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Global best practices for sludge management relevant for the Indian context

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Sammendrag

Denne rapporten gir en oversikt over teknologier og systemer for slambehandling som brukes med gode erfaringer rundt om i verden i dag, samt forurensinger som kan forekomme i slam. Vi går også gjennom de mest brukte regulative rammeverkene for slamhåndtering, spesielt EUs slamdirektiv og den amerikanske standarden kjent som US EPA "Part 503 Rule". Hensikten med rapporten er å gi et kunnskapsgrunnlag for forbedringer av håndtering av slam (behandling og disponering) i det urbane India.

Summary

This report provides an overview over technologies and systems for sewage sludge management used successfully globally as well as contaminants – both well-known and emerging – which commonly occur in sludge. We present a couple of the most influential regulative frameworks for sludge management, in particular, the European Sludge directive and the US EPA "Part 503 Rule". The objective of the report is to provide knowledge for decision support for improving sludge management (treatment and disposal) in urban India.

GODKJENT /APPROVED	**PROSJEKTLEDER /PROJECT LEADER**
ØISTEIN VETHE	**OLA STEDJE HANSERUD**

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Preface

Urbanisation in India is accelerating, and the Indian government wants to prepare and implement a Ganga River Basin Management Plan to secure water quality of the Ganga river in the future. NIBIO signed a Memory of Understanding (MoU) with the Indian Institute of Technology (IIT), Kanpur, which hosts the government supported think-tank Centre for Ganga River Basin Management and Studies (cGanga) in order to produce an investigation report on sludge management from wastewater treatment plants in India to feed into this work. Financing was sought from Norwegian Agency and Development Cooperation (NORAD), which channelled the funds through the private company Cambi Group AS, and the Indian government.

In this Norwegian-Indian collaborative effort NIBIO has taken the responsibility of summarizing best practises of sludge management and present case studies from other countries, while cGanga will summarize the current sludge management practices and challenges within India. The outcomes of the research will be published separately as respectively a NIBIO and a cGanga report, although should be read jointly to give a comprehensive description of the challenge and possible solutions at hand for developing a sustainable wastewater and sludge management practise in the Ganga river basin.

Ås, Norway, 23.09.21

Ola Stedje Hanserud

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Executive summary

The objective of building sewage treatment plants (STPs) is to treat wastewater before discharging into water bodies in order to protect health and the environment. STPs generate mainly two products – treated wastewater to safely enter the environment and sludge originating from the treatment processes. Letting treated and safe water enter water bodies achieves thus only half of the objective; the other half will be achieved by proper treatment and disposal of sludge.

Sludge can be disposed of through (i) land application (mainly in agriculture - as fertilizer, soil amendment or conditioner), (ii) landfilling, (iii) incineration, and (iv) mixed into construction materials. The regulations for disposal adopted in a specific country and the sludge quality affect the end use. We specifically look into the US EPA rules (Part 503 Biosolids rule) and the European Union's Sludge Directive as two of the most influential regulative frameworks internationally.

Once it is generated, sewage sludge may be treated either at every STP – called decentralized sludge management – or it can be transported to and treated at a centralized sludge treatment centre receiving sludge from several STPs.

Among sludge treatment technologies, we briefly present selected methods that are particularly promising and/or commonly used in different steps of the sludge management chain, namely pre-treatment technologies, stabilization technologies (anaerobic digestion, composting, alkaline stabilization), and dewatering. Anaerobic digestion is a commonly used method for sludge stabilization worldwide. This process generates biogas (rich in methane) for possible energy recovery. The pre-treatment of sludge can increase biogas yields and reduce the volume of sludge to be disposed of.

A concern in the disposal of sludge is the presence of contaminants. We present both well-known and emerging contaminants found in sewage sludge. Heavy metals are among the well-known contaminants, whose concentration in sludge often determines its disposal options according to national rules. Among organic compounds, pharmaceuticals is a group that has gained increasing attention during the last decade. Levels of contaminants can vary greatly between and within countries, as the sludge quality is directly affected by connected industries as well as household practices for what ends up in the wastewater through the drains.

Lastly, we present a set of case-studies for how cities around the world have structured their sludge management given their unique context. The cities/regions presented more in depth are Durban (South Africa) and London (United Kingdom), while we also present Bogota (Colombia), North-West region of England, and Washington DC (US). The case-studies show how choices have been made regarding treatment technologies and sludge management structure and may serve as inspiration or references for the improvement and development of sludge management for Indian cities.

Definitions and abbreviations

Terms	**Meaning**
AD	Anaerobic digestion
AMP	Asset Management Plan
Biosolids	Treated sludge (dewatered, stabilized, and sanitized sludge). The same as Cake.
BPEO	Best practicable environmental option (BPEO)
Cake	Dewatered and treated sludge, same as biosolids
CAPEX	Capital costs
CHP	Combined heat and power
Class A Biosolid	Definition in regulation in USA and UK. Sludge that is hygienic, and pathogens, including viruses, are eliminate due to the treatment process. Class A may be used in areas with public access.
Class B Biosolid	Definition in regulation in USA and UK. The pathogens may exist after sludge treatment and there are time restrictions after application to land related to harvesting crops and turf, for grazing of animals, and public contact.
Co-digestion	Anaerobic treatment of a combination of different organic wastes to increase biogas yield. Example digest sludge and manure and food scrapes together
EPA or US EPA	Environmental Protection Agency (in USA)
GtG	Gas to Grid
LCA	Life Cycle Assessment is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.
OPEX	Operating costs
PAH	Polynuclear aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PFOA	Perfluorinated octanoic carboxylic acid
PFOS	Perfluorinated octane sulfonate
PFRP	Process to Further Reduce Pathogens. A term used by the US EPA
PSRP	Process to Significantly Reduce Pathogens. A term used by the US EPA

PTE	Potentially Toxic Element
Sludge Centre	A treatment plant treating sludge generated from different STPs and are transported to one central sludge treatment plant
SRT	Sludge retention time (theoretical) in the digester
STP	Sewage treatment plant, the same as a WWTP, wastewater treatment plant
THP	Thermal hydrolysis process
TPAD	Temperature-phased anaerobic digestion
UU	United Utilities, a company in UK
WAS	waste activated sludge, mix of primary and secondary sludge
WWTP	Wastewater treatment plant, same as sewage treatment plant, STP

1 Introduction

The true cost of untreated sewage for human health and the environment is being discovered all over the globe and is becoming worse with increasing urbanisation (Polprasert et al, 2015). India has insufficient systems for treatment of sewage and sewage sludge, and a large share of the households are not connected to a sewage system (Rath et al., 2020). The Indian government is now taking serious initiatives to improve the situation by pushing through new legislations and setting aside budget for new installations of sewage treatment plants (STPs)[1]. Along with sewage treatment, a suitable sludge treatment and sludge management system can recover valuable resources in the sewage.

In this report, sludge treatment technologies and sludge management practices are discussed with respect of what could be appropriate solutions for urban areas in India.

The main purpose of sludge treatment is to reduce sludge volumes and stabilize the sludge in order to reduce odour from storage and to sanitize the sludge. The treatment is done to obtain safe handling and easy management whether it is disposed of as waste, landfilled, burned, or used as a safe soil amendment and fertiliser product.

Choosing the right sludge treatment technology is to optimize the combined outcome of various effects, with potentially conflicting goals. One specific technology may be suitable for one goal, but not for another, whereas another technology may just have the opposite effect. Local conditions further complicate the issue. Choosing the most appropriate technology is hence a multidimensional optimization problem that depends on the local conditions. This report discusses the factors that ought to be considered in the selection of the technology. Following is a list of factors relevant for the Indian scenario:

Financial costs: In India, cost is one of the most important factors as the inhabitants must pay for the sewage treatment services either over the tax bill or as user fees. Costs include the cost of acquiring land for treatment facilities - land that is becoming increasingly scarce and expensive in and around rapidly growing cities, as well as the costs of building sewage systems and other wastewater infrastructure. So, minimizing capital costs (capex) and operating costs (opex) for sewage and sludge treatment is important. Some technologies will have higher capex but lower opex and vice versa. To evaluate overall treatment costs over time, converting capex and opex to annual costs over a certain time horizon (for example 15-30 years) can be done. Analysis of life cycle costing (LCC) is another method for cost evaluation.

Odour: Odour emission from untreated sludge (not stabilised) is durable and unpleasant, and any temporary storage of not stabilized sludge in urban areas, will inflict the well-being for people in surrounding neighbourhoods and for employees at the STP. Odour prevention, or -reduction, may therefore be critical for social acceptance of the chosen technologies.

Land requirement: See also Financial costs above. Some sludge treatment technologies require more land area than others, and where land is scarce this may be a decisive factor. Availability of land is also dealt with in Section 2.1 concerning centralized versus decentralized infrastructure.

Environmental impact: Sludge treatment technologies and disposal practices will have different emissions to air and water and thus affect. Emissions of green house gases (GHGs) contribute to climate change, and in some contexts this may be an important factor in designing sludge management systems, such as in the case of London (see Section 5.2.2). Untreated wastewater and improper sludge

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[1] Amongst other initiatives creating the National Mission for Clean Ganga Ministry (Namami Gange) within the Department Water Resources,River Development & Ganga Rejuvenation (Jal Shakti). Centre for Gange River Basin Management and Studies (cGanga) is a think tank at IIT Kanpur formed under the aegis of Namami Gange and is the research partner of NIBIO in this project.

management tend to negatively affect aquatic environments and biodiversity, e.g. a surplus of nutrients in the waterways often causes algal proliferation.

Health effects in water systems and land: Untreated wastewater discharged directly into waterways as well as leachates from improperly treated sludge spreads pathogens, heavy metals, and other contaminants, which may affect human health directly through the waterways as well as in the food chain if improperly applied in agriculture.

Energy use and production: Treating wastewater and sludge require energy, either through solar energy, fossil energy or bioenergy resulting in the process. The energy content of the sludge can further be recovered and even lead to a net surplus of energy in process.

Soils: Sewage sludge contains organic matter and nutrients like nitrogen and minerals like phosphorous that are necessary for plants to grow. Recirculating these into soils, either for agriculture or other land applications, will hence reproduce soils that is today a limited resource.

2 Regulations for land application of sludge

While the aims of regional, national, and over-national regulations for sludge end-use are similar (environmental protection, resource recovery and human health and safety), their approaches vary widely. This section discusses the similarities and differences between directives for regulating land application and surface disposal of biosolids specifically in the United States and European Union. The US rules, in particular, are exhaustive and often used as the standard for other national biosolids rules, albeit with adaptations to local conditions and needs. Other methods of disposal like incineration and landfilling are not included in this discussion.

Biosolids rules regulate some or all of the following, depending on the country: the concentration of potentially toxic elements (PTEs) (heavy metals and other non-organic pollutants) in biosolids and/or in the soil to which biosolids are applied; pathogens and pathogen reduction; vector (flies, rats) attraction reduction; the concentration of organic pollutants; permitted uses, types of land and other guidelines (i.e., quarantine before human or animal contact, distance to open water) for applying biosolids; and labelling. This list is not exhaustive and varies between countries and even between regions within countries. In the EU, for example, member states are free to set their own standards as long as they meet the minimum standards set by the EU. The same applies to individual states in the US.

One challenge with biosolids management that is not specifically addressed by the US and EU rules is odour control, other than being mentioned as something to be aware of. General air quality is regulated by other rules and are enforceable if it is proven that there are harmful or toxic gasses present. Otherwise, it is up to local authorities or private citizens to hold biosolids management companies accountable for controlling nuisance odours. As is quoted in the document *Biosolids and Residuals Management Fact Sheet: Odour Control in Biosolids Management*, "Biosolids odours may not pose a public health threat, but odours are killing public support for biosolids recycling programs" (U.S. EPA, 2000). In order for biosolids management projects to be publicly accepted and succeed, it is essential to include plans for odour management for all stages of biosolids treatment and application.

Ceiling concentration limits for PTEs for the USA and the EU vary, with the US in general allowing for higher concentrations (Table 1). Another difference is that the US divides biosolids into four quality classes for land application based on a combination of PTE concentration, method of pathogen reduction and method used for vector attraction reduction. Each of these quality classes comes with certain allowances and restrictions for type of distribution (i.e., in bulk for large-scale application vs. in bags for household use), application (i.e., agricultural land vs. park) and management post-application (i.e., length of time after application before harvesting crops). The EU has only one quality class of biosolid based on ceiling PTE concentrations, though individual member states can have additional quality classes. In addition, the US does not specify PTE concentration levels in the soil to which biosolids are applied, whereas the EU does. Below are more specific examples of how the respective governing bodies regulate land application of biosolids. Iranpour et al. (2004) presents a thorough comparison of regulations for biosolids land application in the US and EU.

2.1 US EPA Part 503 Biosolids Rule

Biosolids management in the United States falls under the jurisdiction of the Environmental Protection Agency's (EPA) Clean Water Act and is regulated by *The Standards for the Use or Disposal of Sewage Sludge,* also known as the US EPA "Part 503 Rule" (Title 40 of the Code of Federal Regulations, Part 503) (U.S. EPA, 1993). It was enacted in 1993 "to protect public health and the environment from any reasonably anticipated adverse effects of certain pollutants that might be present in sewage sludge biosolids." Part 503 establishes requirements for the final use or disposal of biosolids when they are applied to land as a soil conditioner or fertilizer, placed on a surface disposal site for final disposal, or incinerated.

The 503 Rule applies three categories of indicators to determine sludge quality (in descending order of importance) and therefore how and where it can be applied: 1) the concentrations of PTE's in the biosolids; 2) method of pathogen reduction; and 3) method of vector attraction reduction. It also sets restrictions for whether biosolids can be sold in bulk (i.e., large containers that are not labeled) or bags (pre-packaged with a label) and in what context it can be applied. Heavy metal concentration limits in soil are not mentioned in the Part 503 Rule nor are limits for organic pollutants, though there have been proposals to include maximum limits (or ML, also referred to as ceiling concentrations) for up to 31 additional pollutants (Bastian, 1995). In addition to ceiling concentrations for heavy metals in all biosolids that are land applied, the 503 Rule includes alternatives for calculating the maximum allowed biosolid application based on PTE concentrations per area ("Cumulative Pollutant Loading Rate" option, or CPLR, measured in kg ha^{-1}) and per area over time ("Annual Pollutant Loading Rate" option, or APLR, measured in kg ha^{-1} 365 $days^{-1}$). They have a so-called "Pollutant Concentration Limit for EQ and PC Biosolids" with PTE concentrations lower than the ceiling concentrations. EQ stands for the "Exceptional Quality" option and PC stands for the "Pollutant Concentration" option. Biosolids with concentrations below these limits can be applied without site restrictions. See table 1 for specific ceiling concentration limits.

The Part 503 Rule lists six alternatives for pathogen reduction. The first is specified as a combination of time and temperature, the second a combination of high pH and high temperature. The other alternatives are less defined but entail process monitoring to ensure that levels of pathogens are reduced. The extent to which pathogens are reduced determines whether biosolids achieve Class A (the first two methods) or Class B status. Biosolids that have not been subjected to one of the six methods or do not have documented pathogen reduction are not approved for land application. There are 12 options for vector attraction reduction. These entail one or more of the following: Biological processes which breakdown volatile solids, reducing the available food nutrients for microbial activities and odour producing potential; chemical or physical conditions which stop microbial activity, or; physical barriers between vectors and volatile solids in the sewage sludge.

The 503 Biosolids Rule is very specific about requirements for land application and we recommend reviewing the documents "A Plain English Guide to the EPA Part 503 Biosolids Rule" (Walker, 1994), "Biosolids Management Handbook" (Bastian, 1995) and "Environmental Regulations and Technology: Control of Pathogens and Vector Attraction in Sewage Sludge" (U.S. EPA, 2003) for details about the biosolids quality classes, application, and methods for pathogen and vector attraction reduction.

Table 1. Comparison of permissible concentration limits for PTEs in the US and EU.

PTE	US				EU		
	Ceiling Concentration (mg kg^{-1} DM)	Pollutant Concentration Limits for EQ and PC Biosolids (mg kg^{-1} DM)	Cumulative Pollutant Loading Rates (kg ha^{-1})	Annual Pollutant Loading Rate Limits (kg ha^{-1} 365-day period^{-1})	Ceiling Concentration (mg kg^{-1} DM)	Limit Values, 10-Year Average (mg kg^{-1} DM yr^{-1})	Limit Values in Soil (mg kg^{-1} DM)
ARSENIC	75	41	41	2.0	-	-	-
CADMIUM	85	39	39	1.9	20-40	0.15	1-3
CHROMIUM	3000	1200	3000	150	-	-	-
COPPER	4300	1500	1500	75	1000-1750	12	50-140
LEAD	840	300	300	15	750-1200	15	50-300
MERCURY	57	17	17	0.85	16-25	0.1	1-1.5
MOLYBDENUM	75	-	-	-	-	-	-
NICKEL	420	420	420	21	300-400	3	30-75
SELENIUM	100	36	100	5.0	-	-	-
ZINC	7500	2800	2800	140	2500-4000	30	150-

2.2 EU Sludge Directive

Biosolids management in the European Union is regulated by *The Council Directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture*, also known as “The European Sludge Directive” (Directive 86/278/CEE). It was passed in 1986 with the purpose of regulating “the use of sewage sludge in agriculture in such a way as to prevent harmful effects in soil, vegetation, animals and man, thereby encouraging the correct use of such sewage sludge”. It sets limits on PTE concentrations in biosolids *and* in the soil on which it is applied. However, individual member states can choose whether they enforce limit values in sludge, in soil, or both. Every nation has chosen both, except the UK which only enforces limit values for soil (Collivignarelli et al., 2019). As with the USA, the EU directive allows for averaging the amounts of PTE’s applied over time (kg/ha/yr), in this case over a ten-year time span. Pathogen and vector attraction reduction are not mentioned in the EU sludge directive and it is up to individual nations to regulate these. The majority of nations enforce standards for these either for upstream raw materials (i.e. animal by-products, industry residues) or for specific treatment methods (i.e., AD and composting). A proposal to include limits on selected organic pollutants in the directive was proposed in 2000 but rejected. Currently, approximately 15 EU member states have set ceiling concentration limits on selected organic pollutants. In addition, approximately 17 member nations have established ceiling concentration limits for PTEs that are stricter than the EU directive, or include additional elements such as such as molybdenum, cobalt, arsenic, selenium, and fluoride (see Table 2). The regulation of organic farming production (Commission regulation EC No 889/2008) has criteria which prohibits sewage sludge, compost or digestate mixed with sewage sludge or other organic waste from mixed municipal solid waste to be used as fertilizer or soil improvement in organic agriculture.

Table 2. Comparison of EPA and EU sludge directives. ML=Maximum limits; PTE=Potentially toxic elements.

REGULATION	USA	EU	EU/EEA MEMBER STATES	NORWAY
ML OF PTE’S IN SLUDGE	Yes	Yes	All (except UK)	Yes
ML OF PTE’S IN SOIL	No	Yes	All	Yes
ML ORGANIC COMPOUNDS	No	No	Germany, France, Italy, Austria, Sweden, Portugal, Finland, Denmark, Belgium, Luxembourg, Hungary, Check Republic, Romania, Slovakia, Croatia	No
ML PATHOGENS/ PATHOGEN REDUCTION	Yes	No	Austria, Bulgaria, Czech Republic, Denmark, Finland, France, Italy, Lithuania, Luxembourg, Malta, Poland, Portugal, Slovakia, UK	Yes (salmonella, TCB, parasite eggs)
VECTOR ATTRACTION REDUCTION	Yes	No	Not applicable	Must be stable and odour-free

3 Sludge treatment technologies

Generally, sludge from STPs consists of two types: primary sludge from the primary physical wastewater treatment and secondary sludge (mainly waste activated sludge – WAS) from biological wastewater treatment. The primary and secondary sludge have different characteristics, but in practice they are often mixed upstream of the sludge treatment line (Gherghel et al., 2019) and treated together. The most common steps in sludge management is thickening, stabilization, dewatering and final disposal (Wang et al., 2017) – see Figure 1 and 2.

The treatment and disposal of sludge is costly, contributing up to 50% of the operational costs of a STP (Gherghel et al., 2019), and it therefore motivates the development and use of technology that increases treatment efficiencies and promotes reuse of sludge (Zhang et al., 2017). It also promotes the reduction of the sludge volume to be disposed of and its quality improvement.

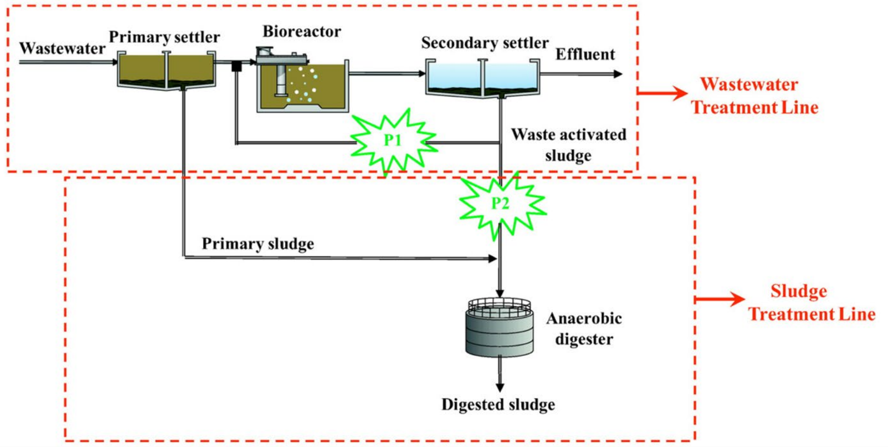

Figure 1. Potential locations for sludge reduction technologies in a typical wastewater treatment plant (WWTP). P1 indicates the location integrated into wastewater treatment line. P2 indicates the location applied in sludge treatment line (Wang et al., 2017).

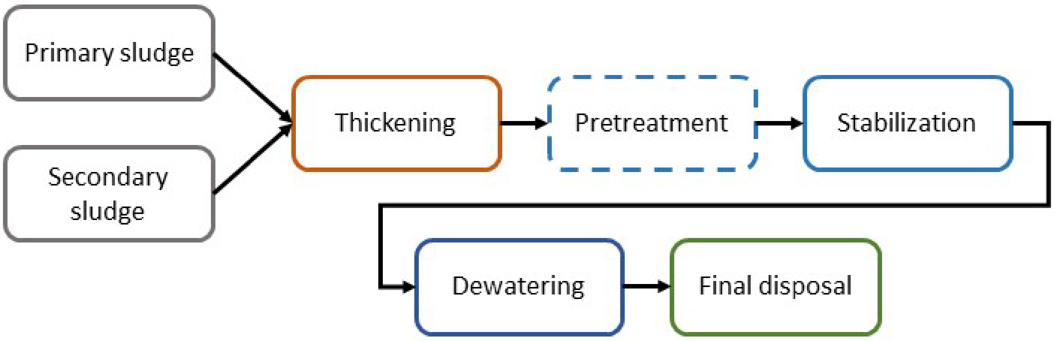

Figure 2. The main steps in the sludge management chain. The use of pretreatment depends largely on the choice of stabilization technology and is therefore shown with a dashed line.

For sludge stabilization anaerobic digestion (AD) is most commonly used for its ability to convert organic carbon into valuable biogas, thereby also reducing the amount of sludge to be disposed of in the end, and inactivate pathogens in the sludge (Appels et al., 2008). However, on its own, AD is able to convert only a limited part of the organic matter in the sludge, and is therefore often combined with some form of pre-treatment that can enhance the biogas yield and further reduce the sludge volume – also by increasing its dewaterability (Wang et al., 2017). As disposal of treated sludge (biosolids) can be expensive the use of sludge reducing technologies may be a necessary and best practice.

Wang et al. (2017) review sludge reducing technologies that are either applied in the wastewater treatment line or in the sludge treatment line, but usually not in both. Sludge reduction technologies in the wastewater treatment line are typically applied in small STPs where AD is not used, while technologies to reduce sludge production in the sludge treatment line are employed in larger STPs in combination with anaerobic digesters (see Figure 1) – often as a step preceding AD and therefore termed "pre-treatment". In the following, we therefore focus on the sludge reduction technologies that are used in the sludge treatment line in combination with AD. We present some of the pre-treatment methods and technologies in Section 3.3.1.

3.1 Centralized versus decentralized sludge management

Anaerobic digestion (AD) with subsequent dewatering of the digestate and handling of biogas requires a certain STP size to make economic sense and benefit from economies of scale, preferably treating a minimum of 10 MLD (million litres per day) [2] of sewage (Kacprzak et al., 2017). With smaller STPs, a centralized sludge management could be considered, in which sludge generated at different STPs is transported to one central sludge treatment facility for further processing and safe disposal (Figure 2). This would reduce the amount of land required at each STP site, but it requires transportation by road or rail, which can be costly and increase climate gas emissions. The central sludge treatment facility can be at an existing STP where it also receives and processes external sludge from other STPs. Alternatively, the central sludge treatment facility can also be a standalone facility where it processes sludge from multiple STPs. Central sludge treatment facilities, which also can be referred to as sludge treatment centre, are popular in Europe and many parts of the world – in this report exemplified by Davyhulme wastewater works in North-West England (Section 5.3.2).

In this context, decentralized sludge management is then to carry out sludge treatment on-site at each STP. This does require more land at each site, but it does eliminate the need for transportation of sludge between generation and processing.

The management and treatment of fecal sludge from off-grid facilities such as septic tanks for the collection of toilet waste is a major concern in many parts of the world, including India. Both the centralized and decentralized structure for sludge management may have arrangements for receiving fecal sludge transported by trucks collected form separate off-grid sanitation units.

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[2] Kacprzak and colleagues (2017, Fig.4) refer to 50.000 population equivalents (PE) as the minimum for AD to be a rational choice at the STP. If we assume 200 litres of sewage generated per PE then 50.000 PE equals 10.000.000 litres.

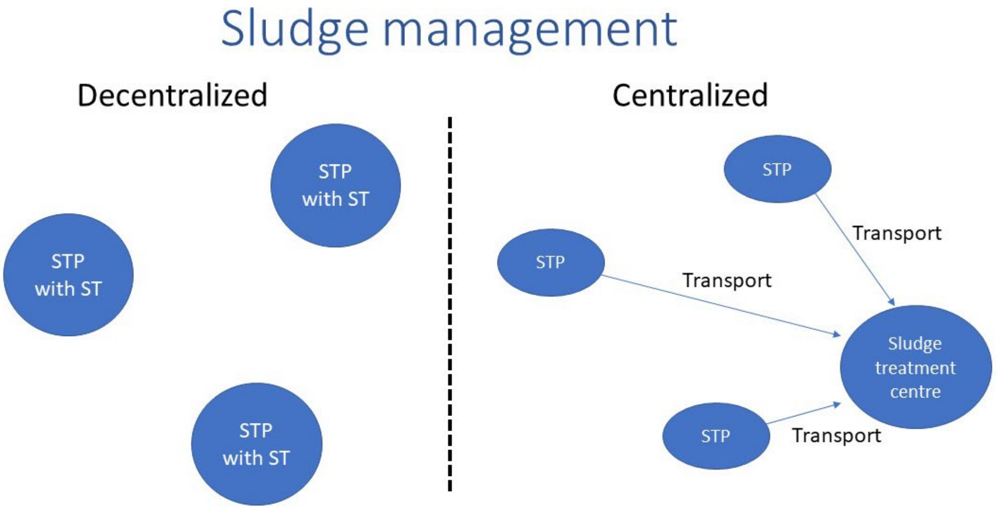

Figure 3. Centralized versus decentralized sludge management. STP = sewage treatment plant; ST = sludge treatment. The sewer infrastructure connected to each STP is not shown for the sake of readability.

3.2 Final disposal of sewage sludge

A key part of sludge management is the final disposal of treated sludge, with the main disposal ways being application in agriculture, landfilling, incineration (and subsequent storage or use of ashes), and reuse for production of cement, bricks, and asphalt (Gherghel et al., 2019). Application in agriculture is the most common disposal route worldwide (Schnell et al., 2020). The choice or preference of disposal method can be a combination of technical, environmental, socio-economic, psychological, and political factors (Ekane et al., 2021).

In the EU, about 40% of the sludge is applied in agriculture, and the disposal of sludge to agriculture is termed a “best practicable environmental option” (BPEO) since it recycles organic matter and nutrients back to food production (Kacprzak et al., 2017), thus saving for example energy-demanding production of mineral fertilizer.

Countries have differing evaluations of the risks involved with the application of treated sludge in agriculture (Kacprzak et al., 2017). In the EU, Sweden and Germany are examples of countries with a differing, although possibly converging, evaluation or perception of risk involved in applying sludge to agriculture in terms of the potential negative effects on human health from contaminants. In Sweden, about one third of the sewage sludge is currently spread on farmland, but there is an ongoing debate on whether this is an acceptable practice or not (Ekane et al., 2021). In Germany, the public and political opinion has led to an increasing use of incineration and thermal treatment processes in general, not willing to risk the spread of pollutants on agricultural land (Schnell et al., 2020).

There is a trend towards focusing on recovery and recycling resources in the sludge and promoting environmentally beneficial solutions, but choosing sludge management systems also needs to consider economic and social aspects to be sustainable over time (Spinosa, 2011).

3.3 Sludge treatment technologies

The technologies presented in the following sub-sections are used in different stages of the sludge management chain – see Figure 2 and Table 3. Technology chosen will depend on the quality of sludge (biosolids) to be achieved and the intended disposal method. As an extra resource, Appendix A summarizes the recommended technologies according to the EPA 503 Rule in the USA.

For thickening and dewatering, a variety of different mechanical methods – e.g., gravity thickening/sedimentation, dissolved-air floatation, centrifuge – are used to increase the dry matter content of the sewage sludge. We will not go further into these. For each of the following steps – pre-treatment, stabilization, and dewatering – we present selected methods that are particularly promising and/or commonly used.

Table 3. Summary of presented sludge treatment technologies

Stage	Technology
Pre-treatment	Physical, chemical, and biological technologies
Stabilization	Anaerobic digestion Composting Alkaline stabilizsation
Dewatering	Drying

3.3.1 AD pre-treatment

AD supported by pre-treatment is used to enhance the hydrolysis of sewage sludge that in consequence improve biogas production and shortening the production time and increase the solid removal and enhance the sludge quality regarding lowering the odour potential and dewatering ability. Particularly, solubilization of intracellular biopolymers and their conversion to lower molecular weight compounds are enhanced through pre-treatment (Pilli et al., 2015). The pre-treatment can be applied to primary, secondary, or mixed sludge. Different pre-treatment methods are available, and they can be divided into various categories such as thermal, chemical, mechanical, biological, physical, and combined (e.g., thermochemical, physicochemical). The physical, thermal and their combination are most used and studied. For example, the high temperature pre-treatment up 170-180 °C combined with pressure 19-21 bar increased the biogas production by 75% (Wett et al., 2010). Intermediate temperature treatment <100 °C (70 °C) for prolonged period of the time (up to 7 days) increased the biogas production by 50% (Climent et al., 2007). Similar range of solubilization enhancement as for temperatures <100 °C can be regarded for most of the physical pre-treatment methods (Neumann et al., 2016).

Regarding chemical pre-treatment the alkaline pre-treatment or ozonation were found efficient to increase the biogas production. In case of ozonation, it has been reported that up to 200% increase of biogas production was noted while for alkaline pre-treatment up to 120% (while using NaOH) (Neumann et al., 2016). Biological pre-treatment methods represent mostly anaerobic pre-treatments (e.g., temperature phased anaerobic digestion), enzyme addition or aerobic digestion. For example, temperature phased anaerobic digestion employing the thermophilic (65 °C) hydrolytic step followed by another thermophilic digestion (55 °C) could give 48% higher biogas yield compared to conventional AD (Bolzonella et al., 2012).

Amongst the reviewed sludge reducing pre-treatment technologies[3] by Wang et al. (2017) the heat-related pre-treatment (e.g., thermal pre-treatment and temperature-phased AD) stand out as beneficial for dewaterability, increased biogas yield, as well as high pathogen inactivation. Thermal pre-treatment and temperature-phased AD are recognized as superior approaches when it comes to pathogen

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[3] Technologies for sludge reduction in the sludge treatment line reviewed by Wang et al. (2017) are grouped by three approaches: physical, chemical, and biological pre-treatment. Thermal pre-treatment belongs to the physical approach, while temperature-phased AD belongs to the biological approach.

inactivation achieving Class A biosolids quality. Additionally, the thermal pre-treatment requires lower investment costs compared to the temperature-phased AD (Wang et al. 2017). Similar conclusions were drawn by Gherghel et al. (2019) who point that thermal hydrolysis is the most promising sludge reduction technology for the sludge treatment at large STPs.

3.3.2 Anaerobic digestion (AD)

AD is a mature technology and one of the most widely used for sludge stabilization. For example, around 66% of sewage sludge produced in UK and 90% in Germany is treated using AD (Tao et al., 2017). AD occurs in an oxygen-free environment in e.g., meso- or thermophilic conditions and produces biogas (mixture of methane (CH4), carbon dioxide (CO2) and small quantities of other gases) through by biological activity. AD is a complex biochemical process that involves four steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Biogas (consisting of 60-80% of CH4) obtained during this process can be used as an energy carrier for heat/electricity generation or as transportation fuel. Application of AD also significantly reduces the sludge volume up to 50% (Horttanainen et al., 2010). Regarding the sewage sludge use for AD, it has been found that high molecular weight compounds and complex organic matter in sludge limits the hydrolysis step of AD (Pilli et al., 2015). Therefore, only the readily biodegradable fraction is recovered from sludge. This, in consequence, requires larger reactor volumes and longer retention times to achieve a satisfactory stabilization of sewage sludge. To mitigate this issue and enhance the degradation of organic matter, the co-digestion of sewage sludge with different organic wastes (e.g., food waste) is frequently applied (Neumann et al., 2016). In AD process, the nitrogen and phosphorus nutrients are mostly conserved in the digestate and can be further used e.g., as fertilizer. Reviewing world-wide tenders for STPs in cities, almost all include AD as required sludge treatment, whether the resulting digested sludge (biosolids) go to agriculture, incineration, landfill or other end-use.

3.3.3 Composting

Composting of organic waste requires conditions that ensure fast degradation and safe sanitation of the organic material. The aerobic composting process can be done mesophilic at 37 °C (e.g. vermicomposting with the use of earthworms) and thermophilic over 55 °C. The composting process is dependent on effective gas transmission, O_2 in and CO_2 out of the compost. The required aeration is related to type and amount of bulking agent(s) and the organic waste. The pH and dry matter of the waste influence the composting process.

Thermophilic processes are most effective in degradation of organic material from 12 - 30 days. The high-rate composting phase is characterized by high thermophilic microbial respiration at temperatures above 45 °C. Full scale composting plants for food waste have reported problems in the establishment of the high-rate composting phase. This is often related to slow degradation of organic matter and problems to achieve thermophilic conditions in the composting materials. It is suggested that this is related to formation of short-chained organic acids (mainly lactic and acetic acid) during pre-storage of waste and during initial phases of composting (Beck-Friis et al., 2003). Actions to reduce these problems are for instance maintaining mesophilic microorganisms in the composting materials until the pH rises above 5.5 (Smårs et al., 2001); yeast inoculation as an activator in cases of composting failure (Choi and Park, 1998); using a starter culture of active compost with fed-batch composting of food waste to prevent low pH conditions (Sundberg and Jönsson, 2005); and addition of 5 % lime (Ca(OH)2) or extra bulking agent to establish thermophilic microorganisms and high-rate respiration in composting of acidic source separated organic household (Bergersen et al., 2009).

Regarding reduction of organic contaminants during composting, the composition of the microbial communities (bacteria, actinomycetes and fungi) changes during different temperature phases. Actinomycetes and fungi are likely to be involved in removal of contaminants with optimal degradation at lower temperatures than bacteria, which are more likely to cause degradation of contaminants with optimal removal at higher temperature. While some contaminants show removal over a wide range of temperatures thereby indicating degradation by several types of microorganisms, others had a narrower optimal temperature range, suggesting that fewer types of microorganisms are involved in removal.

Under optimally run composting, easily degradable organic contaminants will be highly reduced. For persistent organic compounds the reduction can be rather low. A recent critical review (Lü et al., 2021) showed that PCBs and dioxin-like compounds are very persistent during composting, and are influenced by different pollutants, bulking agents, composting methods and processes. Thus, the composting process can be optimized to improve the reduction of organic contaminants.

3.3.4 Alkaline stabilization (liming)

Lime is one of the most common materials used for sewage sludge stabilization. Application of lime increases the pH value of lime-sludge mixture for extended periods (Samaras et al., 2008), thereby reducing the availability of heavy metals and lowering the environmental risk (Wong and Selvam, 2006). Additionally, it prevents odor problems (Wong and Fang, 2000). For example, dewatered sewage sludge treated with 10% of quicklime was considered hygienically safe and agronomically acceptable for farmland application (Akrivos et al., 2000). The degree to which lime is applied highly depends on local lime availability, costs and required stabilization period. However, through the alkaline stabilization only Class B of biosolids can be achieved (Bean et al., 2007).

3.3.5 Drying

Drying, and in particular solar drying, can be applied after aerobic/anaerobic digestion. Solar drying takes the advantage of free solar energy, reducing the operation costs. Through solar drying the quantity of sludge can be reduced (dewatering) while it plays also a role in pathogen reduction (Bennamoun, 2012). It has been regarded as alternative to liming reducing lime costs and decreasing the transportation and landfilling costs (Kamil Salihoglu et al., 2007). The performance of solar drying depends on the operational conditions that change with time, geographical location, and the sludge origin. These parameters significantly affect the drying kinetics. Alternatively, to open solar drying systems covered solar drying was found operating more efficiently (Bennamoun, 2012). Given the large land-area needed solar dryers are usually located outside big cities.

4 Contaminants in sewage sludge

4.1 Introduction to potential hazardous compounds in sludge

Sludge from STPs reflects the different metals and chemicals people are in contact with in their everyday life. Some of these compounds are hazardous and may pose environmental and health risk. The term "hazardous compounds" is often used interchangeably with "pollutants" and "contaminants". These terms include inorganic elements such as heavy metals, where the most commonly regulated are Cd, Cu, Cr, Hg, Ni, Pb and Zn, and organic compounds used as additives in personal care products such as cosmetics and sunscreen products.

Previously, industries were the main sources of unwanted contaminants, but as they are now often obliged to treat their effluents before being discharged into a sewer system, the levels of heavy metals and organic chemicals have decreased significantly in sludge. However, it is now well known that housekeeping products and daily life activities are important sources that contribute with contaminants that enter the wastewater treatment system and are subsequently found in sewage sludge. You may say that contaminants in biosolids are a fingerprint of our civilisation and any attention to contaminants in biosolids is beneficial to find and understand and manage the sources. Stopping contaminants at the source is the best way to control the global threat of emerging contaminants from entering waters and rivers and potential sludge-based fertilizers. The second-best option is to reduce the content in biosolids as much as possible when contaminants have already entered the sludge. This chapter has a particular focus on organic contaminants.

4.2 Well-known and emerging contaminants (EC)

There are several factors that influence the concentrations of contaminants in sludge, both upstream the STPs (e.g. sewage discharges from different sources, size and socioeconomic composition of the population that feeds the STP), and in the wastewater treatment processes (e.g. the wastewater composition, and the types, sequence order, and physical arrangements of the different treatment processes that are applied) (Eggen and Vogelsang, 2015). It is important to bear in mind that the many influencing factors result in a high variation in measured concentrations of contaminants in sewage sludge.

Well-known and regulated compounds like PCBs, dioxins, and chlororganic pesticides such as DDT and lindane were early recognized as contaminants. The Stockholm Convention on Persistent Organic Pollutants (POPs)[4] allows elimination and/or restriction in the production and use of chemicals defined as POPs. In addition to the well-known organic contaminants such as PCBs and dioxins, the PFAS, PFOA-related compounds and PFHxS-related compounds are on the POPs list (on the list Annex A, for elimination). More recently recognized hazardous organic contaminants that are not yet regulated are commonly referred to as emerging contaminants (EC). Emerging contaminants are often found in sewage sludge.

Many countries have regularly mapping surveys, e.g., in surface water, biota, sediments, urban soil, air, where a long list of ECs in addition to the regulated compounds are analysed for, and several national reports and some scientific papers have been prepared. Different countries might have separate priority list of contaminants, e.g. the Norwegian priority list of contaminants contains 442 compounds[5]. The list of priority pollutants will change over time as it is continuously updated.

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[4] For definition see http://chm.pops.int/TheConvention/ThePOPs/tabid/673/Default.aspx

[5] Norwegian Environmental Agency (NEA)
https://www.miljodirektoratet.no/ansvarsomrader/kjemikalier/regelverk/prioritetslista

Pharmaceuticals are a group of organic compounds which has gained much attention during the last decade (often termed PhAC for pharmaceutically active compounds). They are designed as biological active compounds and they might have adverse effects on non-target organisms in the environment at low concentrations. Thousands of different substances are used in medicines such as painkillers, antibiotics, contraceptives, beta-blockers and lipid regulators. There are also thousands of chemicals that are used in personal care products (PCPs) in high consumption volume products, such as skin care products, dental care products, soaps, sunscreen agents and hairstyle products etc (Ternes et al., 2004). Pharmaceuticals will be excreted in a combination of intact and metabolized pharmaceuticals, while personal care products will enter the wastewater after their regular use during showering or bathing. The effluents from domestic wastewater treatment plants are recognized as important entry routes for pharmaceuticals and personal care products (PPCPs) into the environment (Boxall et al., 2004). Many pharmaceuticals will in a similar manner as other organic contaminants be found in sewage sludge (Verlicchi and Zambello, 2015).

In a review from 2018, a comprehensive mapping of emerging contaminants in Asia, EU and US are presented (Tran et al., 2018). It includes 60 ECs measured in influent, treated effluent, sludge and biosolids in WWTPs. A long list of PhACs, hormones, X-ray contrast media, UV-filters, stimulants, artificial sweeteners, insect repellents, and plasticizer were detected. As most literature has been concerned with dissolved ECs (in influent and effluent wastewaters), Tran and colleagues call for more studies on the fate and occurrence of ECs in the particulate phases of sludge and biosolids.

Musk compounds (found in high levels in sewage sludge, in orders of magnitude mg/kg dry weight), PFOS and PFOA (persistent, toxic, carcinogenic) are relative new ECs and commonly included in sewage sludge monitoring programs in Nordic countries. The more well-known PCBs, phthalate, PAHs, and short-chain chlorinated paraffins are often included in monitoring programs.

There are also other papers and book chapters on EC in WWTPs and sewage sludge, e.g. Guerra et al. (2014), Rout et al. (2021), and Eggen and Vogelsang (2015) to mention some. The occurrence and fate of many of the ECs in sewage sludge are yet not so well documented, probably due to lack of sensitive analytical methods and the complexity of the matrix.

An overview of selected ECs and well-known contaminants commonly measured for in influent, effluent and sewage sludge is present in Appendix B. Their structure is included to indicate their different physicochemical properties which highly influence their fate and toxicity. Many are recognised as priority contaminants.

4.3 Heavy metals (Potential Toxic Elements - PTEs)

The most commonly regulated inorganic elements are the heavy metals cadmium (Cd), chromium (CrIII + CrVI), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni) and zinc (Zn) but lately also arsenic (As), which is not a heavy metal, thus leading to the use of the broader term *potential toxic elements* (PTE). Although some of these elements are essential to plants, animals and humans in small amounts, high enough concentrations can be toxic.

In many countries PTEs are regularly measured in sewage sludge from WWTPs and reported and collected in data. In a recent published review where use of sewage sludge as a soil amendment in relation to current international guidelines is discussed (Nunes et al., 2021), an overview of heavy metal analysis in different countries as well as different regions in India are presented (Table 4). As seen in the table, the content of heavy metals might vary highly between countries and between different regions. For example, Chinese regions has particularly high concentrations of Cu and Zn. Copper and zinc, in addition to being potentially toxic, have been found to be drivers for the development of antibiotic resistance (Lima et al., 2020).

Table 4. Analysis of heavy metals in sewage sludge from different countries and regions. Values for heavy metals given in mg kg^{-1} DW (from Nunes et al. (2021))

Country/City	pH	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Argentina/Buenos Aires		3.9±1.9	155.6±51.8	360.3±80.9		85.5±76.1	322.7±151.6	1526±523
Australia/Brisbane		1.8	16.7±0.3	447.7±1.5		19.8±0.2	41.7±0.3	830.6±4.2
Brazil/Jaboticabal		11	808	722		231	186	2159
China/Hebei	5. 8	0.3	83.51	221.9		32.62	73.31	
China/Taiyuan		22.1	245.8	1122	20.6*		118.5	3059
Denmark/Copenhagen	7.7	1.4	98	244		31	178	1041
Finland/Helsinki	7.2	0.4	30	270		20	20	470
India/New Delhi	6.4			173			78	1853
India/Uttarakhand	9	10.24±0.14	8.63±1.06	18.96±1.09			9.33±1.01	11.25±1.00
India/Varanasi	7	154.5± 2.52	35.5±0.76	317.7±1.92		18.9±0.09	60±5.77	785.3±16.69
Morocco/Meknès-SaÏs	6.1	1.15±0.2	32.8±2.4	17.9±1.2	0.44±0.1	20.9±1.7	81±4.5	215±12.4
Pakistan/Multan	6.9	5.5		145		35	20	
Pakistan/Multan	7.6	26				160	13	
Spain/Alicante	6.5	1.6	16.6	157	n.d.	n.d.	40.8	470

5 Case studies

Countries around the world differs in income level, institutional capacity, political system and culture in general. Technology and systems that works well in rich countries with a long history of urbanization, might easily fail in fast growing cities with immigrants from the countryside in poor countries.

Domestic wastewater was used for irrigation by prehistoric civilizations (e.g. Mesopotamian, Indus valley and Minoan) since the Bronze Age (ca. 3200-1100 BC), while wastewater was used for disposal, irrigation, and fertilization purposes by Hellenic civilizations and later by Romans in areas surrounding cities, e.g. Athens and Rome[6]. On the other hand, rural dwellers in Africa, Latin America, and Asia still "walk into the cornfield" as they say in the Peruvian highland, although a practice becoming less common as the government programs build pit latrines also in the countryside.

Although no country or system is equal, we expect that Indian cities, which now plan the wastewater treatment system for the coming century, can learn a lot from experiences elsewhere. We have hence chosen two different cities that bring different experiences that will be relevant for India of different reasons. London is a modern city in the technological metropole of United Kingdom, amongst the richest and most technologically advanced in the world. The wastewater treatment plants (WWTPs) are up and running, demonstrating good results. Then we look at Durban, the second largest city in South Africa, a medium income country with large differences in income level and housing standards. City centres and residential areas are connected to the grid, while parts of the informal settlements are not connected, representing a challenge that Indian cities also must overcome in order to achieve a wastewater collection and treatment system that is considered health, climate and environmentally friendly.

The choice of WWTP technology for a given geographic area will depend on the requirement set in the government regulations. South Africa regulates pathogens, contaminants and stability of the sludge for different treatment methods as most other countries, but the allowed levels differ from the levels set in the US Environmental Protection Agency (EPA) regulations. USA implemented their regulations in the early 1990s with the protection of the environment and health of the population in mind. Since then, there has been an increasing attention to global warming and hence policies that will reduce emissions of greenhouse gases. Circular economy is now a key concept that reflects a paradigm shift in the use of natural resources, from tap-use-dispose to tap-use-reuse. So optimal sludge management from the *circular economy* point of view will now imply the capture of the energy as well as the nutrients in the sludge. Application to land and agriculture is then vital. EPA 503 then sets limits to the level of (i) heavy metal (ii) pathogens and (iii) vector volatility in sludge to be applicable on land, although less restrictive of application on land that is not directly linked to the production of food for human consumption.

The optimal requirements for sewage sludge treatment and quality will depend on both political and economic factors. More advanced processing costs more, but give more benefits, e.g. possibility to apply nutrients and phosphorus in agriculture, produce energy and cut CO2 emissions. However, whether advanced sewage processing is the most cost-efficient mean to achieve these ends is an open question and depend on the existing alternatives in that country.

Institutional arrangements, power equilibria, culture and other barriers could also impede society to pick first best solutions, e.g., the most cost-efficient solution to achieve a given end, forcing decision makers to settle for second best solutions instead. The reader must hence assess what lessons from the 2 case studies of Durban and London are relevant for Indian cities. Our intention is only to report the main drivers of the changes in the sewage sludge policy and practice in these locations. There was a considerable change in UK when sea dumping of raw sewage sludge was prohibited in 1998, when the industry first tested incineration and later moved to land application. South Africa has so far simply

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[6] https://en.wikipedia.org/wiki/History_of_water_supply_and_sanitation#Wastewater_reuse_activities

stockpiled solar dried sludge in landfills, but these are now filling up and they need to find other more sustainable solutions.

However, there is normally underinvestment in sewage sludge treatment in most developing countries as negative externalities through runoffs and emissions causing harm on the environment, climate and human health especially for the poor segments of the population is not considered by policymakers. The "pollutant pays" principle, e.g. the industry compensates users of polluted rivers or pays for the effects of global warming for the harm done upon them, is seldom applied. It is hence proper that the governments introduce stricter regulations of the wastewater industry with strong enforcement to approach the first best solution.

5.1 Durban, South Africa

5.1.1 Current sanitation provision

The sewage treatment plants in South Africa were developed under the Apartheid regime, with a focus on urban and middle-class suburbia areas and the waterborne sewage pipes hence normally bypassed informal settlements lacking planning and public facilities. We will exemplify the South African experience by studying the second biggest city in the country, Durban, situated in the eThekwini municipality that also comprises semi-urban and rural areas far from the city centre. The red areas in the left part of Figure 2 below indicate the connected areas, where the white areas in between consist of informal townships and unpopulated areas.

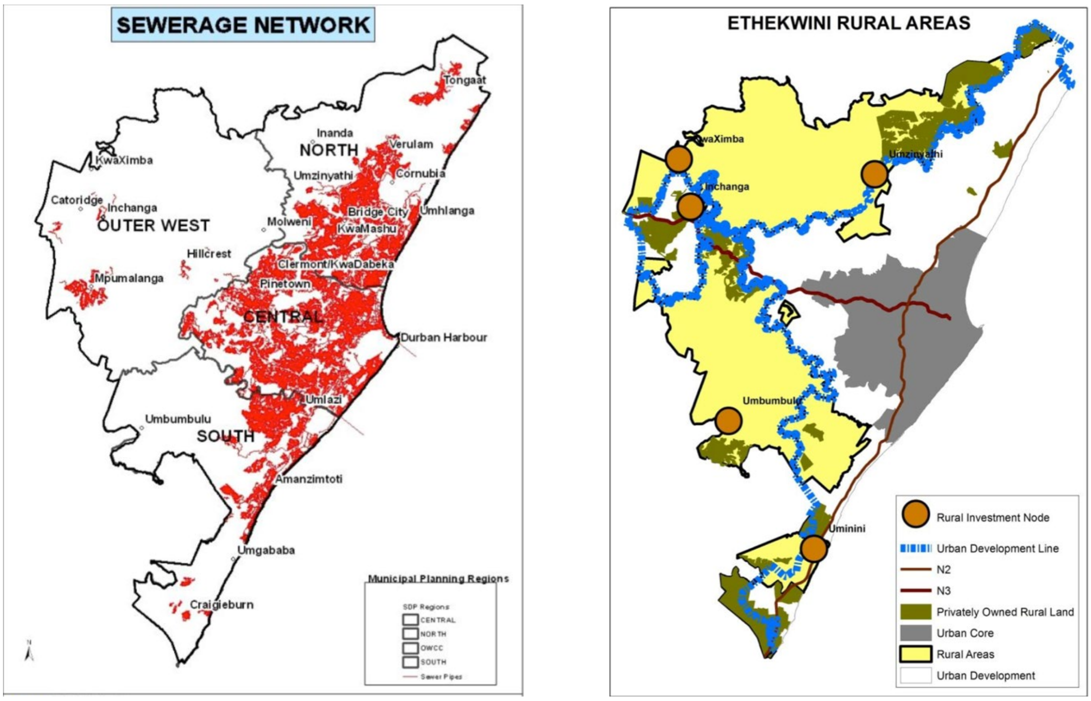

Figure 4. Sewerage network and Urban Development Line dividing urban from rural areas (eThekwini Municipality, 2015b), as quoted in Cross and Buckley (2016).

The share of households connected to wastewater solutions in eThekwini is given by the municipality in Tshangela (2019) as follows; water born sewage 48%, septic tanks 11%, ventilated improved pit (VIP) latrines 4%, ablution blocks 5%, urine diversion 8% and other (backlog, free sanitation) 24%.

There are no sanitation services for a quarter of the households, which probably implies a higher share of the population. However, there government launches concrete initiatives to connect them. Most of these unconnected household are in the rural areas where the municipality both has less activity and furthermore less power to enforce regulations since the land is in the ownership of the Ingonyama Trust with considerable autonomy since they do not have to adhere to the rules of the municipality (Cross and Buckley, 2016).

About 28% of the households are hence given collective sanitation solutions. The Ablution blocks are water sewage connected community point with tap water, showers, washing and water closet facilities. Private companies collect from septic tanks and then delivers to the WWTP for treatment. This implies that 64% of the households are treated in the WWTPs in some way or another. The exempted are ventilated improved pit (VIP) latrines and urine diversion (UD) toilets, i.e. faecal matter separated and emptied by the municipality, while the urine is diverted to soak away on site.

Cross and Buckley (2016) summarizes 56% of the households is connected to the centralized sewage system while 74% has safely managed sanitation. The remaining 26% is not treated in an acceptable way.

5.1.2 The wastewater treatment works

The eThekwini municipality informs that they got 27 WWTPs, comprising of 19 configured activated sludge processes, 6 Biological filtration processes and 2 sea outfalls (Tshangela, 2019). The installed capacity is in total approximately 500 Megalitres per day (MLD), treating approximately 450 MLD. 48% of households has access to waterborne sewage.

The Cross and Buckley (2016) study is based on key informants interviewed in the public administration and wastewater facilities. The municipal policy and practices document lay out the responsibility of eThekwini Water Service (EWS) with regards to water and sanitation access and their role of providing those in need with free basic services. Sewer network maintenance and operation, wastewater and sludge treatment work and providing of toilets for low-income areas with collection and sludge treatment of these toilets is all under the responsibility of EWS.

Innovative designs and trial projects are carried out by independent organisations such as the Pollution Research Group at the University of KwaZulu-Natal (UKZN) and other academic institutions. These external stakeholders work with EWS in order to develop better means of treatment, containment, and management of the sanitation systems.

From the Green Drop reports and the annual average inflow to each central WWTP, it was estimated that 88% of the wastewater is treated effectively at these works, making 7% of the total excreta not safely treated on disposal (Department of Water and Sanitation, 2014). While there are sludge treatment methods for the sewage sludge at all STPs (aside from the Central and Southern works that utilize the sea outfall pipes to dispose of the sludge), there is little reuse currently and the sludge either accumulates in ponds or is dried and stockpiled. There is a project in place to implement a pelletizing contract to allow for reuse of the sludge at many of the treatment works.

The sludge that is received at the Southern Works from septic tanks and conservancy tanks is mixed with the preliminary treated wastewater (screening and de-gritting) and is sent to sea via the sea outfall pipe. Cross and Buckley (2016) claim that the sludge treatment is not as well monitored or regulated as the wastewater treatment process and because of this is open to fraudulent tenders and corruption as has occurred in the past. This is a gap in the sanitation chain that is often neglected due to the social taboo around sludge waste and because it is seen as secondary to the wastewater treatment process.

Sludge treatment is not very well recorded or monitored with the results that the end use or final disposal of the sludge is also not clear. From individual interviews, some believed that the sludge was simply being stockpiled at most plants due to contractual issues, while some mentioned that the sludge was already being used on sugar cane fields for farming purposes. At the KwaMashu works only, there is a dryer and fluidized bed incinerator that has not previously been functional due to lack of skilled personnel and the expensive nature of this operation (eThekwini Municipality, 2012a). Some of the treatment works still send their dried sludge to the landfill. The only landfill that is still in operation is the Shongweni landfill operated privately by EnviroServ (eThekwini Municipality, 2015a). This option for sludge disposal may be problematic in the future, as the Environmental Affairs will soon be banning liquids on landfill sites and despite being dried, the sludge is still relatively wet on disposal. Landfill disposal is also quite expensive for the city at R700 to R910 per wet ton (eThekwini Municipality, 2012a). The plan to contract a private company to pelletize the sludge should generate an income that will break even (eThekwini Municipality, 2012a).

5.2 London

5.2.1 Thames Water

Thames Water is the UK's largest water and wastewater services provider with 15 million customers, 4,700 employees and turnover of £1.9bn. It is committed to recovering as many resources – both energy and nutrients – from the sewage sludge as possible in the most cost-effective way possible. Advanced digestion following thermal hydrolysis process (THP) is a key component to achieve this objective. These STPs process the sewage sludge onsite and some of them serve as sludge treatment centres for smaller works.

Thames Water built the first THP project in the UK in 1998 and later contracted operations to the technology provider. The plant had initial problems relating to odour and pumping. The technology provider relentlessly supported the resolution of such teething problems at the plant, which eventually turned out to be an economic and environmental success for Thames Water. This led to a change in the sludge strategy and resulted in seven more large-scale STPs implementing this technology in the London area from 2008 until 2018, treating approximately more than 500 raw dry tonnes per day (or 6-7 million population equivalent).

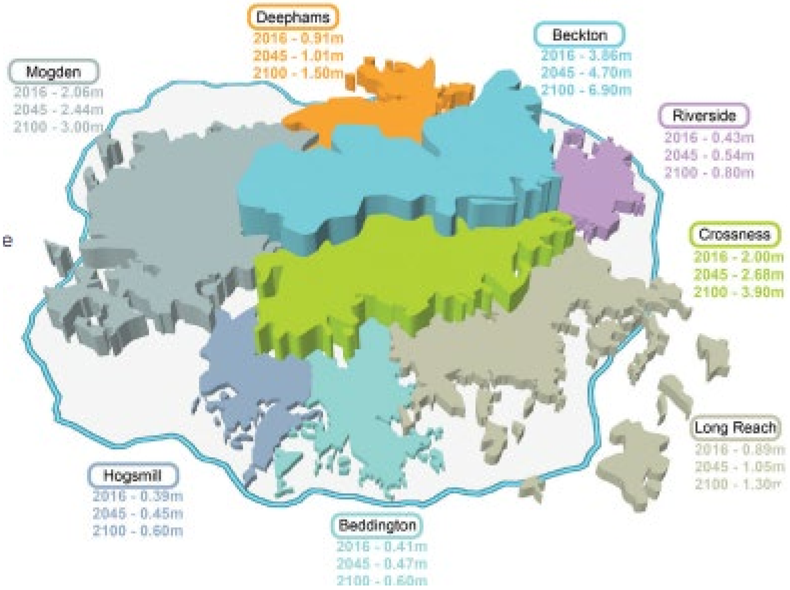

Figure 5. The STPs of Thames Water in London, source: Thames Water

5.2.2 CO_2 regulation as driver of change

The largest of these THP projects - Beckton and Crossness STPs - came online in 2014 combined with high dry-solids dewatering equipment and subsequent incineration, but with the flexibility of also taking it as an enhanced treated product (Class A) to agriculture. About 95% of all sludge is applied on land in the UK.

Most STPs in UK have moved away from incineration towards sludge processing for land applications over the last decades due to changes in regulations related to climate change. The UK politicians and bureaucracy set targets for both total CO2 emissions and renewable energy production in the country. These policies were later transferred to the wastewater sector through the 5 year- plans that included economic incentives to change treatment methods and well as funds to invest in STP upgrading and change. Interestingly, this took place at the same time as less heavy metals were emitted from the industry to the sewage in the UK, thereby making land application more environmentally acceptable. The concept of circular economy with recirculation of nutrients through land application came later and was not the initial driving force behind the policy change.

5.2.3 THP preferred solution

The Thames Water company has chosen to install THP treatment preceding AD in their STPs. However, they do differ in the final processing of whether only to produce energy or also sludge for land application.

There is an ongoing discussion on possible changes in the regulation about disposal of sludge on agricultural lands. If there is more emphasis on renewable energy, and possible polluting substances for agriculture, then there are alternative ways for renewable energy instead. A study comparing both the environmental footprint and the economy of AD and THP+AD solutions in British STPs find that the optimal environmental choice depends on type of energy actually substituted (Mills et al., 2014). They compared:

- Mesophilic anaerobic digestion (AD), biogas for combined heat and power (CHP) for electricity production (Bar number 1 in Figure 1 below)
- THP pre-treatment and AD, biogas for CHP for electricity production (2nd bar).
- THP pre-treatment and AD, biogas mixed with propane to produce biomethane for gas grid (3rd bar)
- THP pre-treatment and AD, biogas for CHP to produce electricity and dry sludge to produce coal for coal power plants (4th bar)
- THP pre-treatment and AD, biogas for CHP to produce electricity and dry sludge to be burned in Pyrolysis to produce electricity (5th bar)

When evaluating through Life Cycle Analysis (LCA) applying six different sustainability criteria (global warming potential, eutrophication, etc.) as one summarized weighted indicator, the authors find that pre-treatment with THP before AD, and then use the resulting biogas in a combined heat and power (CHP) to produce electricity as well as heat to dry the remaining sludge into coal, which will replace fossil coal in the coal power plants, is the most sustainable solution, see Figure 6 below.

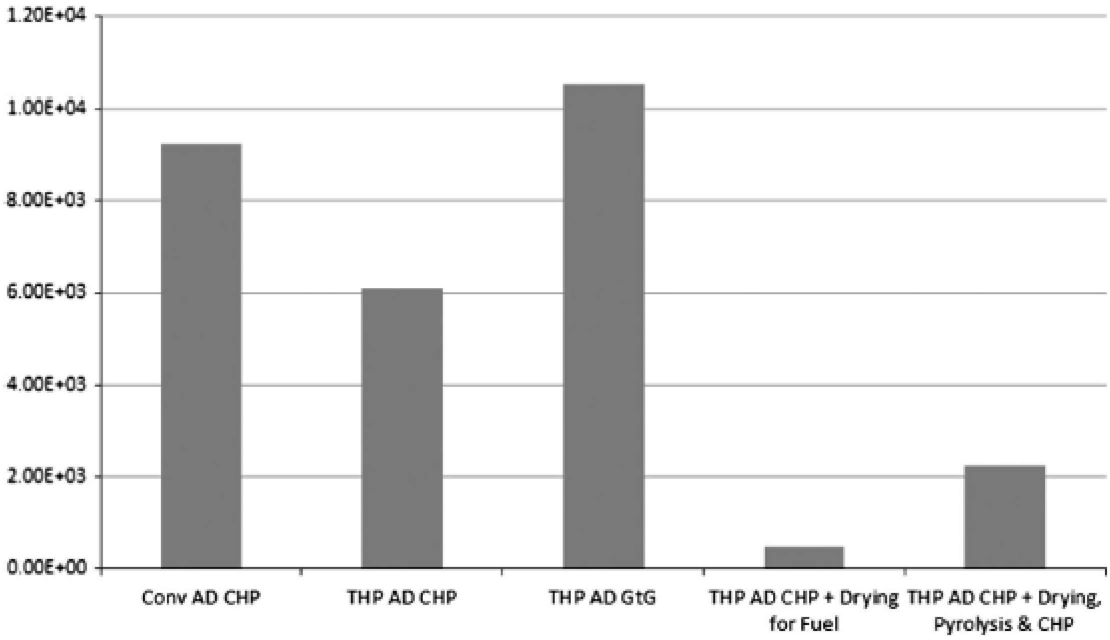

Figure 6. The weighted LCA impact (no unit) of six different sustainability indicators for the processing of secondary sludge in a UK context. The fourth column "THP AD CHP + Drying for Fuel" had the least damaging impact, measure is Weighted net impact CML 2001 – December 07, experts IKP (Northern Europe) method (Mills et al., 2014).

The decisive point for sustainability measurement is the climate and environmental impact of the energy that is substituted by renewable sludge energy. In Britain a large share of the electricity is currently produced by coal fire plants using polluting fossil coal, which replaced by biological coal from sludge will reduce the total greenhouse gas emissions considerably. The emission substitution effect would be smaller when produce biogas for the gas grid (GtG) or electricity for the electricity grid. The ranking might have been very different in another country where the climate and pollution effect of the substituted energy is different.

The ranking in economic viability differs from the sustainability ranking. Then the gas to grid solution is the most profitable, while thermal drying of sludge is rather expensive. However, this is mostly due to government incentives. If the subsidies are eliminated investment in upgrading the WWTP would become unprofitable as the authors calculated a negative internal rate of return (IRR). Furthermore, study finds that conventional AD and THP seems to be comparable financially, however the numbers do not include "…benefit bought from a superior (THP) sludge cake. The product is preferred by farmers and as such reduces disposal risk. In addition, THP allows for much larger throughput on the same footprint, on urban treatment sites land is limited so conventional AD, with large anaerobic digesters with their associated large footprint, is simply not feasible" (Mills et al., 2014, p. 191). In addition, Thames Water, in a presentation in Nov. 2020 point out that four times the land area is needed to store conventional biosolids compared with THP biosolids due to volume reduction of THP biosolids.

The long-term viability of the UK sludge for agricultural application, and relevance for other countries, will depend on both the absolute and perception of risk. In general, the heavy metal content in sludge is going down as the government can enforce the industry to clean their sewage before it is released into the public sewer grid. On the other hand, chapter 3 demonstrates an ongoing debate on risks associated with old and new contaminants. Especially Germany has become very restrictive about sludge application to land due to fear of pollutants (Schnell et al., 2020, p.1), but also surplus of organic waste (manure) vs. land available, as well as pressure from incineration lobby, etc. The balancing between two positive concepts of circular economy advocating the reuse of nutrients and phosphorus on one side and protecting nature, animals and humans from polluting substances in sludge on the other side, will be decisive for future regulations affecting the wastewater industry in all countries. However, as can be seen from the examples of Washington DC (presented below), once you make a product (soil improver/fertilizer) at the end there will be increasing pressure to control pollutants at source to protect the quality of the product.

5.3 Other cities

Many cities around the world are now preparing management plans for future sewage treatment systems in which they compare available technologies for future building and upgrading of STPs. As indicated at the start of this chapter local conditions like institutional capacity, pollution challenges, land availability and other cost, and CO2 policies can all influence the actual choice of technology. Although conditions might differ, it will still be useful for planners of Indian sewage treatment plants to know what technologies are chosen by other cities in the world.

5.3.1 Reducing metals from industrial point source in Bogota, Colombia

The Canoas STP south in the capital city of Bogota will treat the sewage from nearly 6 million people once it is constructed in the next few years, with prognosis of above 7 million people by 2040. The consultancy INGESAM of CDM-Smith was commissioned by the water authorities of Bogota to evaluate different technical solutions for a possible upgrading of the Canoas WWTP. Considering 4-5 alternatives within each part of the process (primary and secondary treatment, removal of nitrogen and phosphorous, disinfection, sludge pre-treatment, AD, dewatering of sludge, control of odour) in a multiple criteria analysis they recommend a specific solution in their final report (INGESAM, 2014):

"Anaerobic digestion: The Multicriteria decision analysis shows that the option to include thermal hydrolysis technology for sludge pre-treatment before conventional mesophilic anaerobic digestion is the most suitable to implement in the STP Canoes. This solution is in line with the current world trend in the management of sludge from municipal wastewater treatment plants, which considers maximizing the potential benefits of sludge processing, to achieve benefits such as, for example, optimizing the energy balance in the plant and obtaining a class A biosolids, with greater possibilities of commercial use. Other advantages of implementation of this solution include the lower volume requirements of the anaerobic digesters and the lower production of biosolids, which ultimately results in lower space requirements and lower operating and maintenance costs than when only conventional mesophilic anaerobic digestion is considered."

5.3.2 Centralized sludge treatment in North-West England

United Utilities (UU) manage the STPs in North-West region of England that including populous cities like Manchester and Liverpool. The company send sludge from each of the 8 STPs to one large sludge processing facility at the Davyhulme wastewater works situated in an industrial park just north of Manchester. UU converted the conventional digestion process to one with thermal hydrolysis and thereby more than tripled the loading rate in order to increase sludge processing from 39,000 to 121,000 tDS/a or an equivalent of 4.4 million people. This allowed UU to avoid expanding its incineration capacity and ultimately send more of the resulting Class A biosolids to land application.

The raw sludge from Davyhulme wastewater work itself is thickened to about 25% dry solids, while sludge cake is imported to Davyhulme from seven regional satellite sites operated by United Utilities. Both sources are then fed into the 20 hydrolyses reactors treating the sludge at 165°Celsius for 30 minutes before they are processed in the 8 anaerobic digesters.

Edgington et al. (2014) explains that UU sludge strategy had focussed on a balance of recycling and disposal due to the land bank constraints; more recently (over the last few Asset Management Plans, (AMPs)) this focus has shifted towards provision of an enhanced treated sludge. The significant shift towards the enhanced treated product quality standard has been driven by the land bank constraints, more stringent environmental regulations and competition. UU needed to provide a sustainable outlet for sludge in this part of the region, reduce costs and its operational carbon footprint.

This strategy to recover the valuable resource in sludge was developed in UU's AMP that identify the key drivers as:

- Reduce the land bank risk.
- Produce a sludge cake that obtained enhanced quality status for recycling to agriculture.
- Minimise the digested sludge quantities by greater solids destruction.
- Obtain an improvement in dewaterability of the digested sludge, hence reducing the quantity of wet mass for recycling.
- Maximise energy generation.
- Fully utilise, where possible, existing assets at Davyhulme.
- Replace the ageing lime facilities at seven sites.
- Reduce the Company's carbon dioxide emissions by 21%.

5.3.3 Upgraded Class A biosolids for agriculture in Washington DC, USA

The utility companies in UK distributes sludge to farmers mostly for free, either as dewatered and limed raw sludge or after the THP pre-treatment before anaerobic digestion and post-dewatered sludge. 95% of the sludge with nutrients and important minerals is hence recirculated either to agriculture or land improvements in one way or another. However, as there is only a limited suitable area available the utility companies are willing to hand out this organic land improvement for free.

DC Water in Washington DC, USA, who uses the same THP, AD and dewatering process as in the UK in their Blue Plains STP and thereby producing a similar end-product, has successfully been able to brand and market their biosolids product to paying customers in the DC region under the trademark "Bloom". They emphasise towards the public the circular economy effect both when it comes to nutrients and minerals in the soils as well as the biogas energy captured from the processing. Furthermore, the slow release of both nitrogen and phosphorus in this soil-improver is marketed as a positive characteristic. Circular economy arguments in combination with high quality product is now giving a positive value for different segments. The director of resource recovery in DC Waster, Chris Peot, explains the success of the marketing strategy through product differentiation and stagewise introduction (Peot, 2020): "Fresh Bloom" is a biosolids straight from process for farming and industrial application. The product freshness limits the use in home gardening that prefers "Cured Bloom (100% Bloom)". This dried/windrowed material is granular and easy to use and has a higher nutrient content. The last category is "Blended product" where upgraded biosolids is blended with wood chips or sand sawdust to improve texture and concentrate organic matter.

DC Water got a permit to market the first product in 2016 but jump-starting one year earlier by giving out free samples. The volume has increases steadily ever since, with first daily production sell-out in 2018, first bagged product in stores same year and month sell-out in April 2019. The successful DC Water strategy for marketing of "Bloom" had five key elements:

1. focus on soil blenders, landscapers, nurseries, bulk suppliers, turf growers, farms, government agencies
2. trade shows, public speaking and tours
3. employee and community giveaways

4. purchased our own delivery vehicles and
5. low price for early adopters, but otherwise insisting on market rate.

The cost implications for DC Water have been a reduction in average cost of previously lime-stabilized raw sludge cake at more than $22 mill. per year to less than $5 mill today. The amount was reduced from 1200 tons per day of lime-stabilized cake to less than 450 tons per day of Class A cake, and the average disposal cost per tonne of about $50 to average disposal cost today of less than USD 30 and sinking as more and more of the Class A cake is sold as Bloomsoil products.

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Appendix A

Technologies recommended from EPA 503 Rule summarized below.

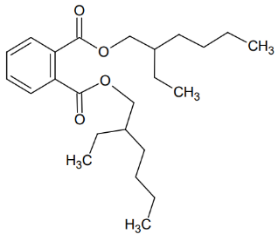
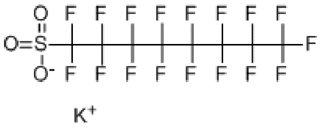
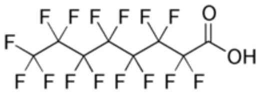
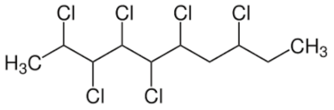
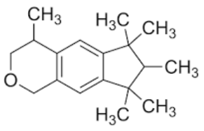
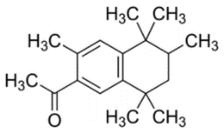
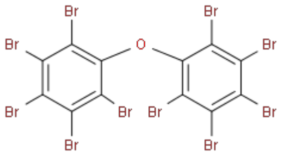
Tech Type	**Technology**	**Class B**	**Class A**
PSRP & PFRP	Aerobic Digestion	Between SRT 40 days @20C and SRT 60 days @15C	Thermophilic Aerobic Digestion – SRT 10 days @ 55-60 ^{0}C
	Drying	Air Drying - on paved/unpaved basins for min 3 months	Heat Drying – Dried to ≥ 90% Solids
	Anaerobic Digestion	SRT 15 days @35 - 55C SRT 60 days @20C	
	Composting	Within vessel/static aerated pile/windrow ≥ 40 C for 5 days & > 55 C for 4 hrs	Within vessel/static aerated pile ≥ 55 ^{0}C for 3 days Windrow ≥ 55 ^{0}C for 15 days
PSRP	Lime Stabilization	pH = 12 for 2 hrs	NA
PFRP	Heat Treatment	NA	≥ 180 ^{0}C for 30 mins
	Pasteurization	NA	≥ 70 ^{0}C for ≥ 30 mins
	Beta Ray Irradiation	NA	≥ 1 megarad at room temperature
	Gamma Ray Irradiation	NA	Gamma ray irradiation at room temperature
Class A - Alt 1	Time – Temp	NA	For < 7% Solids $D = 50{,}070{,}000 / 10^{0.14t}$ For other $D = 131{,}700{,}000 / 10^{0.14t}$ D = days; t = temp in ^{0}C
Class A - Alt 2	High pH & Temp	NA	0 – 72 hr = pH 12 of which 12 hr = pH 12 & Temp > 52 ^{0}C > 72 hr = Air drying to 50% solids

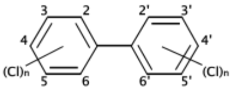
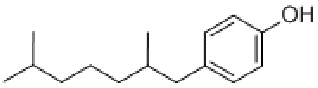
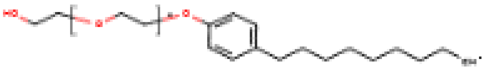
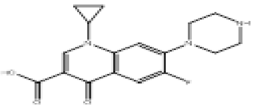
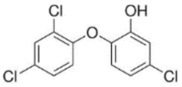
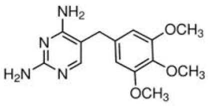
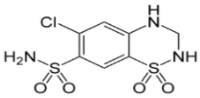
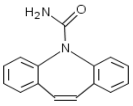
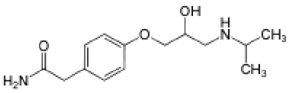
The above are only recommended technologies by EPA. Installation of the above recommended technologies do not waive the requirement to meet the Fecal Coliform/Salmonella Standards required by Class A. No matter what technology is installed, the biosolids must meet the standards for Fecal Coliform/Salmonella at the point of use. There are several other technologies that have demonstrated meeting the Class A requirement. Some of the common technologies used for Class A are:

THP, TPAD, Thermophilic, and enzymatic hydrolysis. Other technologies that are entering the market are: UV, Chemical Disinfection, Pyrolysis, Gasification, and Wet air oxidation.

Appendix B

Overview of structures of selected well-known - and regulated - and ECs commonly measured in influent, effluent, and sewage sludge. The structures and functional groups influence strongly on the chemicals' fate during the treatment processes.

Name/Compound type (common abbrev.)	**Structure**
Diethylhexyl Phthalate/Phthalate(DEHP)	
Perfluorinated octane sulfonate/ Synthetic perfluorinated compound (PFOS)	
Perfluorinated octanoic carboxylic acid/Synthetic perfluorinated compound (PFOA)	
Short-chain chlorinated paraffins (C10-13)/Chloroparaffins (SCCP)	Mixture of chlorinated alkanes with various degree of chlorination, e.g. 2,3,4,5,6,8-hexachlorodecane 
Galaxolide/Polycyclic musk (HHCB)	
Tonalide/Polycyclic musk (AHTN)	
Decabromo- diphenyl ether/brominated diphenyl ether (BDE-209, Deca-BCE)	

Name/Compound type (common abbrev.)	**Structure**
Polychlorinated Biphenyls/poly chlorinated biphenyls (PCBs)	
Nonylphenol/Surfactant (NP)	 Several isomers
nonyl phenol ethoxylates/Surfactant (NPE)	
Ciprofloxacin	
Triclosan	
Trimethoprim	
Hydrochloro-thiazide/Diabetic	
Carbamazepine/Psychiantric drugs	
Atenolol/Beta-blo	

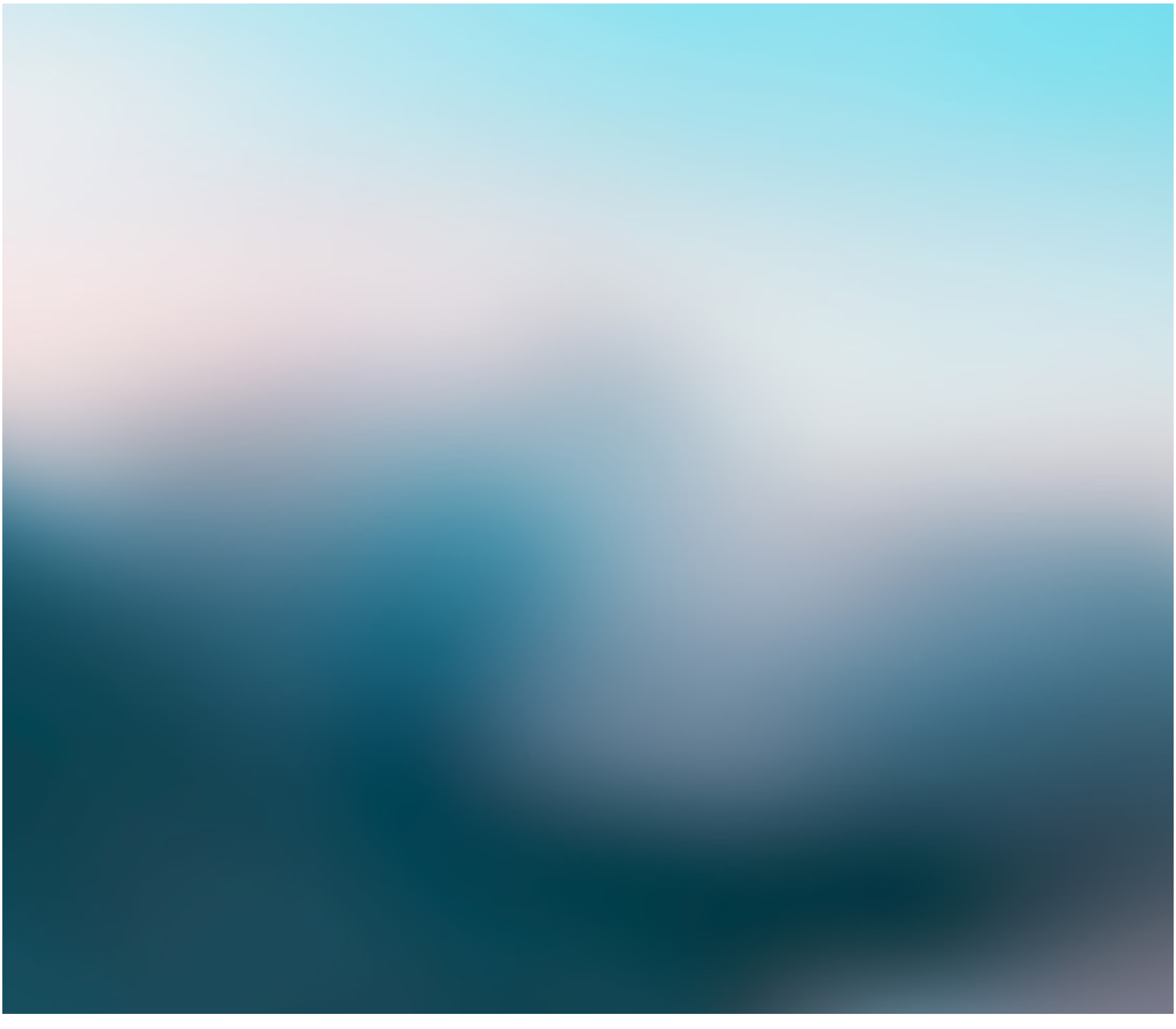
NIBIO
NORSK INSTITUTT FOR
BIOØKONOMI

Norsk institutt for bioøkonomi (NIBIO) ble opprettet 1. juli 2015 som en fusjon av Bioforsk, Norsk institutt for landbruksøkonomisk forskning (NILF) og Norsk institutt for skog og landskap.

Bioøkonomi baserer seg på utnyttelse og forvaltning av biologiske ressurser fra jord og hav, fremfor en fossil økonomi som er basert på kull, olje og gass. NIBIO skal være nasjonalt ledende for utvikling av kunnskap om bioøkonomi.

Gjennom forskning og kunnskapsproduksjon skal instituttet bidra til matsikkerhet, bærekraftig ressursforvaltning, innovasjon og verdiskaping innenfor verdikjedene for mat, skog og andre biobaserte næringer. Instituttet skal levere forskning, forvaltningsstøtte og kunnskap til anvendelse i nasjonal beredskap, forvaltning, næringsliv og samfunnet for øvrig.

NIBIO er eid av Landbruks- og matdepartementet som et forvaltningsorgan med særskilte fullmakter og eget styre. Hovedkontoret er på Ås. Instituttet har flere regionale enheter og et avdelingskontor i Oslo.



Front side photo: Ragnar Våga Pedersen/NIBIO

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