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Composition, Production, and Treatment of Sewage Sludge

Rodrigo de Freitas Bueno

Abstract

Sewage treatment ultimately culminates in the concentration of the solid phase. Sludge are separated mainly in primary or secondary decanters. Even in biological treatment, where biological degradation of organic matter actually occurs, there is the separation of excess sludge concentrated in the bottom of the secondary settlers of activated sludge systems or biological filters. In fact, the production of sludge is an important differential in the choice of the treatment system. While purely aerobic systems such as activated sludge or high-rate biological filters can produce 0.6–0.8 kgSS/kgBOD applied, sludge production in an upflow anaerobic sludge blanket (UASB) reactor is only about 0.2 kgSS/kgCOD applied. Even the mixed anaerobic/aerobic system leads to less sludge production than that of an exclusively aerobic system. This advantage is very important nowadays, especially since, besides reducing the treatment needs, the difficulties with the final disposal of the sludge are usually very large.

Keywords: sewage sludge, densification, digestion, anaerobic sludge digestors, dimensioning

1. Introduction

At first, the main concern in relation to sewage treatment is to solve the problem of the liquid phase, leaving in the background the solution of the problem of the sludge generated in the treatment of this liquid phase. When there is a sewage treatment in which the generation of sludge is quite significant and the main concern with this sludge, at first, is restricted to its stabilization and dewatering to reach a solid content of the sludge in the range of 15–40%, aiming almost exclusively at its removal from the wastewater treatment plant (WWTP) area by trucks, however, has no clear definition of its final destination. In many cases, it is difficult to find suitable areas and conditions for the disposal of these sludge generated in the WWTPs [1]. Thus, the choice of the solution to be given to the sewage problem must also consider the solution to be given to the sludge generated in the treatment of the liquid phase. In order to study the alternatives for the treatment and disposal of sewage and the sludge generated in the treatment of the liquid phase, it is necessary to first know the possibilities of treating a sewage, in view of the quality of the final effluent to be obtained, as well as the quantities and qualities of the sludge produced in the WWTPs, which constitutes the main objectives of this work. In addition, an estimate of the costs of implementing WWTPs is presented for various types of sewage treatment systems. Currently, a very serious environmental

problem, observed in metropolitan regions and medium-sized cities that have implemented sanitary sewage treatment systems, is related to the destination of the sludge produced in their WWTPs [2].

For an adequate solution of this problem, it is necessary initially to know the sludge production according to the used scrubber system. In terms of sludge production, considering only the quantitative aspect of solids produced in a WWTP, this work presents “per capita” values that can be useful to the technicians involved with the problem of the sludge destination considered here. However, the solid content (or moisture) of the sludge is another important parameter for the final disposal of the sludge and depends fundamentally on the type of stabilization used (anaerobic or aerobic biological or chemical) and the type of dewatering equipment used. In principle, the following ranges of solid content values should be considered [1, 3]:

- Anaerobically digested sludge, dehydrated by:
 - Plate press filter—solid content from 30 to 40%
 - Belt press filter—solid content from 16 to 25%
 - Centrifuges—solid content from 25 to 30%
 - Drying beds—solid content from 20 to 30%
- Aerobically digested sludge, dehydrated by:
 - Plate press filter—solid content from 25 to 35%
 - Belt press filter—solid content from 13 to 18%
 - Centrifuges—solid content from 20 to 25%
 - Drying beds—solid content from 20 to 30%

For the design of the new WWTPs, it is recommended that, in addition to the quality of the effluent to be required depending on the receiving body, the destination to be given to the sludge is also considered, as this aspect may be preponderant for the definition of the sewage treatment system and sludge to be adopted.

2. Sludge treatment steps

Sludge treatment can be subdivided into three main stages, although depending on the sewage treatment system adopted, some of them can be suppressed. This is the case, for example, with the activated sludge system with prolonged aeration, where the process operates in a range where the digestion of excess sludge can be dispensed with. Sludge discharged from upflow anaerobic sludge blanket (UASB) reactors also requires no densification and complementary digestion. Sludge densification may not be mandatory in activated sludge systems or aerobic biological filters, but, except in small systems, its inclusion is made possible by the benefits brought to later sludge treatment units [1]. When sewage treatment is carried out by pond processes, then the system operates in such a way that the sludge thickens and digests at the bottom of the stabilization or settling ponds, in the

case of mechanically aerated pond systems. The problem becomes how to produce sludge removal mechanisms for final dehydration before being sent for disposal [2]. Depending on the use to be made of the sludge to be removed from the sewage treatment station, other treatment steps may be necessary, such as its disinfection for application on agricultural soil [4].

The objective of sludge densification is to reduce its moisture content, remove water and thus volume, and increase the solid content. The sludge discharged from “secondary” settlers of activated sludge systems with prolonged aeration has a solid content of less than 1%, and when a densifier raises it to 2%, there is a reduction in the sludge volume of 100% to be dehydrated. In a system of conventional activated sludge or aerobic biological filters, the sludge is mixed, primary and secondary. It is generated with a solid content between 1.0 and 1.5%, and its increase to about 4% allows an even greater reduction in volume, being able to prove the advantage of incorporating it into the system, in view of the much smaller required volume of anaerobic sludge digesters [1, 5, 6].

The purpose of sludge digestion is to complement its biochemical stabilization, that is, to increase the degree of mineralization. The sludge generated in conventional activated sludge systems and aerobic biological filters has a high volatile suspended solid/total suspended solid (VSS/TSS) ratio (e.g., 0.8) and thus does not allow good conditions for natural or mechanical dehydration. As what prevails in a sludge digestion stage is endogenous metabolism with destruction of VSS, this ratio is reduced (e.g., to 0.4), and the more mineralized sludge has better conditions for final dehydration. The objective of final dehydration is to remove water in order to achieve solid content above 20%, thereby drastically reducing the volume of sludge to be transported and making it compatible with applications such as disposal in landfills or agriculture [4, 6, 7].

2.1 Sludge densification

Sludge densification can be done by three main alternative processes. Gravity densification is applicable to both primary settler sludge and secondary settler sludge, that is, excess biological sludge, as well as to mixed primary and secondary sludge. Flotation densification with dissolved air can be an interesting alternative for the densification of excess biological sludge [3, 6, 8]. They result in solid contents higher than that of the gravity-densified sludge, and higher sludge loads per surface area of densifiers can be applied, resulting in the need for smaller areas of densifiers. The structure, however, is much more complex. Part of the final effluent from the WWTP, that is, from the treated sewage, feeds into the pressurization tank where the air is injected and, at a pressure of 4.0 kgf/cm^2 , dissolves in the liquid in the form of microbubbles. Then, it is mixed with the sludge at the entrance from the bottom of the flotation chamber, with scraping removal of the densified sludge at the top and the sub-liquid to return to the entrance of the WWTP. Recently, machines for the mechanical thickening of sludge have been developed [5, 7]. They are machines designed to provide only a partial dehydration of the sludge, around 4–5%, for later final dehydration that can also be mechanized. Recent research has demonstrated the possibility of obtaining interesting advantages through the chemical conditioning of sludge prior to its densification. In this text, greater emphasis will be given to gravity densification [2].

2.2 Gravity density

Gravity densifiers are units similar to circular planter decanters, being fed with sludge through the center and at the top, inside a bulkhead that directs it to the

bottom, from where it is removed after undergoing densification. Meanwhile, the supernatant liquid flows through the perimeter spillways positioned on the surface of the condenser and can be recirculated at the entrance of the WWTP [1, 3, 9].

Figure 1 shows a photograph of an empty gravity densifier.

2.2.1 Dimensioning of gravity densifiers

The main dimensioning factor of gravity densifiers is the rate of application of solids, which is the mass flow of solids applied per unit of surface area of the densifiers. It depends on the type of sludge to be densified. The following ranges of values are proposed (**Table 1**).

The rate of application of solids should be the most restrictive factor in determining the surface area of the densifiers; however, the flow rate, sludge flow applied per unit of the surface area of the densifiers, must be kept within a certain limit, that is, $f_A = F/S_A < 16 \text{ m}^3/\text{m}^2 \text{ day}$. Additional recommendations, such as minimum useful depth of densifiers equal to 3.0 m, maximum hydraulic holding time of 24 h, and mandatory mechanized sludge removal when diameters are greater than 3.0 m, are used. The maximum time limit for sludge retention in the compactor is characterized when there is a possibility of anaerobic decomposition and giving off of bad odors. When holding times greater than 24 h result from dimensioning, a portion of the treated sewage, the final effluent from the WWTP, can be recirculated, with a flow calculated to ensure compliance with the limit value.

Sizing example.

Data:

- Sludge type: primary + activated sludge.
- Sludge production: $\Delta X = 2254 \text{ kg SS/day}$.
- Specific sludge mass: 1020 kg/m^3 .
- Sludge solid content: 1%.
- Sludge flow: $F = 2254 \div (0.01 \times 1020) = 221 \text{ m}^3/\text{day}$.



Figure 1. Sludge densifier by gravity. WWTP-Sabesp, São Paulo, Brazil (source: the author).

Sludge Type	Solid Application Rate (kgSS/m ² .day)	Solids content in the sludge Dense (%)
Primary	100 – 150	6 – 12
Biological Filter	40 – 50	4 – 10
Activated Sludges	20 – 40	1,5 – 4,0
Primer + Biological Filter	60 – 100	4 – 10
Primary + Activated Sludge	40 - 80	3 - 10

Table 1.
 Application rate of solids according to the type of sludge. Source: adapted of Metcalf & Eddy, Inc. [3].

Solid application rate: 60 kgSS/m² day (adopted).
 Required density area:

$$A_{\text{densifier}} = 2254 \div 60 = 37.6 \text{ m}^2 \text{ (diameter } D = 6.9 \text{ m)} \quad (1)$$

Adopting the diameter $D = 7 \text{ m}$, the area of the densifier will be 38.5 m^2 , and the resulting solid application rate will be $2254 \div 38.5 = 58.5 \text{ kgSS/m}^2 \text{ day}$.

Adopted useful depth: $H_u = 4 \text{ m}$.

Resulting useful volume: $V_u = 4 \times 38.5 = 154 \text{ m}^3$.

Hydraulic retention time: $\text{HRT} = V \div F = 154 \div 221 = 0.7 \text{ day} = 16.7 \text{ h}$.

Runoff rate: $f_A = F \div S_A = 221 \div 38.5 = 5.7 \text{ m}^3/\text{m}^2 \text{ day}$.

Solid content in dense sludge: 4% (estimated).

Flow of thick sludge, for specific mass of 1030 kg/m^3 :

$F_{\text{Sludge.Densifier}} = 2254 \div (0.04 \times 1030) = 54.7 \text{ m}^3/\text{day}$.

Recirculation flow: $221 - 54.7 = 166.3 \text{ m}^3/\text{day}$.

The compactor must have mechanized sludge remover.

3. Sludge digestion

Depending on the type of sewage treatment and its operational conditions, the sludge from the solid separation units may require complementary biochemical stabilization. For that, aerobic or anaerobic digesters can be used; in both cases the reduction of sludge volatile content via endogenous metabolism is desired. Aerobic digesters are tanks equipped with an aeration system such as those used in activated sludge reactors. In view of the faster growth of these microorganisms in relation to anaerobes, it can be understood that the volumes of reactors are relatively smaller, which may lead to lower implantation costs than others, even though an aeration equipment is required [4]. However, for the aeration of concentrated sludge, the consumption of electric energy is quite high, and the difference between operating costs has led to the widespread use of anaerobic digesters in activated sludge systems and aerobic biological filters [7]. For this reason, a greater emphasis will be placed here on anaerobic sludge digestion.

3.1 Anaerobic sludge digestors

Anaerobic digestion can be considered as:

- a. Conventional when the VSS application rate on the digester is equal to or less than $1.2 \text{ kg/m}^3 \text{ day}$.
- b. High rate when the rate of application of VSS on the digester is greater than $1.2 \text{ kg/m}^3 \text{ day}$ and equal to or less than $4.8 \text{ kg/m}^3 \text{ day}$.

It is admitted to obtain a typical destruction of up to 50% of VSS and never exceeding 60%, according to the digestion and design conditions.

When selecting the VSS application rate, the influence of the internal temperature of the digester must be considered, and the need for heating of the unit must be verified. Anaerobic digestion should preferably be processed in the temperature range of 30–35°C (mesophilic digestion) or in the range of 50–57°C (thermophilic digestion) [1]. Lower temperatures result in less efficient digestion, to be considered in the project. High-speed primary digesters, with a VSS application rate equal to or greater than 0.5 kg/m³ day, must be homogenized by one of the following devices: turbine mixer, gas homogenization system, and sludge recirculation pumps.

Digestion time should be:

- a. For non-homogenized digester, ≥ 45 days.
- b. For homogenized conventional digester, ≥ 30 days.
- c. For high-rate digester, ≥ 18 days.

Second-stage digesters can be used for sludge storage and supernatant removal. The volume of the second-stage digester is about 1/3 of the volume of the first stage, determined by the criteria presented. **Figure 2** shows a photograph of the set of anaerobic digesters from WWTP.

Example of sizing a low-rate anaerobic digester.

Data:

- Sludge production: $\Delta X = 2254$ kg SS/day.
- Volatile fraction: $\Delta X_v = 1757$ kg VSS/day.
- Sludge solid content: 4%.
- Sludge flow: $F = 54.7$ m³/day.

VSS application rate: 0.5 kg VSS/m³ day (adopted).



Figure 2.
Anaerobic digester. WWTP-Sabesp, São Paulo, Brazil (source: the author).

Required volume of anaerobic digesters:

$$V_{\text{Anaerobic.digester}} = 1757 \div 0.5 = 3514 \text{ m}^3 \quad (2)$$

To meet the minimum detention time of 45 h, we have:

$$V_{\text{Anaerobic.digester}} = 45 \times 54.7 = 2461.5 \text{ m}^3 \quad (3)$$

Three digesters of 1200 m³ each should be adopted, making a total useful volume of 3600 m³.

4. Sludge dehydration

The purpose of sludge dehydration is to raise the solid content generally above 20%, in order to reduce the volume to be transported and to allow its final disposal in landfills, agriculture, etc. It can be done naturally or mechanically. Natural drying can be done in drying beds or mud ponds. Sludge ponds should not be considered as a very suitable final solution. The sludge drying beds should be used more advantageously in small treatment systems. The required bed area is relatively large, on the order of 0.1 m² per inhabitant [2]. The cost of its structure, the operational difficulties with the removal of dehydrated sludge, and the excessive presence of rainwater can make its use unfeasible, especially in large treatment systems. Dewatering machines have grown in use in recent years, mainly plate press filters or conveyors, as well as centrifugal decanters. Despite the relatively high cost of these machines, the operational ease has enabled their adoption. For application of the machines, the previous conditioning of the sludge is required. In Brazil, chemical conditioning with ferric chloride and lime is common practice, a progressive practice of substitution of the use of polyelectrolytes [7, 8].

4.1 Sludge drying beds

The sludge drying beds are structures composed of bricks, arranged two by two and with joints filled with coarse sand. Under the bricks, layers of coarse sand and gravel of increasing granulometry are placed toward the bottom, an impermeable slab from which the liquid that infiltrates is drained and returned to the entrance of the WWTP. The sludge is disposed on the bricks, drying by infiltration of water in the bed and by evaporation in the sun. The beds are fed on a rotating basis, from channels with gates. A typical drying bed operation cycle, commonly adopted in projects in our region, is 30 days in total, with 20 days reserved for dewatering the sludge and 10 days for removing the dry sludge and rearranging the bed. Solids in the dehydrated sludge above 30% can be expected. For the determination of the necessary drying bed area, an application rate of solids as a criterion which cannot exceed 15 kg SS/m² × cycle is recommended. The rates in the region of 10–12 kg SS/m² × cycle are used in our region (Brazil). Once the total bed area is determined, it is subdivided into a number of beds that should not be too large to reduce operational difficulties [3]. **Figure 3** shows a view of the sludge drying beds.

Example of sizing sludge drying beds.

Data:

- Sludge production: $\Delta X = 2254 \text{ kg SS/day}$.
- Volatile fraction: $\Delta X_v = 1757 \text{ kg VSS/day}$.



Figure 3.
Drying beds. WWTP-Sabesp, São Paulo, Brazil (source: the author).

Considering that, prior to drying, the sludge will suffer a 55% reduction in volatile solids due to anaerobic digestion, we have:

$$\begin{aligned} VX_v, \text{RED} &= 0.55 \times 1757 = 966 \text{ kg VSS/day.} \\ \Delta X_p/\text{drying} &= 2254 - 966 = 1288 \text{ kg SS/day.} \\ \Delta X_p/\text{drying} &= 1288 \times 365 = 470,120 \text{ kg SS/year.} \\ \text{Adopting 12 drying cycles per year, we have:} \\ \Delta X_p/\text{drying} &= 470,120 \div 12 = 39,177 \text{ kg SS/cycle.} \end{aligned}$$

Adopting the rate of $12.5 \text{ kg SS/m}^2 \times \text{cycle}$, we have the following required area of sludge drying beds:

$$A_{\text{dry.sludge}} = 39,177 \div 12.5 = 3134 \text{ m}^2 \quad (4)$$

Twenty-seven sludge drying beds of $6.0 \times 20.0 \text{ m}$ in dimensions in each plant are proposed. **Figure 4** shows an example schematic of a sludge drying bed.

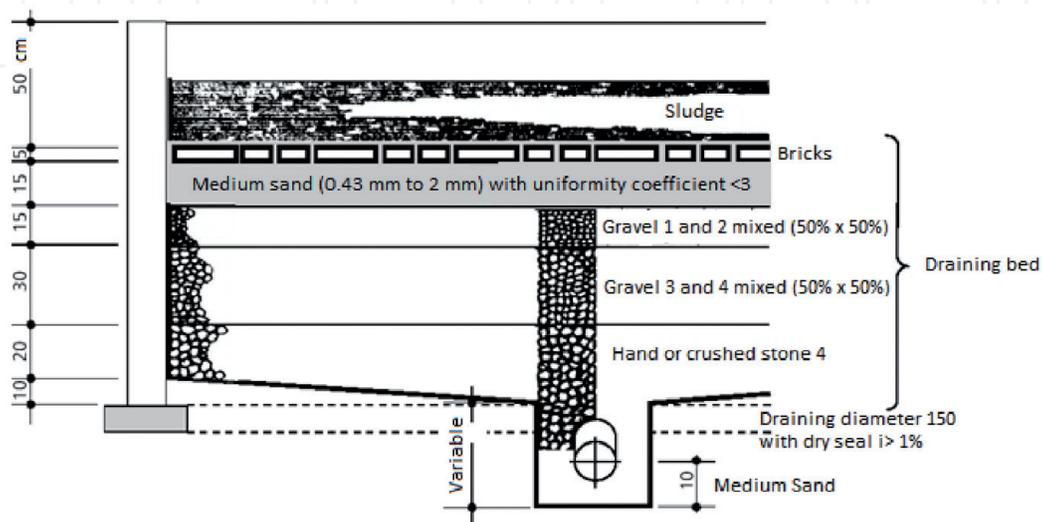


Figure 4.
Schematic cut of a sludge drying bed (source: the author).

4.2 Mechanical sludge dehydration

The main types of machines available on the market are plate press filters, continuous belt press filters, vacuum filters, and centrifugal decanters. When plate filter presses are used in activated sludge stations, dosages of ferric chloride, FeCl_3 , of 7 kg/100 kg SS and hydrated lime, $\text{Ca}(\text{OH})_2$, of 15 kg/100 kg SS are required, which makes this stage of the WWTP expensive, increases the volume of sludge, and hinders the agricultural disposal of sludge. When only polyelectrolytes are used, dosages of the order of 0.5–0.6 kg/100 kg SS are normally required [1, 2, 8]. The type of sludge conditioning and the dosages depend fundamentally on the state in which the sludge is generated, mainly its degree of mineralization, with less mineralized sludge being more difficult to dehydrate. **Figures 5 and 6** shows the diagram of the operation of a plate filter press.

Example of sizing a plate filter press

$$V = 100 (\text{SS}) \div N \times P \times \rho \quad (5)$$

where V, volume of the filter press (L); (SS), suspended solids load (kg/day); N, number of presses per day; P, cake solid content (%); ρ , cake specific mass (kg/L).

Data:

$$\Delta X = 6825 \text{ kg SS/day.}$$

$$N = 4.$$

$$P = 30\%.$$

$$\rho = 1.06.$$

Volume of the filter press:

$$V = (100 \times 6825) \div (4 \times 30 \times 1.06) = 5366 \text{ L} \quad (6)$$

Using plates (1.5 m × 1.5 m) of 3 cm thick, we have:

$$V_{\text{accumulated}} = 1.5 \times 1.5 \times 0.03 = 0.0675 \text{ m}^3 = 67.5 \text{ L} \quad (7)$$

$$\text{Number of plates} = 5366 \div 67.5 = 80 \quad (8)$$

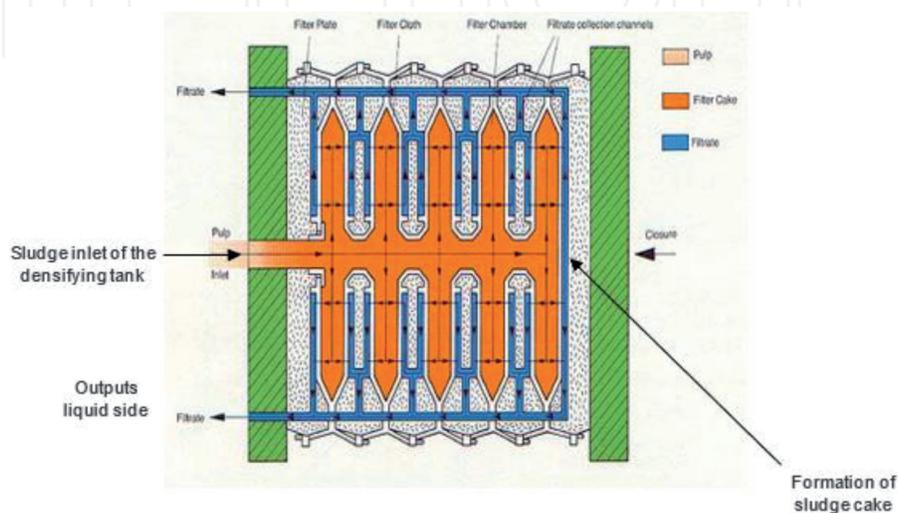


Figure 5.
 Plate filter press (source: Andreoli [1]).



Figure 6.
Plate filter press in operation. WWTP-Sabesp, São Paulo, Brazil (source: the author).

Example of sizing a continuous belt filter press.

Data:

- $\Delta X = 8212 \text{ kg SS/day}$.
- $\rho = 1030 \text{ kg/m}^3$.
- Solid content: 5%.
- Sludge flow: $Q_{\text{SLUDGE}} = 8212 \div (0.05 \times 1030) = 160 \text{ m}^3/\text{day}$.

Using the application rate of $300 \text{ kg SS/m} \times \text{h}$ and two filters with 1 m belt width, we have the following number of daily operating hours:

$$\text{No. of hours} \div \text{day} = 8212 \div (300 \div 2) = 14. \quad (9)$$

Polyelectrolyte consumption:

Medium: 6 kg/1000 kg SS.

Maximum: 8 kg/1000 kg SS.

Solid content in dehydrated sludge: 30%.

Volume of dehydrated sludge, with $\rho = 1060 \text{ kg/m}^3$ and 90% solid capture.

$$\text{Dry sludge} = (0.9 \times 8212) \div (0.3 \times 1060) = 23 \text{ m}^3/\text{day}. \quad (10)$$

Figure 7 shows a continuous belt filter press.

4.3 Alternative design of a centrifugal decanter

Choosing a centrifuge with a feeding capacity of $10 \text{ m}^3/\text{h}$, we have the following number of daily operating hours:

$$\text{No. of hours} \div \text{day} = 160 \div 10 = 16 \quad (11)$$



Figure 7.
Belt filter press. WWTP-Sabesp, São Paulo, Brazil (source: the author).

Considering the dehydrated sludge at 20% solids, $\rho = 1060 \text{ kg/m}^3$, and 90% solid capture, we have the following flow of dehydrated sludge:

$$\text{Dry sludge} = (0.9 \times 8212) \div (0.2 \times 1060) = 35 \text{ m}^3/\text{day} \quad (12)$$

Figure 8 shows a centrifugal decanter.

4.4 Disinfection

Among the processes of sewage disinfection, chlorination and ultraviolet disinfection have been the most considered alternatives, with chlorination currently being the most economically interesting. Despite the potential for the formation of by-products, which can present toxicity, chlorination has been the solution used in almost all WWTPs, without using dechlorination for the time being. Another process used is heat treatment. This treatment effectively reduces pathogenic viruses,



Figure 8.
Photograph of a centrifugal decanter. WWTP-Sabesp, São Paulo, Brazil (source: the author).

bacteria, and helminth eggs to levels below those detectable. For the thermal inactivation of 99.9% of viable eggs in digested logos, an exposure time of 35 min at 58°C is required [3, 4].

5. Conclusion

This chapter covered the classic processes applied to the treatment, digestion, and drying of sewage sludge. Aerobic sewage treatment processes generate much more sludge than anaerobic systems. Of the sewage treatment systems, the stabilization ponds are the ones that generate the lowest amount of sludge, while conventional activated sludge systems have the highest volume of sludge to be treated. This is due to the fact that the sludge produced in the lagoons is retained for several years, undergoing digestion and densification, which induces a reduction in its volume.

Sludge digestion in the conventional activated sludge system is low due to the short sludge residence time in this system. The sludge filtration process leads to a higher concentration of solids than the thickening process. In filtrations with chemical conditions, the concentration of solids can increase in the order of 20–40% depending on the type of sludge and the form of filtration.

In the case of drying beds, it can be observed that in the period of 10–60 days of sludge rest, the concentration of solids increases to approximately 40%.

Aerobic digestion produces sludge with low dehydration capacity due to the destruction of the flake structure during the process of endogenous respiration that occurs in the aerobic digester. Anaerobic digestion can reduce the concentration of volatile solids in the sewage sludge by up to 60%.

The treatment, disposal, and reuse of WWTPs sludge are gaining more and more expression on the world stage, due to the increase in the number of installed sewage treatment plants and the need to meet the environmental requirements and currently the need for resource recovery natural.

Conflict of interest

The authors declare no conflict of interest.

Appendices and nomenclature

ΔX	sludge production
BOD	biochemical oxygen demand
COD	chemical oxygen demand
F	flow
S_A	surface area
SABESP	sanitation company of the state of São Paulo, Brazil
TSS or SS	total suspended solids
UASB	upflow anaerobic sludge blanket
VSS	volatile suspended solids
WWTP	wastewater treatment plant
X_v	volatile fraction

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