Sludge Management: Current Scenario, Available Solutions and Way Forward

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ABSTRACT

Sewage sludge is a consequence of wastewater treatment that is produced in vast amounts all over the world, posing the responsibility of properly handling organic waste. The two primary disposal techniques for municipal sewage sludge management are reuse, which includes agricultural or landscaping applications, and ultimate disposal. Because there are a variety of concerns with final disposal techniques across the world, preparing sewage sludge for reuse, also known as sludge processing, provides another option. The goal of this review paper was to investigate sludge management strategies throughout the world and highlight its use in the agricultural sector in developing nations like India. The use of sewage sludge as a fertilizer is ecologically beneficial and results in the reuse of potentially hazardous wastes, in addition to contributing in waste reduction. The quantity of heavy metals, on the other hand, is the most significant criteria for the safe use of sewage sludge in agriculture, followed by pathogen reduction. If sewage sludge is correctly processed with appropriate technology, it has the potential to lessen our dependency on chemical fertilizers and so fall within the scope of our government's 'waste to wealth' initiative.

Keywords: Sludge, Agriculture, Technology, Management practices, Fertilizer

Introduction

Sewage sludge is a byproduct of wastewater treatment that is mass-produced all over the world. Municipal sewage sludge is generally termed as sewage sludge which is produced after the municipal wastewater treatment process. It contains organic and inorganic components, as well as a high concentration of nutrients, organic compounds, and pathogenic organisms. Therefore, proper treatment of the sludge is critically important in order to reduce the sludge's environmental impact. This organic waste must be carefully managed due to massive sewage sludge production all over the world. For the complete and suitable management of the municipal sewage is mainly depend on the two strategies, one is its reuse for agriculture or landscaping and second is the final disposal. There are several ways for reusing sewage sludge, but there are also many limitations to using a particular management strategy (Kacprzak et al., 2017). The recovery, or recycling or recovery of organic compounds, is the most essential notion linked with the transformation of sewage sludge (Petric et al., 2022). The global population is growing and condensing in metropolitan areas and this trend is especially pronounced in emerging nations and as per the United Nation (2012) reports, an extra 2.1 billion people are predicted to live in cities by 2030 (Martin, 2012).

Every year, urban cities generate billions of tonnes of trash, including sludge and wastewater. These wastes can have a variety of outcomes depending on the local context: they can be collected or not, treated or not, and eventually used directly, indirectly, or not at all. With few and partial exceptions, data on these waste streams is rare and dispersed in the literature, and thorough studies and analyses at the global level are lacking. However, recent initiatives by global organizations such as the FAO/IWMI through AQUASTAT, UN-Habitat (2008), and the Global Water Intelligence (GWI 2014) have allowed these evaluations to be renewed and updated (Mateo-Sagasta, 2015; Gude, 2016).

Water, organic matter, energy, and nutrients (e.g., nitrogen and phosphorus) are all significant resources in municipal wastewater and sludge that may be recovered for a variety of economic, social, and environmental objectives. Sludge / sewage sludge is created when suspended particles are removed from wastewater and soluble organic compounds are transformed to bacterial biomass, which is then added to the sludge (Figure 1).

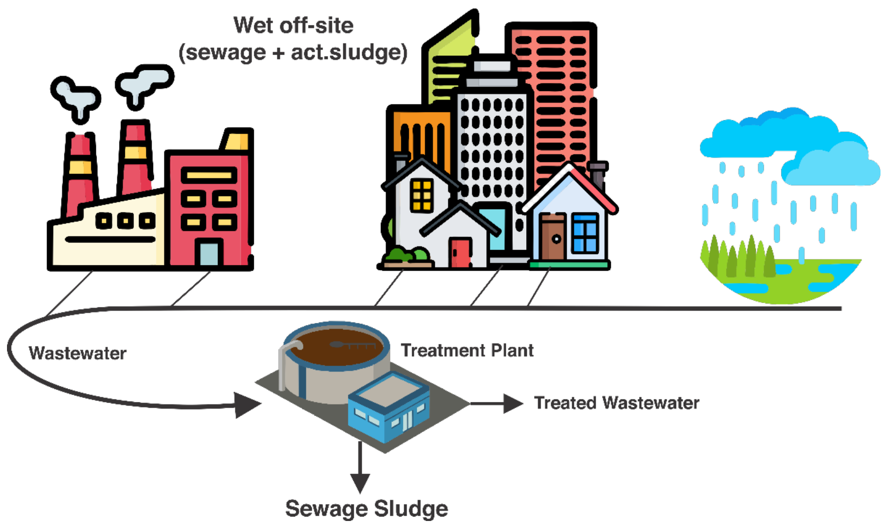


Figure 1. Sewage Sludge Production Process

Worldwide Sludge Treatment, Statistics and Processing

For wastewater treatment plants, the World Water Environment Federation (WEF) has adopted the "NEW" paradigm (Nutrient-Energy-Water). This concept is centered on converting individual wastewater treatment plants into units that produce recovered resources. Climate change and population shifts are the foundations of this paradigm, as increasing biogenic contamination of water, which accelerates the eutrophication process, and the need for sustainable development. Developed countries now have the biggest sewage sludge output (Yesil et al., 2021). Sludge utilization is largely limited to sewage sludge and biosolids, and it is only reported in industrialized nations (LeBlanc et al., 2009). Many of these nations had trouble disposing of sewage sludge from treatment facilities after recognizing that traditional sewage sludge disposal in landfills was no longer an option.

With the increased use of wastewater treatment, many nations are tackling one problem while creating a new one: managing or disposing of sewage sludge. While wastewater treatment results in cleaner water being released to oceans, rivers, and lakes, it also results in a substantial volume of sewage sludge being created (Table 1).

Table 1. Sewage Sludge Production from Urban Wastewater Treatment Plants

GEO/TIME	2014	2015	2016	2017	2018	2019
Bulgaria	54.90	57.40	65.80	68.60	53.10	:
Czechia	238.59	210.24	206.71	223.27	228.22	221.09
Denmark	:	:	:	:	:	:
Germany (until 1990 former territory of the FRG)	1,830.82	1,820.57	1,794.36	1,785.55	1,761.62	1,749.86
Estonia	19.91	19.11	18.65	20.94	25.54	24.94
Ireland	53.54	58.39	56.02	58.77	55.23	58.63
Greece	116.11	119.77	119.77	103.28	103.28	:
Spain	1,131.60	1,152.60	1,174.40	1,192.00	1,210.40	:
France	1,059.00	1,238.00	1,006.00	1,174.00	:	:
Croatia	16.31	17.94	19.72	17.60	19.23	20.65
Italy	:	:	:	:	:	:
Cyprus	6.16	6.70	7.41	7.17	8.41	:
Latvia	22.08	21.92	25.92	24.94	24.59	24.18
Lithuania	40.71	44.45	44.42	42.49	44.19	39.94
Luxembourg	:	9.16	8.92	9.32	9.08	8.89
Hungary	163.12	177.70	217.96	266.84	233.66	227.89
Malta	8.50	8.44	10.77	10.30	8.28	9.69
Netherlands	345.00	354.60	347.60	:	341.03	:
Austria	239.04	:	237.94	:	234.48	233.56
Poland	556.00	568.00	568.33	584.45	583.07	574.64
Portugal	85.89	:	119.17	:	:	:
Romania	192.33	210.45	240.41	283.34	247.76	230.59
Slovenia	28.30	29.10	32.80	36.70	38.10	34.80
Slovakia	56.88	56.24	53.05	54.52	55.93	54.83
Finland	115.70	146.00	146.99	161.19	146.62	:
Sweden	200.50	197.50	204.30	205.60	211.60	:
Iceland	:	:	:	:	:	:
Norway	:	:	:	:	147.60	141.35
Switzerland	:	:	:	177.00	:	:
United Kingdom	:	:	:	:	:	:
Albania	91.00	91.54	94.50	98.12	94.50	96.20
Serbia	8.30	10.80	11.20	13.30	9.60	9.60
Turkey	:	:	299.30	:	318.50	:
Bosnia and Herzegovina	1.30	1.30	9.50	9.50	9.50	9.50

** Data in Thousand tonnes*

(Source: EUROSTAT, 2022)

This data demonstrates that, in different nations how much sludge was produced after the wastewater treatment and undoubtedly it shows that various national governments are concerned about the water management and environment, but sludge disposal data is also parallelly important. Based on the statistical data of Eurostat (2019), the worldwide disposal of sewage sludge using different disposal methods, is shown in Table 2 and Figure 2.

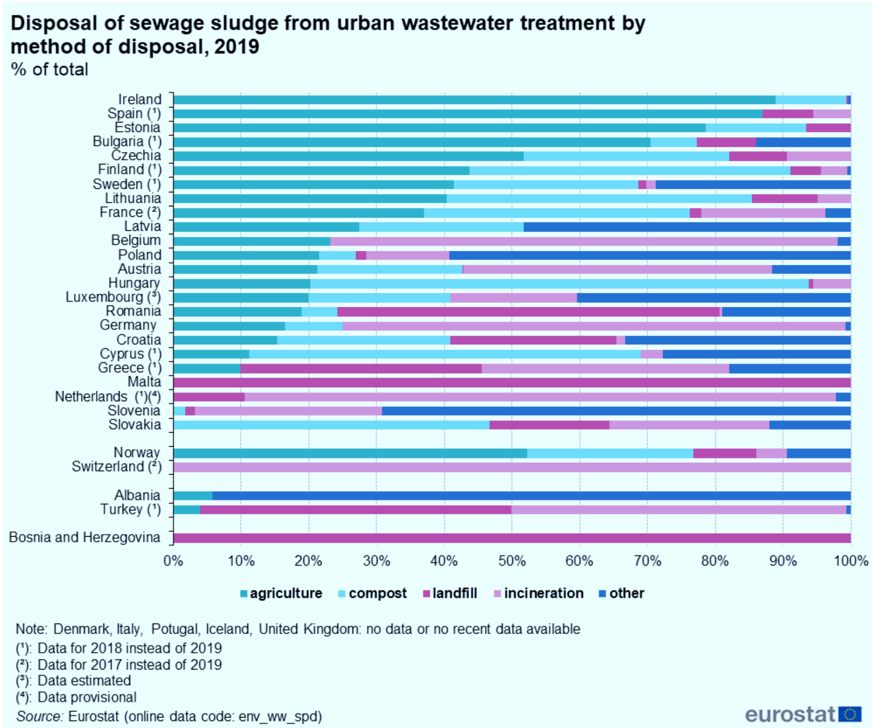
Table 2. Total Sewage sludge disposal from urban wastewater treatment plants

GEO/TIME	2014	2015	2016	2017	2018	2019
Belgium	157.53	153.62	158.95	151.65	155.48	154.62
Bulgaria	32.60	47.20	47.10	45.30	42.30	:

GEO/TIME	2014	2015	2016	2017	2018	2019
Czechia	238.59	210.24	206.71	223.27	228.22	221.09
Denmark	:	:	:	:	:	:
Germany (until 1990 former territory of the FRG)	1,802.99	1,803.09	1,773.19	1,713.19	1,747.23	1,740.09
Estonia	18.37	17.93	17.11	19.13	20.13	22.33
Ireland	53.54	58.39	56.02	58.77	55.23	58.63
Greece	118.61	119.77	119.77	103.28	103.28	:
Spain	1,131.60	1,152.60	1,174.40	1,192.00	1,210.40	:
France	986.00	833.00	801.00	809.00	:	:
Croatia	15.44	17.41	8.43	3.37	3.95	3.07
Italy	:	:	:	:	:	:
Cyprus	6.16	6.70	7.41	7.17	8.41	:
Latvia	22.71	22.80	25.19	24.47	24.13	22.66
Lithuania	23.17	26.78	28.96	40.87	38.68	37.31
Luxembourg	:	9.16	8.92	9.32	9.08	8.89
Hungary	105.73	102.48	216.59	241.76	231.48	217.12
Malta	8.50	8.44	10.77	10.30	8.28	9.69
Netherlands	319.70	325.36	325.13	:	303.75	:
Austria	239.04	:	237.94	:	234.48	233.56
Poland	556.00	568.00	568.33	584.45	583.07	574.64
Portugal	:	:	:	:	:	:
Romania	192.33	155.81	240.41	283.34	247.76	230.59
Slovenia	28.00	29.00	32.70	36.60	38.00	34.80
Slovakia	56.88	56.24	53.05	54.52	55.93	54.83
Finland	:	:	146.99	161.19	146.62	:
Sweden	183.90	:	191.40	:	198.90	:
Iceland	:	:	:	:	:	:
Norway	122.30	114.40	113.80	121.30	111.70	108.37
Switzerland	:	:	:	177.00	:	:
United Kingdom	:	:	:	:	:	:
Albania	91.00	91.54	94.50	98.12	94.50	96.20
Serbia	8.30	10.80	8.30	13.00	9.50	8.10
Turkey	:	:	266.45	:	288.91	:
Bosnia and Herzegovina	1.30	1.30	9.50	9.50	9.50	9.50

** Data in Thousand tonnes*

(Source: EUROSTAT, 2022)



(Source: EUROSTAT, 2022)

Figure 2 . Disposal of sewage sludge from urban wastewater treatment

Sludge Characteristics

The origin and quantity of flushing water (public toilet, private toilet), its collection type (on-site, off-site), and subsequent treatment degree, such as digesting, all influence the properties of sludge. Raw and processed sewage sludge have different characteristics, as seen in Table 3. (Kacprzak et al., 2017). Fresh, untreated sludge has many pathogens, contains a large amount of water, has a high biochemical oxygen demand (BOD), and is typically rotten and odorous. Once stabilized, the organic carbon in the sludge can be used as a soil conditioner, improving soil structure for plant roots, or converted into energy by bio-digestion or cremation. Because sewage may obtain dangerous contaminants (e.g., heavy metals, pharmaceuticals) from industry and other activities that might build in its sludge, sludge collected from on-site systems is usually regarded safer for reuse unless homeowners utilize their toilets for general waste disposal.

Table 3 . Comparison between raw and digested sludge

Raw sewage sludge
High water content High biodegradable fraction in the organic matter High potential in the generation of odors High concer

The better management of sludge in a technical manner and its subsequent processing can be understand by different step wise step process as shown in figure 3 which includes two crucial steps i.e., primary and secondary settling sludge (Janosz Rajczyk, 2014).

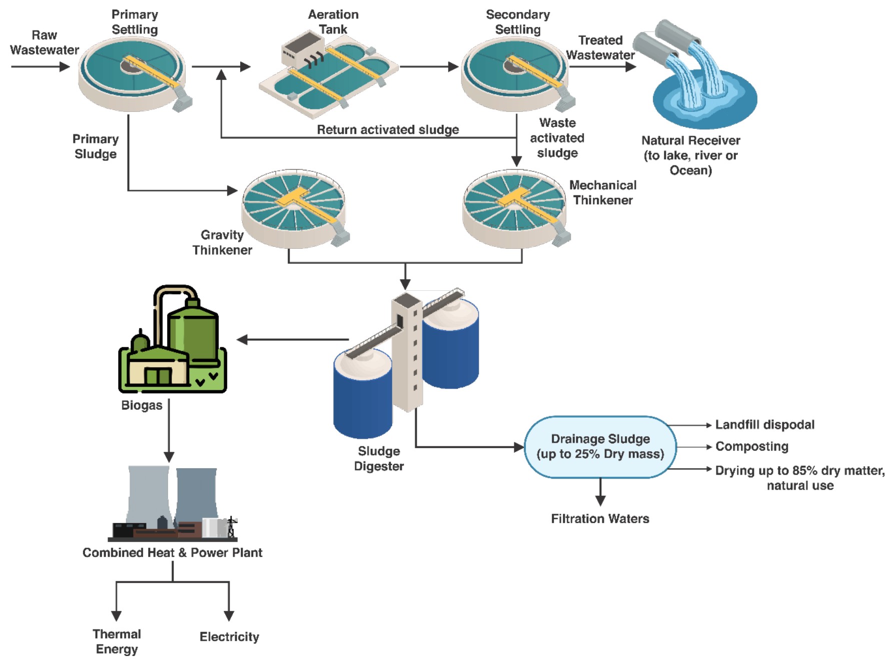


Figure 3. Generation of sewage sludge in the sewage treatment plant

Each treatment plant generates sludge with different physicochemical properties whose common features include: high water content (from 99% in the case of raw sewage sludge, 55%–80% for dewatered sludge and below 10% for thermally dried sludge), high organic components (from 75% d.m. in raw sludge to 45%–55% d.m. in stabilized sludge), high content of nitrogen compounds (2%–7% d.m.) and lower content of phosphorus and potassium (Yu et al., 2019).

Heavy metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), adsorbable organic halides (AOXs), polychlorinated dibenzodioxins (PCDDs), and polychlorinated dibenzofurans are examples of potentially harmful pollutants present in the treated sewage (Saravanan et al., 2021). Due to the existence of many harmful organisms, sewage sludge that has not been treated in the hygiene procedures might provide an epidemiological risk. *Ascaris lumbricoides, Trichuris sp.* , and *Toxocara sp.* are the most common parasite eggs recovered from sewage sludge (Kacprzak et al., 2015; Reimers et al., 1986). *Escherichia coli, Salmonella spp., Shigella spp., Bacillus anthracis, Pseudomonas aeruginosa, Listeria monocytogenes, Vibrio cholerae, Proteus vulgaris, Clostridium perfringens, Mycobacterium tuberculosis,* and *Streptococcus pyogenes* are among the microorganisms found in sewage. Viruses, particularly polyviruses that cause poliomyelitis, rotaviruses, and HIV and HCV viruses, are among the many harmful microbes. Fungi, such as Penicillium, Verticillium, Mortierelta, Fusarium, Aspergillus, Mucor, Geotrichum, and Trichoderma, are the most often isolated microbes from sewage sludge (Pepper et al., 2006; Amin, 1988). Different physicochemical components and parameters of a municipal sewage sludge is shown in Table 4.

Table 4. Characteristics of municipal sewage sludge

Parameter	**Type of sludge** **Untreated primary sludge**	**Type of sludge** **Digested primary sludge**	**Type of sludge** **Digested prima**
		Poor	Moderate
pH	5.0-7.0	6.5-7.0	6.8-7.3
Total dry solids-TS (%)	2.0-8.0	4-12	4-12
Volatile solids (% of TS)	60-80	55-80	55-80
Volatile fatty acids ($mgCH_3COOH/dm^3$)	1800-3600	2500-4000	1000-2500

Nitrogen (% of TS)	2-7	1-5	1-3.5
Phosphorus (% of TS)	0.4-3	0.9-1.5	0.8-2.6
Potassium (% of TS)	0.1-0.7	0.1-0.3	0.1-0.3
Filtration option (m/Kg)	10^{11}-10^{13}	51.0^{11}-5.10^{13}	10^{11}-10^{12}
Heating value (kJ/g)	16-20	15-18	12.5-16

(Source: Grobelak, et al., 2019)

Both sludge and wastewater include organic pollutants that are high in three nutrients (NPK), which may be recovered and used in a variety of ways. Because nutrients are concentrated in sewage flows arising from urine (the richest), human excreta, and detergents (both rich in P), the sludge is accurately referred to as 'organic concentrates.'. These nutrients can be utilized for agriculture and other reasons, while the organic carbon can be used as a soil conditioner or a natural fertilizer (Karamina et al., 2020).

Sludge Processing

Thickening is frequently the initial stage in sludge treatment which is carried out in a tank known as a gravity thickener (Pahl et al., 2013). A thickener may decrease sludge volume to less than half of its original size. The sludge digesting process begins once all the solids from the sewage sludge have been collected. This is a process that decomposes the organic materials in the sludge into stable chemicals. The sludge then flows into the second tank where it is converted by other bacteria to produce a mixture of carbon dioxide (CO_2) and methane (Gurjar, 2021). The leftover sludge is dewatered before ultimate disposal after valuable gases and other byproducts have been extracted. Despite its hardened appearance, dewatered sludge frequently includes a large quantity of water, up to 70% in certain situations. Depending on its chemical makeup, sludge can be buried underground in a sanitary landfill or utilized as fertilizer once it has been adequately dewatered (Lee et al., 2018). If the sludge is too poisonous to be reused or buried, it can be incinerated and turned into ash (Zhou et al., 2020). While sewage sludge is typically treated with a standard plan of action, it is critical to consider factors such as the source of the sewage, the treatment process used to reduce the sewage to sludge, and the possible byproducts that can be recovered from it for further use before deciding on a sludge treatment plan.

Pathogen removal is another big task in the sludge treatment. Sludge pathogenicity can be lowered significantly using stabilizing procedures like as aerobic or anaerobic digestion. In wastewater treatment, the term digestion refers to the stabilization of organic materials by bacteria under contact with sludge in circumstances that are advantageous for their development and reproduction. Anaerobic, aerobic, or a mix of both digestion processes are possible. There is different process involved in the pathogenesis treatment which are incorporated in tabular form (Table 5) with the mark of their importance.

Table 5 . Comparison of various sludge pathogens removal technologies

	Against pathogens	**Against pathogens**	**Against pathogens**	**Sludge**	**Sludge**	**Sludge**	
Process	**Bacteria**	**Viruses**	**Eggs**	**Sludge stability**	**Volume reduction**	**Odor potential**	**Remarks**
Composting	+++	++	+++	+++	|	+++	Effect depends on mixture

	Against pathogens	**Against pathogens**	**Against pathogens**	**Sludge**	**Sludge**	**Sludge**	
Autothermal aerobic digestion	+++	+++	+++	++	++	++	Effect depends on operational regime
Pasteurization	+++	+++	+++	++	+	++	Must be previously stabilized
Lime treatment	+++	+++	+++	++	|	+++	Effect depends on maintaining pH
Thermal drying	+++	+++	+++	+++	+++	+	Stabilization and total inactivation
Incineration	+++	+++	+++	+++	+++	+	Stabilization and total inactivation

(Source: Andreoli et al., 2007)

+++: Significant importance; ++: Moderate importance; +: Little or non-existent importance

|: Volume increase

To generate pathogen-free sludge, operators must ensure that Salmonella, enteroviruses, and viable helminth eggs concentrations are below the present analytical methodology's detection criteria. Other species are likely to be below the permissible limits if the quantities of these indicator organisms are kept under control (Bergwerff, & Debast, 2021). Viruses and helminths cannot reappear in the sludge after being inactivated, unless in the case of external recontamination, and if the sludge is sufficiently stabilized, ambient parameters (temperature and pH) are controlled, and there is no cross-contamination.

Assessment of sludge treatment and disposal alternatives

Sludge final disposal is influenced by the plant's conceptual design, which influences sludge amount and characteristics, as well as unit activities such as sludge stabilization, dewatering, pathogen removal, storage, and handling. Due to poor planning, a lot of treatment facilities lack the basic infrastructure required for such operations, necessitating retrofitting in order to effectively operate the generated sludge (Spinosa & Doshi, 2021). Sludge processing and final technologies are selected based on the type, size, and location of the treatment facility (Wu et al., 2019). For the selection of processing and/or final disposal choices, there can be no fixed rule, but rather a careful analysis on a case-by-case basis to pick the best available option in terms of operational and economic issues. A flow chart of proper sludge disposal is shown in figure 4.

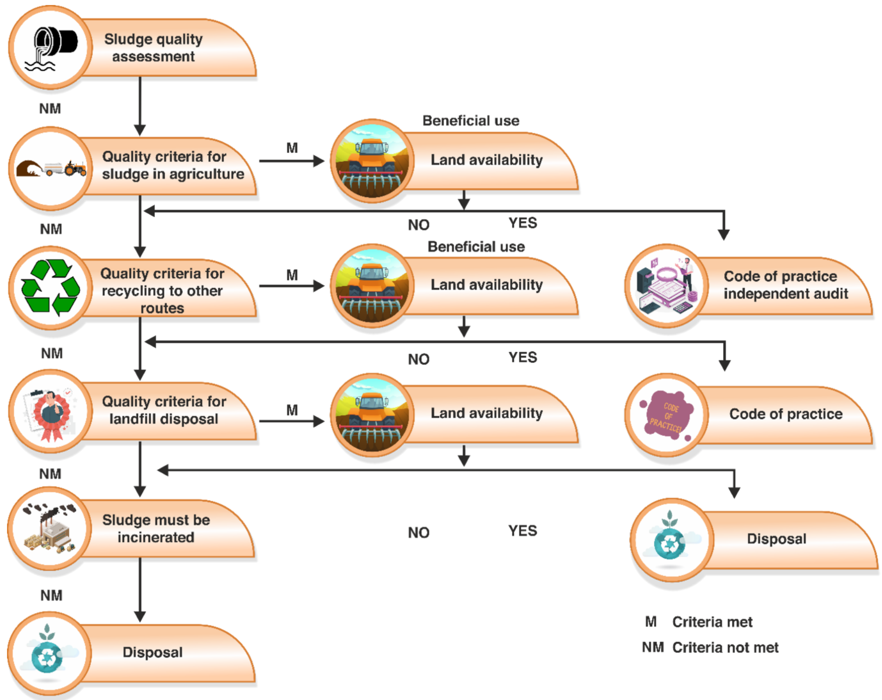


Figure 4. Simplified flow-chart for identifying sludge disposal or recycling routes

Landfilling or incineration should only be considered from a sustainable standpoint if the sludge quality renders beneficial usage impossible. Several nations have previously enacted economic and legal tools to encourage sludge recycling while tightening landfill restrictions, significantly influencing decisions about the final disposal of wastewater sludges.

Sludge Management Trends in Developed Nations

As a result of the expansion of sewage and treatment systems in many affluent nations as well as sections of the developing globe, sludge output is skyrocketing. More stricter rules in terms of higher biosolids quality are increasingly being implemented in tandem with the growth in sludge production, with the goal of minimizing negative sanitary and environmental repercussions (Rolsky et al., 2020). Mechanical dewatering systems have gained popularity due to their increased water removal efficiency; additionally, there is growing interest in thermal drying, sludge palletization, and other advanced biosolids quality-improving processes such as composting, alkaline stabilization, and a number of patented systems (Hyrycz et al., 2022). Because of rising transportation costs and environmental regulations, landfills are gradually being recognized as unviable. Disposal options for agricultural techniques must be guided by strong technological principles in order to ensure an ecologically safe and cost-effective means of increasing farmers' revenue (Zhou et al., 2020). As quality and environmental regulations become more stringent, the expense of such operations is on the rise.

Many factors influence sludge management strategies in different nations, the most significant of which are population density, arable land area, economic considerations, and societal acceptability. Minimization of trash output is desired followed by recycling in the European and North American countries. For example, by land application if possible, however, landfilling is usually not a good solution in these countries. In contrast, more sludge is landfilled or disposed of on uncontrolled areas in developing nations like India. European and North American industrialized countries have complex law frameworks for sewage sludge control. Sewage sludge management in the EU is regulated both at the international level (by directives) and at the national level. In general, there are three types of legal regulations regarding sewage sludge in EU member states:

- EU directives and other legal acts
- Laws of EU member states created to implement EU directives
- Standards and norms from non-EU countries.

Waste recycling, including sewage sludge, is governed by the Waste Framework Directive (European Parliament and Council Directive 2008/98/EC on sewage). According to the directive, the first priority is waste avoidance, followed by waste preparation for reuse, recycling, or other types of recovery, and ultimately garbage disposal.

In general, the use of sewage sludge for agricultural purposes has increased considerably across recent years in Europe (Placek et al., 2017). The direct use of sewage sludge in agriculture and for land restoration in the EU is controlled by Sludge Use in Agriculture Directive 86/278/EEC. According to this guideline, the use of sewage sludge shall not have an adverse effect on soil quality or yield. When the concentration of heavy metals in sludge and soil exceeds the directive's limitations, the use of sewage sludge is forbidden. Stricter regulations have been established for agricultural compost use. The use of sludge for agricultural purposes is prohibited across several German states too, and Germany is also regarded as a pioneer in phosphorus recovery from sludge (Mininni and Dentel, 2013). The majority of created sludge in the United States is utilized on agriculture (Christodoulou and Stamatelatou, 2016). In the United States, agricultural sludge usage is governed by the "Standards for the Use or Disposal of Sewage Sludge," which were created in 1993 (40 CFR Part 503). Around the world, sewage sludge is utilised in agriculture (37%), incineration (11%), and landfill (40%), with the remaining 12% employed in forestry or land restoration (Fytili and Zabaniotou, 2008).

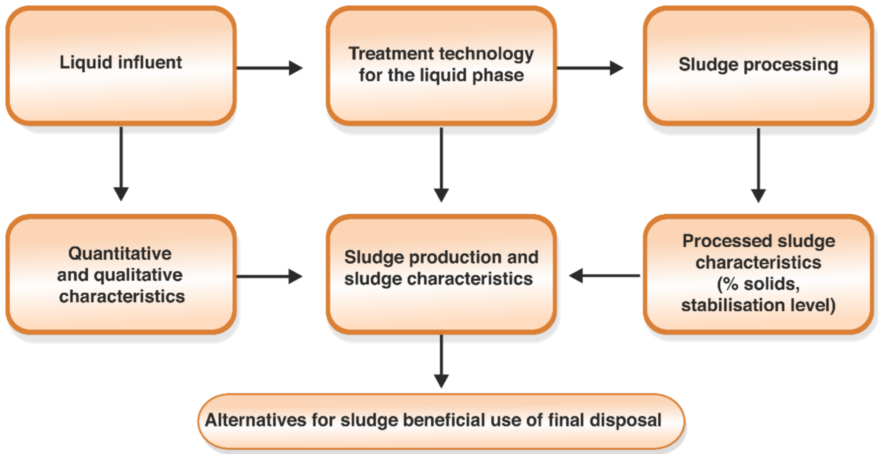
Currently, the EU has greater regulations than the US, particularly in terms of metal standards. The usage of sludge in these nations is frequently restricted due to its nitrogen concentration, as the EU's permissible nitrogen application rate has been cut from 210 kgN/ha to 170 kgN/ha (Botter et al., 2020). Odor issues during sludge processing and storage are by far the most important factor affecting public acceptance. Serious alternatives are being investigated, as some development in processing technologies has lately been achieved, as more and more rules aimed at safe sludge in terms of metal content and sanitary concerns have been enacted. An effective sludge management technique, on the other hand, requires community participation, as well as proper information and transparent findings from the environmental monitoring program (Shaddel et al., 2019). The principal biosolids are listed in Table 6 below.

Table 6 . Biosolid management trends in the United States and Europe

Processes	**United States**	**Europe**
Sludge production	Increasing	Increasing
More efficient dewatering processes	Increasing	Increasing
More advanced techniques for pathogen removal	Increasing	Increasing
Sludge recycling	Increasing	Increasing
Landfill disposal	Decreasing	Decreasing
Incineration	Decreasing	Increasing
Ocean disposal	Banned	Decreasing
Legal requirements	Increasing	Increasing
Metal concentrations in biosolid	Decreasing	Decreasing
Power efficiency and energy recovery	Increasing	Increasing
Biosolids management outsourcing	Increasing	Increasing
Biosolids management costs	Increasing	Increasing
Social demands related to environmental conditions	Increasing	Increasing
Farmers' demands regarding biosolids quality	Increasing	Increasing

(Source: Andreoli et al., 2007)

Demands for higher environmental quality from society and environmental organizations are being absorbed by public and commercial water and sanitation corporations in emerging nations like India. In these nations, wastewater treatment plants are progressively being installed, resulting in a rise in sludge production. Before financing and/or licensing a wastewater treatment facility, certain nations have recently published land application standards that now demand a workable sludge disposal plan. A relationship chart between influent sewage, treatment technique, sludge generation, and disposal alternatives are shown in Figure 4.



(Source: Andreoli et al., 2007)

Figure 4 . Relationship chart of sewage, treatment technology, generated sludge and the disposal options

A successful sludge management technique should not be limited to the solid waste created by the process, but should interact with and influence the whole wastewater treatment system, including the entire sludge cycle from generation to disposal (Johnson & Affam, 2019). All factors of wastewater quality, treatment technology, sludge production size, environmental laws and local regulations, and soil and area agriculture must be examined before any assessment of sludge processing possibilities can be made.

One of the most crucial problems concerns future policy orientations for sludge management. Are they biological, ecologically beneficial, and allow for the recycling of nutrients into the environment? The issue is the scarcity of arable land and the poor quality of sludge. Measures and methods to enhance sludge quality, such as heavy metals leaching from this waste material, are critical. Furthermore, circular economy technologies, such as phosphorus recovery from sludge, offer a viable alternative to traditional management strategies. Composting sewage sludge is one option for direct agricultural usage. This approach ensures sludge stability, pathogen killing, and a decrease in sludge bulk and water content. Aside from sludge disposal, one significant goal of composting is the ability to reuse sludge in the economy and the environment. Thermal treatment of sewage sludge based on incineration and co-incineration are suitable procedures that are becoming more prevalent in EU nations, according to data. It's also popular in Japan. Thermal treatments are expensive, and in certain countries, there is little societal approval for burning garbage. As a result, this form of sludge disposal is one of the most contentious, and its use is influenced by a variety of local conditions.

Applications of Sewage Sludge

Organic matter has been regarded a significant soil fertilizer for thousands of years, and organic wastes from human activities were employed as fertilizers by Chinese, Japanese, and Indians in ancient times (Kiehl, 1985; Poudyal, 2020). The most common approach of sludge management is land use or land application, which was first conceived in the form of sewage disposal throughout the nineteenth and twentieth centuries. However, as technology has progressed, sewage is now subjected to specific procedures such as primary, secondary, and even tertiary treatment in order to remove particles in the form of sewage sludge, which is subsequently disposed of.

Land Application: Beneficial Uses and its impact on environment

Sludge consists of nutrients that are important to plants, and their availability is dependent on the quality of the influent sewage and the wastewater and sludge treatment techniques utilized (Tarpani, & Azapagic, 2018). Except in the sludge treated by alkaline stabilization, nitrogen and phosphorus are abundant, whereas calcium and magnesium are few. Sludge has low levels of potassium and phosphorus. Moreover, the use of sludge on land, principally in agriculture, compared to incineration or sanitary landfill, has lower costs. The use of sludge in the agricultural sector varies greatly among different European nations (Lamastra, et al., 2018). While using sewage sludge to add nutrients and organic matter to the soil may be helpful, it also poses a danger owing to the presence of pollutants such as heavy metals, organic compounds, and infections. This, in turn, has harmful consequences on humans, plants, and animals, both terrestrial and aquatic (Balkrishna et al, 2022). Researchers, on the other hand have attempted to make use of sewage treatment plant sludge by composting it and turning it to agricultural fertilizers. This study describes the conversion of sludge to compost and its usage as a component in the production of three agricultural input products by substituting compost with farmyard manure. The physicochemical characteristics and metal content of the revised goods were found to be within the norms prescribed (our ref).

Sludge nutrient concentrations may not meet all plant demands, necessitating the use of organic or inorganic fertilizers to meet the crop's nutritional requirements (Pitas et al., 2020). Because crop plants are the most sensitive to nitrogen, it is the element in the sludge with the highest economic value. The organic component of the sludge contains the majority of the nitrogen, ranging from 70% to 90% depending on the type and age of the sludge (Quoc et al., 2021). Residues, microorganism cells generated during wastewater treatment, and phosphate-containing detergents and soaps are all sources of phosphorus in sludge. The majority of the chemical fertilization of P is fixed by the soil, and only a small amount is actually assimilated by the plants for their growth and reproduction.

Sludge can also be used as a soil conditioner, which increases pH, decreases hazardous levels of Al and Mn, supplies Ca and Mg, enhances nutrient absorption, and stimulates microbial activity (Fei et al., 2019). Organic fertilizer promotes water infiltration and retention, as well as soil stability and erosion resistance. Sludge organic content, when applied to silty clay to sandy clay soil types, causes a favorable change in texture, allowing for greater air and water circulation and hence better crop response. When added to coarse soils like sandy soil, it causes particle agglomeration, which allows for improved water retention. Sludge boosts the soil's cationic exchange capacity, functioning as a storage for nutritional materials while also increasing pH buffering and microbial activity.

According to Andreoli et al., (2007), sludge treatment on land improves the structure and fertility of waste-lands. It produces a cost-effective element with the use of chemical fertilisers, which might be reduced if sludge is used for medium-term physical, chemical, and biological changes in the soil. Table 10 shows a number of physical and chemical impacts from biosolids application on land, as well as the implications for natural resource conservation.

Table 7 . Effects of sludge land application on the soil erosion and environment

Sludge	**Soil action**	**Consequences**	**Environmental effects**
Organic content	Aggregation of soil particles CEC improvement	Increases water infiltration Increases resistance against rainfall impact Reduces nutrient leaching losses Improves soil fertility	Reduces surface run-off Reduces surface water pollution Reduces nutrients leaching and groundwater contamination

Other nutrients	Improvement of soil structure Plant nourishment	Fosters plant growth Increases microbial biomass Accelerates plant growth	Increases soil covering Improves soil aggregation

When carried out within safe parameters, land application is a low-cost option with favorable environmental effects. However, effective planning based on trustworthy information on wastewater flow and characteristics, suitable agricultural regions at reasonable distances, management capability to meet farmer demand, and good environmental monitoring are all necessary. Sludge supply must offer a decent output for farmers while also protecting public health and the environment.

Risks associated with Sludge land Application

There are in fact some drawbacks to using land application as an alternative sludge disposal practice, which includes soil contamination by metals and pathogenic organisms, and ground and surface water contamination by phosphorus and nitrogen (Liew et al., 2022). A more concerted effort can be seen around the world right now aiming for a lower chemical as well as biological contaminants in the sludge through improved wastewater technologies steadily leading towards better sewer acceptance criteria. As we have discussed the contaminants in the sludge, in this section focus in on associated risks with land application of sludge.

There are certain disadvantages to adopting land application as an alternate sludge disposal method, including soil contamination by metals and pathogenic organisms, as well as phosphorus and nitrogen pollution of ground and surface water. A more concentrated effort is currently underway across the world to reduce chemical and biological pollutants in sludge through improved wastewater technology, which is gradually leading to better sewer acceptance requirements. The main risk associated with the land application of sludge are as follows:

Metals content

When heavy metals are present in concentrations that exceed established limits, they can be harmful to human and plant health (Martin & Griswold, 2009). Because everything is concentrated in the sludge, heavy metals are frequently high in sludge (Veeken, A. H. M., & Hamelers, 1999). There should be an eye to limit all the toxic chemicals to limit the hazards. Arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), molybdenum (Mo), lead (Pb), selenium (Se), zinc (Zn), and cobalt (Co) are the principal elements of concern (Agoro et al., 2020). However, as previously stated, concentrations fluctuate depending on the source of wastewater and the treatment process used. It is a major constraint to sludge land use in various nations, including India.

Pathogens

During the treatment process, several disease-causing organisms, such as bacteria, viruses, protozoans, and helminths, tend to concentrate in the sludge and pose a serious threat to human and animal health because they can be transmitted through food, surface water, run-off water, and vectors such as insects, rodents, and birds. To reduce this danger, sludge must be subjected to a pathogen elimination procedure prior to its intended usage. The pathogen elimination method used has an impact on biosolids management, processing, and application (Lopes et al., 2020). Sludge properties are improved by alkaline stabilization, such as the addition of lime, making it more acceptable for use in soil applications (Mendez et al., 2002). Similarly, composting can be done until the sludge is completely stabilized, at which point it can be used as a soil conditioner once the organic matter has been transformed to humus.

Organic pollutants

The majority of organic contaminants are volatized during biological treatment, while some may reach the sludge processing line and contaminate the finished sludge. Pesticides, aromatic and phenolic hydrocarbons, polybrominated biphenyls (PBB) and polychlorinated biphenyls (PCB), which are very harmful and persistent organic micro-pollutants, are examples of such pollutants (Katsoyiannis & Samara, 2005). They may breakdown by solar light (photo-oxidation) and undergo volatilization or biodegradation when applied to land with sewage sludge, which may significantly affect their structure or toxicity properties. Some organic micro-pollutants are transported by capillary capillaries and reach the plant's aerial portions when absorbed directly by plant roots.

Sewage Sludge Disposal Alternatives: Pros and Cons

Dry biosolids can be spread to the ground using the same machinery as is used to apply animal manure. Pathogen-free biosolids can range in consistency from loose to solid depending on moisture content. Heat-dried granular biosolids may be handled, distributed, and land-applied with traditional agricultural equipment, such as spreaders for lime, moist lime, fertilizer, poultry litter, bedding, compost, gypsum, sand, salt, cement, fly ash, and any other bulk material. Sludge soil incorporation can also be done using traditional farming equipment, in which digested or undigested sludge is put directly below the soil surface using tractors equipped with specific ploughers that split the ground surface and inject the sludge beneath it (Kekacs et al., 2015). A summarized view of all the disposal alternatives have been presented in Table 8 with their advantages and disadvantages:

Table 8 : Advantages and disadvantages of the main methods of sludge disposal

Disposal alternative	**Advantages**	**Disadvantages**
Incineration	Drastic volume reduction Sterilization Energetic valorization of sludges Low sensitivity to sludge composition Minimization of odors, due to closed systems and high temperature	High costs Ash disposal Atmospheric pollution
Landfill disposal	Low cost	Problems with locations near urban centers Gas and landfill leachate production Difficulty in reintegrating the area after decommissioning Requirement of large areas Requirement of special soil characteristics
Thermal drying	Total destruction of organic matter and total mineralization of sewage sludge The possibility of burning both stabilized and unstable sewage sludge Up to 10-fold reduction of sludge volume Energy recovery No odor emission	Large investment cost, high operating costs Energy consumption of the installation The necessity of using pre-dried, dehydrated sediments; Emission of dusts, gases (SO_x, NO_x, HCL, HF) The need to store the resulting ashes

Composting	The possibility of burning both stabilized and unstable sewage sludge Sewage sludge mass and volume reduction Sludge water content reduction The product can be used as a fertilizer as it contains nitrogen, phosphorus, potassium, and microelements, and it improves soil properties Easy operation of the installation	Windrow and aerated static pile composting require relatively large areas, and odor control is a common problem Ambient temperatures and weather conditions influence windrow and aerated static pile composting In-vessel reactors have limited flexibility to handle changing conditions and are maintenance intensive
Agricultural reuse	Large area availability Potential as a fertilizer Positive effects for the soil Positive outcome for the crops Long-term solution	Contamination of the soil by metals Odors Limitations regarding composition and application rates Food contamination with toxic elements and pathogenic

(Source: Kwarciak-Kozłowska, 2019)

Sludge Transformation Methods

Adoption of sludge treatment and disposal options inside the wastewater treatment plant area, such as incineration and moist air oxidation, is rising because to increased competition for space in landfills, disposal prices, legislative limits, and incentives to sludge recycling countries (Kelessidis & Stasinakis, 2012). Sludge combustion, on the other hand, raises severe problems about air pollution and the proper disposal of remaining ashes. The following sludge transformation processes are covered in this section with their advantages and disadvantages:

Thermal Drying

Thermal drying is a very adaptable procedure for making pellets for agricultural reuse, sanitary landfill disposal, or incinerated. Heat is used to remove the moisture in the sludge (Andres, 2011). The pellets generated can be utilized to power boilers, industrial heaters, cement kilns, and other appliances. Thermal air heaters, tray dryers, and a condenser are used in the drying process. It has the following benefits and drawbacks (Table 9).

Table 9. Advantages and disadvantages thermal drying process in sludge transformation

Advantages
Reduction in sludge volume Reduction in storage and freight costs Final product stabilization, resulting in easy transport, s

(Source: Author)

Wet air oxidation

This method was initially designed for the paper industry, but it has since been modified for use in sewage treatment facilities, particularly for the treatment of high-toxicity industrial liquid effluent (Li et al., 2020). It is advised, however, when the effluent is too diluted to be burnt and too hazardous to be treated biologically. It is used to oxidize organic material, converting carbon and nitrogen to carbon dioxide and water in most cases (Suarez-Ojeda et al., 2007). The oxidation procedure reduces the amount of sludge while increasing its dewaterability for thermal treatment. The pros and cons are shown in the table below (Table 10).

Table 10 . Principal advantages and disadvantages of wet air oxidation transformation procedure in sludge transformation

Advantages
Mineralization of the pollutants Rapid degradation Efficient for recalcitrant molecules (dyes, drugs, etc.) Little or no consun

(Source: Crini & Lichtfouse, 2019)

Incineration

The sludge stabilization procedure that gives the largest volume decrease is incineration. Incinerators may accept sludge from many treatment facilities and are often larger in size. Through burning in the presence of extra oxygen, sludge incineration eliminates organic compounds and harmful organisms (Schnell et al., 2020). Carbon, sulphur, and hydrogen, which are present as fat, carbohydrates, and proteins, are the combustible components found in sludge (Dmitrienko et al., 2020). Water vapour, carbon dioxide, Sulphur dioxide, and inert ashes are the byproducts of full sludge combustion. The quantity of oxygen required for full combustion of organic materials may be calculated using the organic components' identification (Stasta et al., 2006). Due to the high price and complex operations required, incinerators are only used in sludge treatment in wastewater treatment plants serving big urban areas.

Landfill disposal

Landfilling is a process for safely disposing of solid urban garbage onto soil with minimal health risks and environmental implications, employing engineering approaches to confine the discarded waste to the lowest feasible area and volume, covered by a soil layer (Wang et al., 2010). Landfilling is likely the easiest approach in terms of management and materials handling (Oyedele et al., 2013). Landfilling now compares favorably to other alternatives in terms of cost. Landfilling, from an environmental aspect, inhibits the discharge of any sludge-borne contaminants or pathogens by concentrating the sludge in one place. The benefits and drawbacks of landfill disposal are summarized here (Table 11).

Table 11 . Advantages and disadvantages of landfill disposal

Advantages
Easy and cheap to construct Prevents environmental dumping Possible energy production Can be closed and ground be use

(Source: Author)

Environmental impact assessment and monitoring

The fundamental priority of the chosen sludge disposal option should be the preservation of human health and the environment. The following principles should be followed in standard waste management: all wastes should be reduced; reuse and recycling should be undertaken wherever feasible; and any residual residue should be appropriately disposed (Dean & Suess, 1985; Giusti, 2009). However, this necessitates a thorough study of the environmental consequences and dangers associated with the chosen disposal strategy, with the goal of minimizing negative impacts while emphasizing beneficial ones. Along with technical, economic, operational, and environmental elements of the problem, waste water treatment plant planning and design should incorporate a beneficial use or final disposal choices for the generated sludge.

The use of appropriate environmental indicators is required for effective monitoring. Each sludge disposal technique includes a corresponding indication for assessing the impact of the chosen option. Monitoring water quality, for example, may be more appropriate and relevant for a given disposal option than odor emission. Obviously, both must be regulated, but the influence on water quality resources is more significant and significant than unpleasant odors since it may affect a larger number of people. For each indication, analytical parameters must be defined in order to offer quantitative and qualitative data in the monitoring process that can lead to conclusions about the sludge disposal technique. The primary metrics linked to the consequences of sewage sludge disposal alternatives are shown in Table 12.

Table 12 . Sewage sludge disposal impact and indicators

Impact	Indicators
Water pollution	Changes in water quality Concentration of contaminants Bioindicator species
Air pollution	Presence of gases and other toxic substances Particulate matter Odor
Soil pollution	Physical, chemical and biological changes in the soil properties Concentration of contaminants
Disease transmission	Pathogens' density in soil Rodents and insects Pathogenic organism and toxic compounds Concentration in crops
Food chain contamination	Contaminant concentration in water, soil and crops Bioindicator species
Aesthetic and social problems	Social acceptability Properties depreciation near sludge disposal area

(Source: Andreoli et al., 2001)

Monitoring plan is useful instruments to control and assess the efficacy of the entire sludge disposal operation. A plan allows to:

- Control and supervise impacts,
- Follow the implementation and execution of the control measures,
- Adjust, calibrate and validate models and parameters, and
- Serve as reference for future studies monitoring propositions

The parties involved, such as the environmental agency, the entrepreneur, other governmental and departmental agencies, and the community, should all establish their monitoring responsibilities. Furthermore, monitoring efficacy necessitates a strategy that identifies impacts, indicators, and parameters, as well as sample frequencies, sampling sites, and analytical procedures that result in comparable and publishable data.

Conclusion

Sludge is an inevitable byproduct of wastewater treatment purification system. This review summarized the challenges and technology related to sludge management, including sludge disposal. Around the world's most developed economies, the usage of sewage sludge is mostly focused as an energy source to help their CO_2 emission reduction policies. However, one thing where everyone agrees on is that Sewage sludge management should be geared toward the sustainable use and circulation of nutrients in the environment, sewage sludge processing, restricting storage, and landfilling. One technique of management is to employ sewage sludges as components in the production of biofortified organic fertilizers or soil substitutes. Although technical improvements have increased our ability to treat sludges efficiently, this does not guarantee that their harmful components have been eliminated. As with every technology, there are advantages and disadvantages. However, when considering the characteristics of the circular economy, it is undeniably a great option for sewage sludge. Wastewater treatment facilities must choose suitable technologies based on the local context, market, and regulatory concerns in order to create "product" rather than "waste."

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Conflict of Interest

The authors describe none conflict of interests.

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