Project deliverable 4.1.

A plan for sludge treatment for wastewater treatment plants of different size

ProLuke, Łukasz Kruszyński

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Lead Partner:
West Pomeranian University of Technology, Szczecin
Electrical Engineering Faculty
West University of Technology, Szczecin
Address: ul. Sikorskiego 37
70-313 Szczecin

Contact:assistant professor dr.hab. inż. Marcin Holub
Phone: +487 (258) 60950
E-mail: marcin.holub@zut.edu.pl

CONTENTS

Executive Summary

Improving the quality of municipal wastewater treatment processes results in an increased amount of sewage sludge, requiring further treatment. Therefore, the effective management of sewage sludge becomes a growing challenge.

The implementation of the European Council Urban Wastewater Treatment Directive (UWWTD) 97/271 / EC (21 May 1991) resulted in significant changes of the approach to sewage sludge management. Banned discharge of sludge to the sea, and the limitation of phosphorus and nitrogen release, which forced the creation of more effective treatment methods and modernization of infrastructure as a result of increasing the amount of sediments, had a significant impact here. The sludge storage -oriented economy model is being replaced by an approach in which stabilization and reuse play a major role.

The sludge treatment process is designed to ensure efficiency and safety in the event of its disposal or reuse. Sewage sludge has various impurities that determine the disposal method. Some sludge generated in small treatment plants, where the inlet stream of pollutants is relatively homogeneous, and the pollutants are non-toxic and known, can be subject to simple treatment methods such as thickening, dewatering and neutralization. Unfortunately, such opportunities are few, because as the industry develops, the use of increasingly diverse fertilizers, crop protection products, chemicals in the food industry, animal breeding, crops, and the situation with sludge becomes more complicated. Therefore, the treatment and pollution control also becomes crucial if we consider the possibility of sludge reuse.

Sewage sludge management however is a broader concept than just processing technology, storage or reuse. When choosing the economy model, three basic criteria are important:

- Environmental impact - emissions to water, soil and air, energy efficiency
- Financial impact - investment and energy costs, life cycle analysis
- Social impact - safety, nuisance (odours, area value loss)

Importantly, when choosing a waste management model, all three criteria must be met simultaneously to ensure its sustainability. This study aims to present different variants of sewage sludge treatment proposed for sewage treatment plants of various sizes. The following division of sewage treatment plants was taken size wise:

- small (PE <10,000)

- medium (PE 10,000 - 100,000)

- large (PE> 100,000)

The study presents the current state of legislation in the field of sludge management in force in Europe. Sludge treatment processes were discussed, with particular emphasis on methods focused on phosphorus recovery and struvite production. The study also contains an analysis of sludge treatment methods considering recovery of valuable materials and possibility of their reuse. It also addresses the aspect of energy efficiency.

1. Introduction

Ambitious wastewater management goals expressed – among the others - in Goal 6.2 of the 2030 Agenda for Sustainable Development require a change in the current approach to the issue of sludge management. It should be treated as a "locomotive" of the entire wastewater management cycle, because it is the locally available options for reuse or disposal of sludge that largely determine the choice of the appropriate wastewater treatment model. New concepts of sludge management should focus on technological issues, such as reducing the amount of sludge produced and improving its quality, as well as on socioeconomic aspects, such as changes in legislation, market mechanisms, and challenges related to institutional dynamics, which are often factors underestimated or even ignored[i]. The wastewater treatment industry must choose creative strategies and identify hazards to cope with future challenges.

European regulations are changing towards ecological management of sludge, which leads to increased recovery of valuable raw materials from potentially hazardous waste such as sewage sludge, thus enabling the use of appropriate processed sludge in agriculture, industry or energy

When it comes to the market aspect, sewage sludge is considered an excellent resource from which many benefits can be derived. The sludge treatment market was estimated at $ 3.2 billion in 2018 with the expected growth at a CAGR of 6.51% from 2019 to 2025. At the same time, the value of the nutrient recovery market was estimated at $ 150.9 million with a growth prospect of 13.2% to 2025. A stable increase in energy generated from biogas is expected, and the total energy recovery from sludge is expected to increase at a CAGR of 5.0% from 2019 to 2025[ii].

According to Eurostat data, the amount of sewage sludge generated in Western European countries remains stable with a slight downward trend. Developed water purification technologies have been widely used in this area for many years. In recent years, however, a significant increase in the production of sludge is visible in countries that are younger members of the European Union originating from Central and Eastern Europe. This is linked with the dynamic launch of modern municipal wastewater treatment installations, which in many places before 1989 did not exist at all. In the long term, in the European

Union, due to the development of technology and increased pressure to recover valuable materials, an increase in the amount of sludge generated is expected.

Table 1.1: Total sludge production from urban wastewater treatment plants in selected European countries (thousand tonnes)[iii].

STATE / YEAR	2008	2012	2016
Bulgaria	42,9	59,3	65,8
Czech	220	263,3	206,71
Germany	2 052,6	1 848,854	1 794,443
Estonia	22,2	21,7	18,34
Ireland	103,3	72,429	56,018
Greece	136,1	118,615	119,768
France	1 086,7	1 043	1 006
Cyprus	7,5	6,533	7,408
Latvia	19,3	20,114	25,923
Luxembourg	12,8	7,7	8,918
Hungary	172,2	160,6	215,08
Netherlands	353,2	346,4	347,6
Austria	253,5	266,3	237,938
Poland	567,3	533,3	568,329
Romania	79,2	85,4	240,41
Slovenia	20,1	26,2	32,8
Slovakia	57,82	58,71	53,05
Sweden	213,8	207,5	204,3

1.1 Key Objectives

Choosing the proper sewage sludge management plan depends on many factors. The sludge management process consists of the way it is produced, processed, transported, reused or utilized. When making the choice, the current legislation and its envisaged changes, should be considered as well as knowledge regarding modern technologies and their applicability in the area. The introduction of a sludge management plan requires public and institutional consultation. Such plan should assume the achievement of the following objectives:

- Avoiding harm to human health or environmental damage
- Meeting all the requirements of the relevant legislation
- Choice of an economically effective option
- Selection of effective methods of treatment, disposal and reuse
- Maximizing the use of sludge as a source of valuable materials and nutrients within the limits of economic viability
- Energy recovery while maintaining economic viability
- Minimization of nuisance related to infrastructure and transport of sludge

Sewage sludge management should be carried out in accordance with the EU Action Plan for the Circular Economy (2015). Sludge production cannot be prevented, so minimization and effective reuse should be sought. The European Commission considers the nutrients recovered from the sludge to be an important category of secondary raw materials that can return to the soil in the form of fertilizer, as long as it does not pose a threat to the environment and human and animal health.

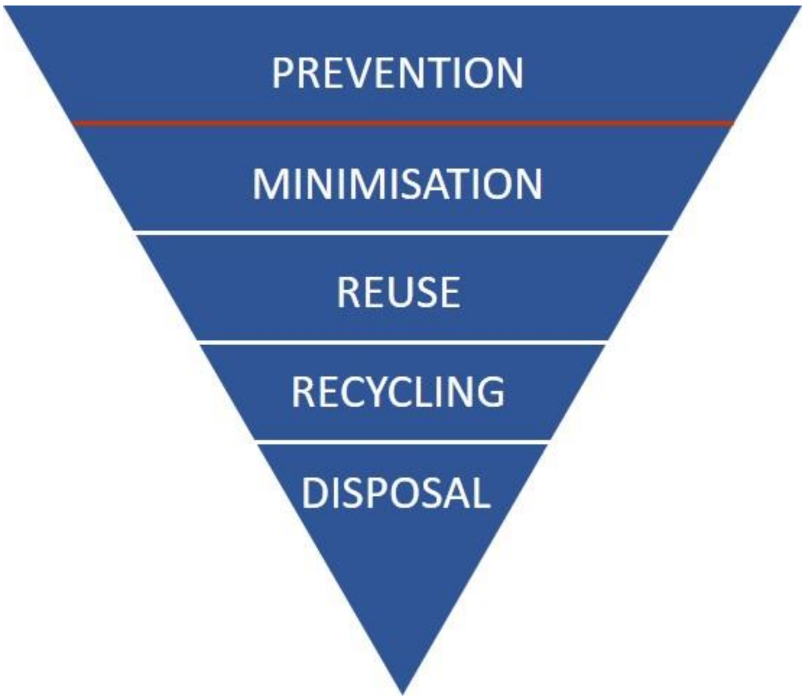

Fig.1.1: Waste management hierarchy

1.2 Wastewater sludge

Sludge is formed in water purification processes. Depending on the source of the wastewater being treated and the treatment methods, sewage sludge may contain a number of impurities, including heavy metals, pathogens and trace amounts of non-degradable organic matter. On the other hand, sludge can be a source of valuable nutrients such as phosphorus and nitrogen, and can contain organic matter useful in soil fertilization.

Sludge generated in sewage treatment plants is an organic by-product consisting of solid particles separated from treated wastewater. The first stage of sludge separation is gravitational sedimentation, which results in a liquid primary sludge with a dry matter content of 1 - 4%. The remaining wastewater passing through the aeration chamber goes to the secondary settler, from which the activated sludge is obtained, part of which is recycled to the aeration chamber. The remaining sludge - called the excessive sludge - usually contains 0.5 to 1% of dry matter; therefore it must be thickened before further treatment. The concentrated excess sludge together with the primary sludge is stabilized. Sediment stabilization is accomplished for two main reasons: to eliminate putrefying and odour production, and to eliminate pathogens. After stabilization, the sludge undergoes a dewatering process, after which it contains on average 15 to 40% dry matter[iv]. Below the generation of sludge in the process of municipal wastewater treatment is shown.

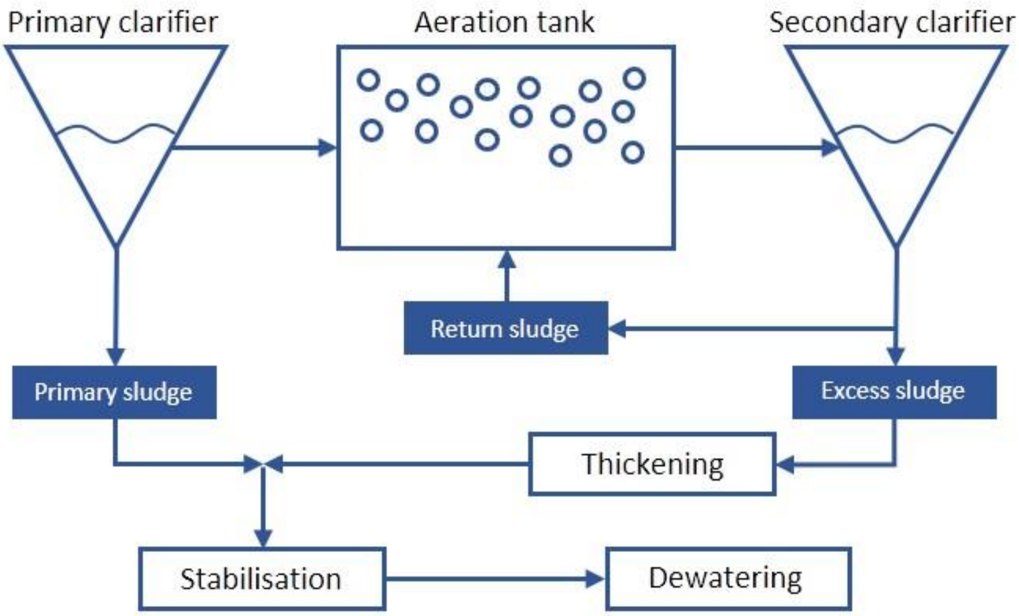

Fig. 1.2: Sludge flow diagram for typical wastewater treatment plant

1.3 Sludge treatment models based on WWT plant size

There are many ways to treat and manage sewage sludge in the industry related to wastewater treatment. Continuous development of new technologies and improvement of known methods can be observed. Due to the size of the treatment plant, typical sludge management models can be distinguished. They may differ in technological details; however the basics of their functioning are similar.

Small and medium treatment plants:

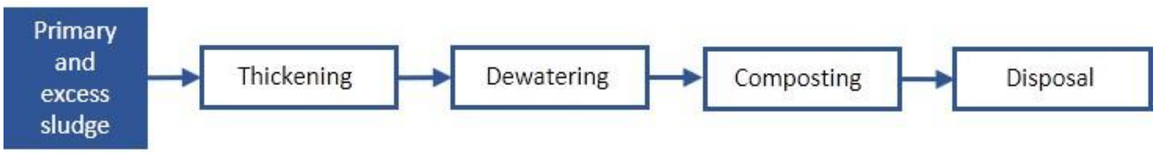

Fig. 1.3: Typical sludge processing model at small and medium WWT plants.

Medium treatment plants:

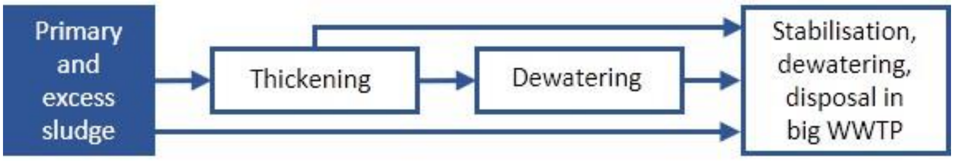

Fig. 1.4: Typical sludge processing model at medium WWT plants.

Medium and large treatment plants:

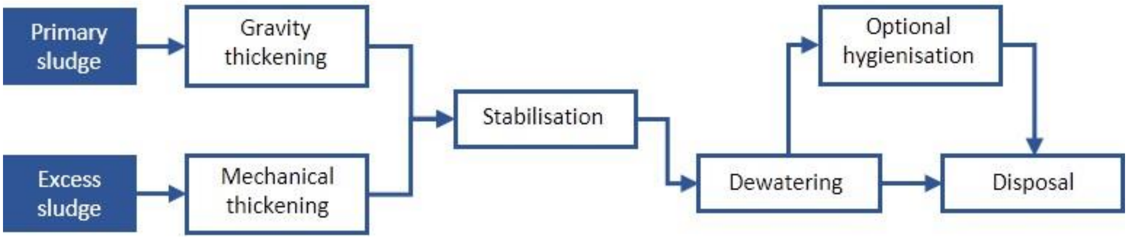

Fig. 1.5: Typical sludge processing model at medium and big WWT plants.

Large treatment plants:

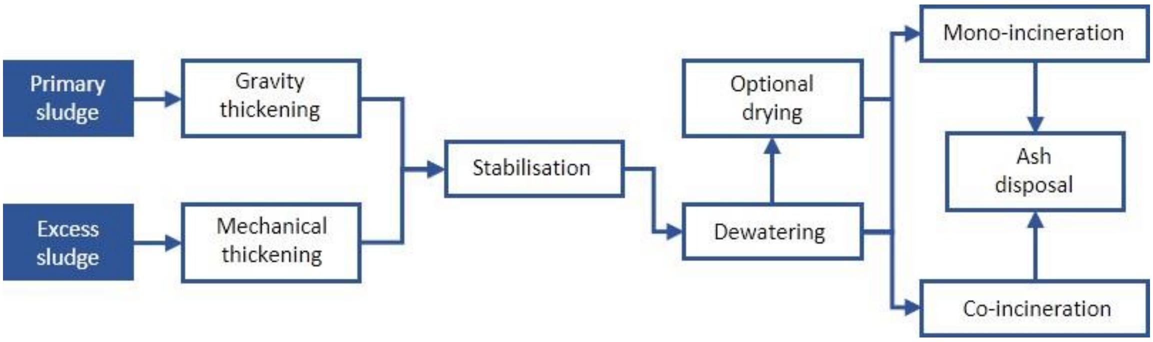

Fig. 1.6: Typical sludge processing model at big WWT plants.

The above examples indicate the dependence of the choice of the sludge management model on the size of the treatment plant. The larger the treatment plant, the more complex and effective the sludge treatment process. It clearly follows that more complicated models have economic justification only for processing larger volumes of sludge.

2. Review of Legislation and trends

2.1 General

The number of regulations regarding sewage sludge management is huge. This is linked to the highly complicated issue which is waste management. A large number of regulations are associated with the use of sludge in agriculture. Some regulations treat sewage sludge as waste, while the Commission Directive 98/15 / EEC contained in the Water Framework Directive recommends treating sludge as an intermediate / substrate rather than as waste. The difference between regulations on water and waste management often causes contradictions. Council Directive 91/271 / EEC of 21 May 1991 concerning urban waste-water treatment indicates the minimum requirements for the collection and treatment of sewage for agglomerations larger than 2,000 people resulting in the production of sludge in the amount of about 30 - 40 kg DS / inhabitant / year. With over 500 inhabitants connected to WWT plants, this gives 15 Mio t DS / year, but the directive does not mention how to deal with this amount of sludge[v]. Member States of the European Union on the basis of the guidelines contained in the directives draw up national regulations, which in some cases cause additional complications.

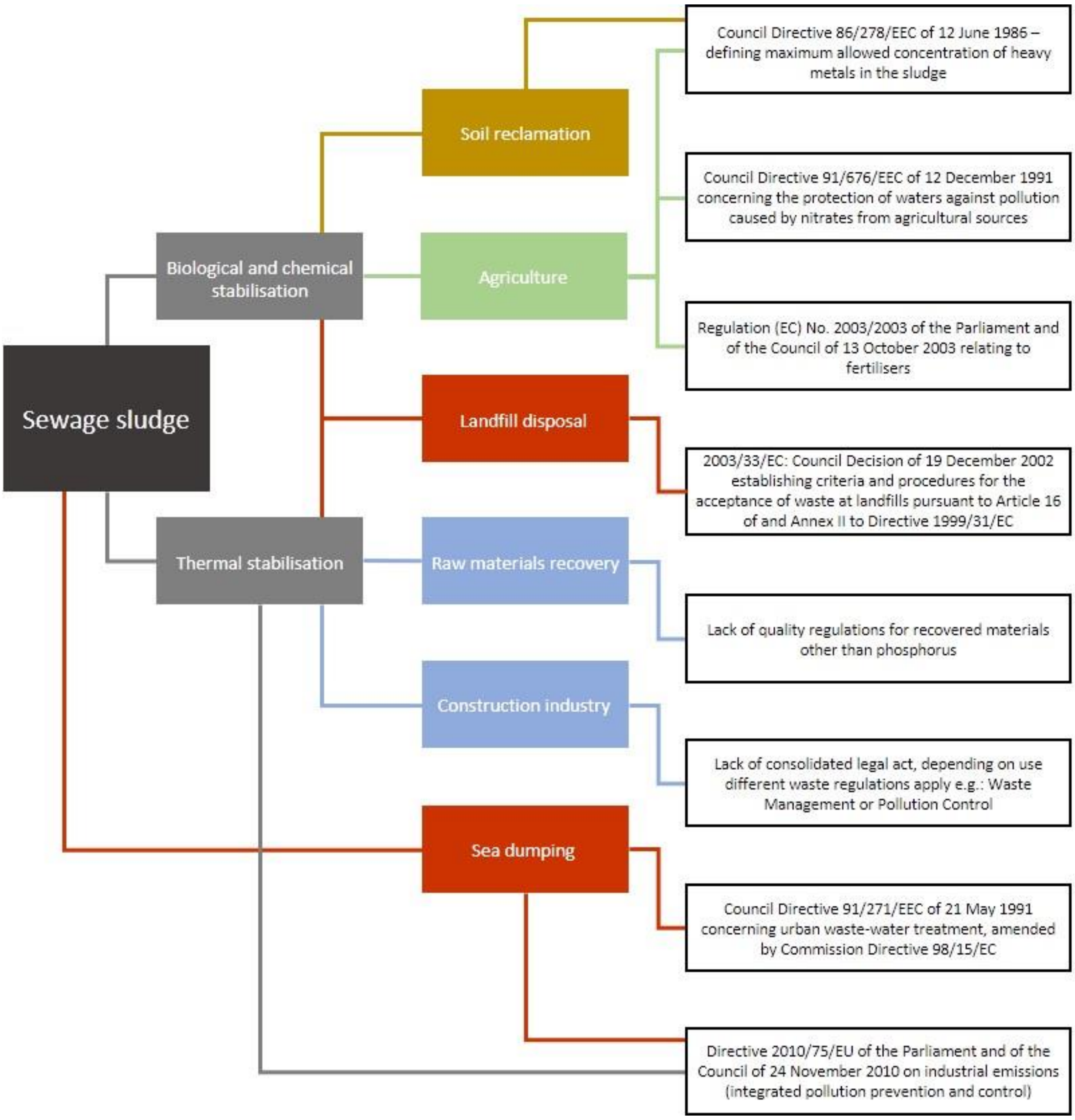

Fig. 2.1: Sludge management methods in connection with respective regulations[vi].

2.2 Current Legislation

As mentioned earlier, the number of regulations related to sludge management is large. The most important of them are discussed below, forming the basis for legislation regarding sewage sludge management.

- Council Directive 86/278 / EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture - "Sewage Sludge Directive"
- Council Directive 91/271 / EEC of 21 May 1991 concerning urban waste-water treatment, amended by Commission Directive 98/15 / EC - "Waste Water Directive"
- Council Directive 91/676 / EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources - "Nitrates Directive"

2.2.1. Sewage Sludge Directive

Council Directive 86/278 / EEC of 12 June 1986 is the main European regulation describing the rules for the use of sludge in agriculture and setting limits on the content of heavy metals in soil and sewage sludge.

Table 2.1: Limit values for heavy metal concentrations in soil

Heavy Metals	mg/kg of dry matter in a representative sample (soil with pH from 5 to 7)
Cadmium	1 to 3
Copper	50 to 140
Nickel	30 to 75
Lead	50 to 300
Zinc	150 to 300
Mercury	1 to 1,5

Table 2.2: limit values for heavy metal concentrations in sludge used in agriculture

Heavy Metals	mg / kg of dry matter
Cadmium	20 to 40
Copper	1000 to 1750
Nickel	300 to 400
Lead	750 to 1200
Zinc	2500 to 4000
Mercury	16 to 25

Table 3.3: limit values for amounts of heavy metals which may be added annually to agricultural land (Based on a ten year average)

Heavy Metals	kg / ha / year
Cadmium	0,15
Copper	12
Nickel	3
Lead	15
Zinc	30
Mercury	0,1

The 2018 implementation report indicates that all 28 Member States have set national limit values for heavy metal concentrations in soil, in line with the requirement.

Apart from Ireland and the United Kingdom, the remaining 26 Member States reported to have set national limit values for heavy metal concentrations in sludge used in agriculture in line with the requirement. The United Kingdom, reported that it has not set limits for heavy metals in sludge because it is the maximum concentration limits of potentially toxic elements in soil which determine sludge application rates, not concentrations in the sewage sludge itself.

A total of 22 Member States reported to have set national limit values for the amount of heavy metals which may be added annually to agricultural land in line with the requirement. Bulgaria, Croatia, the Czech Republic, Germany, Italy and Poland reported to have not set limit values. However, as they reported to have set limit values for heavy metal concentrations in sewage sludge used in agriculture, and as Article 5 (2) allows Member

States to either set such limit values or set maximum quantities for addition to agricultural land, these Member States are reportedly in line with the requirements of the Directive[vii].

2.2.2. Waste Water Directive

Council Directive 91/271 / EEC of 21 May 1991 prohibit the discharge of sludge into surface waters. It introduces the obligation to monitor the wastewater treatment process and the quality of sludge obtained this way. In addition, it obliges Member States to draw up reports on sludge utilization every two years. According to the introduced changes sewage sludge should be reused. This change caused the development of new methods of sewage sludge management.

2.2.3. Nitrates Directive

Council Directive 91/676 / EEC of 12 December 1991 aims at reducing water pollution by nitrates from agriculture and prevent such pollution in the future.

2.3 Plans for legislation changes

Plans to amend Council Directive 86/278 / EEC of 12 June 1986 have been considered for many years. Study of current sludge disposal practices was elaborate for the European Commission, DG Environment under Study Contract DG ENV.G.4 / ETU / 2008/0076. The study considered the agricultural reuse of wastewater sludge in accordance with Directive 86/278 / EEC and the options for changes to this directive as follows:

- Option 1: do-nothing: keeping the Directive as it is;
- Option 2: introduce certain more stringent standards, especially for heavy metals, standards for some organics and pathogens, and more stringent requirements on the application, sampling and monitoring of sludge;
- Option 3: introduce more stringent standards across all substances and bans on application of sludge to some crops;
- Option 4: total ban on the use of sludge on land; and
- Option 5: repeal of the Directive.

The Commission has an a review of EU waste policy and legislation under REFIT which was due to be concluded in 2014.6 It is expected that future legislation will provide a broader protection of soil, in addition to more stringent controls on the use wastewater sludge[viii].

2.4 EU Sludge Treatment Standards

The European Committee for Standardization, CEN, develops and publishes European Standards and technical specifications to meet the needs of European organizations to improve safety, quality and reliability of products, services, processes. CEN have produced a number of Technical Reports in relation to wastewater sludge such as:

- CEN / TR 13097: 2010: Characterization of sludges - Good practice for sludge utilization in agriculture 2010-06-02;
- CEN / TS 13714: 2013: Characterization of sludges - Sludge management in relation to use or disposal 7/24/2013;
- CR 13846: 2000: Recommendations to preserve and extend sludge utilization and disposal routes 2000-03-22;
- CEN / TR 15584: 2007: Characterization of sludges - Guide to risk assessment especially in relation to use and disposal of sludges 2007-07-25;
- CEN / TR 15809: 2008: Characterization of sludges - Hygienic aspects - Treatments November 26, 2008.

3. Sludge Treatment Processes

3.1 Introduction

The aim of this elaboration is to indicate the directions of sewage sludge management. Waste water is generated - among the others - as a result of industrial, agricultural, household activities, etc. This results in waste water contamination with various pollutants. Waste water is then entering the waste water treatment (WWT) plants in order to remove the contaminants and to allow purified water to be returned to the environment.

As mentioned above, the contaminants in the wastewater entering WWT plants vary in their properties depending on their origins. Such impurities include, but are not limited to:

- Inorganic substances in the form of various types of salts, phosphates, heavy metals, toxic compounds, etc.
- Organic substances such as pesticides, petroleum derivatives, phenols, etc.

- various types of bacteria and other biological contaminants
- The most popular waste water treatment technologies are:
- biological treatment,
- chemical treatment,
- mechanical treatment
- combinations of the above.

Each of these technologies causes generation of sewage sludge containing the contaminants mentioned as they migrated from treated waste water. Purified water is discharged to the environment or re-used in the variety processes according to the actual demand.

Sludge treatment processes should lead to reduction of sludge volume with simultaneous biosolids production and eventual valuable secondary raw materials and / or energy recovery.

Sludge treatment process can - in general - be divided into three categories:

- Reduction of sludge volume - mainly performed with thickening and dewatering
- Reduction of sludge quantity
- Sludge biosolids production - including various digestion types, composting, drying etc.

3.2 Reduction of sludge volume

Sludge volume is reduced to achieve the reduction of the cost of transport of sewage sludge. Two main groups of volume reduction processes are thickening and dewatering.

3.2.1 Sludge thickening

Sludge thickening at WWT plants aims at sludge volume reduction and free water removal. This process can be chemically aided e.g. with polyelectrolytes acting as flocculants resulting in generation of bigger and heavier agglomerates, that facilitate decantation thru e.g. gravity forces.

Both gravity and mechanical forces (e.g. centrifugal force or external pressure) are engaged in the thickening process. Devices that use gravity forces include:

- **settling tanks,** (e.g. Dorr type) with a conical bottom, in which the decanted sludge is periodically scraped off with a low-speed "rake" scraper, towards the hole located in the centre of the conical bottom and pumped out for further processing. This type of settling tanks usually has a diameter of a few to several meters, depending on the size of the treatment plant. Due to their size, this type of settling tanks is made of reinforced concrete, protected with a special anti-corrosive coating.

- **tanks for consolidated sludge**, in which sludge decantation also occurs, and from which sludge - like in case of decanters - is periodically pumped out for further treatment. These types of tanks have a diameter of few meters and are made either of special stainless steel, e.g. 316 L or carbon steel, protected with an appropriate anti-corrosion coating. Tanks made of plastic, e.g. PP or polyester resins, e.g. derakane type with adequate mechanical strength are becoming increasingly popular.

- **sedimentary plots**, the hydrated sediment is poured into pools properly protected against leachate penetration into the soil, in which the decantation takes place, the sediment settles and the water is pumped from the surface using e.g. leverage

- **belt thickener**, built of a filter tape slowly rotating between the rollers, where water is drained and the sediment is pushed out of the tape. The thickener is an enclosed device allowing the odours to be sucked out. Special movable baffles are built on the belt. Their task is to evenly feed the sludge to the belt. In order to obtain a better thickening effect, flocculant (polyelectrolyte) is added to the hydrated sludge in a special mixing tank. The construction of such a thickener is made of 304 or 316 stainless steel due to corrosive environment.

- **drum thickener**, uses mechanical forces, its operating principle is that hydrated sludge is introduced into the interior of the perforated drum, covered with filter cloth. The drum rotates very slowly for not to disintegrate / destroy the sediment structure. Water from the sludge is drained through filter cloth. Processing or recycled water can be used for the thickening process. As a rule, before the sludge enters the thickener drum, a flocculant in the form of a polyelectrolyte is first introduced into the hydrated sludge in a special small reactor-mixer. The drum thickener is usually made of 304 or 316 stainless steel due to corrosive environment. Works in a closed housing, often with odours suction available.

Summary of the thickening process

Sludge thickening causes slight dehydration. The dry matter content level of 2-7% can be achieved depending technology used. 5-7% dry matter content can be obtained on drum or belt thickeners only with addition of flocculant in polyelectrolyte form. Such sludge is still a slightly concentrated solution and is mainly directed to further treatment, i.e. dewatering process.

3.2.2 Sludge dewatering

In sludge dewatering mainly mechanical forces such as centrifugal force, external pressure, vacuum, etc., are involved. Such forces are generated in dewatering devices such as:

- decanter centrifuges, operating with the use of centrifugal force are increasingly popular. The concentrated sludge is fed through a pipe into a conical, horizontal centrifuge drum. Inside the drum a sludge collecting screw is installed, rotating in the same direction as the drum, but with lower rotation speed. Sludge in the form of a filter cake deposits on the walls of the drum due to centrifugal force and is collected and moved by a screw towards the conical part, where is being removed through a special hole. The liquid (filtrate) is filtered through drum perforation and removed outside through pipe system. These types of centrifuges work automatically, continuously and the feed of concentrated sludge to the centrifuge automatically regulated. Before being fed to the centrifuge, the concentrated sludge is usually treated with a flocculant in a special tank to achieve a better dewatering effect.

- filtration chamber presses, use the external pressure of the pump feeding the thickened sludge to the press chambers. The maximum pressure that still provides filtration is usually 6 bars. Above, this value the process is stopped, filtration is not carried out. The chamber filter press consists of filter plates covered with a suitable filter cloth. Between the plates empty spaces are created - so called chambers - that have a specific so-called filtering surface. Depending on the number of plates, the filtration surface of a given press is larger or smaller. The plates are usually made of PP, and the compression elements are two steel end plates, which are driven by a hydraulic system of the press. The filtration process involves feeding concentrated sludge into chambers between the plates. The clean filtrate is discharged through the canvases through a system of channels in the plates and discharged outside. The sludge remains in the chambers and after filtration, the plates are moved manually or mechanically (depending on the press) and the sludge falls off the plates and is collected under the press through a hopper directly to the transporting system, e.g. a screw conveyor on to a heap, to a truck or big-bag. The proper selection of canvas (structure) is very important in chamber presses. It affects the filtration rate and dryness of the sludge. Standard plate dimensions are 800 x 800 mm and 1200 x 1200 mm. Filtration goes better when adding concentrated flocculant to the sludge.

- belt presses, the principle of operation is based on mixing the sludge with polyelectrolyte and spreading it on a horizontal, porous filter belt. The pre-concentrated sludge is then compressed through a second filter belt and subject to a further dewatering process through a series of rollers with a decreasing diameter. The adjustable wedge drainage zone initiates the gradual introduction of sludge into the high pressure zone. The final dewatering process is achieved through a roller system, working with a minimum of 180 ° wrapping of the belt. These types of presses guarantee high dewatering rate and consume a relatively low amount of flocculant.

Summary of the dewatering process

The dewatering process is the next step of sludge treatment. The sludge after dewatering contains about 13-40% of dry matter. Such sludge may be directed to further thermal treatment in various temperature conditions to get rid of toxic compounds, both organic and inorganic, or transferred directly to the incineration plant, for combustion at high temperatures resulting in heat and / or electricity recovery.

3.3 Sludge biosolids production

3.3.1 Thermal processes of biosolids production

Sludge thickening and dewatering processes mentioned above are not sufficient for the sludge to be allowed for use e.g. in agriculture or for other useful purposes. These deposits still may include various types of pathogens and dangerous chemical compounds disqualifying them from further use. Several of the thermal sludge treatment processes are described below. These apply mainly to the dewatered sludge.

- mesophilic anaerobic digestion with pre- or post- pasteurization, The characteristic of this process is that the anaerobic digestion process with mesophilic bacteria takes place at relatively low temperatures, because these bacteria develop best at a temperature of about 25-30^{0}C and then they are most efficient. The technological regime must be strictly adhered. Temperature and retention time of treated sludge must not be exceeded. The pasteurization process however takes place at a temperature of about 70^{0}C and a at strictly defined, impassable retention time. Retention time of mesophilic bacteria digestion (hydrolysis) process is usually a minimum of 12 days. The resulting final sludge, after being analysed and commissioned, can be used in agriculture.

- thermophilic anaerobic digestion, requires additional heat input. Retention time for sludge treated this way is at least 48-72 hours, at 50-55^{0}C, including at least one hour sludge retention at a minimum temperature of 70^{0}C. Due to the high energy consumption, this process is relatively rarely used, although some treatment plants utilise it.

- thermophilic aerobic digestion, also requires an external energy source. The process is concluded in batches due to significant changes of sludge loading conditions in summer and winter. All sludge is treated at 50^{0}C for a minimum period of 7 days. A minimum volatile compounds level of at least 38% must be achieved in this process. Due to the need of an external energy source use to heat the process system, this method is not very popular.

- composting, one of the most popular methods of thermal sludge treatment. This process involves mixing dehydrated sludge with fillers containing an external carbon source (e.g. molasses). Such a mixture is collected on an embanked plot, arranged in piles or stored in special tanks. The sludge pasteurization process involves the activity of microorganisms, resulting in the treated sludge temperature increase. This temperature reaches about 55^{0}C and should be maintained for a time specified for each method. For example, if the sludge is kept on embanked plots, this period should last about 15 days with the sludge being circulated approx. 5 times in the meantime. In case of prisms, the storage period at a constant temperature of 55^{0}C is a minimum of 3 days. The advantage of the composting process lies in the low operating costs, but a strict process regime must be maintained to obtain a good product and to avoid troublesome odours. When used in agriculture, composted sludge can be mixed, under strict control, with green vegetation.

- **alkaline stabilization**, consists of adding hydrated or burnt lime to the dewatered sludge and mixing the two components. To achieve full pasteurisation, the pH should be raised above 12 and the sludge should be kept at 55^{0}C for a minimum of 3 hours or at 70^{0}C for a minimum of 1 hour. To achieve such temperatures, excess lime should be used and external heat source introduced. This method of sludge treatment is the cheapest - operating costs are low. However, it results is the increased volume of sludge, because of introducing a certain volume of calcium compounds.

- **thermal drying of sludge**, a very simple method, because the dewatered sludge subject to a direct or indirect drying process, using an external heat source, which can be, e.g. gas, fuel oil, steam, etc. The drying effect is fast and significant because of evaporating water directly from the sludge. Due to the relatively high temperature of the process, pasteurization is one hundred percent. Granulated sludge is obtained, which (if it meets the standards) can be used e.g. in agriculture or as an addition to the production of pellets used in the combustion processes. Thermal drying results in very high sludge dewatering level reaching over 90% of dry matter. Sludge volume is also significantly reduced. The weak point is the relatively high operating costs resulting from the use of an external heat source. Inflammation of the deposits may also occur.

3.3.2 Other thermal sludge processing methods

The only generally commercially available combustion - based sludge treatment process today is incineration. The methods are worldwide well known; with the sludge dewatered to a minimum of approx. 30% the combustion is self-sustaining. The benefits are easy to estimate - heat / energy recovery, huge volume reduction, when mono-incinerated - possibility of phosphorus recovery what seems to be more and more attractive topic in the last few years. Incineration has high capital and operating costs, but due to regulations change - especially regarding agricultural use of sewage sludge - this option might appear more and more feasible.

There are several advanced technologies of thermal sludge conversion. Although there are quite many pilot-scale or even full size installations operating worldwide under different conditions - their viability is still questionable. The advantage comes with the know-how for the future and - as it was proven more than once in history - along with technology development and growing scarcity of fossil fuels and virgin raw materials, some of these methods may become feasible sooner than anyone expects. Here are some examples of advanced thermal conversion:

- wet oxidation
- pyrolysis
- gasification
- melting furnace

3.4 Phosphorus recovery

Phosphorus is one of the - so called - "elements of life". Given the fact that - except singular cases - there are no phosphorus sources in Europe, and the ore deposits located mostly near the banks of north-western Africa are extensively exploited, European Commission in 2014 has added phosphate rock to the list of 20 Critical Raw Materials, for which supply security is at risk and economic importance is high. The consumption of phosphate-based fertilizers on a global scale is very high, because of the demand from food / agriculture sector.

All of the above resulting in search for alternative phosphorus sources, the ones that allow the phosphorus recovery. The fact that sewage sludge is a potential source of phosphorus is obvious for years already. Thanks to many projects and huge amount of research work that is still being performed the phosphorus recovery from sewage sludge concept has many well documented variations. Some of them are being close to or already are viable. Examples of well-documented technologies of phosphorus recovery from sewage sludge:

- KREPRO method, a Kemira company technology - wet method, which was created in the 90's. It is a typical hydrolysis process using a strong oxidant (sulfuric acid). Typical sludge concentration for this process is 4-6% dry matter. Such sludge, after being mixed with sulfuric acid at pH of approx. 1-2,5, is subject to pressure heating in chemical reactor to a temperature of about 140^{0}C at a certain overpressure. After hydrolysis, the reaction mass is emptied into a buffer tank and after cooling, the contents are subject to filtration process either on filter presses or centrifuges. Sludge (organic fraction) with a dry matter content of approx. 45% is obtained. It can be further utilized, e.g. by thermal methods. The solution is placed in a mixer, where after adding a little coagulant in the form of a solution of iron sulphate III and neutralization with sodium hydroxide solution (for pH increase) iron orthophosphates precipitate. Such mixture goes thru filtration process, where a cake in the form of a phosphate with a content of about 35% of dry matter and impure water is obtained. Water is recycled at the waste water treatment plant.

Kemira took the Krepro process to the next stage, which is called the Kemicond process. In this process, which is also a hydrolysis, hydrogen peroxide solution of approx. 50% is used. Hydrolysis takes place at a slightly higher pH, i.e. about 3.5 at a temperature of about 20^{0}C, and the hydrogen peroxide is used as a strong oxidant to prevent the reduction of iron III ions, which are beneficial for the precipitation of iron orthophosphates. Kemira uses both of these methods especially where the wastewater treatment process is carried out with the help of coagulants in the form of iron sulphate or chloride III, precipitating phosphorus very effectively. The combination of these methods also causes that in addition to orthophosphate precipitation, some of the iron salts are also recovered as coagulants.

- Biocon technology, uses ash generated by sludge incineration at a temperature of approx. 900^{0}C. Because ashes - by definition - have diverse granulation, they must be grinded before starting proper process in the reactor for a more efficient reaction with the added chemicals. The ashes are mixed with sulfuric acid, which is a strong oxidant, until a low pH of about 1 is achieved. Under these conditions, orthophosphoric acid contaminated with various metals is created. To get rid of metals, ion exchange is used (anion and cation). Using KCl and HCl for example, metals are converted into solutions of their chloride salts and removed. The resulting pure orthophosphoric acid is neutralized with calcium to become an absorbable character of phosphate in the form of calcium phosphate.

- Aqua Reci technology, - it is a wet technology because it uses sewage sludge e.g. after thickening. This method involves the oxidation of the organic fraction of the sediment in an atmosphere of pure oxygen under supercritical water conditions. Sodium hydroxide is added to the inorganic fraction, with the help of which phosphorus is leached, further subject to react with calcium oxide, resulting in acid calcium phosphate. This process occurs at high pH, due to which the heavy metals contained in the sludge remain undissolved.

- Sephos technology, - uses ash from sludge incineration, containing - among the others - aluminium compounds and heavy metals. The ashes are mixed with sulfuric acid in the reactor, maintaining the pH below 1.5. The post-reaction suspension is transferred into a filtration device, e.g. a filter press or centrifuge, where the so-called filtrate is separated from the filter cake. The solution is fed to another reactor and sodium hydroxide is added to raise the pH to about 3.5. This process produces aluminium phosphate. At the same time, most heavy metal compounds precipitate. The slurry from the reactor is subject to another filtration process, where the solution (filtrate) is separated in the form of waste reaction acid, which is recycled to the beginning of the process and mixed with ashes. Meanwhile the precipitate created after filtration is fed to another reactor, to which sodium hydroxide is added to raise the pH to a value of about 13. As a result of this neutralization process, the aluminium phosphate formed in the previous process is dissolved and the remaining metals are separated and transform into a solid state. Such suspension is subject to filtration, as a result of which a cake with heavy metals and other impurities is separated from the phosphate solution. Phosphate solution, in another reactor is treated with calcium oxide. As a result of this process, easily absorbable calcium phosphates are precipitated. The post-reaction suspension is subject to final filtration process, after which the cake is obtained in the form of easily absorbed phosphates. The effluent is recycled to the sewage treatment plant. The filter cake in the form of easily absorbed phosphates can be mixed with other types of fertilizers or directly used for fertilizing.

- LOPROX technology, based on the oxidation of sewage sludge with pure oxygen. The process takes place in the reactor under increased pressure of about 12-28 bar, at a temperature of about 160-220^{0}C in an acidic environment at a low pH of <1,5. An acidic environment is created by adding sulfuric acid to the reaction. As a result of the reaction, the content of organic compounds is significantly reduced. In addition, compounds such as pharmaceuticals, organic micro-impurities and polycyclic aromatic hydrocarbons are degraded. Phosphates migrate into solution. They are mainly in the form of phosphoric acid. The solution is separated from the solid waste by filtration. Acidic solution after the filtration is neutralized with e.g. calcium oxide, resulting in easily digestible fertilizer phosphates.

3.5 Struvite production

3.5.1 Short struvite characteristics

Struvite is a hydrated ammonium magnesium phosphate represented by the following formula: $MgNH_4PO_4 \times 6H_2O$. In nature, it occurs as a mineral with a crystalline structure. It can also be obtained synthetically as a result of the following reaction:

$$Mg^{+2} + NH_4^{+} + PO_4^{-3} + 6H_2O = MgNH_4PO_4 \times 6H_2O$$

The above reaction shows that for the formation of struvite, an appropriate molar ratio of individual components is needed, which, according to research, is 1:1:1, respectively. As a result of further research, its characteristic features were revealed:

- colour - white transparent or translucent,
- fracture - uneven
- specific mass - 1700 kg / m^3
- Mosh hardness -2

The most susceptible place of struvite generation is the set of supply pipelines and devices (e.g. pumps located after the fermentation chamber) within sludge process line. And the process of struvite generation in these places can be characterized as follows: Polyphosphates flowing into the fermentation chambers are hydrolysed to orthophosphates containing $PO4^{-3}$ ions. The aqueous phase of the fermenting sludge, after biological removal of nitrogen and phosphorus, is enriched with orthophosphate and ammonium ions. If magnesium is present in the wastewater, which usually comes from tap water needed at sewage treatment plants, there is nothing to prevent struvite from forming at appropriate concentrations of these ions. This way, struvite is formed in an uncontrolled manner, resulting in the formation of hard deposits of struvite in pipelines, pumps, etc. Hard struvite deposits are difficult to remove and often create huge problems in sewage treatment plants. It also results in increased costs of repairs and replacement of damaged devices.

However, this problem was dealt with at sewage treatment plants by controlled formation of struvite for further use as a life-giving compound for fertilizing crops, because, as already mentioned, it contains life-giving elements such as phosphorus, nitrogen and magnesium. Research centres around the world have faced this problem. As a result a number of technologies of controlled struvite formation were developed.

Two technologies will be discussed here. As for chemistry, each technology is similar to each other. They differ slightly in the way the struvite is manufactured in different apparatuses and process parameters. Struvite technologies originate from phosphorus recovery from sludge mentioned earlier. The difference is that in the previous examples phosphorus was recovered in a form of easily digestible phosphates, e.g. calcium.

3.5.2. Technologies of controlled struvite production

- SEABORNE technology, a complex process in which about 95% of phosphorus contained in sewage is recovered and the production of struvite is about 550 kg / day. First, a mixture of sewage sludge and ashes from thermal transformation is hydrolysed by sulfuric acid in the reactor. The reaction mixture is subject to a filtration process in which the organic sludge for incineration (ash is recycled to the hydrolysis) and the liquid phase in the form of acid phosphates and excess sulfuric acid are separated. Gas from fermentation chambers is passed through such solution, causing its desulphurisation. Precipitated metal sulphides are subject to filtration process from which the solution is used to produce struvite. This solution is treated with sodium carbonate, magnesium compounds and orthophosphates in an ammonia atmosphere to precipitate struvite. Precipitated struvite undergoes a filtration process and leaves the filtering devices in the form of a cake. Contaminated water after filtration is recycled to the treatment plant.

- technology with the "PHOSPHOGREEN" reactor, one of the newer processes of sludge treatment, which ultimately leads to the formation of granulated struvite. It uses biological sludge, from which phosphorus compounds are first released in a special tank. Then such sludge is subject to thickening process, after which the concentration of phosphorus compounds increases. Primary sludge which first undergoes anaerobic digestion and then dewatering is also used in the process of obtaining struvite. The phosphorus-rich solution from dewatering process as well as the one after thickening are fed to the "PHOSPHOGREEN" reactor. The "PHOSPHOGREEN" reactor is a cylindrical fluidized bed reactor, with recirculation and water washing. The lower part of the reactor is narrowed ending with a conical bottom, the upper part is about three times wider than the lower part. A concentric tube is placed in the centre, through which air is introduced from below to lift the layers of formed struvite, while stripping away carbon dioxide. The phosphate-rich solution is introduced from the side at the bottom of the conical reactor, as well as a solution of magnesium chloride and sodium hydroxide. As a result of the reaction, struvite is formed in the form of granules, which are collected from the bottom of the conical reactor and further washed, dried and packaged as a commercial product. Sodium hydroxide serves as a pH stabilizer. The entire reactor is covered with an outer insulation layer to avoid energy loss.

The resulting struvite has the following characteristics:

- granules size 1.0 to 3.0 mm
- phosphorus content approx. 12.0%
- nitrogen content approx. 6.0%
- magnesium content approx. 10.0%

It is therefore a classic fertilizer that can be used directly or as an addition to the production of synthetic fertilizers.

4. Sludge transport

Transportation of sludge has a significant environmental impact. It is also a solid cost share in the wastewater treatment process. EU assessed cost of sludge transport as approx. 30% of the total cost of sludge management[ix]. To assess the viability of sludge transport the whole management process must be reviewed to estimate reasonable transport distances. For each case costs of on-site thickening, dewatering and eventual further treatment may or may not be justified considering not only the transport distances, but also social impact, infrastructure, vehicle pool, storage capabilities. The transport models based on satellite centres and sludge hubs are – in various forms – implemented in different regions of Europe. But such model must always be investigated individually for particular conditions in selected area.

Wastewater treatment plant operations can be strongly affected by the sludge infrastructure. The sludge storage should reflect the needs of particular WWT plants to optimize desludging schedule. The frequency of sludge removal will depend on the treatment process in addition to the storage volume.

5. Options Assessment

5.1 General

As it was mentioned at the beginning of this elaboration, a technological answer to a particular waste water treatment demand in any case is not enough. A holistic approach and thorough study must be performed for the chosen management model to be adequate and sustainable. To pick the proper version of sludge management plan the three main criteria must be covered:

- Environmental impact - emissions to air, water and land, climate change impact and energy use;
- Financial impact - life cycle costs, energy cost and recovery, reliability of technology;
- Social impact - potential nuisance (e.g. odour, noise, traffic), public perception and food safety;

Moreover all three impacts must be considered as complimentary and not be addressed in separation from the others.

Since there is a wide range of options available here a summary of processes, their advantages and disadvantages and threats. This may serve as a helping matrix - a tool for preliminary assessment of chosen sludge management plan[x]. Each sludge management method is depicted separately.

Table 5.1 Sludge management: agriculture

Sludge management method	**Excess sludge processing**	**Disadvantages**	**Advantages**	**Main pollutants**
Use in agriculture	Stabilization using earthworms	Many standards to be met	Possibility of managing all sludge	High organic carbon load
	Composting and stabilization in ponds	A relatively long stabilization time if low-temperature processes are used	Low energy expenditure and reduction in concentrations of heavy metals (if earthworm stabilization is used)	Aromatic hydrocarbons Halogenated organic compounds
	Incineration			Heavy metals
	Phosphorus recovery			

Table 5.2 Sludge management: plants not for human consumption or feeding animals

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Growing plants not intended for human consumption or feeding animals	Stabilization using earthworms	Limited application	Requirements pertaining to the quality of materials are lower than in the case of other uses connected with growing plants	High organic carbon load
	Composting and stabilization in ponds	A relatively long stabilization time		Aromatic hydrocarbons Halogenated organic compounds
				Heavy metals

Table 5.3 Sludge management: soil remediation

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Remediation and adjustment of soil to specific needs	Stabilization using earthworms	This method is not recommended by the European Union	Broad application	High organic carbon load
	Composting and stabilization in ponds		Possibility of managing all sludge	Aromatic hydrocarbons Halogenated organic compounds
				Heavy metals
				Phosphorus

Table 5.4 Sludge management: construction industry

Sludge management method	**Excess sludge processing**	**Disadvantages**	**Advantages**	**Main pollutants**
Use in the construction industry	Vitrification	Problems with obtaining high strength	Partial refund of costs	Heavy metals
	Incineration	Very high energy demand in the case of vitrification	Broad application	Phosphorus
	Cementing	Many standards to be met	Possibility of managing all sludge	Chlorinated species
	Drying and pellet production	The possibility of releasing heavy metals or organic pollutants (depending on the process used)		

Table 5.5 Sludge management: industry

Sludge management method	**Excess sludge processing**	**Disadvantages**	**Advantages**	**Main pollutants**
Use in industry	Drying and pellet production	High investment costs	Partial refund of costs	Heavy metals
	Phosphorus recovery	High costs of unit processes	Recovery of precious materials	Phosphorus
	Recovery of rare metals	Complicated processes		

Table 5.6 Sludge management: energy recovery

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Recovery of energy	Drying and pellet production	High investment costs	Partial refund of costs	Carbon dioxide
	Anaerobic stabilization with biogas recovery	Processes are cost-efficient with large amounts of excess sludge	Generation of energy from renewable resources	
	Conventional incineration and co-incineration	Anaerobic fermentation susceptible to process inhibitors	Fewer odours	

Table 5.7 Sludge management: adsorbents and biooil

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Sludge-based production of adsorbents and biooil	Pyrolytic thermal processing	High energy demand	Partial refund of costs	Aromatic hydrocarbons
		Narrow market	Management of the majority of old residues	Halogenated organic compounds
		Many kinds of waste to be managed		

Table 5.8 Sludge management: fat recovery

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Fat recovery and processing	Sludge treatment	Incomplete management (only some raw materials)	Partial refund of costs	Aromatic hydrocarbons
		It is necessary to install a fat recovery system	Low investment expenditures	Halogenated organic compounds
				Heavy metals

Table 5.9 Sludge management: sludge storage

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Storage at treatment plants and in landfills	Disinfection and chemical stabilization	This method is not recommended by the European Union	Simple methods	High organic carbon load
	Incineration	Incomplete management		Aromatic hydrocarbons
	Vitrification	Incurred management costs are not recovered	Less restrictive standards as compared to other methods	Heavy metals
	Solidification of materials			Phosphorus
				Halogenated organic compounds
				Chlorinated species

6. Conclusions

The quantity of wastewater sludge produced is expected to increase over the next 25 years as new and upgraded wastewater treatment plants are completed.

EU environmental policy tending to eliminate fossil sources and encouraging valuable materials and energy recovery will with high probability promote solutions such as e.g.

phosphorus recovery. While organizing sludge management system a huge impact should be put on stream valorisation minding the fact that even with small systems the whole value chain would probably be much more complex as it was for the same circumstances few years before. The gravity of the problem lays now not in solving the waste problem at any cost but at improving already sophisticated designs, simultaneously facing rapid changes in waste legislation.

Circular economy nowadays is a must! Although even best ideas can face obstacles. An EU action plan for the circular economy released by European Commission in December 2015 covered almost all economy sectors and related waste but not sewage sludge...[xi]

Land application is still the main route for sewage sludge recovery: 50% of sewage sludge is spread on agriculture soils[xii], but the requirements for higher and higher purity of biosolids across EU might change the picture soon.

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