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Properties and production of sewage sludge in Poland with reference to the methods of neutralizing

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Abstract

Each technological process is related to the production of sewage sludge. Therefore, it becomes necessary to identify these wastes, both from the point of view of their properties and methods of disposal. The work, having a review character, concerns systematization, properties and ways of disposing of sewage sludge. In accordance with the act of 27 April 2001 [38] sewage sludge is waste defined as substances which must be disposed of. According to the Polish standard PN-EN 12832:2004 [28], however, sewage sludge is a mixture of water and solids, separated from various types of sewage as a result of natural or artificial processes. In this paper an analysis of the application of disposal methods of sewage sludge was carried out, resulting from the binding criteria of admitting waste for storage

Keywords: sewage sludge, systematization, properties, production, neutralization of sewage sludge

Streszczenie

Każdy proces technologiczny związany jest z produkcją osadów ściekowych. Niezbędne zatem staje się rozpoznanie tych odpadów, zarówno z punktu widzenia ich własności, jak i metod utylizacji. Praca, mająca charakter przeglądowy dotyczy systematyki, właściwości i sposobów unieszkodliwiania osadów ściekowych. Zgodnie z ustawą z dnia 27 kwietnia 2001 r. [34] osady ściekowe to odpady, określone jako substancje, których należy się pozbyć. Według polskiej normy PN-EN 12832:2004 [24] natomiast, osady ściekowe to mieszanina wody i części stałych, oddzielonych od różnego rodzaju ścieków, w wyniku procesów naturalnych lub sztucznych. W pracy przeprowadzono analizę stosowania metod utylizacji osadów ściekowych wynikającą z obowiązujących kryteriów dopuszczania odpadów do składowania.

Słowa kluczowe: sewage sludge, systematization, properties, production, neutralization of sewage sludge

1. Introduction

The problem of sewage sludge management still remains open, due to its significant quantity. Sewage sludges are inevitable by-products of wastewater purification. Consequently, the world is currently undergoing a rapid increase in sludge production that is expected to increase during the next years and it would be necessary to find new uses for these residues [10]. The United States and the European Union each generate around 6900 million dry tons of sewage sludge annually. This is disposed of by land application, landfilling, incineration and other approaches. The rate of production in both the EU and US is growing slowly [5].

In Poland the year 2000 produced a total of 1063.1 thousand $t_{d.w.r.}$ (dry waste residue), and in 2009 – 908.1 thousand $t_{d.w.r}$. Over the years 2000-2009, production of industrial sludge fell by half, while municipal – increased from 359.8 thousand $t_{d.w.r.}$ in 2000 to 563.1 $t_{d.w.r.}$ in 2009. This may be the result of the modernization of old sewage treatment plants and the construction of new ones, using modern technologies of removing biogenic compounds and pollutants in raw sewage. There is a need to implement an appropriate strategy, consistent with the relevant economic and ecological rules. The weight of the issue is increasing with the growing amount of sludge deposited on the premises of treatment plants and beyond. The use of sewage sludge presents a series of challenges because of its heterogeneous nature: pathogens, toxic metals and organic chemicals, eutrophicants, solids, and inorganic material occur together in widely varying proportion [5]. However, elements with high agricultural value (P, K or Ca) are also present [24].

The natural and energetic utilization of sewage sludge should be emphasized. A positive aspect for their agricultural use is the higher content of biogenic compounds compared to natural fertilisers and substances necessary for plant growth. On the other hand, however, it is a source of micropollutants, both mineral and organic. Therefore, also because of the presence of substances of high importunity to the environment, their utilization and storage is limited. Sewage sludge is also a fuel, the combustion of which brings a number of benefits for energy. By use combustion, the high amount of sludge is reduced to a small quantity of ash and heavy metals are retained in the ash [24]. Based on current trends, local conditions and regulations of the EU, it is expected that Poland will increase the amount of sludge sent to composting and combustion [17].

Therefore, the optimal distribution of sewage sludge, its storage and utilization becomes extremely important. For this purpose it is necessary to properly identify their characteristics and composition, which is what the significant part of this paper is dedicated to.

2. Systematization and division of sewage sludge

The author in the work [18] presents the systematization of sewage sludge, based on their chemical composition, referred to the types of organic compounds and fuels. Due to the fact that sewage sludge can be neutralized through combustion, analyzing it in terms of classic fuels becomes justified. In knowing the chemical composition of sewage sludge, it can be appropriately situated in systematization. On fig. 2.1 the area of sewage sludge has been highlighted in Van Krevelen's classification diagram.

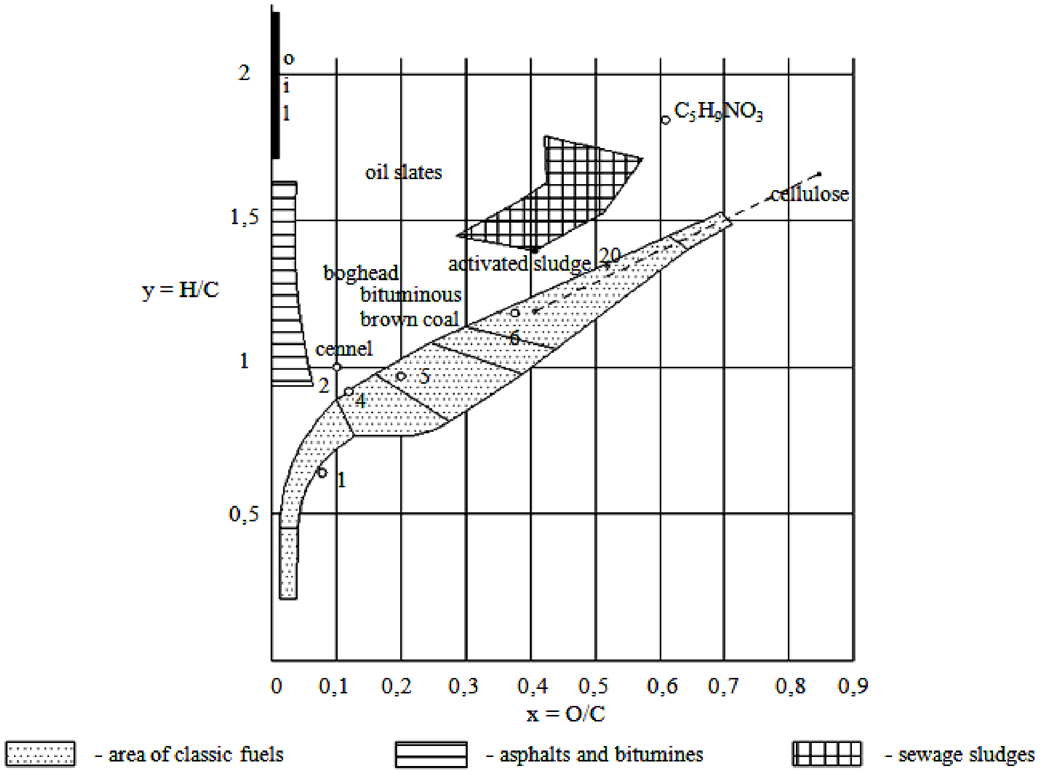


Fig. 2.1. The area of sewage sludge in Van Krevelen's classification diagram: 1 – primary sludge from Emszera river treatment, 2 – primary sludge from Kamen – Körne wastewater treatment, 4 – activated sludge from Emszera experimental treatment, 5 – activated sludge from Seseke experimental treatment, 6 – digested sludge, Bochum Nord treatment, 20 – urban waste [18]

As it can be seen, due to the similar chemical properties, urban sewage sludge can be arranged similarly to peats [18]:

$$0,289 \leq x = O/C \leq 0,566,$$
$$1,41 \leq y = H/C \leq 1,77.$$

The author of the work [18], however, believes that systematization and classification of sewage sludge constitutes an open subject and not fully recognized.

Sludge from wastewater treatment plants can be divided as follows:

- **raw sludge** consisting of [2, 4, 7, 19, 30, 31]:

– *primary sludge* – emerging in primary settling tanks as a result of the process of sedimentation,
– *secondary sludge* – emerging in secondary settling tanks after biological cleaning and sedimentation; as a return (recirculated) sludge, it can be returned to treatment circulation or disposed of as excess sludge,
– *mixed sludge* – a mixture of primary and secondary sludge emerging in primary settling tanks on condition that excess sludge is dosed to raw sludge,
– *chemical sludge* – arising as a result of coagulation or neutralisation of sludge, as well as from the precipitation of colloids and slowly settling suspensions.

The author of the work [29] additionally singles out:

– *bio-chemical sludge* – arising after biological treatment and chemical precipitation, as well as sedimentation in the secondary settling tank,
– *sludge from rinsing filters* – arising on ceramic filters after sewage treatment.

- **mineralized sludge (stabilized)**

Also, the following mineralized sludge has been singled out:

– *digested sludge (mixed, primary, secondary)* – arising after the methane digestion process,
– *stabilized sludge* – emerging after the aerobic treatment process,
– *washed sludge* – emerging from the washing process,
– *thickened sludge* – emerging from the thickening process (hydration percentage within the range from 90 to 95%),
– *dewatered sludge* – hydrated at 50 to 70%,
– *dried sludge* – emerging after specific dehydrating or drying processes, of a very low content of water [4, 7, 29, 30].

In the work [29], the terms gross and net sludge have additionally been singled out. Gross sludge is one arising in sewage treatment processes, while net sludge is sludge extracted from sewage after sedimentation, then subjected to treatment processes.

3. Properties of sewage sludge

Depending on the nature and treatment of sewage, its composition is subject to change, which affects the properties of these wastes. In table 3.1 the composition and properties of sewage sludge has been presented.

Table 3.1**.** Example composition and basic properties of sewage sludge [12, 13]

Properties of sludge	Unit	Type of sludge					
		Primary sludge from mechanical sewage treatment	Secondary sludge (after biofilters or activated sludge chambers)	Badly digested sludge	Weakly digested sludge	Well digested sludge	Very well digested sludge
pH	–	5,0 ÷ 7,0	6,0 ÷ 7,0	6,5 ÷ 7,0	6,8 ÷ 7,3	7,2 ÷ 7,5	7,4 ÷ 7,8
Dry waste residue	%	4 ÷ 8 (biofilters) 0,5 ÷ 3,0 (activated sludge)	4 ÷ 12	4 ÷ 12	4 ÷ 12	4 ÷ 12	4 ÷ 12
Loss on ignition	$\%_{d.w.r.}$*	60 ÷ 75	55 ÷ 80	55 ÷ 80	55 ÷ 80	45 ÷ 55	30 ÷ 45
Alkalinity	$mgCaCO_3/dm^3$ or $mmol/dm^3$	500 ÷ 1000 20 ÷ 40	55 ÷ 1000 (sometimes <500) 20 ÷ 40	100 ÷ 2500 40 ÷ 100	2000 ÷ 3500 80 ÷ 140	3000 ÷ 4500 120 ÷ 180	4000 ÷ 5500 160 ÷ 220
Volatile acids content	mg CH_3COOH/l or $mmol/dm^3$	1800 ÷ 3600 30 ÷ 60	1800 ÷ 3600 30 ÷ 60	2500 ÷ 4000 and more 40 ÷ 70	1000 ÷ 2500 15 ÷ 40	100 ÷ 1000 2 ÷ 15	< 100 < 2
General nitrogen	% N in $_{d.w.r.}$*	2 ÷ 7	1,5 ÷ 50 (biofilters) 3 ÷ 10 (activated sludge)	1 ÷ 5	1 ÷ 3,5	0,5 ÷ 3,0	0,5 ÷ 2,5
General phosphorus	% P in $_{d.w.r.}$*	0,4 ÷ 3	0,9 ÷ 1,5	0,8 ÷ 2,6	0,8 ÷ 2,6	0,8 ÷ 2,6	0,8 ÷ 2,6
Potassium	% K in $_{d.w.r.}$*	0,1 ÷ 0,7	0,1 ÷ 0,8	0,1 ÷ 0,3	0,1 ÷ 0,3	0,1 ÷ 0,3	0,1 ÷ 0,3
Resistivity of filtration	m/kg	$10^{11} \div 10^{13}$	$10^{12} \div 10^{13}$	$10^{11} \div 5 \cdot 10^{13}$	$10^{11} \div 10^{12}$	$10^{10} \div 5 \cdot 10^{11}$	$10^{10} \div 10^{11}$
Calorific value	kJ/g $_{d.w.r.}$*	16 ÷ 20	15 ÷ 21	15 ÷ 18	12,5 ÷ 16	10,5 ÷ 15	8 ÷ 10

* d.w.r. - dry waste residue

The authors of the work [26] distinguish: physical, chemical, sanitary, technological and rheological properties of sewage sludge. Their primary characteristics have been presented below.

3.1. Physical properties of sewage sludge

- **colour and odour** – indicate the origin of sewage sludge. For example, raw sewage from urban sewerage smell and have a grey or yellowish colour. It is possible to distinguish pieces of paper, faeces or food leftovers in it [15]. Well-digested sludge is characterized by a ground-tar odour or of slightly mouldy forest earth. It is black to dark grey in colour. Badly-digested sludge has an unpleasant odour, and it is light gray or brownish in colour. Healthy active sludge is characterized by a brown colour, while recirculated and excess sludge is generally slightly darker [27].
- **structure** – properties of sludge affecting the ability to retain water [26], distinguished as [14]:

– *cellular* – typical for sludge, of which grains form as a result of the force of attracting particles, but without the use of the coagulation process; it is characterized by porosity of more than 50%,
– *flocculent* – characteristic for post-coagulation sludge, as well as active sludge of very high porosity,
– *mixed*.

- **water content** – very varied, which results from the application of various kinds of equipment for sewage treatment. On average, water content of sludge of organic origin amounts from 85 to 99%, while sludge of mineral origin (emerging in grit chambers) from 50 to 70% [2].

The water that remains in the sludge occurs as:

– *free* – the easiest to separate from solids using the thickening process, not bound to solid particles of sludge [22, 37],
– *bound in colloids* – trapped in the pores between particles of the sludge, more difficult to remove due to the binding forces of surface tension [26]; after the destruction of the structure of the flock of sludge, it is possible to partially remove it in devices for mechanical dewatering [22],
– *capillary* – bound by capillary forces (adhesion and cohesion), not possible to completely remove by mechanical dewatering [22], only e.g. by spinning [2]; attached to the surface of the sludge particles [22],

– *biologically bound* – occurring only in living organisms; in order to remove it, it is necessary to destroy the cellular membranes using thermo-chemical methods [2, 26].

The authors of the work [7] provide a classification of water contained in sewage sludge using partitioning in geology:

– *free* – is located in larger intermolecular spaces and depends on the gravity force and atmospheric pressure,
– *capillary* – is located in the capillary channels, does not depend on the force of gravity; a large role played here is the forces of surface tension,
– *physically bound with solid bodies (molecular water)* – composed of adhesive water bound by the forces of intermolecular attraction, as well as hygroscopic water,
– *bound chemically* – being a part of the crystallographic grid of solids.

Another division of waters in sewage sludge has been presented in [9]:

– *free* – unbound to sludge, occurring between the spaces of sludge particles,
– *semi-bound* (cavity water) – found in the flocks of sludge,
– *capillary* – bound by forces of adhesion and cohesion.

Furthermore, the following forms of binding water have been distinguished [9]:

– *physical* – as hygroscopic and colloidal water, bound by electric forces with particles of sludge, appearing at the borders of phases (surface tension),
– *chemical* – being a part of the molecules of chemical compounds [9], bound by the forces of surface tension [37],
– *biological* – in the cells of microorganisms, as well as in the biocolloids surrounding the cells, which form flocks of the sludge [9].

Fig. 3.1.1 shows a diagram of the arrangement of particular waters in sewage sludge.

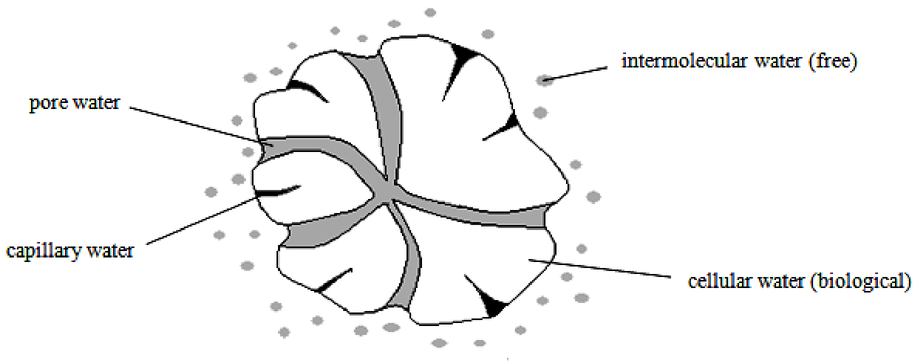


Fig. 3.1.1. Distribution of water in the flock of sludge [26]

The measurement of these fractions of water is carried out by methods of freezing to temperatures of a wide value range, or by evaporation or drying [22].

The author of the paper [37] shows a breakdown of sewage sludge in terms of its ability to bind water:

– sludge of good thickening/dewatering properties (containing a lot of mineral substances),
– sludge of average thickening/dewatering properties (primary and digested excluding industrial sewage, which contains colloidal substances),
– sludge of bad thickening/dewatering properties (active from biological treatment plants, as well as from wetted deposits).

▪ **contents of solids** – share of dry waste residue, constituting organic and inorganic compounds [13]. It constitutes the weight of evaporated and dried at a temperature of $105^{o}C$ sludge sample, expressed in a unit of its volume [g/l, kg/m^3] [26]. Content of solid substances in sludge constitutes an important parameter in the processes of sludge treatment and neutralization. Often, another different indicator is used, i.e. a dry residue of organic substances, enabling the initial identification of the sludge, taking into account susceptibility of the sludge to stability and dewatering. Sludge with a significant content of organic compounds belongs to the group that are difficult to dewater [13].

▪ **density of sludge particles** – dependent on how the process of sewage treatment is conducted. For example, for urban sludge, its value lies in the range 1.4 – 2.1 kg/dm^3 [35].

▪ **size and shape of particles** – extremely crucial in the process of agglomeration, concentration, sedimentation or dewatering [22]. Among the particles of fractions less than 100 μm the following can be distinguished:

- *falling off* – accumulated on the sieve,
- *flaky* – falling off after fifteen minutes of flocculation and one hour of sedimentation,
- *paracolloidal* – accumulated on a filter with pore sizes of 1 μm,
- *colloidal* – accumulated on a filter with pore sizes of 0.001 μm,
- *dissolved* [22].

▪ **the potential of Zeta (ζ) –** specifying the size of the forces of repelling neighbouring colloids of a double ion layer [26]. The measurement of this property can be used before dewatering the sludge in order to determine the dose of chemicals used for its conditioning. Sewage sludge is usually characterized by a negative charge in the range of -10 to -20 mV. In the case when the potential of Zeta has a very high value, the sludge is badly dewatered and flocculates [22]. By adding an inorganic coagulant or positively ionised polyelectrolyte, the force of repelling can be reduced and this potential neutralized. It is assumed that for increasing doses of chemicals the most profitable conditioning effect of sludge can be obtained for the value $\zeta = 0$ [26].

volume of sludge – counted according to the model [13]:

$$V_{os} = (100 \cdot G_{os})/[\rho_{os} \cdot (100 - W)], \ [m^3/day] \qquad (3.1.1)$$

where:

G_{os} – dry residue of solid substances contained in sludge, $kg_{d.w.r.}$/day,

ρ_{os} – density of sludge, $kg_{d.w.r.}/m^3$,

W – sludge hydration, % (by weight).

3.2. Sanitary properties of sewage sludge

In accordance with [31], in sewage sludge there is a significant number of viruses, bacteria, protozoa, as well as helminths' eggs, including pathogenic organisms. The origin of these pathogenic organisms may be varied, ranging from sick people or carriers to landfills, e.g. from slaughterhouses, agriculture, trade and industry. Table 3.2.1 shows the most frequently occurring species of pathogenic organisms in sewage sludge.

In the paper [26] the seriousness was emphasized of the sanitary threat in sewage sludge, resulting from the presence of pathogenic organisms and the need to take into account that fact when utilizing these wastes. During the utilization of municipal sludge in soil, its contamination is possible due to the longevity of pathogenic microorganisms in that environment (for bacteria: from 2 to 15 months, for viruses: from 3 to 6 months, and for worm eggs: from 24 to 28 months). The time the survival of pathogens in the environment is affected by: type, soil pH, humidity, environment temperature, insolation and the type of fertilized crops.

The presence of pathogenic bacteria cannot be directly demonstrated in sewage sludge. Therefore, an indirect method is used being in the discovery of the so-called sanitary indicator [26]. This indicator is *Salmonella,* in accordance with the Ordinance of the Minister of Environment of 13 July 2010 for municipal sewage sludge. This ordinance also distinguishes indicative organisms from nematodes: *Ascaris sp.*, *Toxocara sp.*, *Trichuris sp.* [33], as relevant for the utilization of sludge in the parasitological aspect. In addition, it imposes the obligation, before proceeding to the utilization of sludge, of subjecting it to treatment processes, in order to reduce the quantity or total destruction of pathogenic organisms present in them [26].

Table 3.2.1. Examples of pathogenic organisms appearing in sewage sludge [31]

Pathogenic species	Disease unit
Bacteria:	
Escherichia coli *Salmonella typhi* *Shigella dysenteriae* *Clostridium perfringens* *Vibrio cholerae* *Mycobacterium tuberculosis*	enteritis typhoid diarrhoea enteritis cholera tuberculosis
Viruses:	
Poliovirus *Coxsackievirus A* *Echovirus* *Hepadnavirus* *Calcivirus*	meningitis respiratory diseases rash, diarrhoea hepatitis vomiting, diarrhoea
Protozoa:	
Entamoeba histolytica *Giardia lamblia*	amoebuasus giardiasis
Nematodes:	
Ascaris lumbricoides *Entorobius vermicularis* *Toxsocara*	human ascaridosis enterobiasis canine or feline ascariasis
Tapeworm:	
Taenia solium *Taeniarhynchus saginatus* *Echinococcus granulosis*	cysticercosis of the muscles teniasis echinococcosis
Trematoda:	
Dicrocoelium *Fasciola hepatica*	bile duct diseases liver fasciola
Yeasts and fungi:	
Candida albicans *Cryptococcus neoformans* *Aspergillus sp.* *Phialophora richardsii* *Geotrichum candidum*	may infect animals and humans, cause allergic reactions or produce micro-toxins

3.3. Chemical properties of sewage sludge

They depend on the type of sewage they arise from. For example, they have been shown in table 3.3.1 [16, 26]

Table 3.3.1. Example composition of sewage sludge from urban sewage treatment [16, 26]

Component	Unit *	Average value
nitrogen	$\%_{d.w.r.}$	2,0 ÷ 3,5
phosphorus	$\%_{d.w.r.}$	about 3,0
calcium	$\%_{d.w.r.}$	2,0 ÷ 4,0
lead	$mg/kg_{d.w.r.}$	100 ÷ 500
cadmium	$mg/kg_{d.w.r.}$	1 ÷ 20
zinc	$mg/kg_{d.w.r.}$	2500 ÷ 4000
copper	$mg/kg_{d.w.r.}$	200 ÷ 500
nickel	$mg/kg_{d.w.r.}$	100 ÷ 300
chrome	$mg/kg_{d.w.r.}$	250 ÷ 750
$^{*}{}_{d.w.r.}$ - dry waste residue		

- **pH value –** for the majority of urban sludge it amounts to: 5 ÷ 8 [35]. An exception is sludge emerging in sewage treatment processes, together with the removal of phosphorus. For example, primary sludge and that being in the methane digestion phase has a slightly acidic reaction (pH≈6); whilst digested sludge or remaining in the methane digestion phase has a slightly alkaline reaction (pH = 7 ÷ 7.5). Thus, the indicator of the course of digestion is the pH value of the reaction [13]. Table 3.1 shows the ranges of pH values of the reaction, which sewage sludge can admit. Is it determined on the basis of decantated liquid from over the sludge, using methods excluding the loss of CO_2. For it has a fairly large impact on this property in raw sludge originating from municipal sewage, particularly after digestion. Otherwise, the result is the increase of pH value to the actual output value [26].
- **content of organic compounds** – determined by physical or chemical means. Dry waste residue [$\%_{d.w.r.}$] usually determines the total content of organic compounds. Its value is derived on the basis of the difference in the weight of sludge, dried at a temperature of 105^{o}C and the weight of sludge after combustion at 550^{o}C. Dry waste residue for unstabilized municipal sludge on average amounts from 60 to $85\%_{d.w.r.}$, while for stabilized sludge from 30 to 50%, calculated to dry weight [26].

The contents of organic substances in the sludge is significant, taking into account: the calorific value during combustion, the degree of potential odourization of air during storage or agricultural use, structure-creating abilities during agricultural management, as well as the amount of biogas forming during the digestion of sludge [26].

- **alkalinity** [mg $CaCO_3$/l] – it shows the content of alkaline compounds, dissolved in liquid sludge (table 3.1). The alkalinity of the sludge on average has twice the value of alkalinity of liquid sludge, which stems from the fact that undissolved substances bind certain amounts of acids in the sludge (due to the undissolved $CaCO_3$ in it) [13].

Primary and secondary sludge may have alkalinity ranging from 500 ÷ 1500 $CaCO_3$/l; the alkalinity of digested sludge amounts to (2 ÷ 6)·$10^3$$CaCO_3$/l. Sludge that is characterized by high alkalinity requires greater doses of chemical reagents during dewatering [13, 35]. By washing the digested sludge with treated sewage or water, the alkalinity of the liquid can be reduced significantly, and dissolved colloids and gas, which significantly reduces required doses of reagents, can be removed [13]

- **content of heavy metals** – dependent on the participation of industrial sewage in the total volume of municipal sewage, subjected to treatment. The high concentration value of heavy metals is an important factor that restricts the natural and agricultural use of sludge (table 3.3.2). The most undesirable heavy metals that are toxic for living organisms in sewage sludge includes: cadmium, chromium, lead, nickel and mercury. They show (with the exception of nickel) a major susceptibility to biocumulation [8, 26].

Table 3.3.2. Permissible content of heavy metals in municipal sewage sludge, in accordance with the Ordinance of the Minister of Environment of 13 July 2010 [33]

Metal	Content of heavy metals, mg/$kg_{d.w.r.}$*, not greater than:		
	in the application of municipal sewage sludge:		
	in agriculture, and for the reclamation of lands for agricultural purposes	for the reclamation of lands for non-agricultural purposes	when adjusting lands for specific needs arising from the waste management plans, land development plans or decisions on the conditions developing and managing a premises, for the cultivation of crops intended for the production of compost, for the cultivation of crops not intended for human consumption and the production of animal feed
cadmium (Cd)	20	25	50
copper (Cu)	1000	1200	2000
nickel (Ni)	300	400	500
lead (Pb)	750	1000	1500
zinc (Zn)	2500	3500	5000
mercury (Hg)	16	20	25
chrome (Cr)	500	1000	2500
* d.w.r. - dry waste residue			

In the paper [26], the significance of the contents of heavy metals in sludge has been highlighted, in its storage, especially in the case of an acidic bed of landfills due to the risk of washing metals from sludge. Furthermore, heavy metals during sludge combustion are of great significance, due to the fact that they remain in the ashes and substances after treating combustion gases, where as a result of the reduction in mass of the waste their concentration increases, even by four to five times.

- **content of volatile fatty acids** – VFAs [mg CH_3COOH/l] [11] – determines acids in the sludge that are possible to distil under atmospheric pressure, beginning from low-molecular aliphatic acids, soluble in water, thus formic acid, and ending at hexane acid [14]. The contents of VFAs is a control indicator of sludge in methane digestion process [13], of which the example contents in various types of sludge has been shown in table 3.1.
- **contents of biogenic compounds** – affects the possibility of sludge utilization in agriculture. Due to the fact that sewage sludge has humus compounds, trace elements, as well as other substances necessary for plant growth, they may be treated as valuable fertilizer [13]. The average quantity of the above-mentioned compounds have been provided for example in tables 3.1 and 3.3.1. Table 3.3.3, however, summarizes the content of fertilizer substances in sewage sludge and organic ferti-lisers.

Table 3.3.3. Comparing the contents of fertilizer substances [$\%_{d.w.r.}$] in sludge from municipal sewage treatment plants and natural fertilisers [9, 26]

Fertilizer substances	Sludge from municipal sewage treatment plants		Natural fertilizers	
	Primary sludge	Excess activated sludge	Bovine manure	Bovine farmyard manure
nitrogen (N)	2,0 ÷ 7,0	3,0 ÷ 10,0	0,45	0,12 ÷ 0,45
potassium (K)	0,1 ÷ 0,7	0,1 ÷ 0,8	0,425	0,133 ÷ 0,332
phosphorus (P)	0,4 ÷ 3,0	0,9 ÷ 1,5	0,087	0,017 ÷ 0,10

As it can be seen, sewage sludge in relation to other organic fertilizers contain far more nitrogen and phosphorus and less potassium. It should be noted that nitrogen and phosphorus play a significant role in many biochemical processes [26].

- **toxic substances –** in addition to heavy metals, in sewage sludge there may be other harmful, and even toxic, chemical compounds, deriving not only from industrial sludge, but also household sludge and rainwater sludge from agricultural areas, where pesticides are applied. Toxic pollutants of sludge include: polycyclic aromatic hydrocarbons (PAH), halogenated organic compounds, adsorbed organic compounds of chlorine expressed by a summary indicator (AOX), polychlorinated biphenyls (PCB), polychlorinated dibenzodioxins (PCDD) – dioxins, polychloronated dibenzofurans (PCDF) – furans, linear alkylbenzene sulfonate (LAS), nonylphenol, pesticides, chloroform, nonylphenol polyethoxylates (NPnEO), nonylphenol mono- and diethoxylates (NP1EO, NP2EO) [8, 23, 26, 31].
- **leachability –** a property consisting of dissolving in water or in the direct migration to it of selected components of the solid phase of sludge. The result of it is an increase in their concentration, and consequently, an ease of penetrating deep into the bed, where the sludge is stored or naturally used. This property can be considered a positive (leaching of organic nitrogen from sludge) or negative (leaching pathogenic microorganisms or heavy metal ions from the sludge, for an acid reaction of the soil) for the environment [26]. Leachability is marked at long-term contact of the sludge with distilled water, and then the pollutant should be determined in the water separated from the sludge. Sludge should be subjected to analysis in such a form in which it shall be disposed of at the landfill [14].

It should be noted that sludge exported to landfills may negatively affect both surface waters and groundwater [14].

3.4. Technological properties of sewage sludge

They have a significant impact on the processes of stabilization and utilization methods [26]. They include:

- **characteristics of sedimentation**
  - *sedimentation curve* – shows the relationship of the height of the sludge layer in the function of thickening time, it is determined using a sedimentation test, carried out in a measuring cylinder,
  - *optimal time of thickening* – technological parameter used to determine the capacity of the thickener,
  - *volume index* – determined by sedimentation of the sludge sample for 30 minutes in a branded cylinder with a capacity of one litre, expressed by the model [35]:

$$J = \frac{\text{sludge volume in 1dm3 after 30 minutes of the sedimentation}}{\text{initial content of suspensions in 1dm3 of sludge}}, \frac{\text{cm3}}{\text{g}} \quad (3.4.1)$$

This index has more of a quality importance [35]. If J ≤ 100 ml/$g_{d.w.r.}$ – the sludge sediments well, while if J > 100 ml/$g_{d.w.r.}$ – the sludge is occasionally subjected to gravitational thickening [13].

- **susceptibility to mineralization**

Sewage sludge are subjected to biochemical mineralization until they have living microorganisms and a source of organic carbon, which constitutes an energy substrate for them. In the case where easily assimilated carbon compounds are missing in the sludge liquid, their source is a dead biomass, after initial biomass hydrolysis [26].

The most commonly used indicators of mineralization of sewage sludge includes [26]:

- *the loss of organic matter* **–** in the process of mineralization the share of organic substances gradually decreases over time, and the so-called technical boundary of stabilization assumes a value at 38 ÷ 40% of initial reduction of dry waste residue,
- *digestion module* M_f [%] – enables an arithmetic presentation of the digestion degree of sludge, in accordance with the dependency:

$$M_f = 100 \cdot \{1-[(s.m.m._0 \cdot s.m.o._\tau)/ (s.m.o._0 \cdot s.m.m._\tau)], \quad \%, \quad (3.4.2.)$$

where:
s.m.m.$_0$, s.m.m.$_\tau$ – mineral substance at the beginning of the process and afterwards τ,$\%_{d.w.r.}$,
s.m.o.$_0$, s.m.o.$_\tau$ – organic substance at the beginning of the process and afterwards τ,$\%_{d.w.r.}$,

- *Rawn and Bant's module* – identical with the digestion module, enabling to determine the degree of aerobic decomposition of sludge, defined by the formula:

$$M_{st} = \{1-[(s.m.m._0 \cdot s.m.o._\tau)/ (s.m.o._0 \cdot s.m.m._\tau)] \cdot 100, \quad \%, \quad (3.4.3.)$$

- *quotient of stabilization of sludge* – dimensionless ratio, determining the time after which the sludge practically does not change its chemical properties, defined by:

$$IS = C \cdot H/s.m.m., \quad (3.4.4.)$$

where:
IS – quotient of stabilisation, -,
C, H – respectively, the share of carbon and hydrogen in the sample (components, whose contents are reduced along with the duration of the process), %,
s.m.m. – share of mineral substances in sludge, $\%_{d.w.r.}$,

- *respiration rate* – the rate of oxygen consumption by the sludge, a parameter determining the condition of the sludge. The respiration rate is usually determined by referring to the active sludge being in the reactor of biological treatment. It is also possible to use this indicator as a parameter of dividing the separated aerobic stabilization of the sludge. The rate of oxygen consumption is determined in two stages. Sewage and active sludge, selected from the aeration chamber, or secondary sludge is initially oxygenated to the highest level of oxygen concentration, close to the saturation state in a given temperature (8 ÷ 12 g/m^3). Then, aeration is turned off, and the sewage along with the sludge, or the sludge itself, is stirred. At the same time a reduction in oxygen concentration can be observed, which in respect to time and the quantity of dry residue or dry waste residue indicates the so-called rate of respiration. For example, when the rate of respiration for the active sludge amounts to 20 ÷ 40 g O_2/($kg_{d.w.r.}$·h), then it is known that many active microorganisms enter the composition of the sludge, and there are still organic compounds in the environment, being a substrate for the biomass. However, low rate of respiration (5 ÷ 10 g O_2/($kg_{d.w.r.}$·h) indicates a lack of organic substances and the presence of toxic or stabilized substances of the sludge.

- **filtration properties**

The process of filtration is one of the static methods of dewatering sludge, consisting in dividing the phases of the sludge (solid and liquid) by using the difference of pressures on two sides of the filtration barrier. The difference in pressures, in the case of the vacuum filtration process, can theoretically reach a maximum value of 0.1 MPa, while in the case of pressure filtration it can even reach up to 2.5 MPa [26].

The basic measures of assessment of possibilities of de-watering sludge include: resistivity of filtration, capillary suction time (CST) and the compressibility coefficient. They are indicated in experiments in laboratory conditions [26].

– *resistivity of filtration* – a parameter describing the relative dewatering of sludge using the filtration process. It is defined as the pressure difference needed to initiate unit flow rate of the filtrate, of a given viscosity, through a specific weight of the filter patch. The appropriate resistance value is determined using Büchner's funnel [13, 35].
  In accordance with [13] appropriate resistance can be reduced by:
  – the addition of mineral or organic coagulants, as well as polyelectrolytes,
  – heating,
  – washing,
– *coefficient of compressibility*
  Sewage sludge is a compressible material. Along with the increase of filtration pressure its appropriate resistance generally rises. Depending on the applied pressure, particles of the solid phase of sludge during filtration are subjected to deformation, filling the pores inside the arising cake, according to the equation:

$$r = r_o p^s, \tag{3.4.5}$$

where:
r – appropriate resistance of filtration at pressure p,
r_o – constant that represents the appropriate resistance of the patch of incompressible sludge,
p – pressure of filtration,
s – coefficient of compressibility.

Compressibility measurement is made in order to determine the most relevant range of pressure applied for filtration. In using the test of resistivity of filtration the coefficient of compressibility is determined. When the tests are repeated many times, a graph of resistivity should be made in the function of negative pressure, in a logarithm system of coordinates. The graph log r = f(log p) is a straight line, and the coefficient of compressibility of sludge is the tangent of the angle of inclination of the obtained line, according to fig. 3.4.1, while [26]:

$$s = tg\alpha = (\log r_2 - \log r_1)/(\log p_2 - \log p_1). \tag{3.4.6}$$

For sewage sludge, the coefficient of compressibility is typically from 0.4 to 1.1 [26]. According to [13] it takes on values ranging from 0.6 to 0.9, and even exceeding 1.0. In accordance with [35] the coefficient of compressibility typically amounts from 0.4 to 1.4 and depends on the origin of sludge. Generally, compressibility increases as the flocculation degree rises.

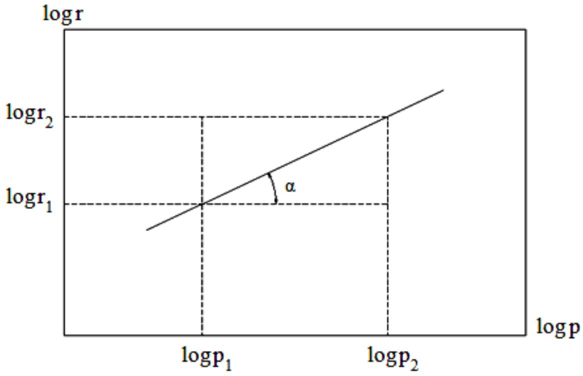


Fig. 3.4.1. Determining the coefficient of compressibility of sludge [25]

– *capillary suction time (CST)* – indicating the filtration capacity of sludge, using the phenomenon of capillary suction occurring during the absorption of moisture by adequate filter paper with standard gradation [13]. *CST* can be correlated with the appropriate resistance of filtration, during a series of samples on *CST* apparatus and Büchner's funnel for the same sample. Capillary suction time is a commonly used indication in choosing chemical auxiliary agents, in order to determine their appropriate doses and determine the impact of variables on filtration parameters of sludge [13, 35].

- **energy properties**

Combustion heat W_g, is a parameter that specifies the amount of energy obtained from incinerating 1 kg of hydrated sludge, after cooling combustion gases to the initial temperature of sludge, while the steam arising as a result of combustion is liquefied. This indication is conducted in a calorimetric bomb. The heat combustion value depends on the quantity and quality of organic compounds in the analyzed sludge [26].
For average sewage sludge produced from urban sewage, the dependency for determining combustion heat has been presented in the work [26]:

$$W_g = (224{,}7\ p_v + 1495) \pm 1722, \quad [kJ/kg], \tag{3.4.7}$$

where:
p_v – share of inflammable substances, kg/kg of moist sludge.

Combustion heat for raw sewage sludge on average amounts to $(23 \div 29)\cdot10^3$kJ/kg, while for stabilized sludge $(9 \div 14)\cdot10^3$kJ/kg , which stems from the fact that they contain less organic matter [31].
Calorific value W_d, is a parameter [26], which specifies the amount of energy obtained during total combustion 1 kg of hydrated sludge, after cooling combustion gases to the initial temperature of sludge, while the steam is not subject to condensation. It is indicated from the heat balance through determining the difference between combustion heat and condensation heat of the entire content of steam originating from the combustion gases, from the moisture of sludge and the hydrogen arising from combustion, under the dependency:

$$W_d = W_g - r_{pw} f, \quad [J/kg], \tag{3.4.8}$$

where:
W_d – calorific value, J/kg,
W_g – combustion heat, J/kg,
r_{pw} – heat of water vaporization, J/kg,
f – share of steam in combustion gases, -[26].

In accordance with [31], raw sludge is characterized by calorific value ranging from 15 ÷ 21 MJ/kg, while stabilized sludge: from 6.3 ÷ 18 MJ/kg.
According to [40], the calorific value of waste is determined by the share of inflammable organic substances, and the ease of incinerating waste is influenced mainly by three factors:

- share of moisture < 50%,
- share of inflammable parts > 25%,
- share of ash < 60%.

Fig. 3.4.2 shows Tanner's diagram, on which the autothermal combustion of waste is visible.

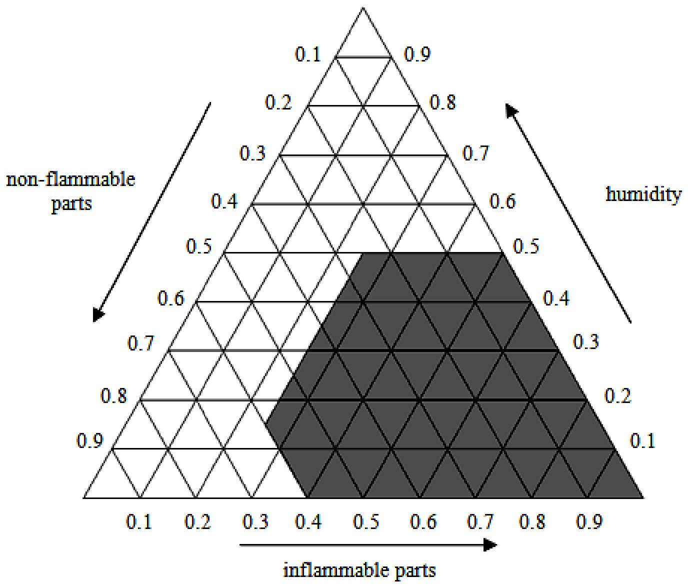


Fig. 3.4.2. Energy characterization of municipal waste in Tanner's triangle (grey field – area of self-sufficient combustion of waste) [40]

Sewage sludge, intended for utilization by combustion must first be dried in order for it to have the appropriate dry residue. In the case of sludge, it is possible to incinerate it without additional fuel, at a content of approx. 60% of dry residue [3]. The authors of the work [3] emphasise that the fuel properties of sewage sludge change over time, especially when it is collected on the premises of sewage treatment plants. Conducted studies have shown a significant decrease in the calorific value and share of inflammable parts in sludge as the time of storage is extended. For example, sludge stored for a period of ten months can reduce its calorific value by even 35%.

- **fertilizer value**

According to [2], the fertilizer value of sewage sludge depends on the share:

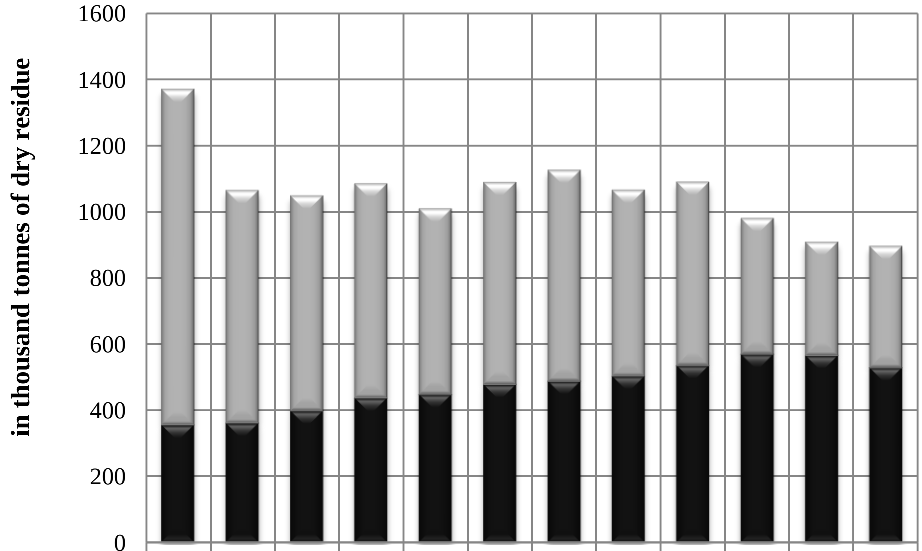
- of organic substances being the environment for the functioning of microorganisms, as well as substances susceptible to the production of humus,
- of priority nutrients for plants, such as: nitrogen, potassium, phosphorus, calcium and magnesium,
- of microelements.

3.5. Rheological properties of sewage sludge

In accordance with [26], properties of rheological sludge include the viscosity and flow boundary, which depend on hydration and temperature. As it is known, viscosity is a variable property in the function of shear speed, while the flow border is the value of shearing stresses below which the maintenance of the system similar to solids is observed, and above to liquids [26].

4. Production of sewage sludge

Fig. 4.1 shows the production of sewage sludge in the years 1999 – 2009, depending on its types. It can be seen that the production of sludge originating from industrial treatment fell in this period by three times, while from municipal treatment it increased by almost one and a half.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
sludge from industrial treatment plants	1014,1	703,3	649,6	648	562,1	611,2	638,2	563,4	555,4	411,6	345	368,4
sludge from municipal treatment plants	354,4	359,8	397,2	435,7	446,5	476,1	486,1	501,3	533,4	567,3	563,1	526,7

Fig. 4.1. Production of sewage sludge depending on type in the years 1999-2010 [21]

Figure 4.2 illustrates the application of sludge from municipal sewage treatment plants in the years 1999-2009. It shows that the quantity of sludge:

- stored temporarily is increasing,
- stored – is decreasing,
- thermally transformed – practically does not change,
- used for agriculture – is increasing,
- used for the reclamation of land, including land for agricultural purposes – is decreasing.

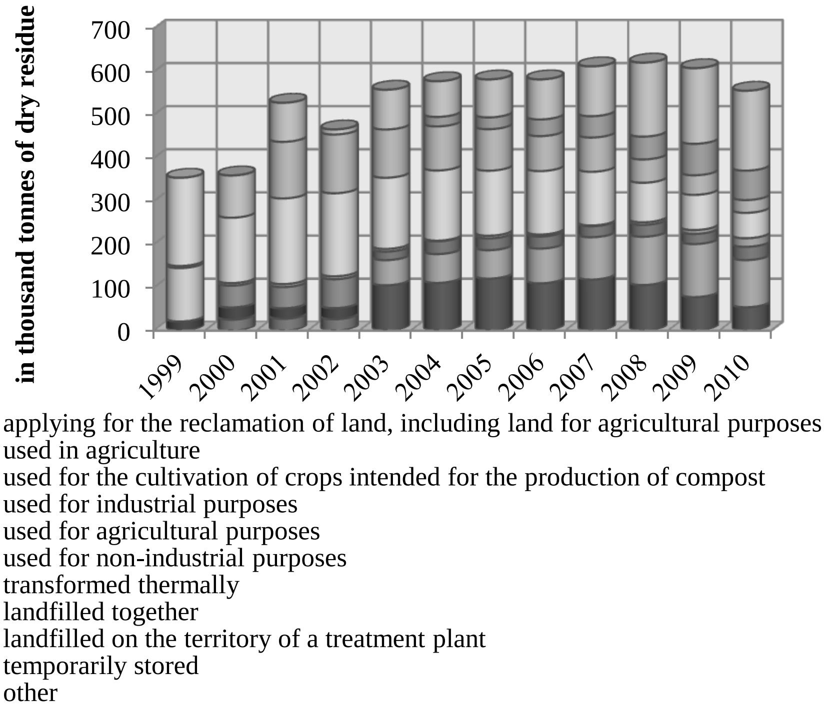


Fig. 4.2. Proceeding with sludge from municipal sewage treatment plants in the years 1999-2010 [21]

Figure 4.3 shows the application of sludge from industrial sewage treatment plants in the years 1999-2009. It can be noticed that the quantity of sludge:

– stored – is decreasing,
– thermally transformed – is greater than sludge originating from municipal sewerage,
– used for agriculture – increases,
– used for the reclamation of land, including land for agricultural purposes – has been decreasing since 2007.

This may result from ousting certain methods of sewage sludge management, depending on the current legislation.

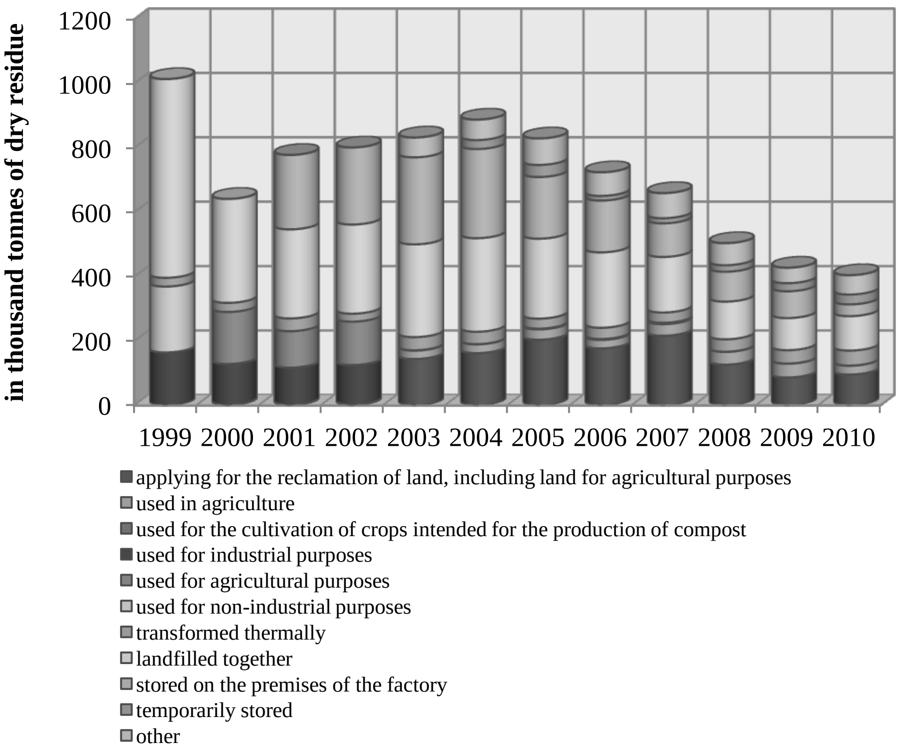


Fig. 4.3. Proceeding with sludge from industrial sewage treatment plants in the years 1999-2010 [21]

5. An overview of the methods of neutralizing sewage sludge

Fig. 5.1. shows the general breakdown of methods of utilizing sewage sludge.

Natural use

One of the criteria for determining the natural usefulness of sewage sludge is their content of humus-creating components and fertilizer components. In the case of the first parameter, its value cannot be less than 30%, while nitrogen – less than 1.2% in dry residue. In the case when in the sludge there is a permissible content of heavy metals, then they can be used to produce compost. Thus it becomes an organic fertilizer. It often happens that the composition of sewage sludge includes significant quantities of heavy metals and "negative" organic compounds originating from the industry, which consequently limits the natural use of sludge [34].

The act on waste of 27 April 2001 [38] says that there is the possibility of utilizing municipal sewage sludge:

– in agriculture (for growing all agricultural foetuses marketed commercially, including crops intended for the production of animal feed),
– for the reclamation of land, including land for agricultural purposes,
– for adapting lands to the specific needs arising from waste management plans, land-use management plans or decisions of conditions for land development and management,
– for the cultivation of plants for the production of compost,

– for the cultivation of plants for human consumption and for the production of animal feed.

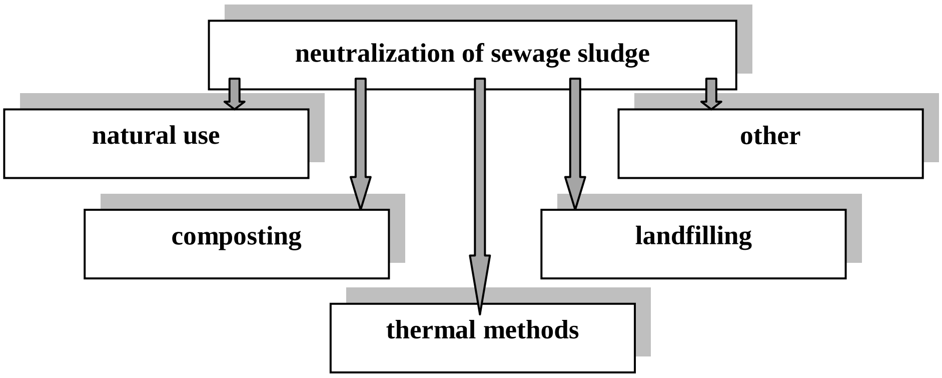


Fig. 5.1. Neutralization of sewage sludge [2]

Municipal sewage sludge may be used if it has been properly stabilised and prepared. For example – when they have been subjected to biological, chemical, thermal treatment or another process that reduces the susceptibility of municipal sludge to moulding and eliminating the threat for the environment or human health.

The Act also requires the manufacturer of municipal sewage sludge to carry out their research before application, as well as research of lands on which they are to be used.

It should be emphasized that it has been prohibited to use municipal sewage sludge:

- in areas of national parks and nature reserves,
- on areas of indirect protection of water protection zones,
- on a strip of land of the width 50 m, directly adjacent to the shores of lakes and streams,
- in inundation areas, temporarily flooded and marshy,
- in areas temporarily frozen and covered by snow,
- on lands with high permeability (loose sands and weak clay, light clay sands), if the level of ground water is located at a depth of less than 1.5 m below the surface of the ground,
- on agricultural lands with a decline exceeding 10%,
- on protection areas of inland water tanks,
- on areas covered by other forms of nature protection not listed (if the sewage sludge was produced outside those areas),
- on areas situated at a distance less than 100 m from the water intake, a residential building or food manufacturing establishment,
- on lands on which plants and vegetables grow, with exception to fruit trees,
- on lands intended for growing berry fruits and vegetables, which edible parts come directly into contact with the ground and are eaten raw (during the 18 months preceding harvest and during harvest),
- on lands used for pastures and meadows,
- on lands used for cultivating under shells.

Composting is the decomposition of organic pollutants, which contains sludge under aerobic conditions, at the presence of other organic wastes and hydration of sludge from 40 to 60%. The structure-creating material is to facilitate the flow of air, as well as obtain an adequate ratio of carbon to nitrogen (26:1) in the mass of the sludge. Biochemical processes are very effective, as a result of which the temperature reaches a value of even 70°C in the compost heap. At such a temperature, the disinfection of sludge takes place, therefore, the destruction of pathogenic microorganisms and parasitological pollutants [20]. Thanks to the composting of sludge, stabilization of organic compounds can be obtained, as well as a decrease of weight and hydration, and a stable, economically valuable end product [1].

Thermal methods

In accordance with the act of 27 April 2001 [38], thermal transformation of waste means:

- waste combustion by oxidation,
- other processes of thermal transformation of waste, including pyrolysis, gasification and the plasma process, insofar as the substances arising from these processes of thermal transformation of wastes are then incinerated.

According to [13] we can highlight the following thermal processes used for the utilization of sewage sludge:

- *combustion* – oxidation of organic compounds to CO_2 and H_2O. The purpose of the process is to reduce the volume of produced sludge. It is used, where it cannot be used in agriculture, due to the high concentrations of heavy metals [11],
- *co-combustion*, and in it:
  - co-combustion of sewage sludge with fixed municipal waste – such a solution reduces investment costs concerning the heat required to evaporate water from sewage sludge and excess heat to create steam, as well as supports the combustion of waste and sludges [13],
  - co-combustion of sewage sludge with coal, where hard coal should be dried on average to $90\%_{d.w.r.}$, while brown coal to a lower value.
    By incinerating sludge in coal boiler rooms good conditions are obtained for the liquidation of organic components found in these wastes, as well as using their energy resources [13],
  - co-combustion of sewage sludge in cement kilns – a safe way of incinerating various organic wastes. They must be dried and have a calorific of even 16 MJ/kg. In addition, the chlorine content should not exceed 5% of the weight of sludge [39],
- *pyrolysis* – the process of thermal transformation of organic substances, rich in carbon, taking place in elevated temperatures in anaerobic conditions or with little of its presence. There is low temperature pyrolysis and high temperature pyrolysis. The first occurs at temperatures below 600^oC, while the other – above this value. As a result, products of the following phases are obtained: gaseous, solid and liquid [39],
- *quasi – pyrolysis* – alternative technology, using the process of pyrolysis and gassification, as well as combustion [13],
- *wet oxidation of sludge* – here only mechanically thickened, unhydrated sludge is used. In the reactor of wet oxidation the temperature is maintained at the level of approx. 250^oC and pressure approx. 40 bar, allowing organic oxidation of the sludge mass [6].

The authors of the work [3] also distinguishes:

- *gasification* – a process in which the total transformation of solid fuels into gas occurs, which happens at temperatures approx. 1000^oC, with the presence the oxidizing factor. The product of the process is hydrogen, carbon monoxide, as well as small amounts of methane, carbon dioxide, water vapour and nitrogen. The gas obtained might have different calorific value, and everything depends on the type of oxidizing agent and amounts from 5 MJ/Nm^3 (for air) to 10 MJ/Nm^3 (for oxygen) [39],
- *vitrification* – a process enabling to change the properties and form of modified material. It consists in appropriate dosage of energy to the substances, which at higher temperatures decomposes with the production of the gaseous phase, after which it is subject to ashing and melting.

Landfilling

Sludge which is impossible to utilize in another way, both for ecological and economic reasons are subject to landfilling [20]. The following technical possibilities for landfilling sludge is distinguished:

- landfilling dewatered and limed sludge,
- landfilling thermally dried sludge,
- placing dewatered municipal sludge with fixed wastes on landfills.

In order to be landfilled, sludge must meet the following conditions:

- on homogeneous landfills:
  - hydration: less than 55%,
  - shear strength: over 25 kN/m^2,
- on common landfills together with municipal waste:
  - hydration: less than 65%,
  - shear strength: more than 10 kN/m^2.

It is prohibited to landfill sludge that contains toxic substances. In these cases separate special landfill sites must be built [20].

Other methods of treatment of municipal sewage sludge

In accordance with [31] the following is also distinguished:
- the production of biogas, having extensive application, e.g. for heating digestion chambers or residential buildings, in ovens incinerating rakings and for driving engines, with a possible secondary recovery of heat;
- the transformation and application of fats from sludge,
- manufacturing plastic masses from active thickened and dewatered sludge,
- the use of active sludge as an additional feed for domestic animals, rich in fertilizer nutrients and protein.

6. Summary

The problem of sewage sludge has a worldwide dimension. This paper presents properties directing at appropriate methods of utilizing sewage sludge. Guidelines for the use of these wastes are indicated by relevant legal acts, among others, Resolution no. 217 of the Council of Ministers of 24 December 2010 on the national waste management plan 2014 [36], Ordinance of the Minister of Economy and Labour of 7 September 2005 on the criteria and procedures for admitting wastes for landfilling on a waste landfill of a given type [32]. For example, in accordance with [32] landfilling sewage sludge is possible in the case of fulfilling a number of criteria, which have been presented in table 6.1.

Table 6.1. The criteria for admitting wastes for landfilling in places designed for waste other than hazardous and inert [32]

Parameter	Border value
Total organic carbon (TOC)	5%
Loss on ignition (LOI)	8%
Combustion heat for municipal processed waste *	max. 6 MJ/kg
* it is unacceptable to mix municipal waste with inert fractions in order to obtain this parameter	

It shows that the current dominating landfilling of sludge, due to economic factors, as well as temporary storage shall be limited.

According to the forecasts of the national waste management plan 2014 [36] in 2022, 746 thousand $t_{d.w.r.}$ municipal sewage sludge will be produced, and the main objectives in the economy for the management of these wastes is to be:
- reducing the landfilling quantity of sewage sludge,
- increasing the quantity of the above wastes intended for processing before introduction into the environment, as well as transformation using thermal methods,
- using at the highest possible degree biogenic substances being in the content of sludge, taking into account the requirements relating to environmental, sanitary and chemical safety.

Each method discussed in the paper of disposal of sewage sludge has both disadvantages and advantages. These qualities of presented methods of using sludge decide which method will find adequate application.

Bearing in mind natural use these waste, attention should be drawn to the possibility of using contained nutrients and organic substances therein. Moreover, taking into account the costs of this project, it is usually the cheapest way to manage them. However, due to the limited state of know ledge concerning micropollutant sand pathogens and their impact on human food chain and animals, the use of these methods is quite limited.

Thanks to composting deposits we get the reduction in the volume of the base material what is comfortable in case of the transport. Apart from that, we control the composition of the received product. However, from the other side costs of composting are considerable, and therefore an adequate market outlets must be assured.

Thermal methods also provide a significant reduction of inputs (and at the same time their energy use), lowsen sitivity tovariation in the composition of these diments, the possibility of using recycled products and what is important – minimizing odors from the waste. The main disadvantages of these methods include, inter alia, high investment and operating costs, and also problems in meeting emission standards (in the case of co-combustion).

Landfilling is cheap way of waste disposal, but not always advisable. It results from the biological decomposition of organic matter in the waste, which is connected with the uncontrolled emission of methane into the atmosphere. The solution to this problem can be recovering and the resulting combustion of methane, but it is a costly and inefficient. The cause of this is a large area of emissions and the associated low levels of methane formed in the atmosphere.

The above analysis shows that, use thermal methods for the utilization of sewage sludge is becoming inevitable. This is mainly favoured by benefits arising from obtaining products which affect the environment to a minimum.

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