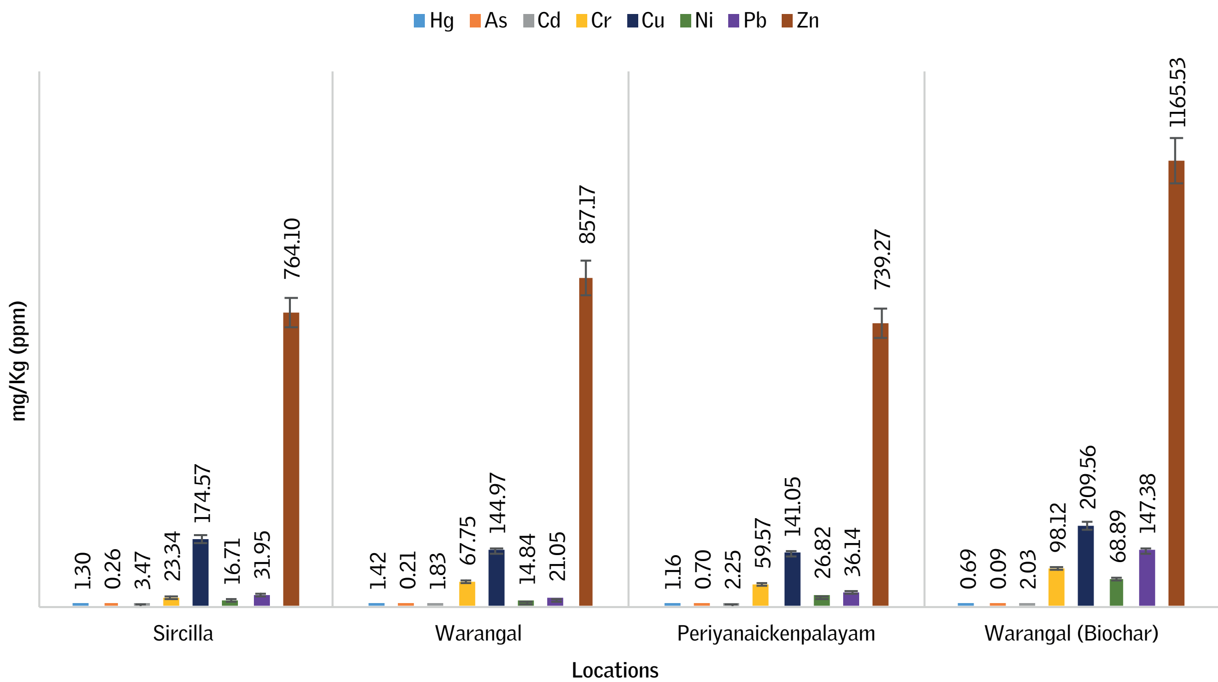
Heavy metals

Heavy metals occur naturally in places but are widely distributed through mining, manufacturing, and energy production. Mercury, copper, cadmium, chromium, lead, nickel, arsenic, zinc and tin are all toxic heavy metals that bio-accumulate because they cannot be easily or efficiently eliminated from the body. The heavy metal concentration of the co-compost and biochar is represented in the table no. 1 and fig. h the highest mercury concentration (1.42 mg kg-1 Hg) has revealed that the strong binding of mercury species to the biosolids organic matter and the low solubility of the mercury compounds present, result in low bioavailability and mobility of this toxic metal.

Table 6: Heavy metal concentration in co-compost and biochar collected from the FSTPs

	Heavy metals (mg/Kg)							
Locations	Hg (mg/kg) max 0.15	As (mg/kg) max. 10.001	Cd (mg/kg) max. 5	Cr (mg/kg) max. 50	Cu (mg/kg) max. 300	Ni (mg/kg) max. 50	Pb (mg/kg) max. 100	Zn (mg/kg) max. 1000
Sircilla (compost)	1.30	0.26	3.47	23.34	174.57	16.71	31.95	764.10
Warangal (compost)	1.42	0.21	1.83	67.75	144.97	14.84	21.05	857.17
Periyanaickenpalayam	1.16	0.70	2.25	59.57	141.05	26.82	36.14	739.27
Warangal (Biochar)	0.69	0.09	2.03	98.12	209.56	68.89	147.38	1165.53

Graph 18: Heavy metals in the co-compost and biochar

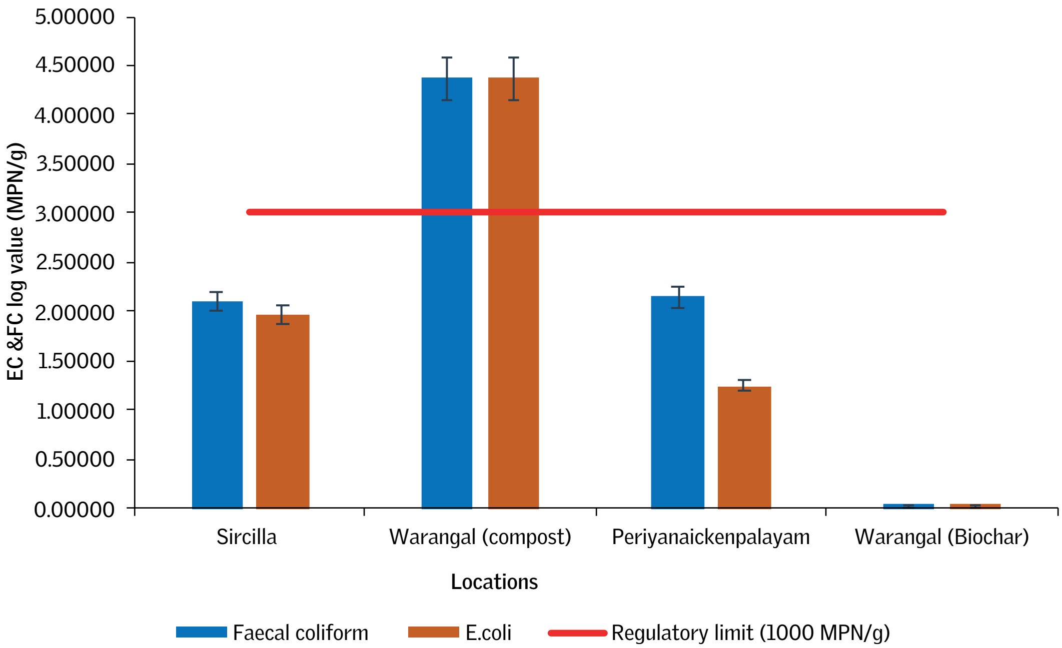


Microbial analysis in compost and biochar

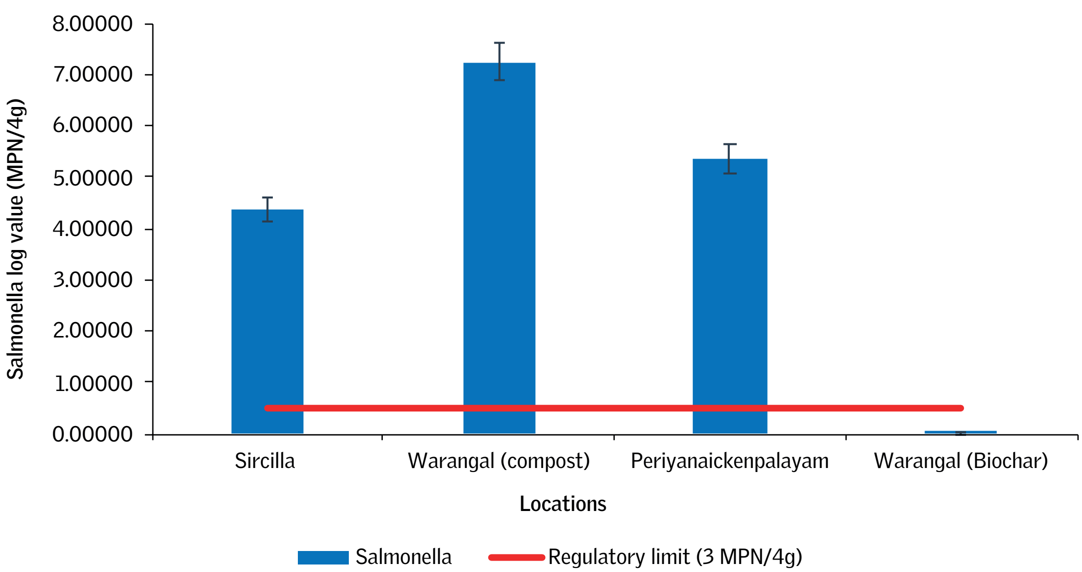
To overcome the risk of biological contamination correlated with sludge disposal and reuse, various processes with variable degrees of pathogen reduction can be implemented. The faecal coliform and *E.coli* in the co-compost from Warangal showed a high bacterial load. This is because no proper drying method was adopted to control the high moisture in the compost. In both Sircilla and PNP compost, the microbial count is lower than the standard limit recommended by USEPA/WHO for bio-solids (<1000MPN/g). According to FCO 2009, the recommendation is very stringent and the compost should be free from pathogens.

Composting is the easiest procedure as stable humus can be produced under aerobic thermophilic conditions for more than 30 days at 55-65°C. Biosolid (faecal sludge) can be converted into biochar and is also a good alternative to remove all types of pathogens, but it requires more technical intervention. The biochar from Warangal was found to be free from all types of microorganisms as the pyrolysis process occurs at high temperatures.

Graph 19: Faecal coliform and E coli load in co-compost and biochar



Graph 20: Salmonella load in co-compost and biochar



Like faecal coliform and *E.coli*, *Salmonella* spp. is also commonly present in the faecal sludge. All the compost samples contain *Salmonella* spp. (more detailed study is required to identify whether the *Salmonella* bacteria are typhoidal or non-typhoidal strains) in significant numbers whereas biochar is free from any kind of microbes. The standard limit of *Salmonella* in compost and bio-solids is very less which is 3MPN/4g by WHO/USEPA.

Helminths analysis

No Helminths eggs were observed in the co-compost and biochar.

SUMMARY OF THE FINDINGS

- 47 FSTPs and 14 co-treatment plants were visited three times to collect samples for analysis.
- A total of 64 samples were analysed to check the chemical and biological quality of the by-product from the FSTPs and STP co-treatment systems.
- Among the 64 samples, 46 biosolid samples from FSTPs, 14 biosolid samples from STPs, three co-compost samples from FSTPs and one biochar from FSTP were subjected to quality analysis.
- The pH of the FSTP biosolid ranges from 5.0 to 8.4 and the STP biosolid ranges from 5.2 to 8.7.
- The electrical conductivity of the biosolid collected from FSTPs and STPs ranges from 0.36 dS/m to 5.1 dS/m and 1.69 dS/m to 3.87 dS/m, respectively.
- The carbon content of the FSTP-derived biosolid ranges from 9.9 to 40.1 per cent, whereas the C/N ratio is within the range of 5:1 to 12:1.
- The total carbon of the STP co-treated biosolid ranges from 8.2 per cent to 31.41 per cent, whereas the C/N ratio is within the range of 3.1 to 12.4.
- The heavy metal (Hg, Cr, Zn) concentration in biosolid (FSTP and STP) is a little higher than the permissible limit set by The Fertilizer (Control) Order (FCO, 2009), which may be due to the accumulation of metals in the sludge.
- Out of 46 biosolid samples derived from FSTPs, 17 samples showed high faecal coliform and E coli count, which is above the standard limit recommended by USEPA/WHO for bio-solids (<1000MPN/g).
- Most of the FSTP biosolids showed the presence of Helminth eggs above the regulatory limit recommended by USEPA/WHO for biosolids (<3 eggs/4g of dry weight).
- Out of 14 co-treated biosolid samples derived from STPs, 12 samples showed high faecal coliform and E.coli count, which is above the standard limit recommended by USEPA/WHO for biosolids (<1000MPN/g).
- Out of 46 FSTP sites and 14 STP co-treatment sites evaluated in this study, only three FSTP locations have adopted technologies for resource recovery from dry faecal sludge.
- Periyanaickenpalayam (PNP) in Tamil Nadu, Sircilla and Warangal in Telangana produce co-compost by using dried faecal sludge and municipal solid waste. Warangal FSTP also produces biochar from faecal sludge using a process called pyrolysis.
- The average pH of the Sircilla, Warangal, and PNP co-compost is 7.3, 8.0, and 7.7, respectively.
- The average pH of biochar from Warangal is very high at 11.8, which is a good soil conditioner for acidic soils.
- The moisture content of the Sircilla compost is 15.6 per cent, whereas in PNP it is 6.1 per cent. The moisture content in compost from Warangal is 55 per cent due to the open space composting.
- The biochar contains a negligible amount of moisture (0.57 per cent) because the process (pyrolysis) goes through very high temperature.
- The C/N ratio of the co-compost from Sircilla, Warangal, and PNP is 10:1, 10:1, and 6:1, respectively whereas the biochar C/N ratio is 13:1. The Fertilizer (Control) Order (FCO 2013) suggested C/N ratio should be below 20:1 and all samples found to be under the limit.
- The sum of NPK values for the co-compost and biochar is considerably high (>4.6) which is well above the recommended value by FCO where it is stated that the sum of NPK should not be less than 1.5.
- Heavy metals are in varying levels in the samples and are a little higher than the permissible limit set by the Fertilizer (Control) Order (FCO, 2009 & 2013)
- The faecal coliform and E coli in the co-compost from Warangal showed a high bacterial load. This is because no proper drying method was adopted to control the high moisture in the compost
- In Sircilla and PNP compost, the microbial count is lower than the standard limit recommended by USEPA/WHO for biosolids (<1000MPN/g).
- All the compost samples contain Salmonella spp. The standard limit of Salmonella in compost and biosolids is very less — 3MPN/4g (WHO/USEPA).
- The biochar from Warangal was found to be free from all types of microorganisms as the pyrolysis process occurs at high temperature.
- No Helminths eggs were observed in the co-compost and biochar.

Recommendations (O&M guidelines)

Composting seems to be an efficient technology as a resource recovery option from biosolids, as it reduces the microbial load. However, the usage of compost obtained from biosolids should be done with caution and restriction till there is a certainty of this method being completely free from pathogens.

Biochar is also another resourceful option as it completely inactivates the pathogens and other microbes present in the sludge. Biochar can be used as a soil amendment as it increases the water-holding capacity of the soil, particularly acidic soil. However, the initial capital investment for the pyrolysis unit is high which can be compensated if energy is recovered during biochar production.

The sludge drying bed is often covered with opaque metal sheets that inhibit the penetration of sunlight. Hence, polycarbonate/polyethylene translucent roofing panels can be used. Another option is to use sliding roofs which have dual benefits as they can be adjusted according to the requirement in rainy or sunny weather.

Mostly, the microbial count and the moisture content of biosolids are observed to be directly proportional as more moisture promotes microbial growth. Therefore, sludge should be harvested from the drying beds only after proper drying has been achieved. For that, there should be alternatively scheduled filling and harvesting of faecal sludge from drying beds.

To reduce the microbial load in the biosolid, it is advisable to shred the biosolid cake into small particle sizes or powder it and then keep it under sunlight or treat it with other techniques like IR radiation.

A well-concreted platform for sludge drying is necessary to ensure proper drying conditions. A clean storage room is required for storing the dried sludge. This is particularly important during the rainy season.

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Annexures

ANNEXURE 1

Table 1: Compost Quality Standards as per Solid Waste Management Rules, 2016; Fertilizer Control Order, 2009; and Fertilizer Control Order, 2013

S. no.	Parameter	Organic compost FCO* 2009	Phosphate-rich organic manure FCO (PROM) 2013
1	Arsenic (mg/kg)	10.001	10
2	Cadmium (mg/kg)	5	5
3	Chromium (mg/kg)	50	50
4	Copper (mg/kg)	300	300
5	Lead (mg/kg)	100	100
6	Mercury (mg/kg)	0.15	0.15
7	Nickel (mg/kg)	50	50
8	Zinc (mg/kg)	1,000	1000
9	C/N ratio	<20	Less than 20:1
10	pH	6.5–7.5	(1:5 solution) maximum 6.7
11	Moisture, % by weight, maximum	15.0–25.0	25.0
12	Bulk density (g/cm^3)	<1.0	Less than 1.6
13	Total organic carbon, % by weight, minimum	12.0	7.9
14	Total nitrogen (N), % by weight, minimum	0.8	0.4
15	Total phosphate (P_2O_5), % by weight, minimum	0.4	10.4
16	Total potassium (K_2O), % by weight, minimum	0.4	–
17	Colour	Dark brown to black	–
18	Odour	Absence of foul odour	–
19	Particle size	Minimum 90% material should pass through 4.0 mm IS sieve	Minimum 90% material should pass through 4.0 mm IS sieve
20.	Conductivity (as dsm-1), not more than	4.0	8.2

Note: * FCO: Fertilizer Control Order; Tolerance limits as per FCO: Compost: The sum of nitrogen, phosphorus and potassium nutrients shall not be less than 1.5 per cent in compost. For PROM: No such directive

Table 2: United States Environmental Protection Agency (USEPA). A plain English guide to the EPA part 503 biosolids rule Washington: EPA Office of Wastewater Management, 1994

Pollutant Limits

Pollutant	Ceiling Concentration Limits for All Biosolids Applied to Land (milligrams per kilogram)[a]	Pollutant Concentration Limits for EQ and PC Biosolids (milligrams per kilogram)[a]	Cumulative Pollutant Loading Rate Limits for CPLR Biosolids (kilograms per hectare)	Annual Pollutant Loading Rate Limits for APLR Biosolids (kilograms per hectare per 365-day period)
Arsenic	75	41	41	2.0
Cadmium	85	39	39	1.9
Chromium	3,000	1,200	3,000	150
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum[b]	75	—	—	—
Nickel	420	420	420	21
Selenium	100	36	100	5.0
Zinc	7,500	2,800	2,800	140
Applies to:	All biosolids that are land applied	Bulk biosolids and bagged biosolids[c]	Bulk biosolids	Bagged biosolids[c]
From Part 503	Table 1, Section 503.13	Table 3, Section 503.13	Table 2, Section 503.13	Table 4, Section 503.13

[a] Dry-weight basis

[b] As a result of the February 25, 1994, Amendment to the rule, the limits for molybdenum were deleted from the Part 503 rule pending EPA reconsideration.

[c] Bagged biosolids are sold or given away in a bag or other container.

Table 3. Consolidated data of the physicochemical and biological parameters of the collected FSTP biosolids

FSTP Locations																						
								Heavy metals (mg/Kg)														
Sl No	FSTP Locations	pH	EC (dS/m)	Moisture %	Total carbon (%)	Total Nitogen (%)	C:N ratio	Sulfur (%)	Hg	As	Cd	Cr	Cu	Ni	Pb	Zn	Total Phos-phate (as P_2O_5) %	Total Potash (as K_2O) %	Faecal coliform (MPN/g)	*E.coli* (MPN/g)	Salmonella (CFU/4g)	Helminths (no/4g)	Calorific values (MJ/Kg)
	Telangana																					
1	Boduppal	7.5	3.52	3.0	25.9	2.7	10	1.33	1.38	0.38	3.06	845.77	197.10	25.15	51.18	3607.3	2.19	0.65	3	3	1334	1.0	12.00
2	Uppal	7.4	4.34	4.9	28.4	2.8	10	1.78	0.83	0.36	3.32	974.90	213.90	32.90	43.34	5658.7	1.72	0.54	1788	1788	11101	18.0	10.10
3	Siddipet	7.4	3.00	10.1	33.2	3.3	10	1.43	1.94	0.30	2.48	39.35	211.10	25.88	25.95	1037.5	2.53	0.64	20	18	18297	8.0	15.69
4	Sircilla	7.3	3.34	17.6	31.7	3.4	9	1.35	1.76	0.31	2.72	25.21	196.83	18.81	26.25	897.1	1.60	0.71	12892	2312	65937	12.0	14.39
5	Nirmal	7.3	2.91	19.3	9.9	1.1	9	1.54	0.84	0.99	4.45	79.60	547.05	52.82	68.15	2316.5	3.29	1.17	1817	237	291	0.0	3.46
6	Kamareddy	7.5	1.99	3.7	21.6	2.1	10	0.82	1.30	0.29	1.75	26.75	164.21	18.37	36.98	808.8	2.44	1.20	374	148	6045	14.0	11.38
7	Nalgonda	7.8	2.96	5.2	30.9	3.2	10	1.44	0.49	0.04	0.59	12.61	47.66	7.56	9.09	192.7	0.68	0.33	35	14	632	8.0	12.87
8	Bongir	8.4	2.97	2.0	25.0	3.0	8	1.61	0.99	0.21	1.75	524.10	114.50	12.96	24.36	3737.0	0.97	0.41	4	4	1	1.0	11.53
	Tamil Nadu																					
9	Periyanaickenpalayam	8.1	1.98	32.0	34.70	4.5	8	2.14	0.29	0.10	0.67	30.65	105.90	17.20	12.78	336.7	0.64	0.27	35296	35296	1482429415	4.0	15.15
10	Thirumangalam	7.3	2.32	24.0	31.20	3.7	8	1.12	1.13	1.62	1.89	29.86	169.43	19.71	28.43	760.7	2.20	0.62	844	88	111490	8.0	13.75
11	Thuraiyar	7.7	4.66	7.2	34.05	3.2	11	1.62	1.04	0.11	2.64	33.92	160.15	21.16	33.14	902.5	2.46	0.62	16	7	195937	18.0	15.60
12	VK Puram	6.8	1.36	10.1	29.80	2.5	12	0.69	5.85	2.33	4.81	48.03	214.14	34.57	37.69	944.9	2.37	0.85	582	167	4548804	12.0	11.50
13	Shenkottai	6.5	3.11	5.7	27.30	3.7	7	1.28	3.06	0.91	3.07	36.22	144.20	25.96	23.97	561.3	1.57	0.97	746	746	466991	14.0	12.79
	Uttar Pradesh																					
14	Jhansi	7.8	3.03	9.9	29.30	3.11	9	0.78	1.67	0.19	5.02	74.26	386.60	40.23	104.90	2891.0	1.75	0.56	83205	25516	10641	8.0	13.14
15	Loni	8.0	2.48	6.8	33.30	2.85	12	1.28	4.48	0.02	5.44	39.01	119.70	25.45	31.12	659.4	1.60	0.71	25753	25753	1029	6.0	14.94
16	Chunar	6.1	1.87	27.6	29.00	5.42	5	0.98	0.80	4.67	2.72	29.25	280.80	20.26	98.53	1231.0	1.84	0.41	717	329	21009	5.0	13.01

FSTP Locations																						
									Heavy metals (mg/Kg)													
Sl No	**FSTP Locations**	pH	EC (dS/m)	Moisture %	Total carbon (%)	Total Nitogen (%)	C:N ratio	Sulfur (%)	Hg	As	Cd	Cr	Cu	Ni	Pb	Zn	Total Phos-phate (as P_2O_5) %	Total Potash (as K_2O) %	Faecal coliform (MPN/g)	*E.coli* (MPN/g)	Salmonella (CFU/4g)	Helminths (no/4g)	Calorific values (MJ/ Kg)
20	Unnao	6.1	3.49	20.3	31.83	2.8	12	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	4719	195	NA	9.0	14.28
Rajasthan																						
17	Lalsot	5.9	3.68	37.7	34.71	3.69	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	296	106	NA	8.0	15.57
18	Phulera	6.4	3.00	35.9	36.55	3.19	11	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	296	272	NA	8.0	16.40
19	Khandela	6.7	3.47	49.0	28.34	2.53	11	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	135407	135407	NA	9.0	12.71
Odisha																						
21	Puri	5.7	3.21	14.6	35.22	3.9	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	25	3	NA	12.0	15.80
22	Cuttack	5.0	2.32	9.2	34.81	3.7	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	43	5	NA	12.0	15.62
23	Balasore	5.8	2.76	15.3	35.10	4.4	8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	32	6	NA	11.0	15.75
24	Baripada	5.7	3.09	12.4	36.62	4.2	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	46	5	NA	6.0	16.43
25	Berhampur	6.3	3.41	50.1	34.44	3.9	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	8170	8116	NA	8.0	15.45
26	Angul	5.8	2.06	6.9	36.61	4.0	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	94	56	NA	9.0	16.42
27	Sambhalpur	6.4	2.75	10.0	38.53	3.7	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	413	301	NA	6.0	17.29
28	Rourkela	5.8	4.40	14.7	37.63	3.7	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	15692	15685	NA	5.0	16.88
29	Bhubaneswar	5.1	3.33	6.4	23.77	2.9	8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	13	4	NA	6.0	10.66
30	Dhenkanal	5.5	1.95	8.5	37.88	3.63	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	18	7	NA	8.00	16.99
31	Jatani	6.3	1.54	19.0	32.47	4.96	7	1.09	2.04	2.13	3.55	54.04	315.97	50.72	71.20	1269.0	2.09	0.58	5126	5126	792733	5.00	14.15
32	Khordha	6.1	3.02	13.2	18.05	3.57	5	1.04	2.34	0.91	2.71	73.38	209.56	37.23	39.56	984.6	2.23	1.36	332	332	1411122	3.00	9.93
33	Chowdar	5.5	2.70	19.0	39.23	5.26	7	1.30	1.41	1.05	3.81	378.67	411.40	59.22	34.86	1969.0	2.44	0.56	19	17	126511	2.00	16.72

FSTP Locations																							
									Heavy metals (mg/Kg)														
Sl No	**FSTP Locations**	pH	EC (dS/m)	Moisture %	Total carbon (%)	Total Nitogen (%)	C:N ratio	Sulfur (%)	Hg	As	Cd	Cr	Cu	Ni	Pb	Zn	Total Phos-phate (as P_2O_5) %	Total Potash (as K_2O) %	Faecal coliform (MPN/g)	*E.coli* (MPN/g)	Salmonella (CFU/4g)	Helminths (no/4g)	Calorific values (MJ/Kg)
34	Bhadrak	6.2	3.34	5.8	24.43	4.15	6	0.88	1.32	1.34	2.83	77.49	236.60	42.16	20.24	1131.0	3.99	0.65	12185	12185	244352	4.00	10.01
35	Kashinagar	6.7	2.90	6.4	31.67	4.66	7	1.01	0.56	1.68	3.90	40.77	347.60	37.97	31.67	1508.7	3.43	0.93	1728	946	18319	4.00	14.21
36	Talcher	6.2	1.93	12.6	40.25	5.01	8	1.19	1.15	1.39	3.93	45.32	393.75	43.82	41.27	1849.5	3.64	0.55	1169	1169	98558	5.00	17.64
37	Hinjicut	5.9	2.37	19.1	31.83	4.78	7	1.04	0.49	2.13	2.44	144.59	264.23	31.66	43.96	1109.8	4.21	0.46	7917	4552	640079	5.00	14.28
38	Asika	6.5	1.78	39.6	32.30	4.92	7	1.10	1.49	1.22	3.36	136.49	300.93	38.26	49.19	1114.0	2.92	0.52	426	254	8349049	5.00	14.49
39	Surada	5.6	1.40	19.4	35.74	4.76	8	0.95	1.32	1.15	2.87	124.78	406.57	41.45	32.31	1442.3	3.31	0.75	6291	6124	6674201	3.00	16.04
40	Nimapada	6.0	0.60	9.0	27.40	3.97	7	0.67	1.68	1.15	2.38	51.21	231.90	34.31	20.43	1115.9	2.44	0.44	369	178	33234	3.00	12.29
41	Jagatsinghpur	6.1	2.36	12.7	33.80	5.14	7	0.99	1.37	0.95	3.24	45.43	312.53	38.37	30.13	1546.7	2.79	0.81	44039	43848	143596	5.00	15.16
42	Parlekhmundi	5.7	4.06	9.3	35.47	4.88	7	1.15	3.33	1.11	3.97	44.85	377.23	41.24	33.47	1748.3	4.52	0.72	12	12	11791	3.00	15.22
	Madhya Pradesh																						
43	Indore	6.0	2.70	22.0	14.67	1.83	8	0.36	0.25	2.42	3.61	443.35	410.05	68.82	49.91	1409.0	4.49	0.89	1171	1152	17457	5.00	6.58
44	Ojus, Jabalpur	6.1	0.80	68.7	40.90	4.13	10	0.48	0.02	0.37	0.12	10.42	23.99	8.32	5.20	60.9	0.44	0.08	15264	15264	12801711	2.00	16.35
45	St.Alosius Jabalpur	6.7	0.39	66.1	38.90	4.17	9	0.47	0.00	0.41	0.11	10.89	23.06	8.25	4.61	75.2	0.43	0.10	38522	38504	2912100	1.00	16.45
46	Elanza Jabalpur	6.8	0.35	86.0	39.50	4.13	10	0.45	0.00	0.04	0.14	10.78	25.38	8.05	4.93	48.6	0.43	0.10	32757	32757	3418115	1.00	15.72
	Mean	6.5	2.6	19.7	31.6	3.7	9	1.1	1.5	1.0	2.8	141.9	236.4	30.9	36.5	1403.9	2.3	0.6	10797.5	9022.0	476744339	6.7	13.97
	Median	6.3	2.8	12.9	32.8	3.7	9	1.1	1.3	0.9	2.9	45.4	214.0	32.3	32.7	1115.0	2.3	0.6	731.4	286.5	105024.2	6.0	14.72
	Max	8.40	4.66	85.96	40.9	5.4	12	2.1	5.9	4.7	5.4	974.9	547.1	68.8	104.9	5658.7	4.5	1.4	135407.0	135407.0	1482429415.4	18.0	17.64
	Min	4.96	0.35	1.99	9.9	1.1	5	0.36	0.00	0.02	0.1	10.4	23.1	7.6	4.6	48.6	0.4	0.1	3.1	3.0	1.0	0.0	3.46

Co-treatment Locations																					
Sl No	Co-treatment Laocations	pH	EC (dS/m)	Moisture %	Total carbon (%)	Total Nitogen (%)	C:N ratio	Sulfur (%)	Hg	As	Cd	Cr	Cu	Ni	Pb	Zn	Total Phos-phate (as P_2O_5) %	Total Potash (as K_2O) %	Faecal coliform (MPN/g)	*E.coli* (MPN/g)	Salmonella (CFU/4g)	Helminths eggs	Calorific values (MJ/Kg)
Telangana																						
1	Khajaguda	7.1	1.69	34.53	14.19	1.1	13	0.46	1.43	0.19	1.37	44.86	63.35	21.86	49.10	223.20	0.677	2.663	36699	6161	157584	1.0	NA
2	Nanakramguda	7.3	2.96	37.36	18.23	1.6	11	0.91	0.49	0.34	2.74	51.29	106.10	31.29	100.73	507.85	1.257	1.917	20235	8094	11772	1.0	NA
Tamil Nadu																						
3	Ukkadam	8.1	2.24	53.54	22.15	4.4	5	1.60	4.25	2.10	15.45	129.58	1052.45	51.91	49.35	611.85	1.867	1.306	39927	39927	291609766	1.0	NA
4	Erode	6.3	3.05	7.53	27.40	5.2	5	1.40	7.72	3.50	2.29	113.20	254.00	102.00	45.81	604.60	2.223	1.090	378	32	2621	0.0	NA
Uttar Pradesh																						
5	Bijnor	8.7	2.57	25.74	17.50	3.69	5	0.6	2.65	1.50	4.91	254.92	151.30	26.01	42.13	819.10	4.328	0.565	148137	148137	495586178	0.0	NA
6	Bingwan	5.5	3.9	3.87	34.54	2.66	13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3014	2964	NA	0.0	NA
7	Bharwara	5.8	3.3	3.29	24.84	2.80	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	208	208	NA	0.0	NA
Uttarakhand																						
8	Lakkarghat	6.6	3.1	3.12	27.69	2.50	11	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	65747	43377	NA	0.0	NA
9	Chorpani	6.0	3.8	3.79	21.94	2.63	8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	190488	189658	NA	0.0	NA
10	Tapovan	6.1	3.1	3.14	23.32	3.30	7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	445891	195506	NA	0.0	NA
11	Mothrowala - I	5.8	3.5	3.48	12.01	1.35	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	34145	30179	NA	0.0	NA
12	Indranagar	5.2	3.7	3.65	12.97	1.93	7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	73447	78252	NA	0.0	NA

Co-treatment Locations																					
Sl No	Co-treatment Laocations	pH	EC (dS/m)	Moisture %	Total carbon (%)	Total Nitogen (%)	C:N ratio	Sulfur (%)	Hg	As	Cd	Cr	Cu	Ni	Pb	Zn	Total Phos-phate (as P_2O_5) %	Total Potash (as K_2O) %	Faecal coliform (MPN/g)	*E.coli* (MPN/g)	Salmonella (CFU/4g)	Helminths eggs	Calorific values (MJ/Kg)
13	Jagjeetpur I	5.8	3.5	3.50	29.37	2.08	14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3725	1840	NA	0.0	NA
14	Sarai I	5.6	3.0	3.04	27.88	3.07	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	98259	53154	NA	0.0	NA
	Mean	6.4	3.1	13.5	22.4	2.7	9	1.0	3.3	1.5	5.4	118.8	325.4	46.6	57.4	553.3	2.1	1.5	82878.6	56963.5	157473584.0	0.2	
	Min	5.2	1.7	3.0	12.0	1.1	5	0.5	0.5	0.2	1.4	44.9	63.4	21.9	42.1	223.2	0.7	0.6	208.0	32.0	2621.0	0.0	
	Max	8.7	3.9	53.5	34.5	5.2	14	1.6	7.7	3.5	15.5	254.9	1052.5	102.0	100.7	819.1	4.3	2.7	445891.0	195506.0	4955861776	1.0	
	Resource recovery locations (Biochar and co-compost)																						
1	Warangal (Biochar)	11.8	1.95	0.57	15.39	1.1	13	0.83	0.69	0.0854	2.0	98.12	209.56	68.89	147.4	1165.5	2.16	1.32	1	**1.0**	**1.00**	**0.00**	**NA**
1	Sircilla (Co-compost)	7.3	3.92	15.66	27.59	2.9	10	0.96	1.30	0.2601	3.5	23.34	174.57	16.71	32.0	764.1	1.61	1.16	127.06383	91.4	22789.04	**0.00**	**NA**
2	Warangal (Co-compost)	8.0	2.39	55.23	28.51	2.8	10	1.53	1.42	0.2111	1.8	67.75	144.97	14.84	21.0	857.2	1.63	0.55	.9955	**23608.0**	**16777989.72**	**0.00**	**NA**
3	PNP (Co-compost)	7.7	4.54	6.18	17.17	2.8	6	0.78	1.16	0.7026	2.3	59.57	141.05	26.82	36.1	739.3	1.31	0.57	143.033497	17.8	228168.59	0.00	NA
	Mean	7.7	3.6	25.7	24.4	2.8	9	1.1	1.3	0.4	2.5	50.2	153.5	19.5	29.7	786.8	1.5	0.8	7959.4	7905.7	5676315.8	0.0	
	Min	7.3	2.4	6.2	17.2	2.8	6	0.8	1.2	0.2	1.8	23.3	141.1	14.8	21.0	739.3	1.3	0.5	127.1	17.8	22789.0	0.0	
	Max	8.0	4.5	55.2	28.5	2.9	10	1.5	1.4	0.7	3.5	67.8	174.6	26.8	36.1	857.2	1.6	1.2	23608.0	23608.0	16777989.7	0.0	

NA- Not analyzed

As described in Table (NA), some samples were not analyzed for heavy metals due to the non-availability of the instrument (ICP-OES) during the study period. Similarly, a few samples were not analyzed for Salmonella as this parameter was not taken into consideration during the study period. Also, the calorific value for all the sludge collected from co-treatment plants was not analyzed as these samples are not considered for resource recovery as fuel.

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