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Basics of Wastewater Treatment

Mechanical pretreatment

Nowadays, the primary wastewater treatment stage is used very rarely or not used at all on its own, because water leaving the treatment does not or only partially complies with regulations. The composition and concentration of initial raw wastewater can show significant differences depending on the origin of wastewater, which greatly influences the choice of the applied technology line. Physical, chemical and biological processes based on each other are used in wastewater treatment.

Mechanical wastewater treatment is one of the oldest methods used. Its engineering structures are designed with fluid dynamics in mind, influenced by physical forces (inertia, gravity, friction and cohesion forces).

The main purpose of mechanical cleaning is:

- removal of larger size contaminants
- protection of the machinery of subsequent technology and making capable the wastewater for next technological steps (e.g. elimination of coarse grained particles and fats)

The structure of the first treatment stage is shown in Figure 1, which follows the sequence of a general mechanical wastewater treatment process.

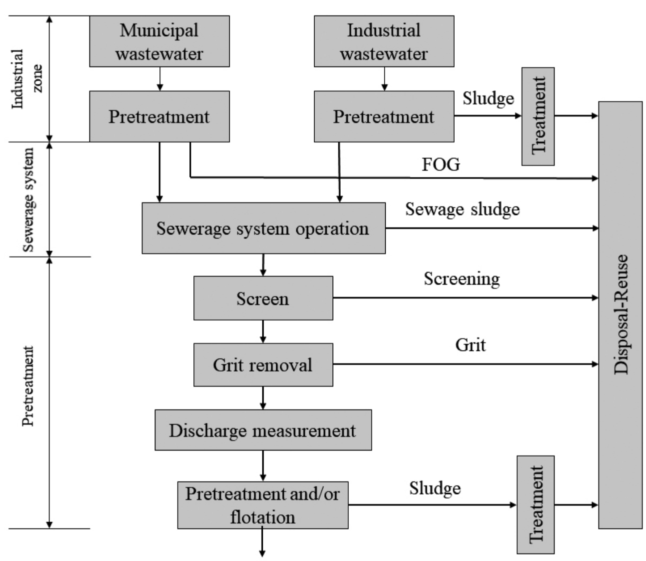

Figure 1
First treatment stage of wastewater treatment (based on [1])

The percentage removal efficiencies estimated for mechanical cleaning for major contaminants are given in Table 1 (values are indicative).

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Table 1
Removal efficiency (detail [2])

Procedure	Settable solids (%)	Total suspended solids (%)	Colloidal suspended solids (%)	BOD_5 (%)	COD (%)	Heavy metal ions (%)
Grid	5–10	2–5	–	–	–	–
Sand trap	20–30	10–20	–	–	–	50–80
Settling	85–95	40–50	10–20	20–30	15–25	20–30

Physical procedures are divided into two major groups according to their operating principle:
- equipment based on the principle of size difference: grids, sieve and fabric filters, particulate filters
- equipment based on the principle of density difference: settlers, floaters (grease and oil traps)

The grouping of different mechanical equipment according to the nature of the waste to be removed is given in Table 2.

Table 2
Classification of mechanical processes [3]

Cleaning equipment	Pollutant to be removed
Stone and gravel pliers, grids, filters, shredders	Large floating and suspended materials
Sand traps	Small floating and mineral substances
Settlers	Small floating and suspended materials
Hydrocyclones	Small floating and suspended solids
Floating equipment, flotation tanks, thickeners, septic tanks	Small suspended and floating, liquid and solid materials

Wastewater can flow into the treatment plant from the public sewer by gravity or from a pressurised system.

Breakdown of coarse pollutants (based on their size and physical properties):
- rolled (gravel, stone debris)
- floating (e.g. tree branch, textile waste, plastic, etc.)
- suspended matter (finer suspended matter)

The main purpose of stone and gravel traps is to retain sediment (5–20 cm in size) from the combined sewer network. Large coarse dirt (floating and suspended solids) is removed by filtration and comminution.

Grids and shredders

Commonly used mechanical equipment of the cleaning technology includes grids, their application is important, e.g. to remove clogging materials in order to protect and relieve subsequent process equipment. When designing grids, flow velocity must be taken into account and the settling in front of the grid must be minimised (min. 0.2–0.3 m/s, or max. 0.7 m/s in case of peak load).

The grids can be used:

- in front of pumps (sewage pumping station)
- at the beginning of the technology (before sand trap and pre-sedimentation)

Grids are usually placed inside a building to protect electrical and mechanical equipment, thereby eliminating odour and the effects of the corrosive atmosphere, thus, increasing service life. In low-capacity plants, mechanical equipment is often located outside the building, in which case it is reasonable to heat it during winter (for normal operation of the technology).

According to the opening of the grid located at the beginning of the technology, some of the materials are retained, so the grids provide resistance in the path of the flowing wastewater, which causes back swelling. During the process, materials left on the grid must be removed by regular machine or manual cleaning. It is common for wastewater treatment plants to use two rows of structures, if this cannot be solved, it is worthwhile to design an emergency bypass (Figure 2) in case of possible malfunctions.

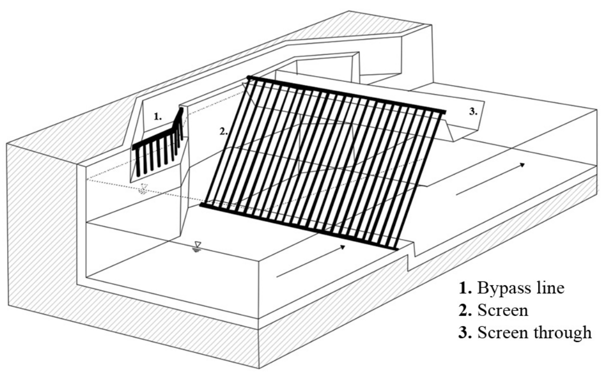

Figure 2
Design of a bypass channel at grids [4]

Grids can be grouped in several ways based on the spacing of rods, their placement, design and means of cleaning.

a) According to their cleaning method:

- manual (for small or intermittent technologies)
- mechanical (for continuous and automated operation)

Mechanical grid cleaning equipment moves slowly, so their electrical power is relatively low (max. 5 kW).

Table 3
Types of machine-cleaned rod grids [5]

Grid Type	Rake	Arched	Spinner	Basket
Built-in	Bending angle 60–80°	Vertical and horizontal	Bending angle 60–80°	–
Application in sewage treatment plant	Small capacity	Small and medium capacity	Medium and high capacity	Sewage network
Equipment	Sewer and grid chamber			Sewer shaft

a) According to rod spacing (MSZ EN 12255-3-2001):
- fine (2–10 mm, usually steel, machine cleaning needed)
- medium (10–20 mm, to prevent clogging)
- coarse (20–50 mm, in case of operation of integrated sewerage networks, screenings is more of a solid waste type, the most commonly used type is flat grid)

b) By position (angle of inclination 20–75°):
- skew
- vertical

c) According to their design:
- flat grid (Geiger filter straight surface consisting of grid bars)
- curved rods (consisting of Parkwood CM curved rods)
- standing rods (consisting of fixed built-in flat or curved grid panels)
- moving grids (consisting of Geiger's articulated grid plates formed as endless strips)

The use of flat grids is more common in larger capacity plants. It is also used for coarse and fine grids; this machine-cleaned flat grid (usually with an inclination of 80°) is illustrated in Figure 3.

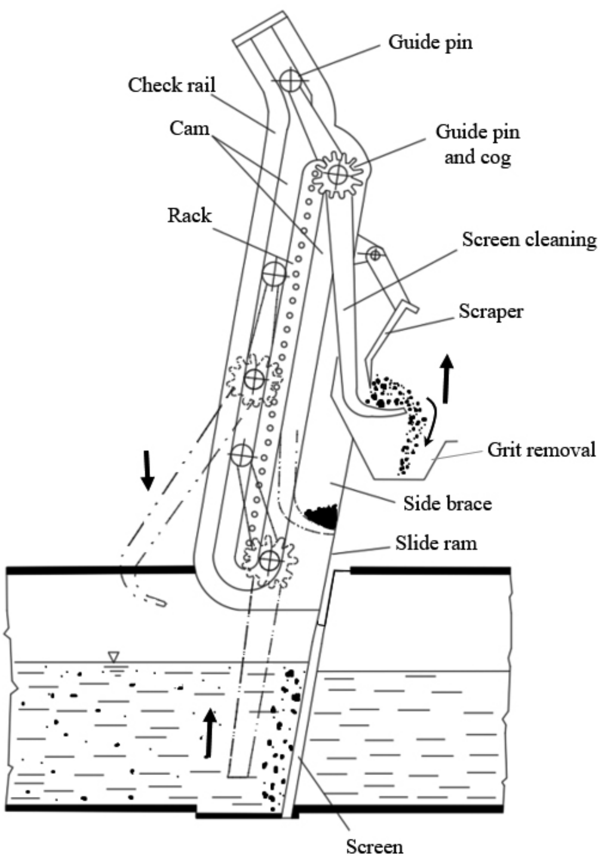

Figure 3
Machine cleaning flat grid [2]

Main types of flat grids:

– operating with an alternating cleaning device
– continuous cleaning (fixed grid)
– continuous cleaning (moving grid)

In hydraulic dimensioning of the grid, the following must be taken into account:

– the flow rate of water movement between rods, which must not exceed 1 m/s (otherwise the flowing water may take along the waste)
– flow velocity into the inlet and outlet channel should be in the range of 0.5–0.8 m/s (to prevent the deposition of minerals)
– for grids used in medium and small settlements, also the grid design and the cleaning system

In the hydraulic sizing of sewage grids, the Kirschmel relation can be applied, with which we can estimate the back swelling effect of local loss, which can be 5 cm on average. By changing the profile of the grid bar with the same dimensions, the degree of back swelling can be reduced.

Kirschmel's relation:

$$h_v = \beta \cdot \left(\frac{d_p}{k_p}\right)^{\frac{4}{3}} \cdot sin\alpha \cdot \frac{v^2}{2g}$$

where

hv: back swelling of the grid [m]
dp: width of the grid bar [m]
kp: free spacing [m]
v: average wastewater flow rate in front of the grid [m/s]
α: angle of the grid with the horizontal plane
β: form factor (depending on the cross-section of the grid cross-section –1.79; for flat steel –2.42; for rounded flat steel –1.64; for flat steel rounded only at one end –1.83)

In practice, the simplest solutions used in wastewater treatment plants below 750 m^3/d include a screening basket that is periodically emptied by manual or machine lifting.

Between 1,500 and 3,000 m^3/d, the use of both curved grids and hand-cleaned flat grids is widespread. In plants with a capacity of more than 3,000 m^3/d, machine-cleaned flat grids are used. Screenings from the equipment contains rapidly decomposing, foul-smelling, infectious substances with a moisture content of 85–90%, the amount of which is determined by the nature of the wastewater and rod space. Further treatment of the screening can be done by digestion (after proper shredding) or composting.

Instead of grids, we can also use shredding equipment, which does not remove coarse waste, but performs shredding. The purpose of shredding is to prevent additional problems during lifting, draining and cleaning; it can also be used to replace fine grid. Shredders can be commutators, barminutors, shredder or grinding wheel pumps can be grouped separately (they also carry sewage at the same time). The most commonly used shredders are commutators (knife shredders) due to their favourable wastewater technology and mechanical advantages. During their operation, wastewater flows through the openings of the drum, larger dirt gets stuck, the fixed knives do the chopping (to a size of 6–20 mm), and then it leaves with the wastewater at the bottom of the drum.

Grits

Grits are mainly used in combined or mixed sewerage networks; they usually follow the sewage grids in the technology line.

The main purpose of its application:

- reducing the content of primary particulate minerals in wastewater to protect subsequent machinery
- sedimentation prevention (in on-site interconnectors)
- reducing inorganic load in additional tanks
- reduction of excavator overload

Grits can be essentially considered settlers, so the operating principle of grits can be determined by Stokes's sedimentation formula. In a stationary environment, particulate matter is subjected to gravitational, buoyant and frictional forces.

Stokes sedimentation formula:

$$v_{ü} = \frac{g \cdot d^2}{18 \cdot v} \cdot \frac{\rho_{sz} - \rho_{water}}{\rho_{water}}$$

where

$v_{ü}$: sedimentation rate [m/s]
υ: kinematic viscosity of the flowing medium[m²/s]
g: acceleration due to gravity [m/s²]
d: average diameter of settled particle [mm]
ρ_{sz}: average density of settled particle [kg/m³]
ρ_{water}: granular inorganic materials of larger density of water [kg/m³]

If the flow rate can be kept between 0.1 and 0.3 m/s, sand and other heavier granular inorganic materials (smaller gravel grains, slag, fruit seeds, etc.) with a diameter of 0.2 mm will settle, but organic pollutants are more difficult to settle. In the case of properly subdivided tanks, sediments can be classified according to size.

The size of sand grains and the composition of the separated sand are influenced by:

- the quantity and quality of domestic effluents
- the type of sewer network (combined or separated)
- the material and condition of the sewer network
- the size of the catchment area
- hydraulic residence time

When choosing grits equipment, take into account:

- construction aspects (e.g. space requirements, groundwater, mechanical design)
- the magnitude and fluctuation of wastewater flow
- the material to be settled (in terms of quantity, storage, extraction, washing, disposal)

Depending on flow direction, grits can be divided into several groups, such as horizontal, vertical and circular flow or rotating cylindrical (horizontal axis-air-blown) grits.

Horizontal flow grits

Optimum flow rate is 0.3 m/s. Constant flow can be ensured even with variable water flow. The most widely used type is the Parshall channel-controlled grit; even Venturi channel and Sutro-tumble can be placed after the grit. Sufficient volume must be provided at the bottom of the grit to store the sand.

Types:

- long flow (Essen, sand excavation with machine excavator)
- ventilated or aerated
- tangential introduction
- vertical flow

Vertical flow grits (cylindrical, column or funnel-shaped)

The most common version is Blunk's, in which wastewater first flows vertically downwards in the structure, thus, settling the mineral (hydraulic sand separation).

Tangential (vertical axis) grits

In the tank, a circulating water movement is created, in which suspended solids are affected by gravity and centrifugal force accelerates phase separation. It is often used in a PISTA system, which is an integrated pretreatment unit where grids and grits are placed together in one unit.

Air-blown grits

It is often used in domestic plants due to its flexible controllability. The flow rate in the structures can be varied within wide limits and the removal of solid particles can be adjusted.

A spiral flow develops in the air-blown grit due to the introduction of coarse bubble (5–8 mm) air. The advantage of the technology over the long-flow grits is that the settling is efficient even in shorter structures. It is advisable to place the air intake in the vicinity of the bottom of the structure at a certain depth (Figure 4), thus, increasing separation efficiency and reducing foaming that may occur due to detergents.

The amount of air introduced into the grit is determined by its size and cross-section, and the optimal value is set on the sites with a manual flow meter, so its amount may vary from site to site. In addition to the function of grits, it is important to separate sand and organic contaminants.

If compared to the ideal air intake:

- less air is introduced, a significant amount of sludge can be deposited in the grit, thus, reducing the efficiency of biodegradation (nitrogen removal)
- air intake is operated with high efficiency (too much air), sand separation can be reduced, it can cause operational problems

The flow in the cross-sectional plane of the basin (mainly in the lower critical zone of the basin bottom) plays a fundamental role (Figure 5) and greatly influences the sand removal efficiency of the structure.

When sizing a grit, the main sizing parameters include residence time, which should be set between 3–10 minutes.

The organic matter content of the sand leaving the plant can be further reduced with a sand scrubber, the organic matter separates with slow stirring and the sand settles in the hydrocyclone.

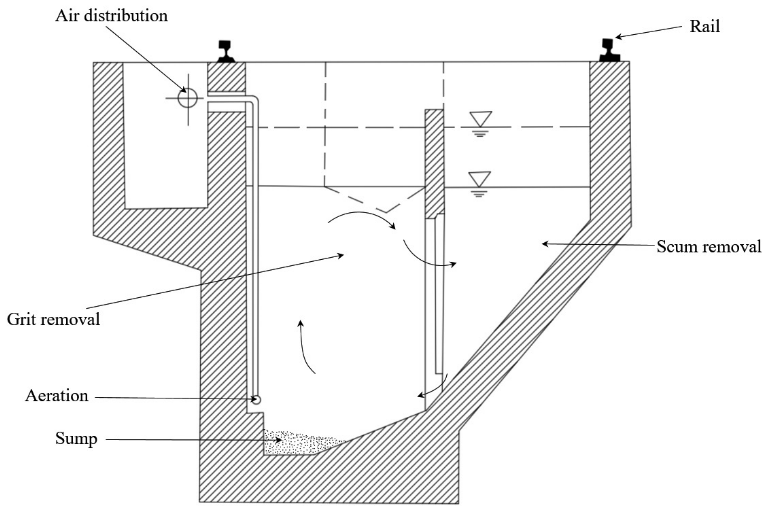

Figure 4
Cross-sectional design of an air-blown sand trap [1]

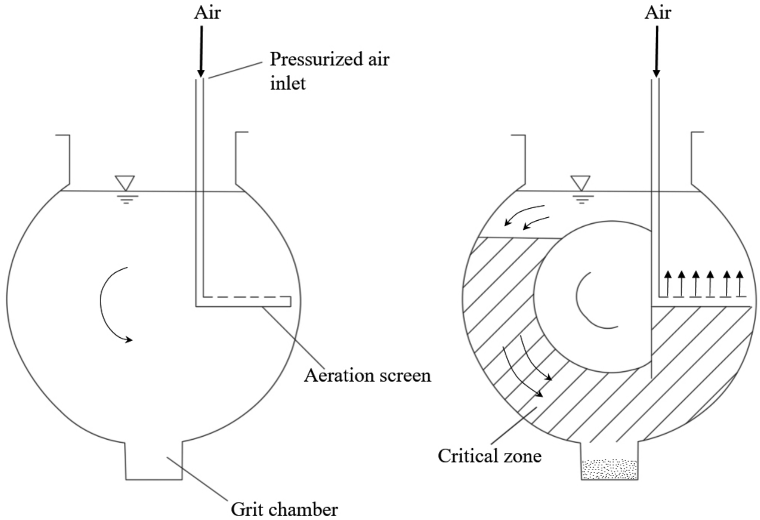

Figure 5
Functional diagram of an air-blown grit [1]

Hydrocyclone

A device operating on the principle of the difference in density; in the water space of a circular structure, the wastewater to be treated is led in a tangential direction, which performs a circular movement with a vertical axis. During the process, due to the centrifugal force the partly solid and partly water-insoluble liquids separate. Two main groups are known: closed and open hydrocyclone. In case of high sand content, a hydrocyclone can be used in parallel with the grit (Figure 6).

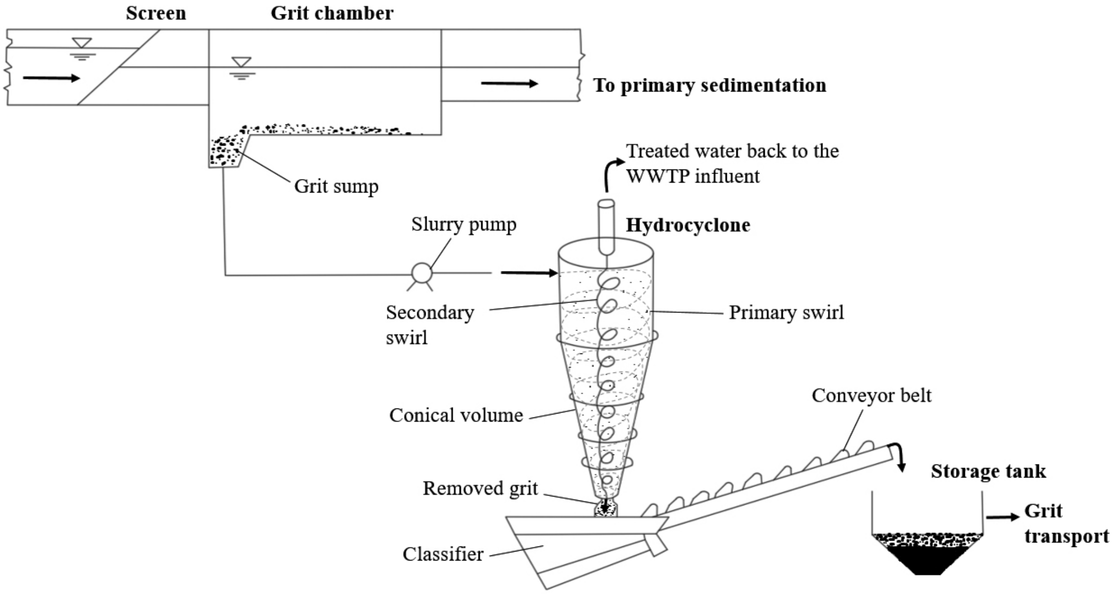

Figure 6
Sand removal by cyclone [1]

The material deposited in the grit contains infectious substances; this must be taken into account when handling it. Prior to deposition, dehydration is required due to volume reduction, for which sand-drying beds or settling tanks are often used.

Floating equipment

Wastewater can contain significant amounts of fats and oils with a lower density than water, so they rise to the surface of the water at a suitable flow rate and can be removed. Its use is necessary not only to protect subsequent machinery, but also to recover valuable material.

Depending on the origin and material of the floating waste, the structure can be:

- grease trap
- oil and gasoline trap
- defoamer
- other sludge traps

Grease and oil traps

The presence of fats and oils entering the plant impairs the efficiency of cleaning; removal of these materials is carried out before settling, mostly in combination with the grit, taking advantage of the flotation effect of the air blowing.

Adequate residence time (2–5 min) and surface area must be provided for efficient operation of the equipment. Its use is necessary if the total fat-oil concentration is higher than 50 g/m^3. Grease and oil trapping, together with sedimentation, should be carried out in a combined structure.

Flotation equipment

In order to increase the efficiency of the floating equipment, it is practical to use flotation equipment for the removal of oil, grease, petrol droplets and colloidal particles that do not float or settle, as well as for separating the emulsion.

Settler

Settlers play a fundamental role in the process of wastewater treatment technologies. These devices operate on the principle of difference in density, which is made possible by low flow rate and gravitational force. In addition to the removal of small suspended and floating materials (TSS), they also enhance the reduction of biological oxygen demand (BOD). A well-designed pre-settler can result in up to 20–50% BOI and 55–70% TSS removal.

Pre-settlers are primarily used in medium and high capacity plants where sludge stabilisation also takes place.

The Stokes law described for grits can also be applied for pre-settlers where discrete particles are deposited.

The settlers are sized for the following parameters, depending on where they are used:

- for surface hydraulic load (m^3/d)
- required theoretical residence time (h)
- surface suspended solids load (kg/m^2* h)
- vertical or horizontal flow rate (cm/s)
- tipping edge load (m^3/m* h)

Pre-settlers can be grouped according to several aspects, such as flow direction and floor plan design.

Depending on the flow direction, settlers can be:

- horizontal flow
  - longitudinal flow (Leipzig)
  - radial flow (Dorr)
- vertical flow (Dortmund)
- transitional version (Uniflow, hydrocyclone)

According to the floor plan [6]:

- rectangle (Leipzig, Uniflow)
- square (Dortmund)
- circle (Dortmund, Dorr, hydrocyclone)

Longitudinal flow (Leipzig)

They can be used primarily for pre-settlers, they are rectangular reinforced concrete structures with a rectangular floor plan, and the flow takes place in the longitudinal direction (Figure 7). The settled sludge is conveyed to the sludge sump by the arm excavator (at a speed of 10–50 mm/s), which is conveyed by centrifugation or by a mammoth pump.

Key implementation solutions:

- impacted against a sinking wall
- it flows into the tank from several nozzles (T-tubes, Stengel head)
- at the influent side of the settler, the wastewater flows through mangers into the basin, in the opposite direction to the main flow direction, and then enters the settling space under an immersion wall
- it flows through a perforated plate or grid from the pre-chamber of the settler to the actual settler

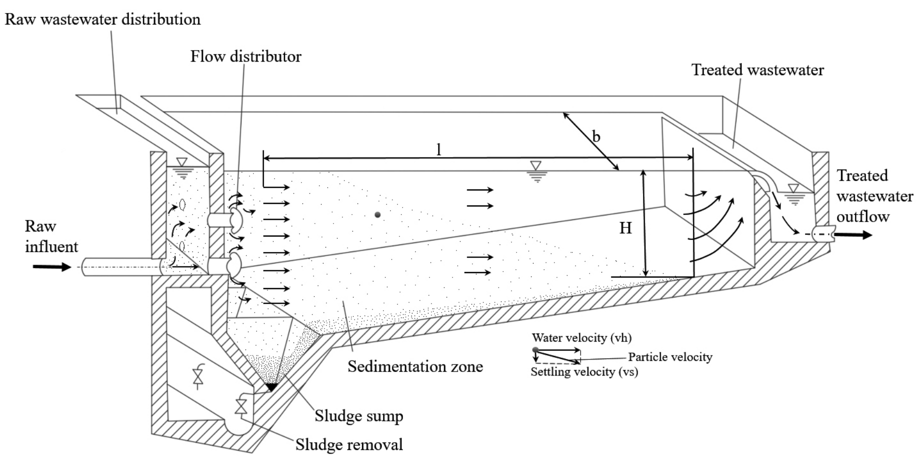

Figure 7
Design of a horizontal (longitudinal) flow Leipzig basin [1]

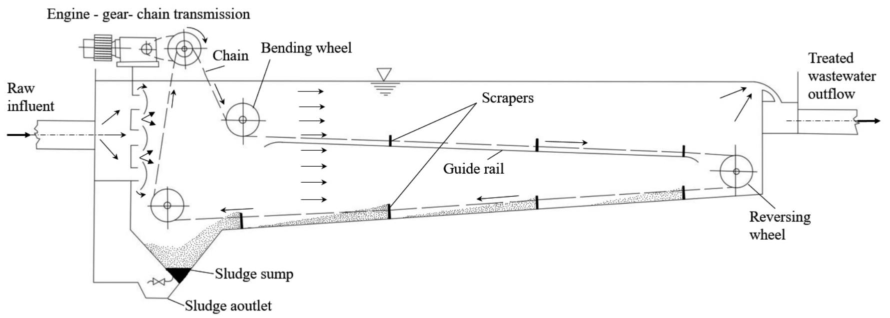

Figure 8
Longitudinal sedimentation with a chain excavator [7]

Circular floor plan, radial flow (Dorr)

According to its floor plan, the Dorr settler has a circular and a corresponding radial flow, which are used for both pre- and post-settlers. Sewage is usually introduced through the manifold of the structure, which has the role of optimising the flow rate. The treated water is drained through a collecting manger with a tipping edge placed around the circumference of the structure. Excavators are used to collect sediment and floating sludge. Dead space should be provided in the vicinity of the sludge collection sump for undisturbed sedimentation.

Vertical flow (Dortmund)

The tanks have a circular floor plan, are made of reinforced concrete, and can be used with good efficiency to settle wastewater containing flaky sludge. It is used partly as a pre-settler and mostly as a post-settler. In terms of its operation, the wastewater enters the damping cylinder, from where it flows downwards to the sludge sump, and the purified water is drained through the weir channel. The sludge leaving the settler is high in organic matter, usually denser than the sludge in the post-settler.

Two-level settlers

According to their place in the technology line, two-level settlers are mentioned together with thickeners. In sewage treatment plants, two-level settlers are becoming less common. These structures (Imhoff Basin or Emscher Fountain) can have a circular or rectangular floor plan. The upper space is the settling space, and the one below is the sludge space, where the settled sludge is decomposed.

Compactors

The process can rather be classified as a sludge treatment process aimed at reducing the volume of sludge to be treated. Settling and compaction are processes occurring at the same time next to each other; a more efficient sludge dewatering is expected.

Compactors and condensation processes can be grouped as follows [6]:

- Gravity compression (naturally or mechanically)

The process can take place in the settling tank, in a separate thickener or in combination with sludge washing. The compaction process can be influenced by several factors such as flow conditions, structure size, environmental conditions and sludge properties (physical, chemical, biological).

- Flotation compaction (air or chemical flotation or biological flotation)
- Static compression
- Dynamic compression (most often vibratory, centrifugal, filtration)

Septic tanks

They provide the supply of settlements or settlement districts that do not have a public sewer network; this small equipment was previously widespread in Hungary. They can be classified partly as settlers and partly as small wastewater treatment plants. Their design depend whether the recipient is soil or surface water.

During operation, some of the suspended solids in the wastewater introduced into the first chamber settle out and some float up. After flowing into the next chamber or chambers (it may be necessary to create 2–3 chambers), smaller suspended solids can settle after a certain residence time. The settled sludge begins to decompose under anaerobic conditions, causing some of the sludge to float up to the floating layer. Of the floated materials, after a certain time, high specific gravity particles may settle in the lower sludge layer. These structures are suitable for receiving and treating relatively small wastewater yields (1–25 m^3/d). Due to their simplicity, they can be implemented with a homemade design and their energy and handling requirements are minimal.

Biological aspects of wastewater treatment

One of the main purposes of wastewater treatment is to prevent the release of pathogens into the environment, to prevent infections and epidemics and to preserve the quality of our waters. Untreated wastewater contains numerous human pathogens. Most wastewater treatment technologies currently in use are not suitable for removing all pollutants and microorganisms, which can survive in the environment for days or even weeks and can be sources of epidemics. For this reason, it is very important to carefully choose the means of wastewater treatment and the way treated wastewater is released into the environment.

Municipal wastewater contains organic matter in high concentration, if discharged to the soil or surface water untreated, it decomposes or mineralises into its constituents, depending on the circumstances. Decomposition products produce significant amounts of carbon dioxide, nitrogen and phosphorus in easily absorbable forms, which can be used as nutrients when entering surface waters. The uptake of nitrogen and phosphorus for photosynthesising, autotrophic organisms (including plants and algae) is generally not unlimited in the environment. N- and P-containing fertilisers (whether organic or inorganic fertilisers) are also applied to agricultural land to make up for the shortfall, thus, higher crop yields are expected. When these substances enter our waters from ground or through untreated wastewater, they are utilised by autotrophic organisms, causing rapid growth of algae in surface waters and leading to the proliferation of higher plants, causing eutrophication.

During wastewater treatment, living matter is transformed by living organisms that are also found in nature, but in the treatment process, the growth of microorganisms is intensified and controlled. During intensive animal husbandry, in order to keep a large number of animals in a small area, a large amount of nutrients must be introduced, appropriate temperatures and conditions must be ensured, diseases and animal deaths must be prevented. Intensive cultivation also takes place during wastewater treatment, but our goal is to achieve the right quality of discharged water. The nutrient is given – although its quality and quantity varies; the goal is to transform wastewater to maintain the bacterial community (to ensure their growth, to exclude inhibitory conditions). In the following chapters, we get an insight into the diverse world of microorganism, their metabolic pathways. We will discuss which groups of organisms participate in wastewater treatment and why it is so difficult to provide conditions suitable for all biological processes needed for the production of treated wastewater that meets requirements.

Metabolic types of prokaryotes

Microbes or microorganisms are living creatures invisible for the naked eye. These can be prokaryotic bacteria or eukaryotes with true nucleus. Organisms that are mostly unicellular and whose DNA is not surrounded by a membrane, i.e. they do not have a true nucleus, are called prokaryotes.

Before 1977, prokaryotes only consisted of bacteria, but later the group was divided into two taxa by Carl Woese and George E. Fox based on 16S ribosomal RNA analysis: Bacteria (bacteria) and Archea (stem bacteria). Thus, organisms are currently classified into three realms (domains), the third group being eukaryotes (true nuclei). The latter includes unicellular photosynthetic eukaryotes (most algae), unicellular animals, and multicellular plants, fungi and animals.

Prokaryotes are found everywhere in the world, their role is prominent and indispensable in the geochemical cycles of the biosphere, they also play a fundamental role in the nitrogen, carbon, and phosphorus cycle, without them most multicellular organisms would perish. Self-cleaning of waters is also largely due to the activity of prokaryotes.

Most bacteria are unicellular, 1–5 micrometres, bounded by a membrane, surrounded by a peptidoglycan cell wall. Their reproduction is asexual, dividing as the cell grows to a certain size, which is called fission. Their shape include chopsticks (bacillus), spherical (coccus), twisted (spirochaeta), filamentous, oval, but their morphological variability – compared to eukaryotes – is relatively small.

The basic properties of living things include metabolism, i.e. the exchange of energy, matter and information in the organism. Microbial metabolism is much more diverse than that of the higher order organisms and can also differ according to energy and carbon source, which is the basis for the practical grouping of bacteria, though it may not reflect their evolutionary relationship. Prokaryotic metabolism is very diverse, with energy production being the most varied. Several microbial metabolic pathways have developed which are not found among higher order organisms.

In humans, after nutrients enter the body (nutrition), the breakdown of starch by the amylase enzymes in saliva begins in the mouth (beginning of metabolic processes). Amylase is a so-called extracellular enzyme that, in this case, exerts its action outside of the cell and cleaves the chemical bonds in starch (a large-molecule biopolymer) to produce smaller molecules. Breakdown of various macromolecules continues in the stomach and intestine. Through the intestinal wall, the already decomposed, smaller size nutrients are absorbed and reach the cells through the bloodstream. Through the cell membrane, substances enter the interior of the cells by active or passive transport.

In general, unicellular organisms cannot absorb large organic molecules (polymers) directly either (with the exception of e.g. DNA). With the help of their extracellular enzymes, they partially break them down and then transport the smaller molecules into the cell by transport processes.

It is very important to note that breakdown can mean several things. It may refer to the breakdown of cells, organelles, extracellular or intracellular molecules or to their transformation. During the digestion of nutrients, multicellular organisms break down macromolecules into smaller units by extracellular enzymes, thus they are easily taken up by the cells.

Biodegradation refers to the activity of decomposers that produce smaller organic or inorganic substances from organic matter in the environment. In the first step of biodegradation extracellular enzymes play an important role, they cleave macromolecules into smaller ones that are easier taken up by the cell and become part of the intermediate metabolism (see below). The leading role in this process is played by heterotrophic decomposers, primarily bacteria and fungi.

Every living thing, in addition to synthesising molecules and building itself from them, it is also able to break them down. In this case, degradation processes are defined as dissimilation that takes place in each cell, during which the cell converts and breaks down macromolecules that it has built itself.

Whether a living cell is unicellular or multicellular, metabolic processes in the cell are called intermediate metabolism.

The intermediate metabolism consists of two *biochemical* process system:

- *biosynthesis* (assimilation, anabolic processes), require energy
- *degradation* (dissimilation v. catabolic processes), produce energy

The energy needed to build cell constituents comes from outside of the cells, either as light energy, which is eventually converted to chemical energy as a result of the conversion of compounds in the cell, or by the conversion of compounds into chemical energy. In both cases ATP (adenosine triphosphate), the central metabolic currency is produced, which is the main energy storing and transport molecule of living organisms.

According to the *energy source,* living organisms can be:

- *phototrophs* (photosynthesis)
- *chemotrophs* (chemosynthesis)

Every living organism has an internal space separated from its environment, in which it maintains relative constancy (homeostasis) by regulated and controlled processes through its metabolic processes. During metabolism, a number of chemical reactions take place; some of them involve redox processes, i.e. electron exchange. The substance that releases the electron is oxidised (this is the reducing agent, the oxidation number increases), the compound that gains electron is reduced (this is the oxidising agent, the oxidation number decreases).

Metabolism (ultimately living organisms, too) can be characterised by the initial electron-donating compound (an electron source, also known as an e-donor).

If the *electron donor* is an:

- organic compound: the metabolism and the organism is *organotrophic*
- inorganic compound (e.g. H_2, NO_3^- SO_4^{2-}): the metabolism and the organism is *lithotrophic*

Organisms are also distinguished on the basis of terminal *electron acceptor:*

- *aerobic respiration:* O_2 is the electron acceptor
- *anaerobic respirators,* the inorganic electron acceptor may be:
  - oxygen containing inorganic compound (e.g. NO_3^-, sulphate reducing agents: $SO_4{}^2$)
  - other inorganic compounds (e.g. H_2S, NH_3, S^{2-}, Fe^{2+}, H^+)
- *fermentation:* organic matter is the electron acceptor (note: these are anaerobic organisms and the e-donor is also organic)

Organisms need carbon to build their cellular materials.

Based on the starting compound, *carbon sources* can be:

- inorganic carbon (CO_2, HCO_3^-, CO_3^{2-}): autotrophic assimilation, *autotrophic* organisms
- organic carbon (C-C bond): heterotrophic assimilation, *heterotrophic* organisms

Based on the types of metabolism described above, organisms can be divided into eight groups:

Table 4
Groups of organisms (compiled by the authors)

Energy source	Electron donor	Carbon source (organic or CO_2)	Name
Light Photo-	Organic –organo-	heterotrophic	1. Photo-organo-heterotrophic
		autotrophic	2. Photo-organo-autotrophic
	Inorganic –litho-	heterotrophic	3. Photo-litho-heterotrophic
		autotrophic	4. Photo-litho-autotrophic
Chemical bonds Chemo-	Organic –organo-	heterotrophic	5. Chemo-organo-heterotrophic
		autotrophic	6. Chemo-organo-autotrophic
	Inorganic –litho-	heterotrophic	7. Chemo-litho-heterotrophic
		autotrophic	8. Chemo-litho-autotrophic

Photosynthesisers convert the radiant energy of the Sun, i.e. the light energy, into chemical energy. Prokaryotic and eukaryotic organisms are also capable of photosynthesis. Phototrophic organisms are usually also autotrophic, as their majority use an inorganic C source, carbon dioxide and its dissolved forms to produce organic compounds. In green plants, under the influence of light, water molecule releases electron (-litho-: electron donor is inorganic), the electron acceptor is oxygen, so the plants are photo-litho-autotrophic, aerobic organisms (Table 4, Group 4).

Cyanobacteria also mainly use this form of metabolism, sequestering carbon dioxide in light conditions and oxygen-rich environments. Most of them are obligate oxygen-producing aerobic photo-litho-autotrophs (4). Several species can switch to anoxic photosynthesis in the presence of sulphide (4). Most of their species are able to survive in the dark as aerobic heterotrophs (5). In this case, they mainly degrade sugars, such as glucose, sucrose and fructose. Cyanobacteria are able to bind atmospheric nitrogen, thus, in many cases they cause water blooms, as the lack of inorganic N source in their habitat (water, soil) does not inhibit their growth.

In surface waters, photosynthesis takes place in shallow lakes, river waters and in the top most layers of deep lakes (epilimnion, photolytic layer). Photosynthesisers play an important role in self-cleaning processes, their main significance is oxygen production; in addition, they incorporate inorganic salts into their bodies as nutrients.

Obligate (meaning: without exception, restricted) aerobes can only survive in the presence of oxygen, while obligate anaerobes only survive in an oxygen-free environment. Facultative anaerobes grow better in an aerobic environment, but are also capable of metabolism in the absence of oxygen. Aerotolerant anaerobes are unable to utilise oxygen, but it is not toxic to them. Microaerophiles exhibit maximum growth at environments containing lower levels of oxygen than that are present in the atmosphere.

Decomposition of organic matter in water can take place aerobically (in the presence of dissolved oxygen) or anaerobically (in the absence of dissolved oxygen). Dissimilatory reactions occurring in the presence of atmospheric oxygen are called biological oxidation or aerobic respiration, in the case of other inorganic electron acceptors (e.g. nitrate, iron) the decomposition processes producing carbon dioxide are called anaerobic respiration. Fermentation is a decomposition process in which anaerobic decomposition of organic matter produces an organic molecule rather than carbon dioxide (e.g. alcohol, lactic acid is the terminal electron acceptor).

The end products of aerobic degradation are the same as the starting compounds for organic matter production, ultimately CO_2 is produced. Aerobic respiration is a typical process in aquatic carbon cycle, which typically takes place in rivers that are not overloaded with organic matter, in shallow lakes, and in the top most water layer (epilimnion) of deep lakes.

Anaerobic conditions can develop in rivers and shallow lakes overloaded with organic matter, as well as in the lower water layer (hypolimnion) of deep lakes. During anaerobic degradation, the oxidation is incomplete and CO_2, CO, CH_4 and small molecular unsaturated organic compounds may be formed as final products. The latter, among other non-carbon compounds, contribute to the development of taste and odour problems in water.

In practice, engineers use the term anoxic conditions when free (dissolved) oxygen is not available, but there is bound oxygen (i.e. in nitrate, sulphate) in the water, which can be utilised by bacteria.

Biologists use the term anoxic condition when there is a lack of atmospheric oxygen.

Organisms may be able to switch between metabolic pathways. It can occur even in human cellular respiration: in the presence of oxygen, glucose is converted to carbon dioxide (glycolysis), while in the absence of oxygen (intensive exercise), glucose breakdown is partial, and pyruvic acid is produced by fermentation.

Mixotrophic organisms, depending on the environment, can use several pathways for optimal energy production. For example, some purple non-sulphur bacteria are also capable of photolithotrophic, photoorganotrophic, chemoorganotrophic respiration and fermentation. Interestingly, not only their mode of ATP production, but the source of reducing force changes, too, as well as they switch between autotrophic and heterotrophic anabolism.

Chemosynthesising bacteria gain their energy by oxidising various substances. With the exception of the aforementioned photosynthesis, primarily all organic matter is assimilated at this level in the food chain.

Heterotrophic organisms dominate in most ecosystems in both number and activity. They can only utilise organic carbon sources. Heterotrophic organisms also gain energy in two ways. Chemo-organo-heterotrophs (Table 4, Group 5) utilise chemical energy. During the self-cleaning of waters, microorganisms belonging to this group have the most significant role in the decomposition of organic matter (biodegradation), but most pathogenic bacteria are also chemo-organo-heterotrophic.

Under anaerobic conditions, some microorganisms may utilise bound oxygen (in nitrate, sulphate and possibly phosphate). Therefore, denitrification, sulphate and phosphate reduction activity may increase under anaerobic conditions. Which process takes place, depends on redox potential. As long as nitrate is present in the water, organisms utilise this source of oxygen (redox potential = –50 mV). For the reduction of sulphate and phosphate, –200 mV and –700 mV redox potential is needed, respectively. These reduction processes are performed by different microorganisms.

All heterotrophic organisms depend on other organisms for nutrition and depending on the type of food, ecology classifies several groups. For example: carnivores, scavengers, herbivores, parasites, symbionts. Symbiosis is a type of – not necessarily nutritional – interaction that provides benefits to both parties. Syntrophy is a commonly used term in microbiology and microbial ecology: a case of symbiosis where the growth of one species is dependent on the product of another species. A term often used in microbiology or microbial ecology. In water bodies, the flow of matter and energy is realised through syntrophic connections.

Biochemical processes of degradation

Communal wastewaters contain organic matter in large concentration, with a majority of macromolecules. Certain molecules undergo physical-chemical transformation e.g. by UV or react with other molecules in the environment. However, many molecules can only be transformed by biochemical processes in living organisms during which building materials and energy is obtained.

Cells, i.e. microorganisms, too, cannot directly take up large organic molecules in their native form, only after partial enzymatic digestion. Enzymes are biocatalysts, they catalyse, speed up biochemical reactions, most of them are protein like molecule.

Breakdown or biodegradation of organic matter starts with extracellular enzymatic mechanisms. These enzymes cleave biopolymers (proteins, nucleic acids, polysaccharides) and other large molecules (e.g. lipids) into their components, oligomers, monomers, which can enter the cell through the cell wall or cell membrane. Molecules taken up are further cleaved or transformed by intracellular enzymes.

During evolution, mutations resulted in numerous degradation pathways, but there are some conservative pathways that can be found in almost every living creature.

The most common types of enzymes are listed below:

- hydrolases
- oxidases
- transferases
- liases
- isomerases

These groups contain many specific and less specific enzymes. Degradation of macromolecules requires the cooperation of several enzymes. For example, the first step in the degradation of biopolymers is hydrolysis. Hydrolases cleave the substrate molecule by the use of water. In this process, the hydroxyl group of the water molecule is transferred to one part of the substrate molecule, while its proton is transferred to other part of the substrate. Glycosidases are responsible for the breakdown of glycosidic bonds in polysaccharides; proteases are responsible for the cleavage of peptide bonds in proteins, while esterases are responsible for the hydrolysis of ester bonds in triglycerides.

Decomposition of carbohydrates

Carbohydrates are composed of carbon, hydrogen and oxygen, they are important nutrient, carbon and energy sources. Monosaccharides are the simplest carbohydrates, such as fructose (fruit sugar), mannose, galactose, glucose, the latter can be found in the form of D-glucose (dextrose) in living organisms. The names blood sugar, grape sugar, or potato sugar refer to their origin, but chemically they are all glucose. Monosaccharides easily dissolve in water, can easily be taken up by the cells and incorporated into metabolic pathways. Disaccharides are composed of two monosaccharides and include the table sugar sucrose (beet sugar), lactose (milk sugar), maltose (malt sugar) as well as cellobiose, the building block of cellulose. The latter one cannot be broken down by the human body. Oligosaccharides are composed of 3–10 monosaccharides; some of them also cannot be degraded by the human body, but provides nutrition for the gut microbiome. Polysaccharides are giant molecules composed of monosaccharide units. Starch is one of the most common polysaccharides, stored as a reserve nutrient in plants and is composed of amylose and amylopectin units consisting of glucose monomers. Extracellular amylase enzymes in bacteria and fungi break it down into smaller units, which are further broken down within the cell during intermediate metabolism.

Pectin is a water-insoluble compound found in the intercellular space of plants. It is broken down by aerobic and facultative anaerobic bacteria as well as fungi.

Cellulose is composed of glucose monomers; it is the structural component of plant cell wall. Cellulose is the most abundant organic polymer on Earth, cannot be broken down by most living things.

Natural breakdown of cellulose begins with physical fragmentation (e.g. by arthropods: ace crabs, crustaceans, twins, insects, earthworms), by increasing the surface area it will be more accessible for degrading organisms (fungi, bacteria). Cellulose breakdown usually occurs in a microbial consortium by several extracellular enzymes, the produced subunits (cellobiose, glucose) can be taken up by the cells.

Bacteria species can utilise a wide variety of carbohydrates and enzymes needed for breakdown are synthesised according to the carbohydrates available.

During wastewater treatment, to maintain a microbial consortium that functions properly, stability and continuous nutrition supply are needed. Thus, small equipment only performs properly if they operate continuously. If the equipment does not get fresh nutrient in the form of wastewater for a few weeks, it is advised to supplement carbon source in an easily absorbable form, e.g. with sucrose (table sugar).

Degradation of lipids

Lipids have a highly variable chemical structure, their common feature is that they have a poor water solubility and are biologically degradable. Examples include phospholipids (cell membrane components), neutral fats (nutrient reserves, e.g. fats and oils), steroids (hormones, cholesterol, vitamin D), and carotenoids (carotene, lycopene, xanthophyll, vitamin A). The majority of lipids cannot be directly absorbed by the cell, their degradation starts by extracellular lipases. Lipid degrading organisms include fungi, e.g. *Rhisopus sp., Geotrichum candidum, Aspergillus niger, Penicillium cyclopium* and bacteria, e.g. members of the genera *Actinomyces, Mycobacterium and Pseudomonas.*

Although microorganisms are capable of degrading lipids, it is important to avoid pouring lipids, e.g. in the forms of used cooking oil, into drains. Plant based oils or animal fats form FOG (fat, oil and grease) deposit in sewers, which over the years decrease the perimeter of the pipe and may cause blockage in both domestic and communal wastewater sewers. Greasy substances cause a coating on the surface of living organisms, decreasing metabolism and may cause the decay of organisms, both microbes and higher order ones. In wastewater treatment plants, removal of floating grease and oil may be removed by mechanical treatment, i.e. grease and oil traps (see earlier).

Degradation of proteins

Proteins are polymers composed of amino acids. Approximately 500 natural amino acids are known, 22 of them are components of proteins and 9 of them are essential for the human body, i.e. humans cannot synthesise them, can only take them up by food. Proteins include enzymes, many hormones (e.g. insulin), structural proteins (e.g. collagen), muscle proteins (actin, myosin), transport proteins (e.g. haemoglobin), toxins (e.g. mushroom toxins, snake venom).

Heterotrophic prokaryotes (Pseudomonadales sp., Eubacteriales sp.) can utilise proteins present in their environment as nutrient and energy source. Without them, they start to break down their own proteins to cover the need for amino acids. Protein degradation also starts with the help of extracellular enzymes (proteases, peptidases); amino acid breakdown is completed inside the cell.

Xenobiotics

The majority of organic pollutants are xenobiotics for most organisms, i.e. they cannot be degraded, these compounds are foreign (= xeno) for their metabolic pathways. This should not be surprising, as the development of metabolic pathways occurred during evolution, when these substances were not available for the organisms to encounter. Some xenobiotics, however, can be biodegraded by the cooperation of certain microbes. Nowadays, it is a great concern that there are no protocols for detecting various substances and their presence in the environment is not regulated. The effect of many substances can only be hypothesised, but data are lacking. Xenobiotics can be inorganic, e.g. toxic metals, but according to the types of compounds and their amount, the number of anthropogenic organic micropollutants is several order of magnitude higher. They include the majority of pharmaceutical compounds, illicit drugs, personal care products, resistance genes, pesticides, lifestyle products, food supplements, surfactants, organic disinfection byproducts, combustion byproducts, organometals, and several other industrial chemicals (e.g. plasticisers, flame retardants, gasoline additives). Some xenobiotics are not toxic to the degrading organisms of wastewater treatment plants, but reaching the recipients, they can be absorbed and accumulated in freshwater organisms and may have severe environmental consequences. Others may be very toxic to microorganisms, may cause their decay, and as a consequence, wastewater treatment cannot be completed. Thus, it is very important to minimise the discharge of chemicals into drains.

The community of activated sludge

During biological wastewater treatment, organic matter degradation, transformation of nitrogen and phosphorous forms are performed by microorganisms that can be attached to surfaces or present inside the activated sludge. Activated sludge is an artificially created and maintained community; its members live in a close network of interdependence. The living community of activated sludge is made up of bacteria, ciliated unicellulars, flagellates, amoebas and multicellular organisms. These organisms occur naturally in wetlands, surface and groundwaters, rivers, lakes. The composition of the community is influenced by artificially created environmental conditions in the wastewater. Technological elements used during wastewater treatment, the design of sewerage and operational practice all influence the species composition of the developing activated sludge.

The main technological factors shaping the community include:

- composition of raw wastewater
- residence time of wastewater in the sewerage system
- biological load of activated sludge (organic matter content)
- dissolved oxygen concentration in the aeration basin
- temperature
- treatment of decanter and leachate
- practice of storing and dewatering sludge

The term activated sludge well describes the concept, because microorganisms that make up the sludge carry out the same life activities in the natural environment as in wastewater treatment plants, but in this artificial environment, the processes take place much faster with the help of different technological elements (e.g. intensive aeration).

In the United States, the name of the sewage treatment plant technologist is bug farmer. The concept delineates a biological approach to wastewater treatment, meaning that the technologist, like a livestock farmer, strives to create optimal living conditions for bacteria.

Bacteria

Bacteria provide the basis for the community of activated sludge. They make up the majority of sludge biomass. In the course of their life activities, pollutants in the effluent entering the sewage treatment plant are consumed and/or transformed, during which bacteria gain energy and multiply. They are able to remove nitrogen, carbon and phosphorus compounds in municipal wastewater.

According to their life activities, they can be divided into three main groups:

- chemo-organo-heterotrophic bacteria: bacteria capable of removing organic matter
- nitrifying bacteria: chemo-litho-autotrophic bacteria capable of biological nitrogen removal – the scientific name of ammonia oxidising bacteria starts with Nitroso- (e.g. *Nitrosomonas*, *Nitrosospira*, *Nitrosolobus, Nitrosovibrio*), while that of nitrite oxidising starts with Nitro- (e.g. *Nitrobacter, Nitrococcus, Nitrospina, Nitrospira*) prefix
- poly-P bacteria: bacteria capable of removing biological phosphorus

Activated sludge bacteria can be present in activated sludge in the following forms:

- free-floating bacteria: bacteria not yet incorporated into the flakes
- flake-forming bacteria: bacteria form a compact community capable of settling in water
- filamentous bacteria: special bacteria whose cells are organised into filaments

Ciliata

According to traditional taxonomy, the group of *Protists* used to incorporate unicellular eukaryotes. Unicellular organisms capable of photosynthesis and plant-like metabolism used to form the various algae groups. The *Protozoa* taxon consisted of heterotrophic organisms with metabolisms similar to fungi or animals, as well as many parasites and pathogens. Some species are able to perform both heterotrophic metabolism as well as photosynthesis, e.g. flagellate Excavata *(Euglenozoa).* The currently used phylogenetic classification is based on species relatedness based on their DNA sequence, which we will not discuss here in detail; for practical reasons, in this chapter we will also use the traditional nomenclature.

Ciliata is a group of unicellular Protozoa. They are named after the cilia distributed on their cells evenly or in fields to promote nutrition and change of position. Cilia are important members of the activated sludge's food web and usually dominant in the unicellular fauna of activated sludge, thus, having a prominent role.

The main diets of ciliated unicellulars are bacteria; therefore, by consuming the bacterial population regularly, they promote their continuous renewal. There are also species that consume their own protozoa counterparts, but the ciliates themselves can also fall prey to wheelworms and other predators. In the activated sludge of sewage treatment plants, we can divide ciliated organisms into two main categories: planktonic and sessile ciliates.

Planktonic ciliated unicellulars swim among flakes formed by bacteria in search of their food, which can be free-floating bacterial cells not yet incorporated into flakes, or poorly attached organic matter on the surface of flakes, possibly living or dead bacteria. The ciliates that graze on the surface of flakes maintain flakes, because their activity help the continuous renewal of the outer surface of flakes and the formation of round, compact flakes with good settling (e.g. *Aspidisca cicada, Holophrya sp., Colpidium sp.*).

Sessile ciliates live anchored to the flakes with a stem and consume planktonic bacteria and organic debris in the space between flakes. With this activity, they allow the incorporation of contaminants with small size into the sludge that would otherwise leave the wastewater treatment plant with the treated water. Some of their species form colonies, connect to the flake with a central stem and then this stem branches and allows multiple cells to attach (e.g. *Epistylis sp.*).

Cilia are indicators of well-functioning activated sludge; their stocks of 5,000–10,000 individuals/ml usually indicate optimal conditions, while a smaller and more monotonous species composition indicates poorer performance and poorer cleaning efficiency. Their complete absence suggests the presence of toxic substances, lack of oxygen, overload, or rot.

Amoebae

The amoebae are also members of the protozoan group. Their cell shape is amorphous, constantly changing, they move with the help of their jaws, during which the internal cell stock of the living organism, the cell plasma, simply flows into the cell membrane protruding at several points of the cell. Numerous species can live in activated sludge; different species can be of different sizes, ranging in size from a few micrometres to as large as 7–800 micrometres. The most common species found in activated sludge are Mayorella sp., Amoeba proteus, or Arcella sp.

They are unicellular, simple in cell structure, surrounded by a thin membrane, the cell membrane. They are creatures with pseudopodia that do not have a flagella or cilia and ingest food with the help of their pseudopodia. Thus, under a light microscope, food-containing cavities (vacuoles) can often be seen in them.

Their diet is heterotrophic, that is, they build the material of their own cells from organic matter derived from the consumption of the cellular materials of other living things. Their presence indicates high concentrations of organic matter in the aqueous phase of the sludge in dissolved form.

Amoebae have one or more true nuclei and reproduce by mitosis. During mitosis, the gene pool of the cell doubles and then divides. The genetic stock of the two cells formed during the process is the same, which is why mitosis is called numerical division.

We distinguish two large groups of amoebae found in activated sludge: testate and non-testate amoebae. The cell structure of testate amoebae is exactly the same as that of non-testate amoebae, but they build an outer shell around themselves of iron and manganese. Their cover is yellowish in colour, which can range from quite pale to dark red.

Non-testate amoebae can be observed floating freely between activated sludge flakes, consuming bacteria, protozoa and organic debris not incorporated into flakes. Testate amoebae feed on debris and organic matter in the sewage flowing through the pores found in their testate into the cells.

Flagellate

Flagellate is a group of unicellular, protozoan organisms. They got their name from their characteristic whip-like appendages called flagella. Depending on the species, they may have one or a few flagella, with which they perform locomotion and orient themselves in their environment. They have a true nucleus and divide by mitosis. Their size is 1–200 micrometres. In the artificial ecosystem of wastewater treatment plants, they feed on organic matter and bacterial cells in wastewater.

Countless flagellate species can survive and reproduce in the activated sludge of sewage treatment plants. Small flagellates, e.g. *Bodo sp.* (size 10–20 micrometres), move with a characteristic somersault movement, while the colourless Euglena in the larger size range, e.g. *Peranema sp.* (size 50–100 micrometres) swim with their flagella extended forward.

They can be used to monitor operational efficiency of wastewater treatment plants, as changes in their numbers provide significant information.

At the beginning of the commissioning of wastewater treatment plants, their numbers are always large, approximately 10–50,000 individuals/ml, but under normal operating conditions, they are pushed into the background or even disappear from the ecosystem.

Most of the species living in the aeration basin are indicators of heavy pollution and high loads, so their proliferation during normal operation indicates rotting processes and a sudden increase in biological load, which may be caused by the following:

- excessively long storage time of removed sludge, from which the leachate returning to the technology contains a large amount of reduced S-bonds formed under anaerobic conditions as well as organic acids
- improper mixing of some reactors (sludge settles here and anaerobic rotting begins)
- permanent organic matter overload
- poor oxygen supply, defective aeration elements, reduced oxygen dissolution

Multicellular organisms

They are highly organised organisms that are very different from the protozoan organisms discussed so far. Cells of multicellular organisms form tissues, tissues form organs, and organs form organ systems. The multicellular community of activated sludge is formed by multicellular animals

(Eumetazoa), plants and fungi are not typical. Their size ranges from 50–100 µm to a few mm. Some *Nematoda sp.* can even be seen with the naked eye under the slide. Identification of higher order taxa is quite easy owing to their easily identifiable identification marks.

Their diet is heterotrophic, they can be carnivorous feeding on bacteria, flagellates, ciliated unicellulars, or their smaller multicellular counterparts, but most of them are omnivorous. They form the top of the food chain of activated sludge organisms, their dominant groups include nematodes *(Nematoda),* roundworms *(Rotifera, Rotatoria),* and ringworms *(Oligochaeta),* although in low load systems gastrotrichs *(Gastrotricha)* and tardigrades *(Tardigrada)* may also appear.

Although their reproduction is typically sexual, the majority of known roundworms is female, they multiply by parthenogenesis. The eggs are often observed in the body of the mother and also among flakes.

The number of metazoan is much lower than that of protozoa, as their reproduction takes significantly longer. Typically, 1–10 individuals can be observed in a droplet (30 µl) of activated sludge sample.

They live mainly in stabilised (old) activated sludge, so they are considered to be its characteristic indicator species. Through their filter feeding, they reduce the number of bacteria outside the flakes as well as they regulate the size of flakes. By loosening the structure of flakes, they increase oxygen supply to the inner areas. Excessive proliferation of multicellular species is undesirable, because with their active movement and nutrition they can prevent the formation of flakes and damage flake structure.

They are usually sensitive to environmental influences (especially toxic substances); decrease in their number of individuals is indicative of the decrease of the sludge age or the presence of toxic substances.

Biochemical processes of activated sludge

The function of municipal wastewater treatment is to purify drinking water contaminated by residential use. The removal of three main components is key during treatment: organic matter, nitrogen and phosphorus.

Phosphorus removal

Biological removal of phosphorus is called bio-phosphorus elimination, in which poly-P bacteria trap phosphorus in their cells. In addition to biological phosphorus removal, wastewater treatment plants often use chemical phosphorus removal using an inorganic coagulant.

When treating the sludge cyclically under aerobic and anaerobic conditions, certain groups of microorganisms (so-called poly-P bacteria) can be encouraged to take up significantly higher amounts of phosphorus and, thus, remove it with the excess sludge. In the aerobic phase, properly developed poly-P bacteria capable of removing excess phosphorus are capable of storing high concentrations of phosphorus in their intercellular stock in the form of polyphosphate.

In an anaerobic environment, however, the stored polyphosphate is depolymerised and released into solution, while the cell is able to absorb simple organic nutrients using the energy obtained from depolymerisation. The anaerobic medium is as stressful for poly-P bacteria as it is for “normal” aerobic bacteria, but they have a selective advantage due to the above-mentioned nutrient uptake. Cells also utilise accumulated polyphosphate as a source of phosphorus and as an energy source in the energy-limited anaerobic medium. Only poly-P bacteria can store such a large amount of phosphorus and only under the outlined operating conditions.

Conditions needed for efficient bio-phosphorus elimination in activated sludge system:

– there should be sufficient, easily absorbed nutrients in the anaerobic system
– the recirculation sludge must be free of dissolved oxygen and nitrate
– the residence time of the sludge in the post-sedimentation should not be too long, because due to the anaerobic conditions the cells can release the absorbed phosphate

Bio-phosphorus removal is the most cost efficient form of phosphorus removal in wastewater.

Nitrogen removal

Nitrogen is removed by the decomposition of nitrogen-containing organic compounds, during which inorganic nitrogen compounds and ultimately nitrogen gas ($N_{2)}$ is formed. The process consists of three consecutive bio-reactions: ammonification, nitrification and denitrification. The nitrogen content entering surface recipients significantly damages aquatic ecosystems in many ways (e.g. ammonia is toxic to fish and nitrate is involved in eutrophication processes), thus, effective removal of nitrogen from wastewater is an essential requirement of modern wastewater treatment technologies.

Ammonification takes place during the breakdown of organic nitrogen containing compounds; in wastewater the process is usually characterised by bacterial enzymes.

Nitrification

Nitrification is the oxidation of ammonia to nitrate in a two-step process performed by chemo-auto-lithotrophic nitrifying bacteria *(Nitrosomonas sp., Nitrobacter sp.).* In the first step, Nitrosomonas bacterial species convert ammonium to nitrite, and then in the second step *Nitrobacter* species convert nitrite to nitrate.

The first step of nitrification (conversion of ammonium to nitrite, *Nitrosomonas sp.*):

$$2\ NH_4^+ + 3\ O_2 = 2\ NO_2^- + 4\ H^+ + 2H_2O + 550\ KJ$$

The second step of nitrification (conversion of nitrite to nitrate, *Nitrobacter sp.*):

$$2\ NO_2^- + O_2 = 2\ N_3^{2-} + 150\ KJ$$

The overall reaction *(Nitrosoman sp.* and *Nitrobacter sp.):*

$$NH_4^+ + 2O_2 = N_3^- + 2H^+ + H_2O + 350\ KJ$$

Nitrification is uninterrupted under suitable environmental conditions. In this case, nitrifying bacteria completely perform the oxidation of ammonium to nitrate. Conditions for efficient, far-reaching nitrification require:

- adequate residence time: the maximum specific growth rate of nitrifying bacteria is approximately one order of magnitude lower than that of a microflora utilising highly biodegradable organic matter; in case of a water temperature of 15–20°C, it is necessary to maintain a sludge age of 5–7 days, while in winter at 10–15°C of water temperature this should be at least three times more, but there are considerable differences between small and large WWTPs in this respect
- suitable pH: pH 8–8.5 is optimal; based on pure culture experiences, the efficiency of nitrification is drastically reduced beyond this pH range
- adequate amount of available dissolved oxygen: practical experience shows that effective nitrification requires at least 1 mg/l dissolved oxygen and at most 3 mg/l can be used to increase nitrification efficiency
- suitable temperature: the optimum temperature for nitrification is 20°C; at lower or higher temperatures, nitrification efficiency decreases – the lowest limit is 12°C, below this, nitrifying bacteria are no longer able to multiply

Disturbed nitrification: if environmental conditions are not appropriate for nitrification, the oxidising capacity of nitrifying bacteria is reduced. In the nitrification process, the slowest and most sensitive process is the oxidation of ammonium to nitrite by *Nitrosomonas sp.,* so nitrite never accumulates in treated wastewater because *Nitrobacter sp.* species rapidly oxidise it to nitrate.

Denitrification

Nitrification is also known as nitrate respiration or nitrate reduction. The process of conversion of nitrate ion to elemental nitrogen gas is the third and final major step in the decomposition of nitrogen-containing organic compounds by facultative anaerobic and heterotrophic denitrifying bacteria. Denitrification is a special form of respiration in which the electron acceptor is nitrate ion instead of oxygen. Organisms performing denitrification do not belong to a single group, either morphologically or biochemically. Bacteria capable of denitrification include the *Bacillus* genus, certain genera of the *Micrococcaceae* family, *Pseudomonas aeruginosa,* or *Thiobacillus denitrificans.*

In case of activated sludge treatment, denitrification takes place in the so-called anoxic basins or reactors and requires *anoxic conditions.* The anoxic tank is one of most cost efficient ways to break down high organic matter content in raw wastewater. The energy demand of an anoxic tank is significantly lower than that of an aeration tank, so the primary goal of wastewater treatment technologists is to ensure organic matter is decomposed under anoxic conditions.

The denitrification process in brief:

$$NO_3^{2-} \rightarrow NO_2^{-} \rightarrow NO^{-} \rightarrow N_2O \rightarrow N_2$$

Denitrification equation:

$$\text{Organic matter} + NO_3^{2-} - \text{Organotrophic bacteria} \rightarrow CO_2 + N_2$$

Conditions for denitrification to take place:

- nitrogen must be present in the form of nitrate (or nitrite)
- dissolved oxygen-free environment (in practice this means that dissolved oxygen concentration on the reactor feed side is negligible, maximum 0.1–0.2 mg/l)
- the presence of degradable organic matter as a carbon source

Denitrification can be inhibited by high concentration of dissolved oxygen in the sludge recycled from the aeration tank. In this case, anoxic condition does not develop; *facultative anaerobic bacteria* will use free dissolved oxygen instead of using nitrate oxygen. Thus, nitrate concentration in the treated wastewater may exceed environmental limits.

Removal of organic matter

Organic matter may be removed in aerobic, *anoxic* or anaerobic ways. They are oxidised aerobically in the aeration tank and anoxically in the anoxic tank as a result of organotrophic bacteria function. From a technological point of view, it is more desirable to implement anoxic decomposition, as this can be achieved with significantly lower operating costs and also reduces nitrate concentration in the treated wastewater. During biological phosphorus removal, poly-P bacteria also incorporate organic matter into their cells in the anaerobic medium.

Biological processes of individual wastewater treatments

Similar processes take place in small wastewater treatment plants, as described in previous chapters, and the microbial community is similar. The biggest difference between the operation of small equipment and sewage treatment plants is coming from, as it is also obvious to non-professionals, their size. Even in a large plant, technological conditions can occur, which can disrupt the operation of activated sludge, therefore continuous, daily inspections and monitoring should be carried out. Changes in temperature, composition of incoming wastewater, and of oxygen content of wastewater can result in a radical change in the composition of activated sludge in a short time. In wastewater treatment plants, the amount of wastewater is relatively large compared to a small plant, which means that the effect of influent toxic substances can be less drastic due to dilution. In case of small equipment, however, drug residues, dishwashing detergents, cleaning agents and disinfectants can inhibit the growth of bacteria even in small amounts, thus, the efficiency of decomposition. Any material that is not biodegradable should not be allowed to enter drains, only materials that we would safely pour into surface waters.

Chemical wastewater treatment

From the first decade of the last century to the middle of the century, wastewater treatment plant with activated sludge system were designed to remove organic materials causing oxygen overload to recipients. However, treated waters containing phosphorus and nitrogen discharged into recipients have caused problems, as microorganisms can only absorb a fraction of nutrients (ideal ratio is C: N: P = 106: 16: 1). Excessive organic and inorganic nitrogen and phosphorus nutrient load accelerates eutrophication. The concentration and limiting factor of existing nutrient sources should be taken into account when removing components. Among the necessary nutrients, primarily phosphorus can be controlled by precipitation from wastewater. In order to protect recipients, municipal treatment technologies must be supplemented with technological stages that can ensure the implementation of regulation 28/2004 (XII.25.) KvVM.

Thus, in addition to the biological stage, in most cases chemical treatment is used (e.g. in industrial wastewater treatment, heavy metal contamination, to improve sedimentation properties, for phosphorus removal, etc.). The purpose of chemical purification is to remove phosphorus (to protect vulnerable recipients), as well as to remove sulphide, suspended and organic matter.

Chemical phosphorus removal

Chemical treatment is mainly used for phosphorus removal, which is more cost effective than biological purification. After biological purification, organic matter decomposes and most of the phosphorus is present in a soluble form (in small amounts it is present in suspended solids as well).

There is a very low concentration of phosphorus in natural waters (it can also be formed from the weathering of rocks and from the bones of vertebrates). Phosphorus gets into wastewater mostly by anthropogenic effect e.g. detergents, human metabolism. Phosphorus may enter the recipient by leaching of fertilisers, from precipitation, or other tributaries. The amount of phosphorus released per residents varies, the amount of which is influenced by our eating habits, but it can be averaged between 0.6–3.7 g/d.

There are three forms of phosphorus in raw sewage: orthophosphate ion, condensed (poly-, meta-, ultra-) phosphates, and organophosphorus compounds. The transformation forms of phosphorus are shown in Figure 9.

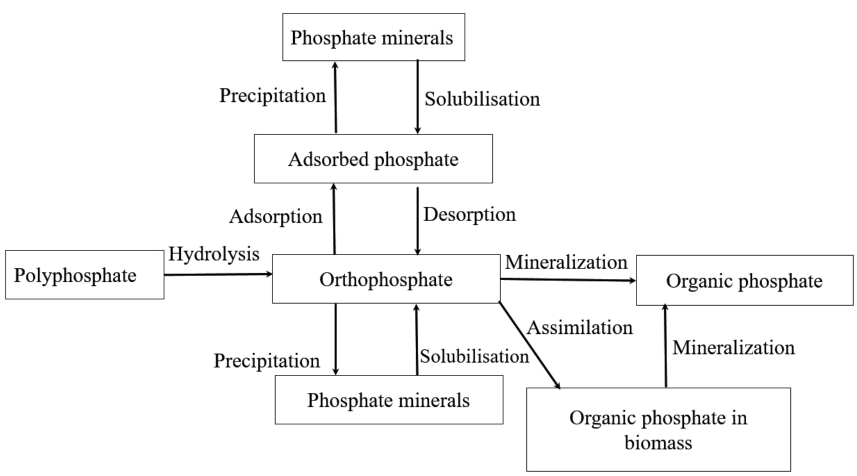

Figure 9
Phosphorus forms and their transformation products [8]

The various forms of orthophosphate are in equilibrium with each other, depending on the pH. Depending on the pH, the phosphate concentration of the system can be calculated by taking into account the solubility constant shown in Figure 10. The optimal pH range for metals is different. $FeSO_4$ and $AlPO_4$ are stable solid phases (based on equilibrium calculations); phosphate is precipitated in a low pH range, whereas calcium forms several insoluble phases with phosphate. When adding calcium compound, the amount of chemical needed and the pH of the system (keeping in mind the buffer capacity during design) should be taken into account.

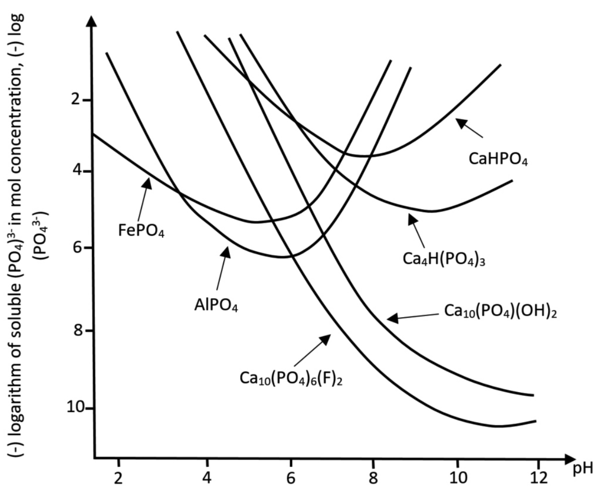

Figure 10
Solubility diagrams of different phosphates [9]

In wastewaters HPO_4^{2} occurs, thus, all phosphorus is detected gP/m^3, the value is independent of the phosphorus form.

Organophosphorus compounds form orthophosphate in which form it is the most easily precipitated. It is important to consider the amount of humic substances in the precipitation as they bind a large amount of Fe (III), thus delaying the deposition of phosphorus.

The process of the formation of metal phosphates consists of several steps:

1. After adding the chemical to the wastewater, a quick stirring for a few minutes is necessary to prevent the formation of metal phosphates or to prevent the formation of metal hydroxides. In addition to the formation of metal phosphates and metal hydroxides, carbonates are also formed.
2. Neutralisation (destabilisation) of colloidal particles with negative surface charge and clustering (coagulation) of the particles into larger units.
3. Adhesion of smaller particles to larger particles (macroflocculates), hydraulic residence time was previously 20–30 minutes. Nowadays, with chemical intensification and smaller pool volume shorter residence time of about 5 minutes can be achieved.
4. Sedimentation and removal of flocculated particles from the aqueous phase.

Factors influencing phosphorus precipitation:

– the quality and quantity of the chemical
– pH value
– raw sewage composition (PO_4-P, COD, dissolved COD, TSS, alkalinity (HCO_3,CO_3),Ca, Mg, etc.)
– mixing intensity
– contact time

The average phosphorus content of wastewater in Hungary is 7–20 g/l. Most divalent metal ions form a poorly soluble precipitate with orthophosphate ion (PO_4^{3}). The most common chemical precipitation method is the addition of aluminum salt.

Practical phosphorus precipitation is carried out using aluminum (Al^{3+}), iron (Fe^{3+}), pre-polymerised metal salt and calcium ion (Ca^{2+}). Effective removal can also be achieved by applying the chemicals together, e.g. polymers in combination with aluminum sulphate and lime.

Main aspects of chemical selection:

– concentration of influent
– suspended solids content
– alkalinity
– chemical costs
– sludge treatment equipment
– final sludge disposal
– compatibility with other treatment processes

Aluminum salts

Aluminum sulphate is the most commonly used among aluminum salts. When the chemical is added to wastewater, the pH is lowered due to the neutralisation of alkalinity and removal of carbon dioxide. The optimum pH for phosphorus removal is between 5.5 and 6.5. Aluminum reacts with the phosphate ion to form aluminum phosphate ($AlPO_4$).

Iron salts

Removal of phosphorus can be performed by e.g. iron (II)-sulphate, iron (III)-sulphate, iron (III)-chloride, all of which reduce the pH of wastewater. They are usually used in a pH range of 7–8, with the addition of lime or sodium hydroxide to raise the pH.

Advantages of applying iron salts and aluminum chloride:

– total phosphorus concentration in treated water can be kept within limits
– treatment efficiency and organic matter decomposition are more effective
– prevents the growth of filamentous bacteria
– increases the dry matter content of the sludge, improves the sedimentation and dewatering efficiency

Lime

Most often lime hydrate is used, resulting in larger amounts of precipitate and sludge to be treated. During lime dosing, the efficiency of phosphorus removal and the alkalinity of the wastewater must also be considered. Regarding the site of application, it can be used in the pre-settler and after the post-settler. Figure 11 shows the operating principle of the phosphorus removal system using lime precipitation.

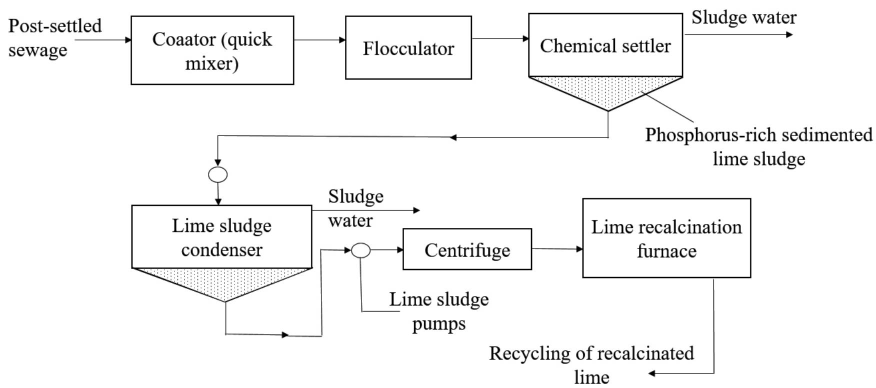

Figure 11
Principle of phosphorus removal by lime precipitation system [10]

The last step in lime precipitation is recarbonisation with one or two stages.

Depending on whether the wastewater treatment technology has biological treatment, several dosing options can be differentiated.

CEPT (Chemically Enhanced Primary Treatment) procedure

For non-biological technologies, we use this direct precipitation method. It is primarily used to increase suspended solid removal efficiency of settlers. The chemical ($FeCl_3$) is added to the grit unit.

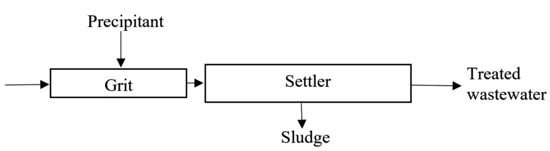

Figure 12
CEPT procedure (compiled by the authors)

Pre-, simultaneous and post-precipitation

Chemical wastewater treatment, either alone or in combination with biological treatment processes, is a more widespread solution. Depending on where the chemical is administered, the options for implementing technologies can be pre-, simultaneous and post-precipitation. It is important to consider the correct mixing of the chemical during application.

Phosphate precipitation can be characterised by the following equation.

$$Me^{3+} + PO_4^{3-} = MePO_4$$

Depending on the pH, the phosphate concentration in the system can be calculated from the solubility constant.

Dissolved phosphorus is converted to a solid by the addition of a chemical, which can then be removed according to the principle of phase separation.

$$Al(H_2O)_6^{3-} + H_2PO_4^- = AlPO_4 + 6H_2O + 2H^+$$

$$Al^{3+} + PO_4^{3-} = \mathbf{AlPO_4}$$

$$FeCl_3 + \ 6H_2O + PO_4^{3-} = FePO_4 + 3Cl^- + 6H_2O_3$$

$$Fe^{3+} + PO_4^{3-} = \mathbf{FePO_4}$$

Thus, based on the stoichiometry equations, 1 mol of a precipitant is sufficient for 1 mol of phosphorus. In practice, however, the amount of the chemical has to be increased because colloids react with metal salts to form iron hydroxide.

Pre-precipitation

The chemical can be added after the grit, into the pre-diffuser, and immediately before the pre-settler (Figure 13). If the chemical is applied before the primary settler, the biological treatment step should be considered, as it can greatly influence the denitrification process, namely less nutrient may remain in the wastewater and BOD_5 of the activated sludge pool may be reduced (by up to 50%). Chemical sludge is settled in the primary settler along with raw sludge, thus, its efficiency may increase (up to ~ 25%). There may be an increase in sludge index, which may cause floating in the post-settler due to the changes of the sludge structure (filamentous abundance).

All of the above-mentioned chemicals are applicable, but iron (II) salts must be prior oxidised in order to be efficiently removed in the primary settler. Pre-precipitation is used in municipal wastewater treatment plants that are overloaded, in a pre-development condition, or in industrial wastewater pretreatment.

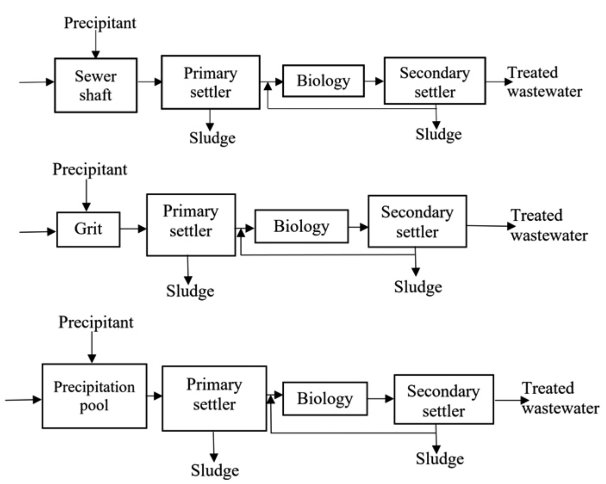

Figure 13
Optional sites for pre-precipitation [2]

Simultaneous precipitation

The most commonly used method is the addition of chemicals directly to the biological stage (possibly added to recirculated sludge). The advantages of the process include no need for building additional structure other than chemical dispensers (low investment cost), small space requirements, activated sludge with good sedimentation and adsorption capacity. The disadvantages of this process are that the chemical cannot be recovered and the phosphorus concentration of the effluent is higher. With the most commonly used technology, 1 mg/l phosphorus concentration can be maintained. Most of the chemicals listed are usable for simultaneous precipitation.

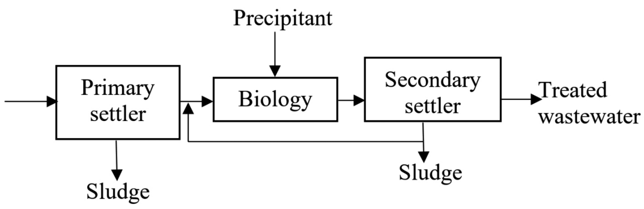

Figure 14
Simultaneous phosphorous precipitation [2]

Post-precipitation

Dosing is done after the biological step. Precipitation results in the formation of sludge, the amount of which depends on the chemical dose (2/3 of the sludge is chemical precipitate, 1/3 of it is organic colloid adsorbed on its surface). The method works reliably even under fluctuating hydraulic loads.

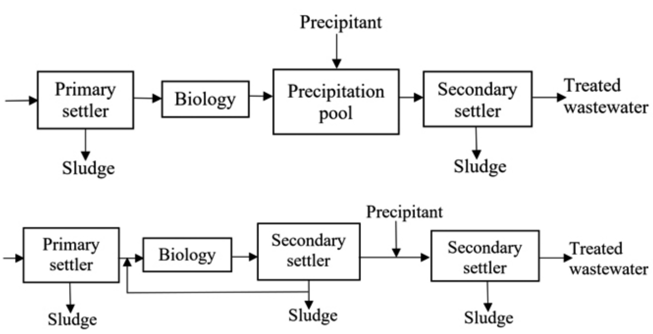

Figure 15
Possible injection sites for post-precipitation [2]

The efficiency of phosphorus removal changes in the technological phases:
- mechanical, biological and pre-precipitation 89% (influent wastewater 8 mg TP/l, effluent 0.9 mg TP/l)
- mechanical, biological and simultaneous precipitation 86% (incoming wastewater 8 mg TP/l, outflow 1.1 mg TP/l)

- mechanical, biological and post-precipitation 92% (influent wastewater 8 mg TP/l, effluent 0.6 mg TP/l)
- mechanical, biological and simultaneous precipitation, coagulation rapid filtration 96% (influent wastewater 8 mg TP/l, effluent 0.3 mg TP/l)

Maintaining the correct pH range is an important consideration for the high efficiency of precipitation and flocculation. The degree of control also depends on the chemical used. For control, acids can be added (e.g. H_2SO_4), that does not cause sludge formation. The addition of excess amounts of metal salt can also be an effective control with the disadvantage of greater sludge formation.

Chemical nitrogen removal

There are several methods for removing excess nitrogen (ammonia) from wastewater, which are the following [1]:

- Precipitation: precipitation of ammonia in the form of $MgNH_4PO_4$, optimum pH 8 (possible with high efficiency), MAP (magnesium ammonium phosphate) is used as precipitant
- Removal by ion exchange from wastewater (a continuous disadvantage of the process is that contaminants can enter the washing water, which are sensitive to suspended and dissolved organic pollutants in biological wastewater, can also clog their mechanical system, and even be chemically contaminated)
- Ammonia stripping, blowing after alkalisation of water (pH about 10)

The specific costs of the above-mentioned methods are high and are therefore less widespread.

Sludge treatment

In the last few decades, wastewater treatment has gone through significant development. However, treatment and disposal of sewage sludge, which is a byproduct of wastewater treatment, did not keep up with this development. As the sanitation and wastewater treatment program progresses, the amount of sewage sludge in Hungary is expected to increase in the upcoming years.

In the various operating units of the treatment process, residues (sand, screenings, floating materials, sludge) are formed, among which the largest mass and volume is sludge.

The type, quantity and nature of residues will depend on:

- the load of treated wastewater, i.e. the amount of wastewater and the type of constituents and their properties
- the treatment processes used, their efficiency and the constituents transformed
- materials and energy used in the treatment processes

The following sludges can be distinguished by their location and state:

- primary sludge: sludge separated in the primary settler, its dry matter content is 2–3%, its nitrogen and phosphorus content is lower compared to secondary sludge
- excess sludge (secondary sludge): sludge produced during biological treatment, mostly it consists of water and is also derived from solid particles
- chemical sludge derived from chemical treatment (tertiary sludge): sludge separated during chemical sewage treatment

– mixed sludge: a mixture of primary and other sludges (excess or chemical) removed from the primary settler
– stabilised (digested) sludge: sludge removed from the system after stabilisation with reduced organic matter content and pathogenicity
– sludge water: water containing dry matter separated during dewatering of sludge

The sites of sludge generation are shown in Figure 16 depicting the technological longitudinal section of treatment with activated sludge system and pre-denitrification.

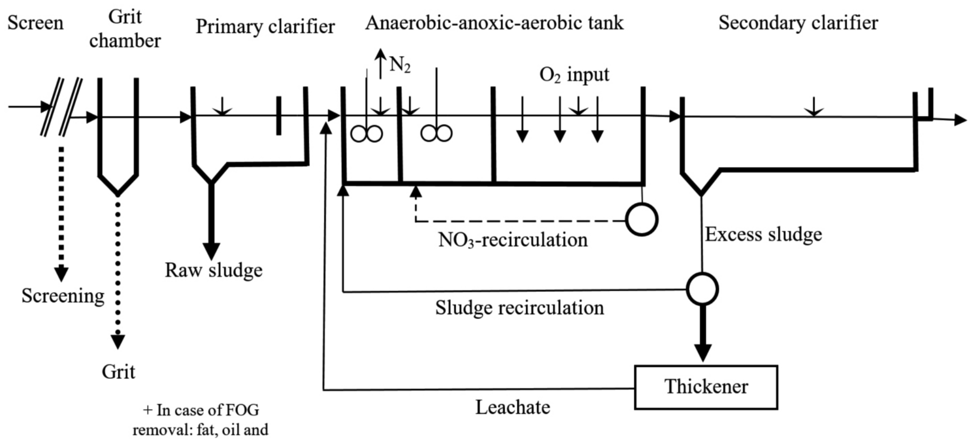

Figure 16
Sites of sludge generation in municipal wastewater treatment (compiled by the authors based on [11])

Wastewater treatment technologies determine, in addition to the composition of wastewater, the properties of residual materials as well. The major part of sewage sludge is water, which is present in three different forms in sludge (free water, bound water and intracellular water content). Based on the composition of sewage sludge, it can be divided into two groups, recoverable and inhibitory substances (Table 5). Table 6 illustrates the general properties of sewage sludge varieties.

Table 5
General composition of sewage sludge [11]

Recyclable materials	Sludge water	Free or easily removable sludge water
		Capillary water (20%)
		Moisture content of flock particles (2%)
		Chemically bound water in cells (8%)
	Crushed, ground mineral particles	Fine and coarse sand
		Other granular materials
	Organic compounds	Carbonaceous residues
	Nutrients	N
		P
		K
	Trace mineral	Metallic elements, organic chemicals

Substances that inhibit recycling (factors increasing risk)	Toxic substances	Heavy metals (Cd, Pb, Hg, Cu, Ni, Zn, Cr)
		Other Toxic Substances (As, Mo, Se, etc.)
	Pathogens	Bacteria
		Viruses
		Parasites
		Fungi
	Anthropogenic substances	Pharmaceutical compounds, personal care products, etc.

Table 6
General composition of sewage sludge varieties [12]

Typical parameters	**Dimension**	**Sludge type**					
		Raw sludge from mechanical treatment	**Excess sludge from biological treatment**	**Badly digested sludge**	**Moderately digested sludge**	**Well digested sludge**	**Fully digested sludge**
pH	–	5.0–7.0	6.0–7.0	5.6–7.1	6.8–7.3	7.2–7.5	7.4–7.8
Dry matter	%	5–10	4–8	4–12	4–12	4–12	4–12
Loss on ignition	%	60–75	55–80	55–70	50–60	45–55	30–45
Acid consumption	mg/l $CaCO_3$ mmol/l	500–1,000 20–40	500–1,000 20–40	1,000–2,500 40–100	2,000–3,500 60–140	3,000–4,500 120–180	4,000–5,500 160–220
Volatile acids	mg/l acetic acid mmol/l	1,800–3,600 30–60	1,800–3,600 30–60	2,500–4,000 * 40–70 *	1,000–2,500 15–40	100–1,000 2–15	< 100 2
Total N	% dry matter	2–7	1.5–5.0	1–5	1–3.5	0.5–3.0	0.5–2.5
Total P		0.4–3.0	0.9–1.5	0.8–2.6	0.8–2.6	0.8–2.6	0.8–2.6
Total potassium		0.1–0.7	0.1–0.8	0.1–0.3	0.1–0.3	0.1–0.3	0.1–0.3
Specific filter resistance	M/kg	10^{11}–10^{13}	10^{12}–10^{13}	5.10^{11}–5.10^{12}	10^{11}–10^{12}	5.10^{10}–5.10^{11}	10^{10}–10^{11}
Calorific value	kJ/g m_T	16–20	15–21	15–18	12.5–16	10.5–15.0	6.3–10.5

The physical properties of sewage sludge can be grouped according to water content:
- liquid (85–100%)
- viscous, non-pumpable (75–85%)
- mushy-plastic, viscous (70–75%)
- crumbly, often solid (40–70%)
- loose, very hard (10–40%)
- powder (10%)

The quality of the sewage sludge is characteristic of the given settlement and the treatment technology, so it may vary from one settlement to another.

The long-term load of 599 domestic agglomerations (602 wastewater treatment plants) is determined by Government Decree 25/2002 on National Municipal Wastewater Collection and Treatment Implementation Program and the VGT. The long-term aggregate load of agglomerations will be 12,041,042 PE (population equivalent) according to the government decree effective as of 21 November 2014. The long-term load of 236 settlements with lower than 2,000 PE is added to this and estimated to be 173,082 PE. The sum of the two gives the long-term sewage load of municipal wastewater treatment plants. Figure 17 shows the expected sludge volumes estimated by the Sewage Sludge Management and Recovery Strategic Program.

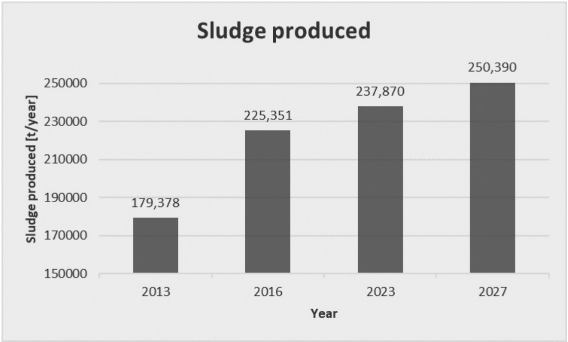

Figure 17
Expected sludge volumes in the upcoming years (compiled by the authors based on Sewage Sludge Management and Recovery Strategy 2014–2023)

Volume reduction and stabilisation procedures

Before sludge disposal, it is necessary to go through several technology units (thickening, dewatering, stabilisation, disinfection and heat treatment drying) in order to reduce its water content, its biodegradability and to decrease pathogenicity.

Sewage sludge treatment is defined as actions performed on the sludge generated at the sewage treatment plant to reduce volume and pathogenicity, and to improve manageability, recycling or disposal.

Further use or disposal determine how sludge is treated and require treatment:
- water content of sludges
- in wastewater treatment plants, the behaviour of similar types of sludge varies during different treatment processes
- presence of infectious (worms, pathogens, bacteria) and toxic substances

The most important steps of sludge treatment are:
- sludge thickening
- sludge conditioning and stabilisation
- disinfection
- dewatering
- disposal

Compaction

The first technological treatment of the primary and secondary sludge is compaction. The purpose of compaction is to reduce the volume of sewage sludge, which is intended to provide more favourable conditions for sludge incineration and disposal. To increase the efficiency of the technology, a polyelectrolyte or metal salt is added to increase solids content by up to 6–10%. Based on the compaction capacity of the sludge, three types can be distinguished, as shown in Table 7. The operator can calculate sludge volume reduction that can be achieved by compaction by taking into account the daily volume (l/d) and dry matter content (%) of pre-settled sludge.

$$
\begin{aligned}
& daily\ dry\ matter\ content\left(\frac{kg}{d}\right) \\
& = volume\ of\ removed\ pre \\
& - settled\ sludge\,\frac{(l) * dry\ matter\ content\ of\ removed\ pre - settled\ sludge(\quad)}{100}
\end{aligned}
$$

Table 7
Sludge thickening and dewatering [11]

Sludge characteristics in terms of water content	Compaction without conditioning agents		Limits of dewatering					
			Belt filter press		Chamber press			
			Conditioning with polymer		Conditioning with iron salt or polymer			
					with lime		without lime	
	DS %	W %	DS %	W %	DS %	W %	DS %	W %
Easily compacting/dewatering sludges e.g. municipal sewage sludge from combined sewer	> 7	< 93	> 30	< 70	> 38	< 62	> 45	< 55
Moderately compacting/ dewatering sludges e.g. municipal primary sludge from segregated sewer system	4–7	96–93	18–30	82–70	28–38	72–62	35–45	65–55
Poorly compacting/dewatering sludges e.g. municipal secondary sludge	< 4	> 96	< 22	> 78	< 28	> 72	30–35	70–65
D – dry matter content								
W – water content								

Gravity compactor is a common technology used in municipal sewage treatment plants, but mechanical compactors are increasingly being used. The advantage of the technology is low specific investment cost. The technological elements of sewage sludge compaction are shown in Figure 18.

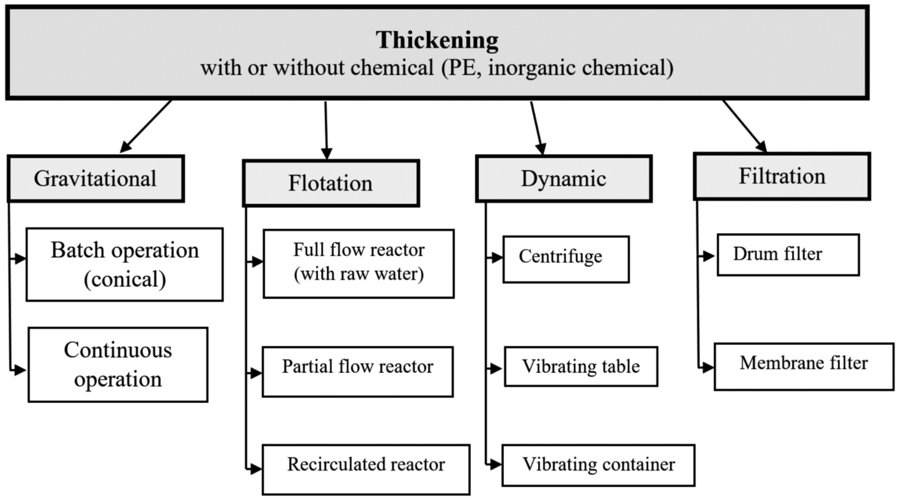

Figure 18
Technological elements of sewage sludge compaction [11]

Gravitational compaction

Gravitational compaction is practically another phase of sedimentation. It can be equally used for compacting raw, excess and mixed sludges.

In terms of structure, the following can be distinguished:

– intermittent – naturally operating "funnel compactors" (only under gravity, with or without sludge excavator and mixer, up to 5,000 PE, at least 2 parallel engineering structures are required)
– continuously operating – artificial "machine" operated (rod compactors, equipped with a mixer, structurally similar to radial flow settlers, used mainly in installations with a load above 5,000–6,000 PE, mainly used for secondary sludge compaction)

The difference between gravity settling and compaction processes is generally less well understood, though closely related. During compaction, the concentration of suspended solids increases as the solids get closer to one another. Compaction occurs in the bottom zone of the structures. During the process, solid particles are compacted by pressure from the weight of the particles above them. The site of sludge feed depends on the shape of the structure (circular – in the centre, rectangular – at one end of the pool). Compacted sludge is removed from the bottom continuously or periodically. Thickeners with circular base are more widespread, its design is illustrated in Figure 19.

The sludge inlet pipe directs the sludge into the zone above the compactor area, the sludge being introduced under the distribution cylinder flows radially into the sedimentation space, from where solid particles larger than liquid settle into the compactor space located at the bottom or into the bottom zone. The slowly rotating sludge excavator moves the compacted sludge into the sludge sump. By the slow rotation of the rods, settled sludge can be kept in slow motion, bridge-like flaking of sludge particles as well as sludge stratification can be prevented. Based on operational experience, drainpipe is a critical component of the compaction process as it has to extract high concentrations of sludge from the sludge sump. Gravity compactors are recommended to use up to

40m³/d of sludge (5,000 PE) before sludge digesters or dewatering equipment. The achievable dry matter content is 2.5–4% for batch operation and 3–6.0% for continuous operation compactors. The residence time of the sludge in the structure is approximately 6h. The operation of gravity compactors is mainly influenced by surface load.

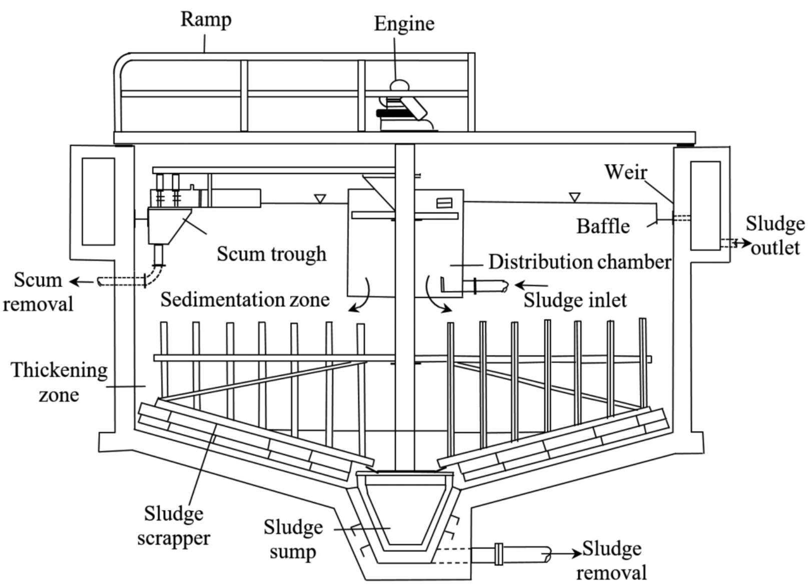

Figure 19
Gravity compactors with circular base [10]

The addition of the chemical improves the gravitational compaction of sludge by a few percent, among conditioners iron and aluminum salts as well as lime hydrates are used. The first two are more potent, the latter is a weaker coagulant. Charged organic polymers are more effective because of their dissociation moieties, since they hold the flakes together not only by hydrogen bond, but also by covalent bonding of the polymer chain. The amount of chemical needed is determined under laboratory conditions as the chemical significantly affects sludge properties.

Flotation

Flotation process is used to remove materials with a density lower than water. Separation of sewage sludge is achieved by the upward movement and flotation of air bubbles adhering to suspended particles. The attachment of bubbles, flocculation can also be improved by the use of chemicals mixed with the sludge.

Classification can be done by operating principle:
- gravitational operation (cheap to operate, but less efficient and requires a large reactor volume)
- forced air
- pressurised
- vacuum
- electroflotation (not used to compact sewage sludge)

The latter four are more efficient, require less reactor volume, but their operation is more expensive and requires expertise.

The flotation unit consists of a pressurised tank – flotation reactor – feed pump and air compressor, which are installed in various combinations due to economic aspects, shown in Figure 20.

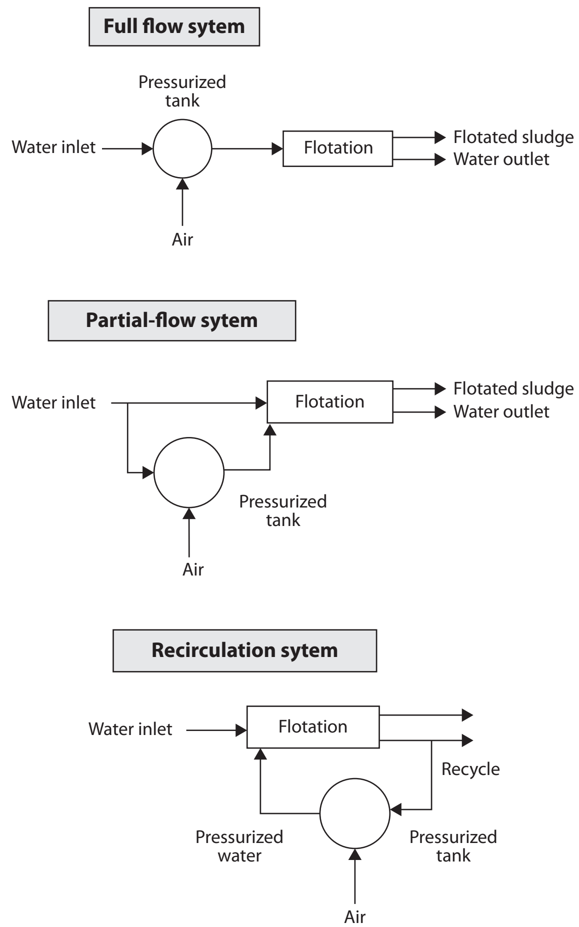

Figure 20
Flotation variations [13]

Factors influencing flotation efficiency:
- type of sludge
- air pressure (influences bubble diameter, dry matter concentration, as well as sludge quality exiting the compactor)
- feed sludge type (pre-settled sludge is generally heavier than post-settled sludge and is therefore more difficult to compact by flotation)
- sludge age (influences to a lesser extent, aged sludges tend to float naturally due to their gas-forming properties)
- recirculation rate (the recirculation fluid conveys air to the site of injection into the compactor)

– hydraulic and sludge load (in case of hydraulic load, the quality of the effluent sludge water is lower, the concentration of floated sludge decreases)
– air (A) solids (S) ratio (A/S, which is 0.02 during activated sludge compaction by flotation)
– thickness of the floated sludge layer and its dry matter content (increasing or decreasing the running speed of the scraping device results in a thinner or more concentrated sludge, respectively)
– chemical addition
– temperature

This is a less common procedure due to its mechanical components requiring more complex and expert handling. Areas of application are wastewater pretreatment units, they play a very important role in water pre-purification in the food industry, in wastewater treatment plants (for the removal of grease, oils, fibrous materials), and in sewage sludge compaction (rarely). Available efficiency is ~ 6% dry matter.

Mechanical compaction

Gravity compactors have been used primarily in municipal wastewater treatment, but recently the use of dynamic compactors is emerging. Dynamic compactors require the use of chemicals to optimise their performance. Even with the addition of a little chemical, 5–8% compacted sludge can be obtained, which is favourable for further treatment. Advantages of the compaction process include small compartment size, located in a closed space, operation is weather-independent, and its compaction efficiency is higher. Disadvantages include high operation costs, special, expensive machinery and chemical need. They can be mainly used at larger plants due to their high, variable "throughput" capacity.

The most commonly used equipment include:
– compaction centrifuges (also used for sludge compaction and dewatering)
– various shaking sieves (compaction tables)
– compacting separators
– mobile compacting (shaking) containers
– drum thickeners (operating on filter principle)

The most commonly used dynamic processes are drum thickeners, which are also used as a grid in small to medium plants, but are generally used in large plants to thicken excess sludge to increase dry matter content before digestion/stabilisation.

Filtering

Currently, the installation of filtration based sludge thickening equipment is only recommended for large plants and for special needs (due to the high costs of maintenance and filter elements). Available dry matter content is expected to be 10–15% depending on filtration. The most common methods are drum and membrane filtration.

Membrane technique is used by the industry in a number of areas, partly for separation and partly for compaction. The process is based on surface filtration that can be microfiltration, ultrafiltration, and nanofiltration. In the field of wastewater treatment, membrane filtration is intended to replace post-settling, but in special cases, it can also be used to thicken sewage sludge. Water passing through the membranes is free of bacterial contamination, thus, a costly disinfection system could be saved.

The efficiency and frequency of application of thickening processes are shown in Table 8.

Table 8
Thickening methods and their relative efficiency [10]

Procedure	Sludge type	Frequency of application and relative effectiveness
Gravity thickener	Primary sludge	Commonly applied. Sometimes (e.g. in industrial wastewater) it is used together with hydrocyclone for sand removal from the sludge.
	Primary and excess sludge	Often applied. In small plants, 4–6% of dry matter can be achieved.
	Excess sludge	Rarely applied. 2–3% of dry matter can be achieved.
Compressed air flotation	Primary sludge	Limited use. Its effectiveness is similar to that of a gravity thickener.
	Excess sludge	Commonly applied. 3.5–5% of dry matter can be achieved.
Decanting centrifuge	Excess sludge	Limited use. Good efficiency: 8–10% of dry matter can be achieved.
Tray centrifuge	Excess sludge	Its application is increasing. 4–6% of dry matter can be achieved.
Belt filter press	Excess sludge	Its application is increasing. Effectiveness: 3–6% of dry matter can be achieved.
Rotary drum dehumidifier	Excess sludge	Limited use. Good efficiency: 5–9% of dry matter can be achieved.

Conditioning

The goal of conditioning is to prepare the sludge for handling (utilisation or disposal) or to facilitate the efficiency of additional treatment steps. The purpose of conditioning is to improve dewatering, stabilise readily decomposing organic matter, to destroy, reduce pathogens and bacteria, and to improve densification and dewatering.

Small sludge particles require conditioning because they are hydrated (bind to water) and usually carry an electrostatic charge on their surface. The conditioning and exploration procedures are illustrated in Figure 21.

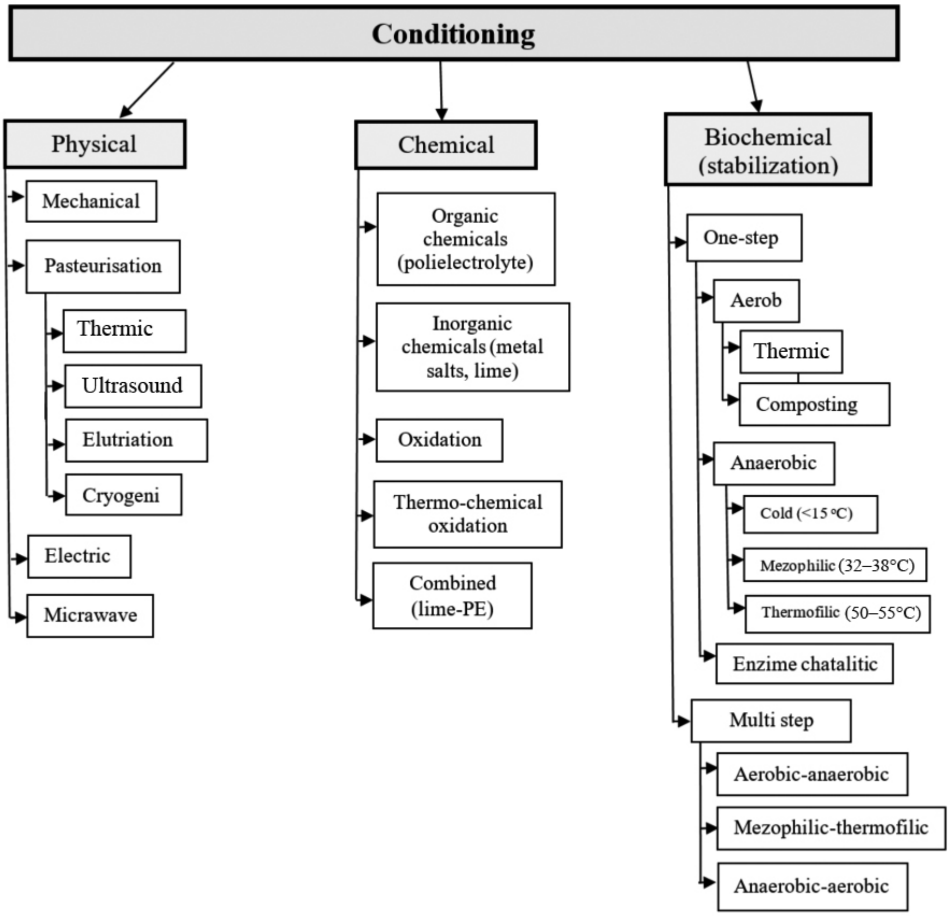

Figure 21
Main conditioning procedures [11]

Mechanical conditioning

It provides shredding of hard or fibrous materials, homogenisation of liquids, and protection of pumps and other equipment, which improves system reliability.

Mechanical digestion/conditioning techniques include shredders (macerators), mills, high-pressure collectors, rotor processes, high-pressure homogenisers and centrifuges (to reduce sludge viscosity for approximately 6%, increase in methane yield in the digester by 30–40% at most).

The advantages of mechanical exploration techniques include:
– simple operation and low investment cost
– increases enzyme activity and gas output
– improves dewatering
– reduces foaming in the digester
– reduces sludge viscosity

Pasteurisation

During the process, the aim is to reduce the number of pathogenic bacteria in raw or digested sludge used for agriculture (the process is carried out between 60–80°C and at a residence time of 15–30 minutes). In continuous operation, a two-stage countercurrent heat exchanger is generally used; the first stage serves the utilisation of heat from the preheating of pasteurised and raw material, while the second stage performs the actual pasteurisation. At larger plants, special reactors operate in batch mode; by increasing the temperature, pasteurisation time can be reduced. The method has been used less frequently because there is a potential for re-contamination in case of a delay in sludge incorporation time and it is expensive to build and operate.

Thermal process

Its purpose is to remove water bound in the cell by digesting the cell wall material of the sludge. Treatment is carried out at a high temperature (180–220°C) and under pressure, after which the sludge can be dehydrated to 40–50% solids by a chamber press and then used in an incinerator for heat production.

Benefits:

- cost-effective operation when based on waste-heat recovery
- improves gas output in the digester
- inactivates pathogens
- improves sludge dewatering (up to 50% dry matter content can be achieved by machine dewatering)
- reduces volatile organic fraction

Disadvantages:

- large amounts of toxic dioxin are produced on the heating surface (impair the efficiency of digestion and accumulate in the sludge as residues)
- the process also destroys enzymes of the biomass (a separately controlled recirculation is required)
- erosion problems
- odour problems (air purification is required)
- organic matter content of leachate is very high (excess load in liquid phase treatment)
- high investment cost

Combined methods of digestion are Cambi and BioThelys.

Ultrasonic procedure

The ultrasonic process produces a material with better filtration resistance for dewatering and also has a detectable disinfectant effect, thus, it is one of the intensive developments in conditioning technology. It has the advantage of being easy to install and operate, and also improves biodegradability (thereby biogas yield).

Washing of sludge (elutriation)

Washing results in the elution or dissolution of fine colloids. Its effect also results in a reduction of the chemical to be used (only used by large plants). Purpose of washing includes:

- reduction of bicarbonate alkalinity in sludge (acid metal salt requirement can be reduced)
- washing digested sludge dilutes sludge and reduces alkalinity
- reducing sludge alkalinity results in a reduction in the amount of lime required for pH control

The most important effect of sludge washing is to wash out 10–45% of fine sludge granules difficult to dewater, thus, improving sludge dewatering, although by directing it back to the beginning of the treatment plant, fine fraction removal is more difficult.

Freezing procedure

In the process, ice crystals break down cell walls, colloids preventing dehydration decompose. Natural winter freezing is used, because artificial cooling is not economical.

Electric conditioning

The sludge is directed into a pulsatile electrostatic space (20–30 kV) to achieve digestion of the sludge. Its advantage is short contact time, while its disadvantages are that large-scale application is not yet perfected and its electrical requirements are high. The method is not proven and rather inefficient.

Microwave conditioning

During microwave treatment, structural and flake forming properties of the sludge may also change.

During microwave energy transfer treatment, the following processes take place due to thermal effect:

- disintegration of sludge flakes
- cell membrane rupture
- hydrolysis of high molecular weight materials

In case of sludges from wastewater treatment technology using flocculants, sludge flakes disintegrate (fragment) in the first part of the treatment period, but due to the presence of flocculants, "reflocculation" mechanisms occur, flakes become more compact and their bound water content is lower than in the original flocks. Microwave processes use the frequency of 2,450 MHz and in some cases 918 MHz, though it is hardly used on large scale because of high costs in both operation and investment.

Chemical conditioning

The effect of chemicals (flocculants) is to improve dewatering and reduce the digesting capacity of the sludge.

Applied chemicals:

- organic chemicals (polyelectrolytes, prestole, zetag, hercoflock, etc.)
- inorganic chemicals (ferrous sulfate, ferric chloride, aluminum sulfate, aluminum chloride, ongroflock, lime, coal dust, etc.)

It is important to determine the appropriate amount of chemicals to be added because overdose, especially for polyelectrolytes, impairs efficiency. Selection of chemicals must also take into account the aspects of recovery and disposal.

Conditioning with organic chemicals

For dewatering of sludges, significantly greater volume reduction and dry matter content can be achieved by conditioning with polyelectrolytes compared to gravity compaction. Polyelectrolytes have a long chain structure binding the flake particles in a bridge-like manner with good efficiency. Polyelectrolytes have been adapted to all sludge conditioning tasks for the following reasons:

- a small amount (15–30%) of excess sludge is formed
- they do not reduce the calorific value of dewatered sludge
- conditioning material handling operations are cleaner
- operation and maintenance problems are reduced

In the field of conditioning agents, the development is continuous; according to the charge of ions, we distinguish three types of polyelectrolytes:

- anionic (negatively charged and used in combination with positively charged aluminum sulphate and ferric chloride)
- non-ionic (contain equal amounts of cationic and anionic polymers, charged are affected by the pH of the solution)
- cationic (positively charged, used alone or in combination with aluminum sulphate)

Cationic polymers are most commonly used to dewater sewage sludge.

The most commonly used inorganic conditioning chemical is ferric chloride, alone or in combination with lime.

- Iron (III) chloride. Upon addition to sludge, ferric chloride forms positively charged soluble iron complexes that attempt to neutralise the surface of negatively charged sludge particles, thereby providing flocculation conditions.
- Lime conditioning. Lime has a dehydrating effect on colloids and is selected for conditioning mainly due to its pH-regulating, odour-reducing and disinfecting properties. Heat generated by inoculating the lime has a disinfecting effect, inhibiting further rotting of the sludge (odour effect) for up to 2–3 months (until it decomposes). In small and medium-sized treatment plants, it is also used during temporary storage of sludge, while in larger plants it is also a preferred flocculant during chamber-filtered sludge dewatering. Lime is available in quicklime form (CaO) and hydrated form [$Ca(OH)_2$]. Hydrated lime is usually used in combination with ferric chloride.
- Oxidising agents. Oxidising agents used are ozone, hydrogen peroxide and oxygen. The advantage of the oxidation process is that it reduces the load on the digester. Disadvantages include high investment cost and significant pH shift.

Biochemical conditioning

In aerobic and anaerobic systems, bacteria further stabilise the sludge during treatment, converting it into simpler forms. Mixture sludge from pre-settlers and from systems using bound biomass and activated sludge is usually pumped into a stabilisation structure for further stabilisation.

Aerobic stabilisation is the “complete oxidation” of sludge, i.e. further aeration. Only 75–80% of the cellular material is oxidisable, the remaining 20–25% is inert and cannot be degraded. Its application is mainly recommended for small and medium capacity (2,000–7,500 m^3/year) plants.

Technology line: pre-compressed → blown mixed reactor → post-compressor.

According to the choice of reactor space, distinction must be made between “combined” and “separated” systems. A combined tank is a tank with significant volume requirement; treatment of the dissolved phase and complete (or partial) stabilisation of sludge takes place with relatively high energy consumption. In “separated” systems sludge (crude and excess activated sludge) separated during the treatment of liquid phase are stabilised separately similarly to the technological process described above, but in a significantly smaller reactor space.

Aerobic sludge stabilisation reactor can be batch-fed or continuous-fed. It is circular or rectangular in shape and open or closed depending on weather conditions.

Conditions of use:

- temperature of the mixture can be kept above +10°C at all times of the year
- periodic change of the load exceeds the ratio 1:2.5–1:3.0
- organic dry matter content of the sludge does not exceed 50 V/V%-o
- toxic industrial effluent inhibits the efficient operation of the anaerobic digester
- the result of energy test is favourable

Composting

Composting is a thermal aerobic process with the main purposes of stabilisation, dewatering and disinfection. On the sludge line, it is usually followed by dewatering.

Composting can be divided into three main parts:

- mesophilic period – appearance of mesophilic bacteria (yeast and other fungi), temperature rises to 50°C, decreases to pH = 4–5, time required: 0.5 days, during which fats, proteins and carbohydrates are broken down
- thermophilic period – thermophilic bacteria, temperature can rise up to 70°C, pH rises to 8–8.8, time required: 2–3 days, around 60–70°C all pathogenic microorganisms are killed within a few hours, except for a few spore-forming ones
- maturation stage – heat production slows down, because thermophilic bacteria have broken down available nutrients, compost gradually cools down, time required: 2–3 months

The composting process can be shortened by enzyme dosing and inoculation. It is only used in special cases due to high costs. During composting, the oxygen, moisture and nitrogen content in the organic matter must be measured (C/N ratio, the literature considers a ratio of 20:1–30:1 to be appropriate). Good compost is stabilised to such an extent that the likelihood of odour formation is greatly reduced, can be stored and transported.

Common fillers for sludge composting include:

- agricultural waste (peat, straw, shavings, shredded reeds, etc.)
- municipal solid waste (garbage)
- industrial waste (organic, non-toxic substances)

Favourable properties of compost include storage, transport, workability, favourable nutrient content, and compliance with health requirements.

The general composition of finished compost as a function of the range of occurrence is given in Table 9.

Table 9
General characteristics of finished compost [8]

Characteristics (g * 100 g^{-1} dry matter)	**Occurrence range**
Humidity	30–50
Inert substance	30–70
Inorganic content	10–30
pH (1:10 water mixture)	6–9
Alkalinity (as CaO)	1–20
Total salt (as KCl)	0.5–2.0
Maximum particle size (mm)	2–10
Elements (g * 100 g^{-1} dry matter)	Occurrence range
Humidity	0.1–1.8
$P(P_2O_5)$	0.1–1.7 (0.2–3.8)
$K(K_2O)$	0.1–2.3 (0.1–2.8)
S	0.5–3.0
Elements (mg * kg^{-1} dry matter)	Occurrence range
B	60–360
Cd	15–40
Cu	90–260
Fe	8,000–15,000
Hg	1–5
Mn	300–1,300
Mo	10
Pb	200–400
Zn	800–1,200

Based on their design, compost systems can be:

- prismatic, open system (batch operation, which can be manual or mechanical, mechanical mixing and mechanical air intake)
- compost, in landfills (instead of mixing, aeration through a perforated pipe system under the compost, continuous operation)
- tank, closed (small area, well controllable process, high investment cost, design: circle, square, tower or tunnel)

Autothermal Thermophilic Aerobic Sludge Stabilisation (ATAD)

Aerobic sludge stabilisation has developed significantly in recent decades. In the ATAD (Autothermal Thermophilic Aerobic Digestion) process, pre-compressed sewage sludge is transferred to aerated, thermally insulated reactors (heat is generated during aerobic decomposition of organic matter by microorganisms). The process also uses intermittently aerated mesophilic reactors operating in the temperature range of about 35°C to reduce ammonium concentration. The energy input and loss of an ATAD reactor is illustrated in Figure 22.

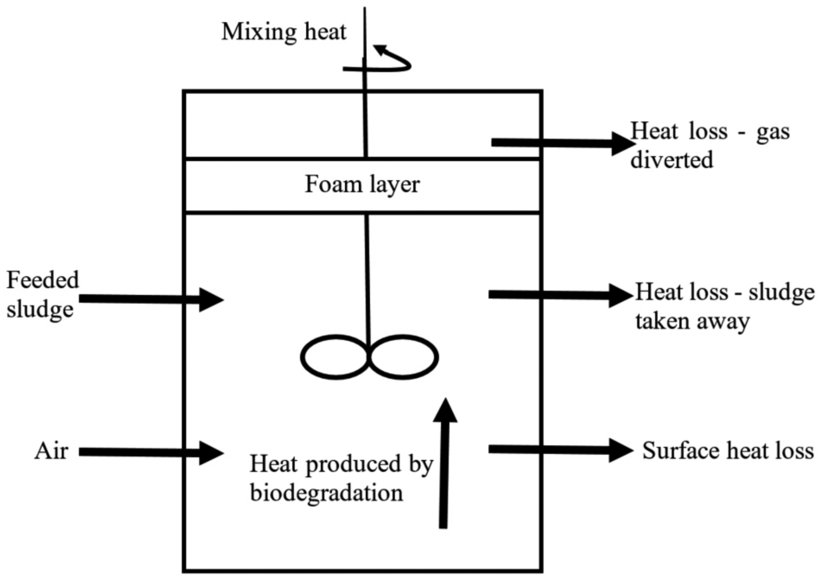

Figure 22
ATAD energy intake and loss (compiled by the authors)

Advantages of ATAD technology compared to mesophilic digestion:
- effective sludge stabilisation
- high organic matter decomposition efficiency
- indoor, odourless reactor
- pasteurised end product, can be used in agriculture without further treatment
- low investment cost
- well-dewatered, stabilised sludge
- the microbial culture tolerates fluctuations in load and food composition well

Disadvantages:
- high electricity consumption
- no recoverable biogas is generated, only heat and CO_2

The technology is autothermic, so they can operate in the thermophilic temperature range (55–70°C) without the use of external thermal energy. During the process, a thin layer of foam is formed, which promotes thermal insulation. A mechanical or hydraulic defoamer is built into the reactors.

Anaerobic stabilisation

The aim of the process is to convert organic compounds of the sludge into stabilised substances, reducing the amount and volume of sludge and forming the final product (methane) that can be used. Only used for plants above 100,000 PE due to heat loss and limited conditions.

Digestion

The process is temperature dependent, based on this the followings can be distinguished:

– cold digestion (< T15°C)

Stabilisation takes place in the sludge space of two-level settlers, residence time is 60–120 days, in sludge storage basins it is t ≅ 6 months, used in small plants, no biogas utilisation).

– mesophilic digestion (T = 30–38°C)

The most commonly used and easiest-to-handle method of digestion requires bacteria to maintain a constant temperature, which is maintained by continuous "heating" (e.g. an external heat exchanger). The residence time of the process is 18–25 days. In order to protect the reactor, the so-called "macerator" is incorporated; biogas utilisation can be a one- or two-step process, the most widely used digestion process.

– thermophilic digestion (t = 50–55°C)

The residence time is reduced to 8–15 days, its use is less recommended due to the unfavourable heat balance and sensitivity to load changes, it has the advantage of better water release of the sludge and more efficient destruction of infectious substances.

Common features include:

– requires a large residence time and reactor volume
– the resulting biogas has high methane content
– sludge dewaterability improves
– pathogen death is significant
– organic matter content decreases
– the amount of residual sludge decreases

Anaerobic digestion can be divided into 4 sub processes:

1. Mainly involves facultative bacteria (proteins, carbohydrates and fats are enzymatically cleaved into smaller compounds, such as amino acids, fatty acids, glycerol and monosaccharides during hydrolysis).
2. Mainly anaerobic bacteria produce mostly alcohols and acids from the products of the previous phase, resulting in a pH decrease.
3. More complex fatty acids are oxidised into acetic acid, carbon dioxide and hydrogen.
4. β-oxidation – methane-forming bacteria produce methane (50–70%) and carbon dioxide (30–50%). The gas produced in the process even contains water vapour.

A summary of the advantages and disadvantages of sewage sludge composting and digestion is shown in Table 10.

Table 10
Advantages and disadvantages of aerobic and anaerobic sludge stabilisation [14]

	Composting		**Digestion**	
	advantage	disadvantage	advantage	disadvantage
Treatment time		min. 60 days	ca. 20 days	
Decomposition of organic matter	fungi also break down lignin compounds			lignin-containing compounds are not degraded, lower organic matter degradation
Breakdown process	less sensitive to changes in waste quality			microbial population is sensitive to environmental factors, waste quality
Energy supply		aeration requires energy	produced biogas can be utilised for heating and mixing the reactors	
Pathogenicity	non-virulent			may contain pathogenic organisms when treated in a mesophilic temperature range
Quantity of final product		the amount of end product increases due to the addition of structural materials and other wastes	sludge decreases in weight and volume (25–50% dry matter)	
End product quality	good quality, directly usable			aerobic post-treatment or storage is required prior to recovery
space requirements		large	smaller	
Investment cost	low			requires large, closed tanks, mixing, heat exchange, gas storage, construction of gas utilisation
Operations		aeration system		mixing, reactors, heating

Two-stage stabilisation processes are used for very high or difficult to decompose organic matter content. Depending on the composition, the role of the first reactor is to mineralise faster decomposing materials and at the same time it helps to reduce the reactor space of the second stage.

More common designs of two-stage systems:

- sequential coupling of anaerobic thermophilic and anaerobic mesophilic digesters
- sequential coupling of anaerobic mesophilic and aerobic stabilisers

Anaerobic systems are also preferred for the treatment of wastewater with very high organic content (winery, citric acid production, etc.).

Post-digestion composting is increasingly being used to stabilise municipal sewage sludge, taking advantage of the combined use of aerobic and anaerobic processes.

Dewatering

Reduction of moisture content of conditioned sludge to the extent appropriate for utilisation and disposal criteria (e.g. evolution of dry matter content: injection: 5–8%, plowing: 25–40%, composting: 15–45%, drying, incineration: 40–50%). The advantages of dewatering include economical transport and optimal water content for subsequent treatment technologies.

The choice of dewatering equipment is mainly influenced by the type of sludge, the area available and the properties of dewatered sludge.

Grouping of dewatering procedures:

- Natural procedures
  - infiltration beds
  - mud reed beds
- Artificial procedures
  - dynamic dewatering (centrifuges, separators, vibratory dewatering, screw press)
  - static compression equipment (belt filter presses, chamber filter presses)
  - vacuum equipment (vacuum beds, vacuum drum filters)
  - membrane procedures
  - other combined procedures

"Natural" dewatering operates by evaporating ¼ and leaking away ¾ of excess moisture content. Infiltration beds, which are heavily exposed to climatic conditions, are now used very rarely; instead vacuum beds and mobile dehumidifiers are preferred. Alternatives to sludge dewatering beds can be sludge dewatering lagoons if sufficient land is available.

Artificial mechanical sludge dewatering covers the entire sludge treatment capacity range. Their application is preferred where, for example, land is expensive and sludge beds are harmful to the environment, or weather conditions give priority to the mechanical process and liquid sludge is expensive to transport compared to on-site dewatering.

Dry matter content obtained with centrifuges is mostly about 18–23% by adding chemicals and 18–35% without chemicals. Main aspects of selecting centrifuges are the following:

- minimum dry matter content according to the use and disposal of the sludge
- required dry matter content to be introduced into the centrifuge
- separation efficiency
- specific energy consumption (average 3.0 kWh/m^3 sludge)

Belt filters can be used for dewatering all types of sludge in small and medium capacity wastewater treatment plants. It is operated in three stages (Figure 23) by chemical conditioning (usually with electrolytes), gravity dewatering and pressure dewatering (between pressure belts).

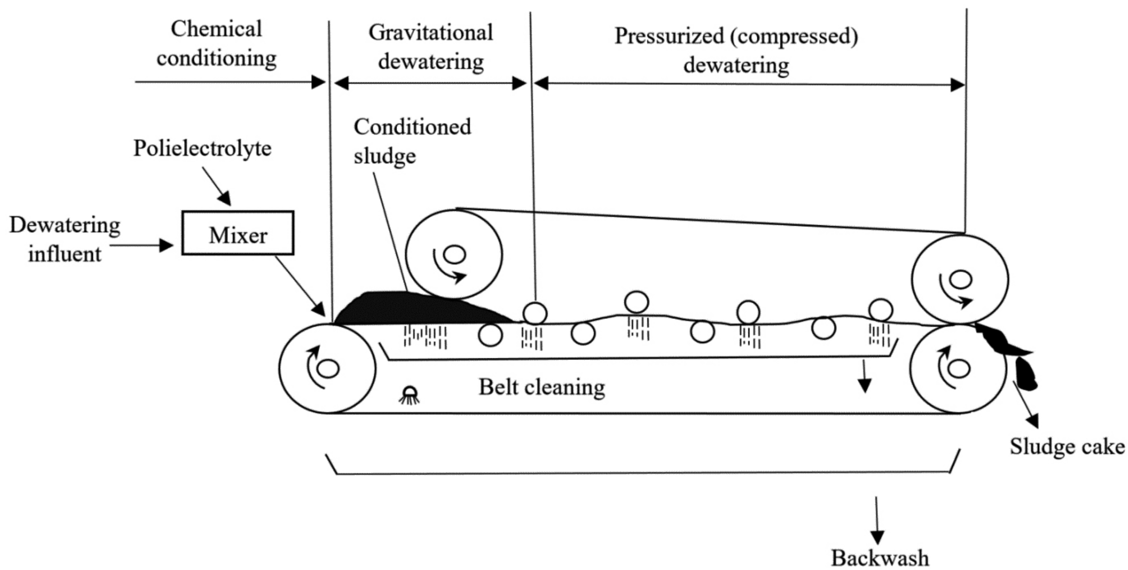

Figure 23
Basic processes of tape filtering [10]

Chamber filter presses are used when the goal is to produce a sludge cake with high dry matter content (40–50%) (incineration, deposition). Only used on larger sites (above 50,000 HPU), intermittent operation (filling, filtration, emptying).

The hydraulic principle of vacuum bed dewatering is the same as that of the sand layer of conventional sludge dewatering beds, the sludge water is always drained in a porous medium. The efficiency of centrifuges strongly depends on the pretreatment of sludge and the amount of dry matter content entering; the available dry matter content varies between 15–20%, organic polyelectrolyte is required to improve efficiency.

Membrane filters are characterised by high dry matter content and high separation efficiency. Membranes that are sensitive to clogging (e.g. greasy sludge) require a relatively large filter surface, have high energy requirements and are not yet widespread in Hungary.

Drying

The phases of water removal present in sludge are usually compaction, mechanical dewatering and drying. Drying of sewage sludge can be considered not only a pretreatment for incineration, but also a pre-drying for composting, as we have seen before. The aim of the process is to ensure that the product can be stored, bagged, transported and used more favourably. Drying also means physical conditioning, which, depending on the drying temperature (65–400°C), can result in significant killing of pathogens, which is required mainly for agricultural use. The process takes place without an adjuvant, the ammonia released during the transformations enters the air space and leaves it together with the drying gas, and therefore its subsequent washing and removal from the drying air is an essential part of ammonia and other odour-causing components removal. The final product in the form of granular material (granules, powder) is 65–85% of the final dry matter.

The most common types of drying equipment used are:

- etage (bunker) furnace (now less used)
- rotary tube furnace (in different versions)
- vortex furnace
- belt dryer
- screw dryer
- solar dryer (solar energy)

The so-called solar dryers, that use solar energy economically, have become widespread. They differ from solar dewatering in that they dewater the sludge mechanically (centrifuge, belt press, chamber press, etc.). In case of solar dryers, the temperature of the sludge, indoor and ambient air temperature, humidity of the air space, strength of the solar radiation, as well as the direction and speed of the wind are controlled. Based on these parameters, the controller operates the drying equipment and regulates drying gas extraction. As a result of biological processes, ammonia, hydrogen sulphide and other odorous compounds are also formed; therefore, they must be retained and removed from the extracted gas in specially designed cleaning stages. Domestically it does not work in winter, so temporary storage is required. There are several advantages to solar drying, including reduced sludge weight and volume, dry matter content output is selectable, reduced odour, a wide range of compatible parameters and low operating costs.

Natural dryers include composting that meets aerobic thermal conditioning conditions. In composting, the moisture content must be reduced to about 50%, while in drying it depends on the actual demand. The temperature and saturation of drying gas are slightly higher, so the amount of air required for drying during composting is less.

Among dryers functioning with dry heat transfer, rotary tube furnaces are the most common. These include a number of solutions for drying temperature, heat generation, direct or indirect heat transfer, vapour and flue gas treatment solutions.

Disinfection

Disinfection of sludge is essential if it is to be used on agricultural land or if it is microbiologically contaminated. Chlorine oxidation, heat treatment, lime treatment and composting are also used as disinfection methods. Aerobic thermal conditioning and ultrasonic treatment can also be considered a successful process. Composting introduced in Hungary also provides a favourable disinfecting effect. (Testing and classification of composts is regulated by MSz-10-509).

The virulence-reducing effect of different sludge treatment methods is shown in Table 11.

Table 11
Infectivity reducing effect of sludge treatment methods [11]

Treatment procedures	Exposure time	Reduction of infectious human pathogens (%)			
		Viruses	Bacteria	Parasites	Fungi
Anaerobic sludge treatment					
mesophilic (30–35°C)	14–30 days	> 90	Decreases by 1–3 orders of magnitude: > 90	Almost complete destruction	Almost complete destruction
mesophilic (30–35°C) long-term storage of treated sludge (at 20°C)	6 months	–	99.9	It has no effect	–
thermophilic (50°C)	6–15 days	> 95	Decreases by 2–4 orders of magnitude: > 90	Almost complete destruction	Total destruction
Aerobic sludge treatment	6 days	It has no effect	~ 20	~ 10	Partial destruction
Chemical lime treatment					
before filtration (pH = 11.5–12.5)	12 hours	–	Decreases by 2–4 orders of magnitude: > 90	Almost complete destruction	–
dewatered sludge (pH = 12.5)	14 days	–	Decreases by 2–4 orders of magnitude: > 90	Total destruction	–
Thermal treatment of liquid sludge (177–240°C and 6,000–12,000 kN/m2 pressure)	15–40 minutes	Total destruction	Total destruction	Total destruction	Total destruction
Disinfection (at 70°C)	30–60 minutes	Total destruction	Total destruction	Total destruction	Total destruction
Sludge drying (at 300–500°C)	20 minutes	Total destruction	Total destruction	Total destruction	–
Composting (at 65°C)	5 days	Almost complete destruction	Total destruction	Total destruction	Total destruction
Independent firing (at 930°C)	20 minutes	Total destruction	Total destruction	Total destruction	Total destruction

Sludge transport

The method of disposal influences the choice of transport (distance, storage capacity, service life, incorporation, dry matter content of the landfill, quantity to be transported) and the two together have an impact on the degree of plant treatment technology (compaction, conditioning, dewatering).

Basic means of transport include axis transport, pipeline transport and a combination of the two (mixed: pipeline shaft).

Factors determining the choice of sludge transport method:
- location/application technology (agricultural cultivation)
- distance between the place of formation and use or disposal of the sludge (km)
- the amount of sludge to be transported (m^3/d)
- traffic conditions (traffic, pavement, load-bearing capacity of bridges, speed limit, etc.)
- climatic conditions
- topography, groundwater (in case of pressure line)
- the planned capacity duration of the place of application
- environmental and public health factors (protected area, etc.)
- intermediate storage design conditions
- economic factors (electricity, liquid fuel, vehicle procurement, staff, utilisation of equipment capacity, etc.)
- the need for material transport for recultivation or cover
- the number of rounds that can be completed in one shift
- the amount of leachate (landfill) to be treated
- maintenance, washing and disinfection of vehicles

When transporting sludge on axis, it may only be transported in closed, mechanically operated, drip-free and odour-free vehicles approved for this purpose, which exclude odours, flies and any other insects. A transport route must be prepared (approved by the authorities) in which inhabited areas must be crossed as little as possible and should have a solid surface that can be walked on in winter and summer. Provision must be made for the possibility of cleaning and disinfection of transport vehicles.

Regulations for mandatory medical examination of operating staff (driver, attendant, etc.) are the same as for other employees of the wastewater treatment plant.

There is a risk of fire and explosion due to possible methane formation during sewage storage and transport. Compliance with the National Fire Protection Regulations, that is Annex 1 of the Decree 35/1996 (XII.29.) of the Ministry of the Interior currently in force, is mandatory. (Moderately flammable class “D”).

Sludge transport via a closed pipeline can also be applied either to agricultural recovery or landfilling. The sludge line is subjected to a permit as an accessory for the treatment plant.

It is recommended to transport sewage sludge by pressure line if:
- reception of the sludge in the area of the end point is ensured for at least 15 years
- the consistency of the sludge allows for clog-free transport over a given distance
- residence time of the sludge in the pipeline does not result in deposition or hazardous methane production (when restarting, the energy demand of the so-called sludge-breaking force requires a significant extra force)
- the capacity utilisation of the pipeline in phase I already reaches 50% (t/24h)
- reception is guaranteed at all times
- regulations related to the construction and maintenance of the pipeline (safety distances, free access, etc.) can be ensured
- regarding the material of the line, it is resistant to dynamic forces and surface wear (pipe erosion) for a specified service life
- failure of the pipeline along the route will not cause irreversible damage, does not endanger water base and other environmental and landscape protection elements, etc.

Disposal and recovery

In Hungary, in terms of disposal and use of sewage sludge, 60% is deposited (mainly in landfills) and 40% has other use (agricultural, anaerobic digestion, landscape rehabilitation). Landfilling cannot be considered a final solution because the capacity of landfills is declining.

A primary consideration in recovery is that sewage sludge should not be considered primarily a waste, but a recoverable secondary raw material.

The main possibilities of utilising sewage sludge:

– agricultural utilisation (composting, injection)
– thermal, energy recovery
– landscape rehabilitation, recultivation
– biogas production (anaerobic digestion)

The conditions of the placement methods require different consistency of material composition, different degree of stabilisation and level of disinfection. In particular, the conditions of disposal are those that change from time to time as a result of central regulation (amount, composition, treatment of sludge). On-site treatment should be chosen to adapt to quantitative and qualitative changes of external conditions.

Agricultural utilisation

The main purpose of agricultural utilisation of sludge is to ensure the demand for plant nutrients (e.g. N, P and other micro- and macronutrients) and to improve its tillage properties. Land need is advised to be sized according to phosphorus and organic matter load while considering Government Decree (IV. 29.) on the detailed rules of the action program for the protection of waters against nitrate pollution of agricultural origin, as well as the Decree on the procedure for data provision and registration.

During sewage sludge utilisation, the greatest danger lays in heavy metals contained in it (e.g. Pb, Zn, Cu, Ni, Cd), that can bind and accumulate in the soil and accumulate in plants. In addition to heavy metals, the second problem is organic micropollutants, the effects of which are still being investigated. Because of these contaminants, analytical testing of sewage sludge prior to use is unavoidable.

Tests may only be performed by laboratories accredited for sampling and testing. Soil authority (testing of soil, groundwater, sewage and sewage sludge) in accordance with Decree 10/2000 [Annex VI2] KöM-EüM-FVM-KHVM on limit values necessary for quality protection of groundwater and geological media) may also extend to the characteristics specified in its joint decree, by establishing individual limit values set out therein. Examination of parameters prescribed in this way and the mandatory application of their limit values are part of the soil expert opinion. The main requirements for disposable sludges are set out in Government Decree (EC) No. 50/2001 (IV.3.) on the rules for the agricultural use and treatment of sewage and sewage sludges (§ 3 b, fixes the concept of treated sludge that can be used in agricultural area, but exclusively regulates the production for agricultural purposes only).

The deposition of sludge on agricultural land is a licensed activity that requires:

– pedological expert opinion
– public health authorities

– environmental protection authority
– opinions of water authorities
– municipal (notarial) contribution

The competent plant health and soil protection station, as a soil protection authority, authorises it in a decision. The permit can be granted for a maximum period of 5 years.

Sewage sludge must not be used on soils which:

– has properties worse than the limit values for soils specified in the government decree
– pH less than 5.5 (if the pH of the soil is between 5.5 and 6.2, use is only possible with the simultaneous application of liming)
– on coarse sand with extreme mechanical composition
– the thickness of the crop layer is less than 60 cm
– the average annual groundwater level is higher than 150 cm

Sewage sludge must not be disposed of:

– in case of liquid sludge, where the slope of the surface is greater than 6%
– in case of dewatered sludge (dry matter 20%), where the slope is above 12%

Protected area required for agricultural disposal of sewage sludge:

– from a populated area
– from residential buildings
– at least 300 m from areas belonging to forestry

In case of agricultural utilisation of sewage sludge, the so-called aerobic thermophilic stabilisation has a favourable disinfection effect. In case of agricultural soils with acidic soils, the use of lime is considered the most favourable.

Industrial uses

There are a number of special options for the utilisation of sewage sludge in industrial areas.

Each use requires a specific set of individual requirements, which can only be met to a very limited extent at the sludge treatment plant. This is mainly limited to meeting dry matter–moisture demand. For all other needs, the treatment plant must be supplemented with a suitable procedure and equipment in accordance with technological instructions.

Thus, from the point of view of industrial utilisation, sewage sludge can be treated as a raw material, the quality of which can only be changed to a limited extent by reducing traditional organic matter content and changing consistency (from compaction to drying, reducing infectivity, etc.).

Environmental restrictions of application technologies must be determined individually for each process, the preparation of which is supported by environmental impact studies.

Some better-known procedures are:

– application as fuel (combustion in boilers)
– during road construction, the "dried" material is applied to the lowest layer as a concrete admixture
– special material is extracted from it (e.g. B12 production)

Deposition

Deposition is the long-term storage (disposal) of sewage sludge by landfilling in order to avoid adverse effects during sludge disposal on land, surface and groundwater, as well as on the environment. Deposition under controlled condition should be accomplished according to Decree 22/2001 (X.10.) of the Ministry of the Environment.

A landfill may be established and permitted if it complies with Article 1 of the Decree (the procedure for the construction of sewage sludge landfills is the same as for landfilling).

Deposition in Hungarian practice is performed in two ways that must be taken into account in a larger perspective:

- separate disposal in a local or regional landfill: industrial landfill, where only sewage sludge is deposited (this is the so-called mono disposal method)
- local or regional landfilling of municipal solid waste (garbage) (this is the so-called mixed disposal method)

In summary, Figure 24 shows potential ways of disposal and/or utilisation, residual material, and treatment options of solids removed from wastewater.

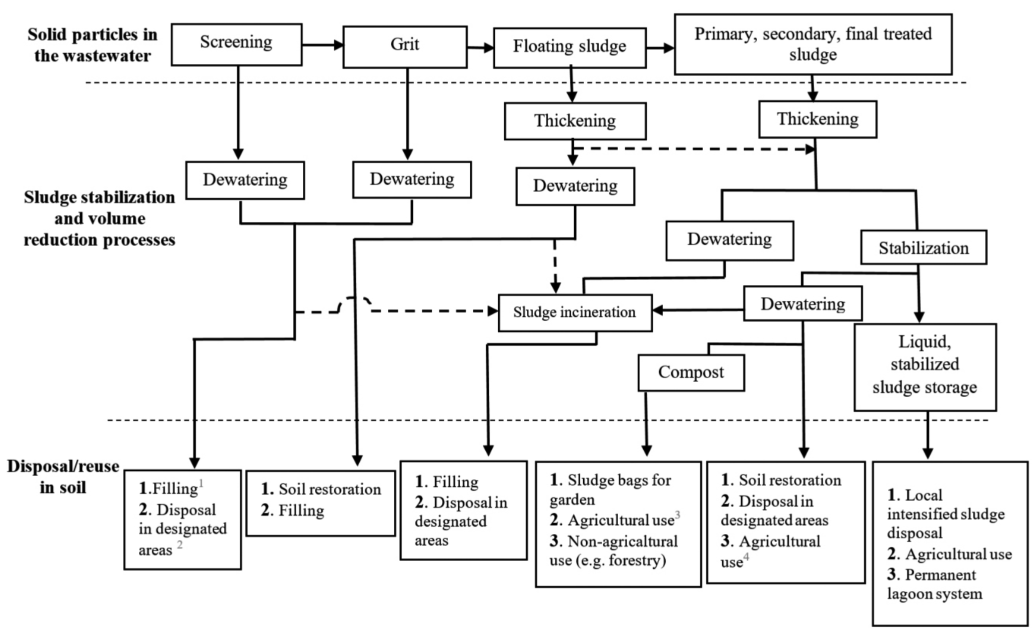

Figure 24

Residual material and treatment possibilities of wastewater treatment [10]

Note: [1] dewatered sludge cake or ashes, [2] liquid or dewatered, [3] liquid, sludge cake, compost, [4] liquid or dewatered

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Questions

1. What is the role of sewage pretreatment?
2. How would you classify grids?
3. What types of grits are used in wastewater treatment?
4. What types of settlers are used in wastewater treatment?
5. List the steps of chemical phosphorus removal.
6. At which technological step can the coagulant be dosed?
7. Explain the essence of CEPT technology.
8. What methods can be used for nitrogen removal from wastewater?
9. What are sewage sludge treatment sites in municipal wastewater treatment?
10. What are the most important steps of sludge treatment?
11. What sludge thickening procedures do you know?
12. What conditioning procedures do you know?
13. What chemical conditioning agents do you know?
14. What is the difference between anaerobic and aerobic stabilisation?
15. How can dewatering procedures be classified?
16. List at least three types of dryers.
17. How efficiently can sludge treatment processes reduce pathogenicity?
18. What factors determine the modes of sludge transport?
19. What kinds of sewage sludge utilisations do you know?
20. What are the main legal rules governing agricultural utilisation?