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Combining sewage sludge and algae biomass to a valuable biosolid composite: Literature review on treatment and applications

Combining sewage sludge and algae biomass to a valuable biosolid composite. Literature review on treatment and applications

Norwegian Institute for Water Research
– an institute in the Environmental Research Alliance of Norway

REPORT

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Abstract
Increasing amount of sewage sludge is produced in Romania and there is stricter requirement to treat and dispose sewage sludge after the EU Landfill Directive and Sludge Directive applied in Europe. In this report, the sludge issue is briefly reviewed from scientific and engineering points of views, with focus on sterilisation of biosolids. Based on the review and the experiences from Norway and other countries in Europe, it is believed that sewage sludge and marine algae from the coast of the Romanian Black Sea can be combined and processed to fulfil the stringent requirements for land applications. However, further studies are required to highlight the possibilities and challenges with such a co-treatment of sludge and alga biomass.

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Combining sewage sludge and algae biomass to a valuable biosolid composite: Literature review on treatment and applications

Preface

An increasing amount of sewage sludge is produced in Romania and there is stricter requirement to treat and dispose sewage sludge after the EU Landfill Directive and Sludge Directive applied in Europe. The eutrophication of Black Sea due to discharge of nutrients from various sources has resulted into an increasing amount of marine algae floated to the coastal lines of Romanian Black Sea, and the disposal of collected marine algae has become a problem in the area.

A Norway Grant project titled **"Wastewater treatment sludge and marine biomass from Romanian Black Sea coast as innovative bio-solid composite"** aims to address the possible combination of sludge and marine algae to a valuable product. After the previous conducted literature review on marine algae from Black Sea, this report is aiming to address the treatment and use of a bio-solid composite made from a mixture of sewage sludge and marine algae.

Oslo, 2010-09-28

Zuliang Liao

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Summary

In the Norway Grant Project KNRIN-2008/115241 titled “Wastewater Treatment sludge and marine biomass from Romanian Black Sea Coast as innovative bio-solid composite” coordinated by ASSOCIATION OF PROTECTION OF THE HUMAN BEING AND THE ENVIRONMENT FOR A SUSTAINABLE DEVELOPMENT IN THE WORLD – ECOM, Norwegian Institute for Water Research (NIVA) is one of the partners responsible for general consulting work in the process of converting sewage sludge and marine algae into a valuable biosolid composite.

An increasing amount of sewage sludge is produced in Romania, and there is stricter requirement to treat and dispose sewage sludge after the EU Landfill Directive and Sludge Directive applied in Europe. In this report, the sludge issue is reviewed from scientific and engineering points of views, with focus on sterilisation of biosolids.

The report is devided into the following parts: First: definitions used in sludge treatment and characteristics of sewage sludge are reviewed, second: the most commonly used wastewater and sludge treatment processes are reviewed, third: a more detailed description of the sludge treatment processes stabilisation and hygenisation (sterilisation) is presented, and fourth: introduction to Norwegian experiences related to sludge handling and use of treated sludge as a biosolid. Norwegian sludge politics and experiences on sludge stabilisation and hygenisation are reviewed. Finally, some suggestions are made on how to combine sewage sludge and marine algae to make a valuable biosolid composite.

Based on the review and the experiences from Norway and other countries in Europe, it is believed that sewage sludge and marine algae from the coast of the Romanian Black Sea can be combined and processed to fulfil the stringent requirement for land applications. Available technology from Norway and other countries of Europe can be applied to obtain such a product. However, further studies are required to highlight the possibilities and challenges with such a co-treatment of sludge and alga biomass to a valuable biosolid.

1. Background for report—Norway Grant Project

The Norway Grant Project KNRIN-2008/115241 titled "Wastewater treatment sludge and marine biomass from Romanian Black Sea Coast as innovative bio-solid composite" is coordinated by ASSOCIATION OF PROTECTION OF THE HUMAN BEING AND THE ENVIRONMENT FOR A SUSTAINABLE DEVELOPMENT IN THE WORLD – ECOM with PhD Eng. Maria Nastac as president. ECOM Association of Constanta, based in 2004, is a professional-science organization, non-profit, with legal personality, operating in accordance with the Romanian legislation and with its own status. The purpose and the mission of the association is to promote the change in the economic operators mentality, state and public administration, civil society, in the direction of realizing a healthy life style in a friendly environment. The association objectives are oriented towards promoting and supporting the scientific activities of Research-Development-Innovation in medicine, industry and agriculture as a friendly alternative, non-harmful to humans and the environment.

Norwegian Institute for Water Research (NIVA) is one of the partners which is responsible for general consulting work related to sludge treatment and application, and the possibilities of making a valuable biosolid by co-treatment of sewage sludge and marine algae from the coast of the Romanian Black Sea. This report addresses the key issues on how sewage sludge and marine algae can be combined and processed to fulfil the strigent requirement for land applications.

2. Sewage Sludge—Definitions and Key Issues

2.1 Definitions

2.1.1 Sewage Sludge

Sludge is a generic term for solids separated from suspension in a liquid. Sludge usually contains significant quantities of water. Commonly sludge refers to the residual, semi-solid material, from industrial wastewater or sewage treatment processes. It can also refer to the settled suspension obtained from conventional drinking water treatment, and numerous other industrial processes.

When fresh sewage or wastewater is added to a settling tank, approximately 50% of the suspended solid matter will settle out in an hour and a half. This collection of solids is known as raw sludge or primary sludge. The sludge will become putrescent in a short time once anaerobic bacteria take over. Excess solids from biological processes such as activated sludge or biofilm processes are often referred to as biological sludge or secondary sludge, which mainly consists of biomass produced in biological treatment.

Sewage sludge is here referred to as sludge produced during wastewater treatment processes, including primary sludge from the primary sedimentation tank, and biological sludge from secondary treatment using micro-organisms.

2.1.2 Biosolids

The term biosolids was formally recognized in 1991 by the Water Environment Federation (WEF) in USA. Biosolids, also referred to as treated sludge, is a term used by the waste water industry to denote the byproduct of domestic and commercial sewage and wastewater treatment. Biosolids are the nutrient-rich solid, semisolid, or liquid organic materials that result from the treatment of domestic wastewater by municipal wastewater treatment plants (WWTPs). These residuals are further treated to reduce pathogens and vector attraction by any of a number of approved methods. Toxic chemicals such as PCBs, dioxin, and brominated flame retardants, and heavy metals may remain in treated sludge. Depending on their level of treatment and resultant pollutant content, biosolids can be used in regulated applications for non-food agriculture, food agriculture, or distribution for unlimited use. Local municipalities typically decide how to manage the treated sewage sludge ("biosolids"), such as to recycle them as a fertilizer, incinerate them, or bury them in a landfill (U.S. EPA).

Land application of sewage sludge or biosolids is regulated in European Council (Directive 86/278/EEC, 1986) with potential revision lately and in U.S. (40 CFR 503 standards, US EPA, 1992). Individual countries in Europe adapt the Directive 86/278/EEC to their own situations, and have normally more stringent requirements for many parameters like heavy metals.

2.2 Key issues

Sludge originates from the process of treatment of waste water. Due to the physical-chemical processes involved in the treatment, the sludge tends to concentrate heavy metals and poorly biodegradable trace organic compounds as well as potentially pathogenic organisms (viruses, bacteria etc) present in waste waters. Sludge is, however, rich in nutrients such as nitrogen and phosphorous and contains valuable organic matter that is useful when soils are depleted or subject to erosion. The organic matter and nutrients are the two main elements that make the spreading of this kind of waste on land as a fertiliser or an organic soil improver suitable.

2.2.1 Amount of sewage sludge

The progressive implementation of the Urban Waste Water Treatment Directive 91/271/EEC (EEA) in all Member States is increasing the quantities of sewage sludge requiring disposal. From an annual production of some 5.5 million tonnes of dry matter in 1992, the Community is heading towards nearly 9 million tonnes by the end of 2005. This increase is mainly due to the practical implementation of the Directive as well as the slow but constant rise in the number of households connected to sewers and the increase in the level of treatment (up to tertiary treatment with removal of nutrients in some Member States). The Directive sets the following targets for secondary treatment of waste waters coming from agglomerations:

- at the latest by 31 December 2000 for agglomerations of more than 15,000 p.e. (population equivalent);
- at the latest by 31 December 2005 for agglomerations between 10,000 and 15,000 p.e.;
- at the latest by 31 December 2005 for agglomerations of between 2,000 and 10,000 p.e. discharging to fresh waters and estuaries.

There are more stringent provisions for agglomerations discharging into sensitive areas such as fresh waters or estuaries.

Water and wastewater services in Romania are under a re-engineering process that aims to establish a system of efficient regional water and wastewater operators (Maria Christina Nitoiu 2009). More than 79% (2009) of Romania's wastewater is either untreated or insufficiently treated and flows directly into natural receivers (such as groundwater, aquifers, rivers, etc.). Only 52% of Romania's population of approximately 21.5 million inhabitants is connected both to running water and sewage services. The part of the population with a water supply but not connected to a sewage system is about 16%, with nearly a third of the population (32%) with neither water supply nor sewage system. The issue is even more apparent in rural areas, where 67% of rural inhabitants do not have access to water supply, and more than 90% are not connected to sewage systems.

The percentage of wastewater treatment is anticipated to increase from around 50% in 2010 to close to 100% in 2018. The total amount of sludge produced in wastewater treatment is then expected to increase dramatically.

2.2.2 Land application of biosolids due to legislative requirement

The Sewage Sludge Directive 86/278/EEC seeks to encourage the use of sewage sludge in agriculture and to regulate its use in such a way as to prevent harmful effects on soil, vegetation, animals and man. To this end, it prohibits the use of untreated sludge on agricultural land unless it is injected or incorporated into the soil. Treated sludge is defined as having undergone "biological, chemical or heat treatment, long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use". To provide protection against potential health risks from residual pathogens, sludge must not be applied to soil in which fruit and vegetable crops are growing or grown, or less than ten months before fruit and vegetable crops are to be harvested. Grazing animals must not be allowed access to grassland or forage land less than three weeks after the application of sludge. The Directive also requires that sludge should be used in such a way that account is taken of the nutrient requirements of plants and that the quality of the soil and of the surface and groundwater is not impaired.

Although at Community level the reuse of sludge accounts for about 40% of the overall sludge production, landfilling as well as incineration in some Member States are the most widely used disposal outlets despite their environmental drawbacks.

In Romania, the Directive 86/278/CEE has been transposed through the Order of the Minister of Agriculture, Forests, Waters and Environment no. 344/2004 for the approval of Technical Guidelines on the protection of the environment and in particular of the soils when sewage sludge is used in agriculture (MO No. 344/2004). In accordance with the MO No 344 /2004, untreated sludge cannot be use in agriculture.

2.2.3 Stabilisation of sewage sludge

Due to high content of organic matters in sewage sludge, when it is utilised to soil or landfill, the organic matters will be decomposed by microorganisms in soil and sludge, and results into negative environmental impacts in soil, in underground water and in air. Degradation of organic matters in sludge is assumed to be important in sludge treatment before disposal in the end.

2.2.4 Hygenisation or sterilisation of sewage sludge

Sidhu and Tose (2009) reviewed the human pathogens in biosolids. Enteric viruses, bacterial pathogens, protozoan parasites, and heminths were reviewed in concentrations in wastewater and sludge after different treatment processes. As regulated in EU and US EPA, the occurrences in different pathogenic microorganisms should be below the limits in order to guarantee minimum heath risk when human beings and animals have access to the products related biosolids applied soils.

2.2.5 Heavy metal issue

Pathak et al (2009) reviewed heavy metals such as Cu, Cd, Pb, Ni, Zn, Cr, Hg, and Mn in sewage sludge and bioleaching processes to remove heavy metals, otherwise the presence of heavy metals restricts the use of biosolids as fertilizers. Regular control of heavy metal contents in biosolids before its application to land ensures the safe use for recycling of nutrient in biosolids.

Smith (2009) reviewed that bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge.

Pathak et al (2009) reviewed the bioleaching of heavy metals from sludge. Heavy metals in sludge exists in the different countries can be summarised in table 1.

Table 1. Heavy metals in sludge from different countries

Heavy metals content of various sludges (mg kg^{-1} of dry sludge solids).

Country	Cu	Ni	Zn	Cr	Cd	Pb	References
Canada	180–2300	37–179	354–640	66–2021	2.3–10	26–465	Tyagi et al. (1988); Benmoussa et al. (1997); Meknassi et al. (2000)
China	131.2–394.5	49.3–95.5	783.4–3096	45.8–78.4	5.9–13	57.5–109.3	Dai et al. (2007)
Germany	275	23.3	834	50	1.5	67.7	CEC (1999)
Hong Kong	112–255	44.5–622	1009–2823	663	–	52.5–57	Xiang et al. (2000); Wong and Selvam (2006)
India	280–543	192–293	870–1510	102–8110	41–54	91–129	Singh et al. (2004); Pathak et al. (2008)
Italy	370	19	1500		2.1	72	Lazzari et al. (2000)
Spain	204–337	23.2–36.5	871–1626	54.4–3809	2.37–18.3	167–223	Alvarez et al., (2001)
UK	562	58.5	778	159.5	3.5	221.5	CEC (1999)
USA	616	71	1285	178	25	170	Bastian, 1997

2.2.6 Persistent organic pollutants

Harrison et al (2006) summarised organic chemicals in sludge. Totally 556 chemicals were screened into 15 classes, and identify the soil screening limits (SSLs) in USA. A small fraction of chemicals were targeted for detailed identification, like pesticides, PAHs and PCBs as the primary groups. High concentration of the primary organic chemicals poses threat of using the biosolids as fertilizers.

McClellan and Halden (2010) reviewed pharmaceuticals and personal care products (PPCPs) in biosolids in US EPA survey in 2001. 72 PPCPs were analysed for 110 biosolids samples to identify the most ocurrenced chemicals.

2.2.7 Nutrient recycling

Elliot and O'Connor (2007) reviewed especially phosphorous management in biosolids recycling in US. Biosolids is rather rich in nutrients especially phosphorous which have been recently considered as very limited resources on the Earth. Application of biosolids on land may result into accumulation of soil phosphorous. This has considerable influence on the regulations on how the biosolids should be applied on land in amount, frequency and modes. Sustainable management of biosolids related phosphorous management is then called for.

Pathak et al (2009) summarised the nutrient contents in sludge from different countries as in table 2.

Table 2. Nutrient content of municipal sludge (mg/kg dry solids)

Nutrient content of municipal sludges (mg kg^{-1} of dry sludge solids).

Country	Total nitrogen	Total phosphorus	References
Argentina	19,300	7200	Torri and Lavado (2008)
Canada	32,500–53,700	8700–16,900	Warman and Termeer (2005)
China	22,600	11,500	Wang et al. (2008)
Hong Kong	43,800–65,000	10,600–21,800	Wong et al. (2001); Chan et al. (2003)
India	26,000–38,700	13,400–14,400	Nandakumar et al., (1998); Pathak et al. (2008)
Spain	16,300–45,600	4200–16,700	Fuentes et al., 2004
UK	38,000	22,000	UK Environment Agency (1999)
USA	20,000–60,000	2000–30,000	McMahon (1996)

Bioleaching is defined as ''the solubilization of metals from solid substrates either directly by the metabolism of leaching bacteria or indirectly by the products of metabolism'' (Rulkens et al., 1995).
Now-a-days bioleaching is gaining importance as a low cost environment friendly process for the treatment of the contaminated sewage sludge, solid waste and other industrial wastes (Krebs et al.,

1997). A schematic diagram of the overall bioleaching process is shown in figure 1.

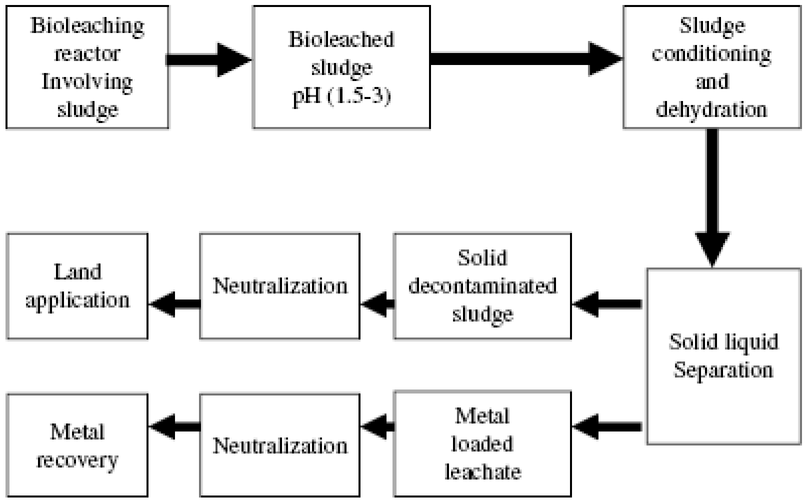


Figure 1. Bioleaching processes for heavy metals removal from sludge (Pathak et al 2009)

Bioleaching uses mesophilic sulphur-oxidizing bacteria or thermophilic Archeans to conduct bioleaching process. The heavy metals are consequently bleached out of sludge into soluble state, and then recovered as resources for industrial use.

2.2.8 Energy recovery

Energy issue comes to be a vital issue in the near future for sludge treatment and disposal and this is recently related to carbon footprint for sludge handling (Barber 2009). The final product biosolids are made through a series of treatment processes, therefore the energy may required for the treatment (for aeration etc) or the energy may be partially recovered through anaerobic processes. The potential of energy recovery during the treatment processes may be great up to balancing of the energy input and the production especially via advanced anaerobic digestion of sewage sludge. A Norwegian case will be mentioned in the last chapters.

3. Sewage Sludge Characterizations

Sewage sludge can be characterised by physical, chemical, physio-chemical, biological, pathogenic, and energical aspects.

3.1 Physical characterisation

The physical characterisation of sewage sludge can be classified into moisture content, distribution of water, solid concentration, specific gravity, viscosity, particle size, and colour.

3.1.1 Specific gravity

Specific gravity is defined as the ratio of the weight of the material to that of an equal volume of water. Most sludge in original state has the specific gravity of almost 1.0, meaning almost the weight of water. The specific gravity is increased when the solids concentration is increased. Often the real specific gravity of sludge solids material is not easy to obtain due to the packing effect of solids particles. Therefore a specific gravity of 1.0 is often used for calculation.

3.1.2 Solids concentration and moisture

The relative solid and liquid fractions of sludge are most commonly described as Solids Concentration, which is expressed as mg/l or % solids. If assuming the specific gravity is around 1, then the solids concentration can be defined as

10 000 mg solids/l of volume = 1% solids.

The % solids is often used to describe the moisture potential. When the sludge is 1% solids (often called as DS% (dry solids %), the solids in 1 Litre of sludge is almost 10000 mg, or 10 g, and the water content is then 1 kg- 10g = 990 g.

The moisture is defined as the water content in sludge. It is almost described as

% DS (solids) = 100-% moisture

When the solids concentration is increased to 10 DS% (or moisture as 90%), then the solid weight is 100 g over 1 Liter, and the water content is around 1 kg-100g= 900 g. A relationship between DS% solids, % moisture, water content, and solid concentration, and the volume reduction together with relative volume reduction can be listed up in Table 3.

Table 3. Solid concentrations and the water content (moisture) assuming specific gravity of 1.0

% solids	% moisture	Water content	Solid concentration	Volume reduction with respect to solids content	Relative volume reduction compared with lower DS%
0.3-0.5 % DS	99.5-99.7%	995-997 g water/l	3-5 g/l (normal MLSS in activated sludge process)	200-333%	
1% DS	99%	990 g water/l	10 g/l (Returned sludge in activated sludge process)	100%	50-70%
4% DS	96%	960 g water/l	40 g/l (Thickened sludge)	25%	75%
20% DS	80%	800 g water/l	200 g/l (normal dewatered sludge)	5%	80%
35% DS	65%	650 g water/l	350 g/l (required for sludge for landfill and for direct spreading to land application if pathogens killed)	2.85%	43%
50% DS	50%	500 g water/l	500 g/l (required for feed into incinerator)	2 %	42.5%

It is critical to reduce the water content in order to reduce the total sludge volume to disposal.
It is also noticed that the specific gravity of sludge is not 1.0 (higher than 1.0), therefore the data in the above table should be corrected to a relative smaller volume of sludge when DS% is higher when the total weight is the same. The water content in sludge is connected to different forms, which again results into various difficulties to reduce the moisture in practice.

3.1.3 Distribution of water in sludge

Vesilind (1974) defined the distribution of water in sludge into four types:

First, Free Water is defined as the water not attached to sludge solids in any way, so it is easy to remove by simple gravitational settling.

Second, Floc Water is defined as water trapped into flocs in sludge and can travel with flocs. By mechanical dewatering, the Floc Water can be removed.

Third, Capillary Water is defined as water adhering to individual particles and can only be squeezed out due shape deforming and compacting.

Fourth, Particle Water (or bound water) is chemically bounded to the individual particles, and can only be removed by disintegrating the particles partially or entirely by chemical or thermal methods.

A typical sludge from MLSS in activated sludge process can be illustrated in Table 4.

Table 4. A typical distribution of water in an activated sludge (solids concentration as 5000 mg/l)

Items	Free water	Floc water	Capillary water	Particle water	Solids	Total
%volume	75%	20%	2%	2.5%	0.5%	100%

3.1.4 Rheology (viscosity)

One common rheological (of flow properties) measurement for sludge is viscosity (g/cm/s or mPa.s), defined as the rate of displacement of a fluid with a given shear force. The higher the viscosity, the more force is required to replace the same amount of material, so the higher energy consumption for pumping the fluid. The viscosity of sludge is both related to the solids concentration or %DS, and other properties.

A typical viscosity of water is illustrated in Fig 2 with respect to temperature.

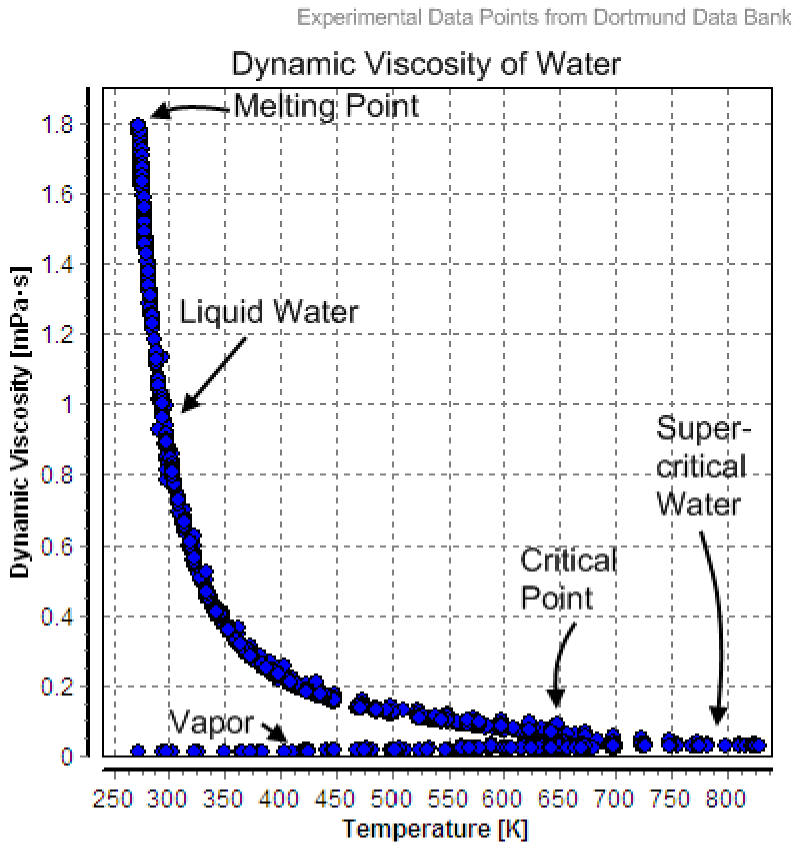


Figure 2. Dynamic viscosity of water with respect to temperature (K).

Guibaud et al (2010) investigated anaerobic granular sludge and the viscosity with respect to the particle size under certain shear forces as shown in Fig 3. Bigger particles and higher SS resulted into much higher viscosity.

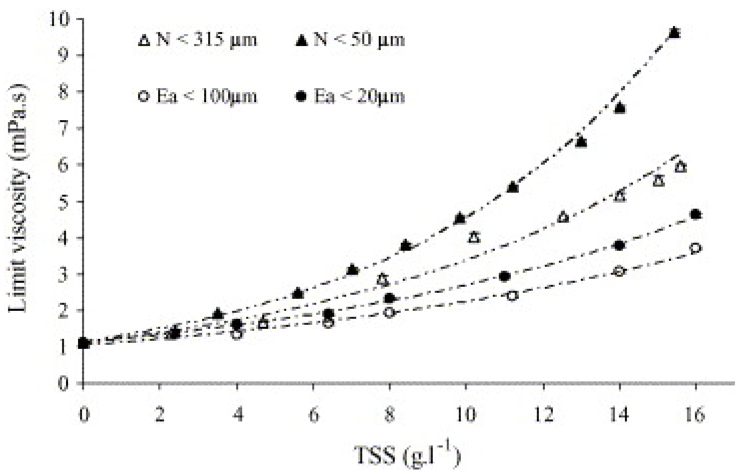


Figure 3. Limit viscosity versus TSS content for N and Ea granular sludges sieved on different diameter mesh sizes (20, 50, 100 or 315 µm) at shear force as 500 s^{-1}.

By using thermal hydrolysis as pre-treatment to raw sludge, the viscosity reduced dramatically (Wang et al, 2009) (Fig 4). The improvement of viscosity in sludge brought about significant improvement in sludge dewatering afterwards.

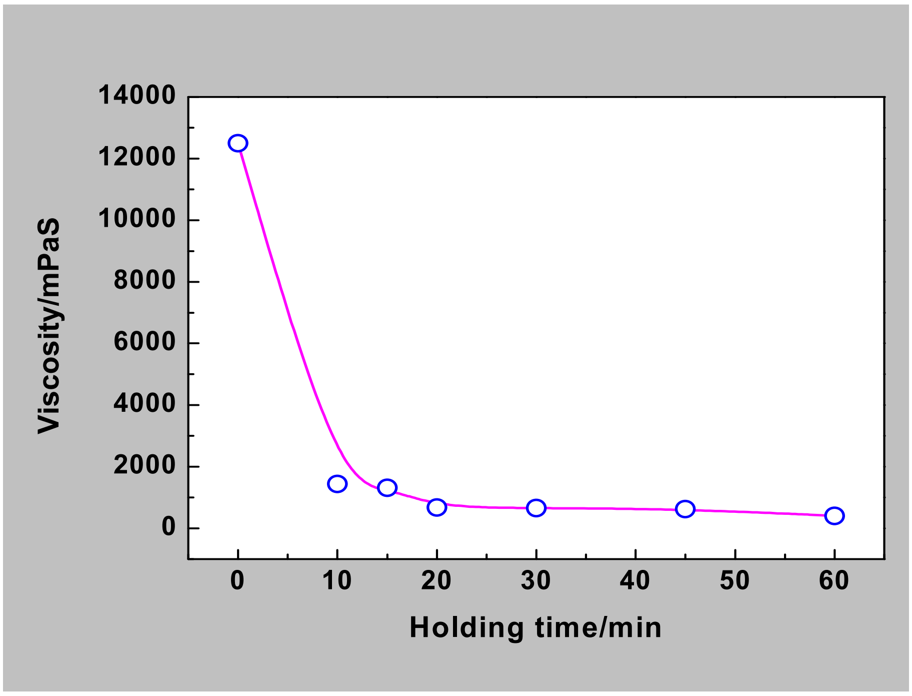


Figure 4. Thermal hydrolysis: influence of holding time (min) on the viscosity of dewatered sludge

It is noted that sludge follows a non-Newton fluids.

3.2 Chemical characterisation

Sewage sludge consists of inorganic matters like grit and sands, organic matters from biomass formed during biological treatment and the organic matters from the feeds into wastewater. The chemical composition can include C, H, O, N, P, K, S, and metals like Al, Si, Fe, Na, and heavy metals like Pb, Cd, Cr, Ni, Cu, Zn, Hg, etc, and persistent organic matters including PCBs, PAHs, etc which have become a problem in sludge utilisation back to land.

The macro elements like C, N, P, and K are often referred to nutrient value in sludge. Indeed, sludge has long been used as fertilisers before the industrial wastewater was not discharged into. Despite the potential pathogenic threat, the most of sludge in developing countries is used back to agriculture.

It is critical to point out the P content in sludge has been considered an important resources which will soon be used up from mineral P production. Therefore there is an urgent need to recover P from sludge and apply back to land for food supply (Elliot and O'Connor (2007)).

3.3 Biological and pathogenic characterisation

Vesilind (1974) summarised the main biological and pathogenic characteristics, which can be expressed in taxonomy (the classification of organisms) and the presence of pathogenic organisms. It is almost impossible to list up how many types of organisms in sludge, but a brief classification of the organisms as intestinal tract oriented, bacterial oriented, biological treatment oriented, viruses, helminths, etc.

A large number of human pathogens, which primarily originate from human feces, can find their way into biosolids (Sidhu and Tose (2009)). The diversity and number of pathogens in biosolids depend upon the general health of the contributing population and the presence of hospitals and abattoirs in the area. During wastewater treatment pathogens become concentrated in the sludge produced by the separation of solids from wastewater. A variable fraction, as high as 50% of the enteric virus present in the raw sewage, has been reported to be associated with the solids; hence the numbers of pathogens in biosolids can be higher than in wastewater. Moreover, many microorganisms are known to survive better in wastewater when they are associated with the solid particles rather than in suspended state. It is therefore likely that these microorganisms will survive longer in biosolids.Enteric virus, protozoa and parasites are obligatory parasites and hence unable to multiply in biosolids, whereas bacteria may multiply under favourable conditions. Generally, pathogenic viruses and bacteria die within 1–3months whereas protozoan oo(cysts) and helminth ova can survive for up to a year in wastewater and possibly much longer in biosolids. The inactivation of pathogens in the biosolids depends upon a number of factors such as temperature, moisture content and competition from indigenous microflora. Other factors such as predation, pH, sunlight, oxygen, soil type and texture also influence pathogen inactivation. The degree to which these factors influence survival of pathogens can vary from pathogen to pathogen and with the type of sludge treatment.

Due to the large numbers of pathogenic organisms, indicators have been developed to indicate the extent of inactivation of pathogens, but it is still to some extent uncertain that the non-presence of indicators means there is no pathogens. Alternative indicators are often required to indicate different types of pathogens like helminths egg, etc. Furthermore, the regrowth of pathogens induced environmental factors after treatment comes to be an important issue of health risks for using biosolids (Kim et al 2009).

3.4 Energical characterisation

Due to the organic contents in sludge, the sludge carries out heat or energy value. The energy value is highest for raw sludge (ca 15000 kJ/kg DS) and it is decreased when the organic matter is removed or degraded by digestion (ca 10 000 kJ/kg DS) (Barber 2009). While addressed as moisture included, the energy value is dropped dramatically due to the energy for remove water content in sludge. A typical energy value of 1500 to 2500 kJ/kg wet solids can be assumed for digested dewatered sludge and dewatered raw sludge (with moisture between 20-25%). Increase in DS% in sludge will increase the heat value dramatically, which is then also a bottleneck for effective treatment of sludge.

The energy in sludge can be utilised in several ways. Anaerobic digestion of sludge has long been used for biogas production (Demirel et al 2010). Incineration is often used to combine the sludge treatment and disposal with municipal solid wastes.

4. Sewage Sludge Treatment and Disposal methods

4.1 Overall description for sewage sludge treatment and disposal

4.1.1 Pre-treatment—Screens and grit and grease removal

The sewage sludge is produced through the wastewater treatment processes. The wastewater treatment processes are at the same time processes of separation of particulate matters from liquid during and after other (physical and biological treatment). First, the raw wastewater comes through coarse screen (Fig 5) to remove very big particles, then the wastewater passes through the fine screen (Fig 6) to further remove the finer but still rather big particles. An innovative type of screen is developed by Norwegian company called Salsnes Filter using rotating sieve cloth with different opening (0.05-4 mm) (www.salsnes-filter.no) to substitute the fine screen and primary settling (Fig 7 and Fig 8). Then wastewater flow through a grit and grease chamber where heavy particles like sands and light particles like grease and oil are removed at the same time. In grit and grease chamber, an aeration pipe can be installed to wash the sands before removal.

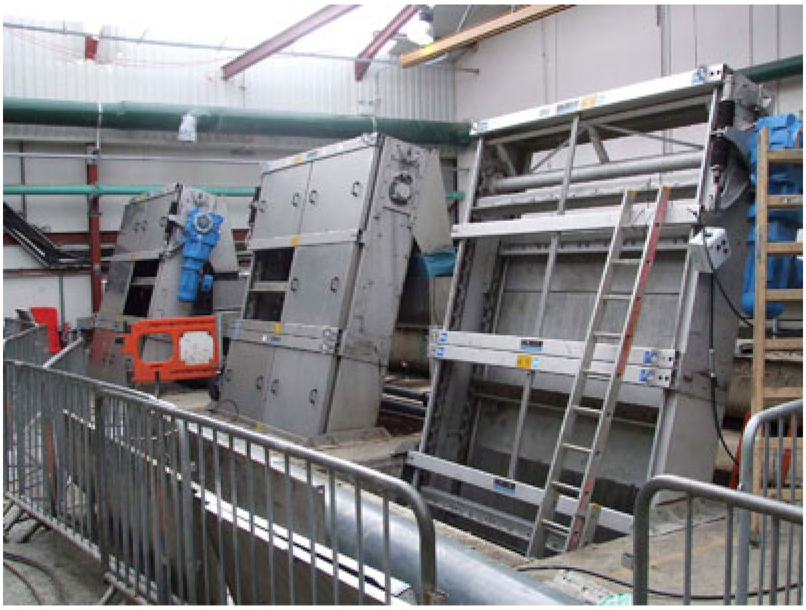


Figure 5. Coarse screen for removal of bigger particles

Figure 6. Fine screen for removal of fine particles

Figure 7. Salsnes filter developed by Salsnes Filter Company in Norway (http://www.innovasjonnorge.no/TP_fs/Design/107-0730_IMG.JPG)

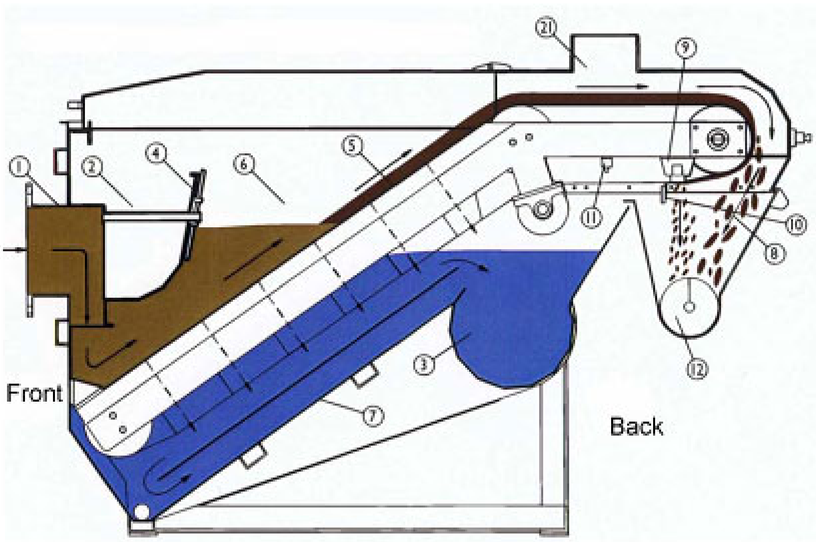


Figure 8. Structure chart of Salsnes Filter (http://www.evergreenengineering.ie/images/salsnes_dia_side.jpg)

4.1.2 Primary treatment by sedimentation

The primary sludge is the sedimentary solids at the bottom of primary settler or sedimentation tanks. It contains water as the main part, and the rest is solids from fine sands, dirt, and especially particulate organic matters discharged into wastewater. The soluble organic matters go through the primary settling tanks and will be treated in the following stage. Therefore in the primary sludge, more organic matter is available for degradation, therefore unstable. A typical circular primary sedimentation tank can be illustrated in Fig 9. The shape of tanks can also be rectangular (not shown in figures).

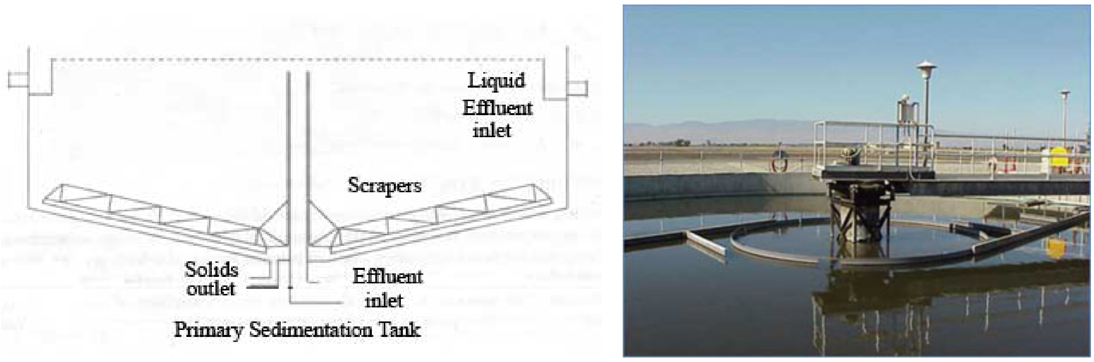


Figure 9. A typical circular primary sedimentation tank—The profile (left) and overview (right)

The settled solids are collected for sludge treatment afterwards.

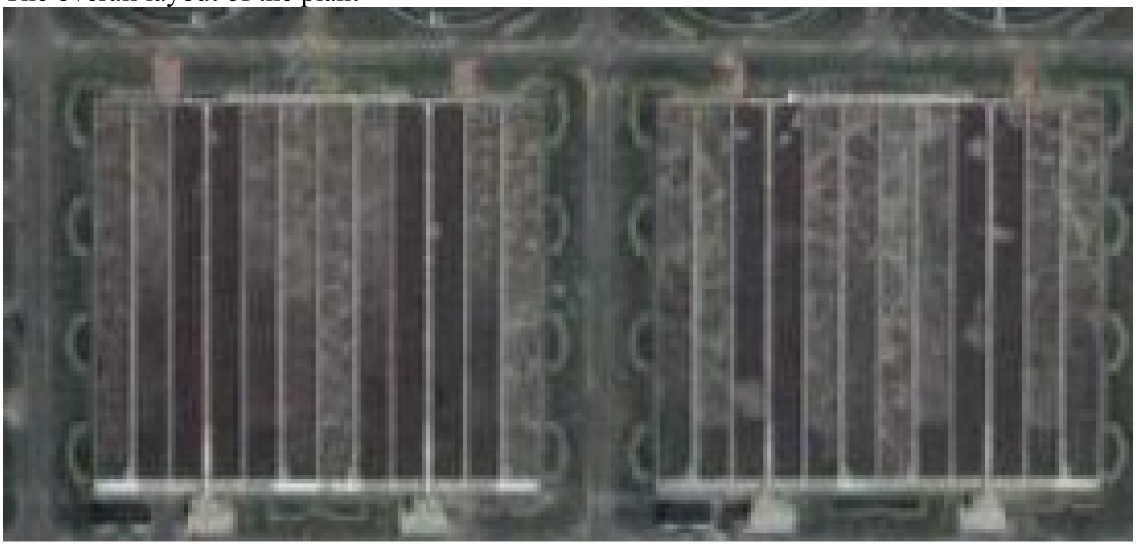
During primary sedimentation, chemical coagulants and flocculants can be dosed in order to improve the sedimentation of particles by coagulation and flocculation. More particle removal is achieved, in which much are particulate organic matters. At the same time, phosphorous is removed by chemical precipitation of phosphate incorporated with particulate matters. The chemical added primary treatment is often called Chemically Enhanced Primary Treatment (CEPT) (Ødegaard and Liao 2004). Chemical sludge is produced consequently.

4.1.3 Biological treatment

After primary sedimentation, there is still considerable amount of organic matters and nutrients including nitrogen and phosphorous. There are many types of biological treatment processes, but the common characteristics are to enhance various types of microorganisms to “eat up” the organic matters and nutrients during the treatment by supplying either with or without oxygen by aeration, depending on the biochemical pathways. There are several types of processes widely used in wastewater biological treatment, such as oxidation ditch processes (Fig 10), Anaerobic-anoxic and aerobic processes (AAO processes) (Fig 11), sequence batch processes (SBR processes) (Fig 12), and biological aerated filter processes (BAF processes) (Fig 13), and Moving Bed Biofilm processes (MBBR processes) (Fig. 14). During those biological processes, both heterotrophic bacteria and autotrophic bacteria have been contributing to degrade organic matters and use up nutrients for their growth; the products are the biomass or biological sludge.

Figure 10. Carrousel oxidation ditch process developed by DHV
(http://water.dhv.com/NL/waterbehandeling/afvalwater/Documents/Leaflet_Carrousel.pdf)

The overall layout of the plant



The detailed layout of biological treatment using AAO processes

Figure 11. Google Earth photo of Beijing Xiaohongmen WWTP (600 000 m3/d capacity) using anaerobic-anoxic-oxic process (AAO process)-The middle parts with many long channels are the biological treatment processes.

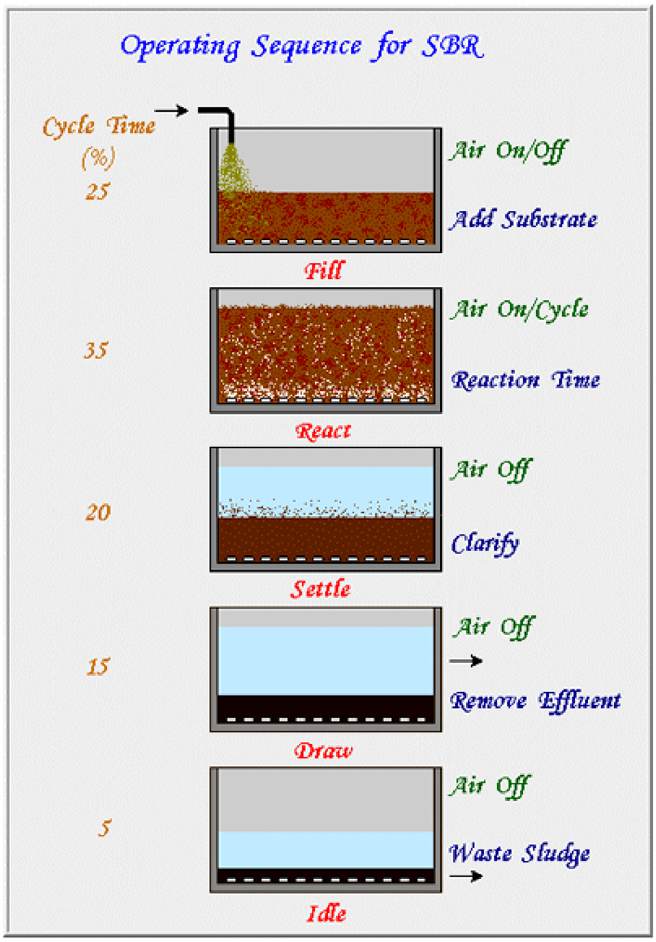


Figure 12. The principle of sequence batch processes for biological treatment (http://www.enviroenergysystems.co.in/images/sbr1.jpg)

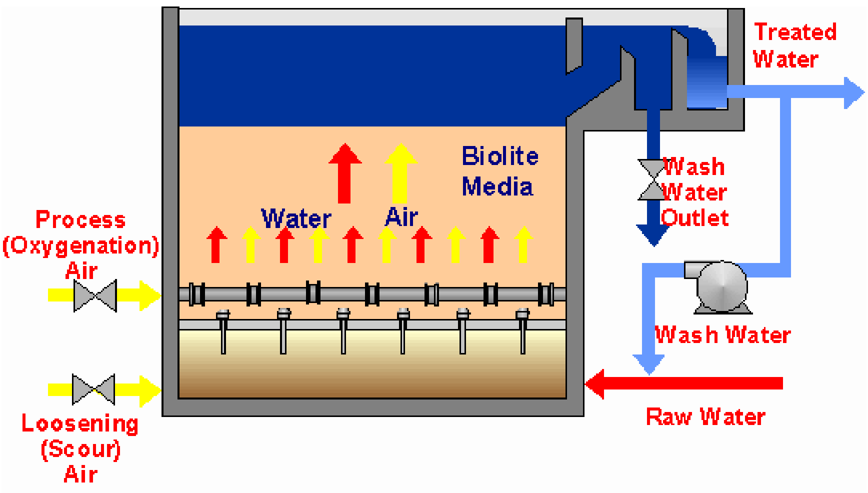


Figure 13. Biofor® BAF process—The principle

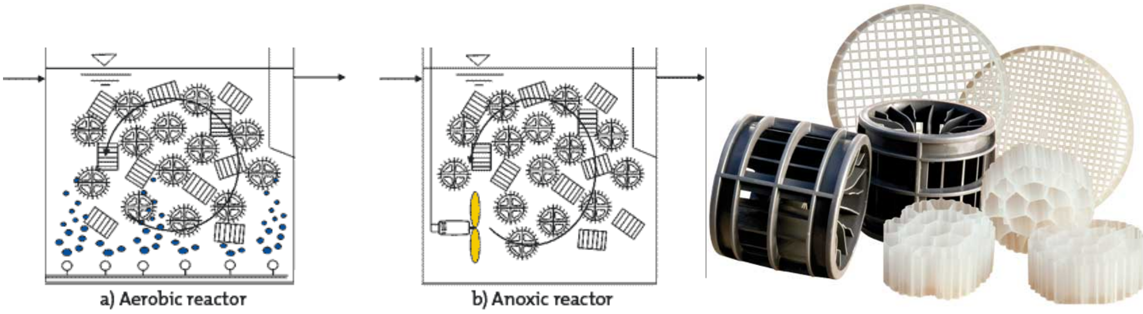


Figure 14. The principle of Moving Bed Biofilm Reactor process (MBBR) and potential media types by Anox Kaldnes (www.anoxkaldnes.com)

4.1.4 Secondary clarifier

During biological treatment, the biomass is formed with the treatment of wastewater, i.e., removal of organic matters, and nutrient removal. The biomass should then be removed from water, and water after treatment is called effluent and is discharged into water recipients like rivers, lakes, and seas. The separation of biomass from water is finished in secondary clarifier. Fig 15 illustrates the structure of secondary clarifier. During the clarification, a stable flow pattern is established so the particles are easy to settle down to the bottom of the tank, and then removed by the scrapers to the middle dune for further removal.

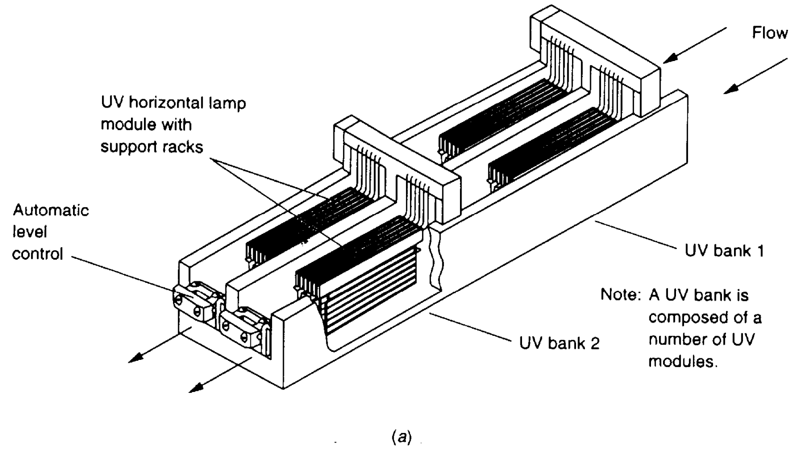
Figure 15. Structure of a secondary clarifier (http://www.hrsd.state.va.us/images/ATP/Secondary%20Clarifier%20Equipment.jpg)

4.1.5 Disinfection of effluent before discharge

The effluent is required to disinfect in order to further reduce the occurrence of pathogens coming into water bodies. Chlorination is often not considered as good practice due to potential formation of THMs. UV disinfection is now widely used for the disinfection of effluent.

An Ultraviolet (UV) disinfection system transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA). When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. UV radiation, generated by an electrical discharge through mercury vapour, penetrates the genetic material of microorganisms and retards their ability to reproduce. The effectiveness of a UV disinfection system depends on the characteristics of the wastewater, the intensity of UV radiation, the amount of time the microorganisms are exposed to the radiation, and the reactor configuration. For any one treatment plant, disinfection success is directly related to the concentration of colloidal and particulate constituents in the wastewater (US EPA 1999).

The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either the low-pressure or medium-pressure mercury arc lamp with low or high intensities (Fig16 and Fig 17).



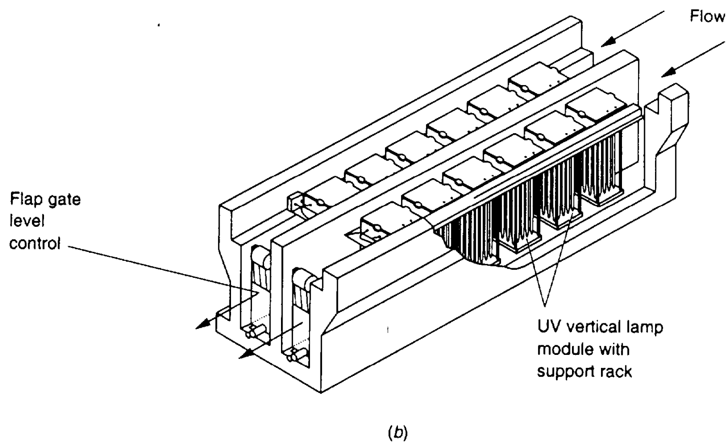


Figure 16. The layout of UV disinfection (US EPA)

Advantages and disadvantages of UV disinfection of wastewater effluent

The advantages may include:

- UV disinfection is effective at inactivating most viruses, spores, and cysts.
- UV disinfection is a physical process rather than a chemical disinfectant, which eliminates the need to generate, handle, transport, or store toxic/hazardous or corrosive chemicals.
- There is no residual effect that can be harmful to humans or aquatic life.
- UV disinfection is user-friendly for operators.
- UV disinfection has a shorter contact time when compared with other disinfectants (approximately 20 to 30 seconds with low-pressure lamps).
- UV disinfection equipment requires less space than other methods.

Disadvantages may have following aspects:

- Low dosage may not effectively inactivate some viruses, spores, and cysts.
- Organisms can sometimes repair and reverse the destructive effects of UV through a "repair mechanism," known as photo reactivation, or in the absence of light known as "dark repair."

Figure 17. UV disinfection of wastewater effluent (http://www.mindfully.org/Water/UV-Disinfection-Wastewater.jpg)

4.2 Thickening

Sewage sludge from primary sedimentation and secondary clarifiers are often mixed with very low DS% (around 1%-2%). Therefore the first step for sludge treatment is to thicken the sludge by separating free water from solids until DS% 3-5%. By thickening, the water content is reduced by more than 100% so to reduce the total sludge volume to further treatment.

There are several ways to thicken the sludge, either by gravitational thickening tank, or by flotation thickening, or by mechanical thickening.

Gravitational thickener is used to thicken sludge by gravity of the sludge particles. The structure of thickener is similar to primary sedimentation tanks (Fig 18).

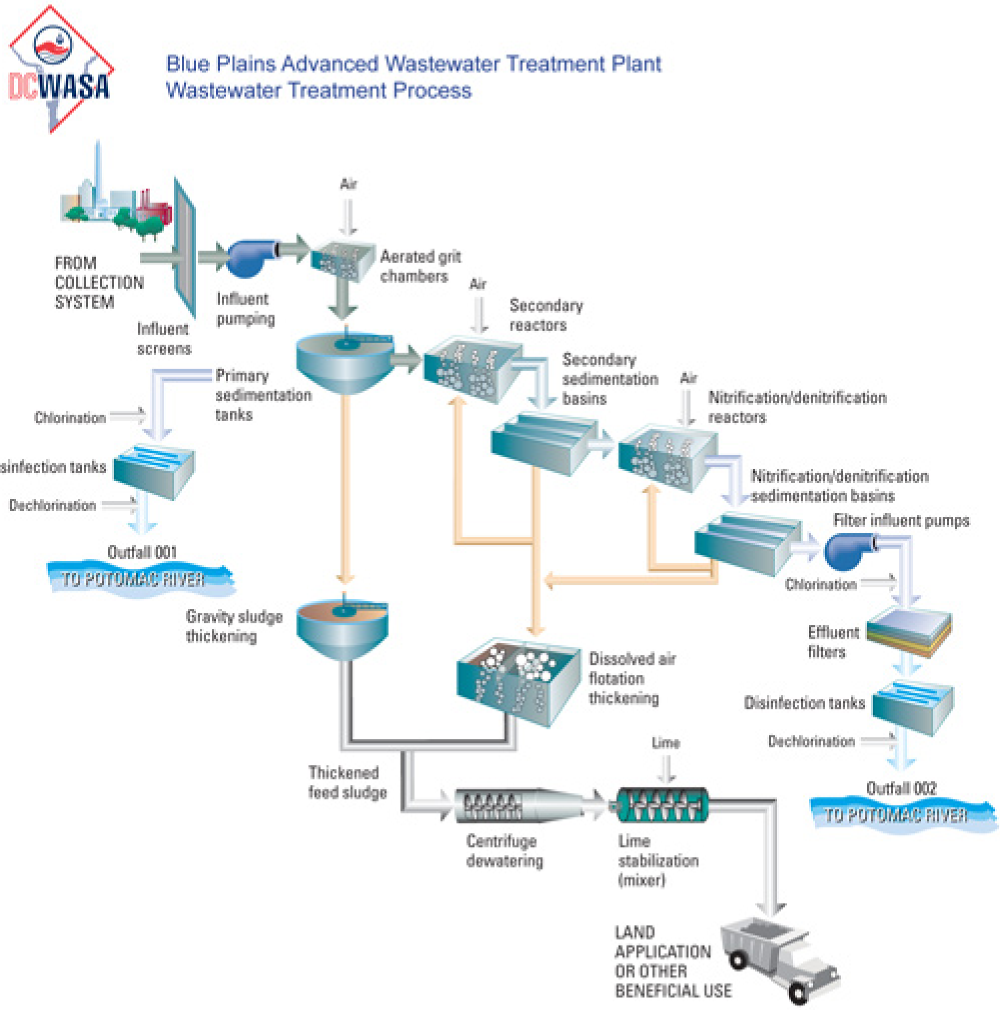


Figure 18. Process layout of WASA plant in Washington DC, USA, using gravity sludge thickening (http://www.dcwasa.com/wastewater/wwt_process.jpg)

While flotation for sludge thickening is to use the air bubble for aggregate with the sludge particles and float up by buoyant force. The principle of the flotation for thickening can be illustrated in Fig 19.

The efficiency of flotation thickener is higher than traditional gravity thickener, and is widely used especially in industrial wastewater sludge treatment due to its compactness.

Another type is the mechanical belt thickener (see Fig 20). The belt filter is often used to sludge dewatering also.

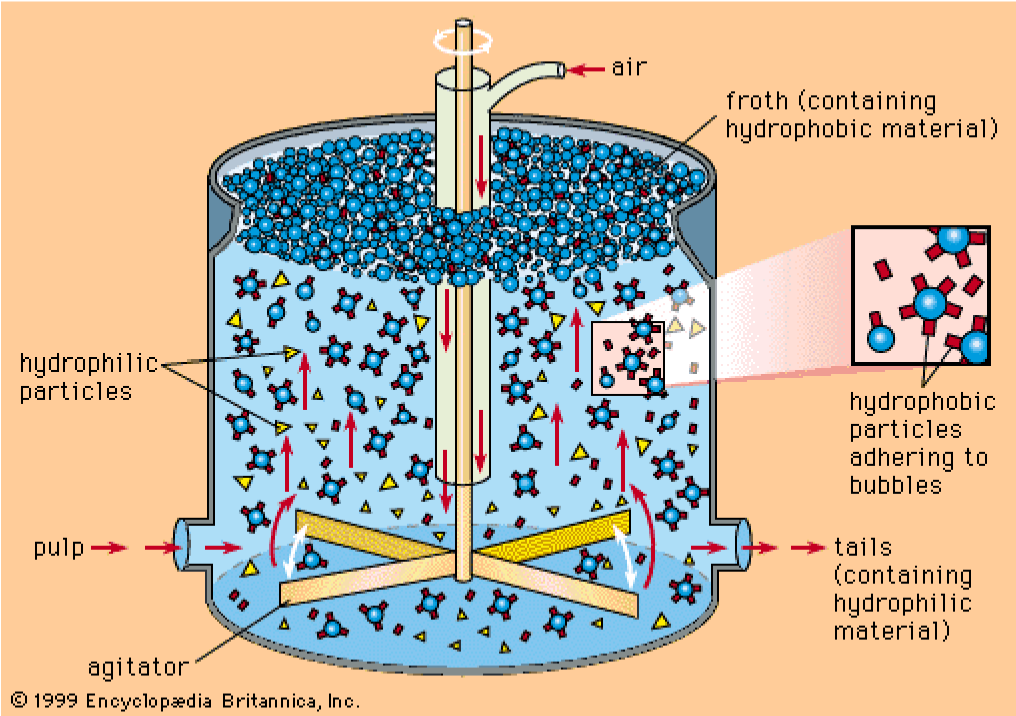


Figure 19. Principle of flotation for sludge thickening (http://media-2.web.britannica.com/eb-media/34/1534-004-5BBDA0CA.gif)

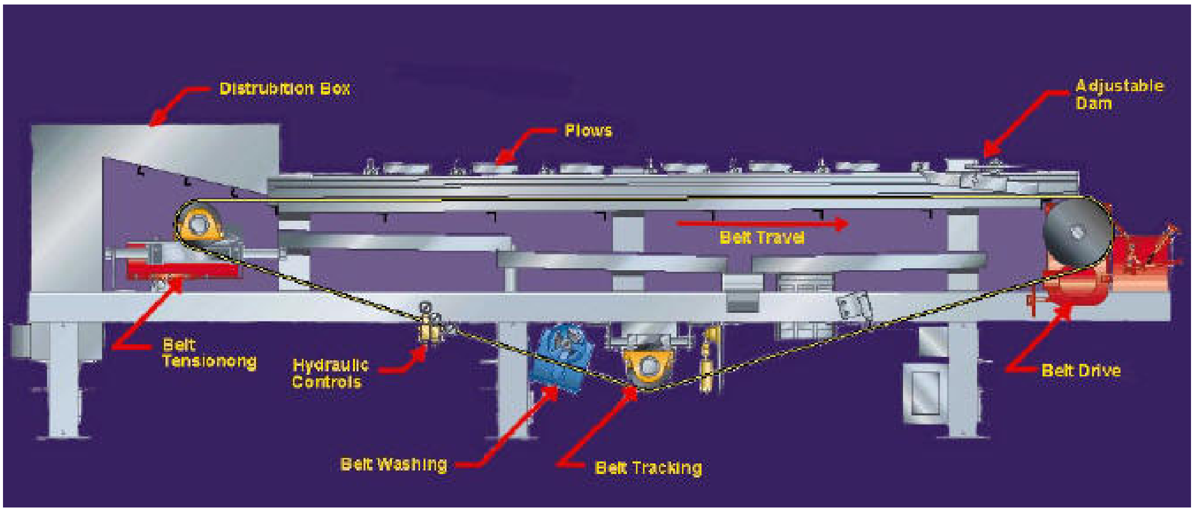


Figure 20. Belt thickener (http://www.princeton-indiana.com/wastewater/Media/wastewater/biosolids/gravity-belt-thickner-2.jpg)

4.3 Dewatering

Dewatering is a further step to produce sludge with higher DS% (or less water content) in order to facilitate the conditions for final disposal. As described earlier, the DS% is a key parameter for potential application in landfill, which required that the minimum DS% to be allowed is 30-35% (Spinosa and Vesilind 2001).

In order to further reduce moisture in sludge especially the water combined with sludge particles, a certain mechanical processes like belt filter presses or centrifuges are used (Novak 2001). In order to improve the dewatering properties, chemicals like coagulants and flocculants are often added. The dewaterbility is directly related to the pressures applied in belt filter presses, and the specific gravity charged in centrifuges.

4.3.1 Belt filter

Through belt filter, the cake can be dewatered to DS% up to 20-25% depending on the individual sludge properties. Various testing of belt filter is required to determine the operational range of dewatering properties. Fig 21 illustrates a type of belt filter machine.

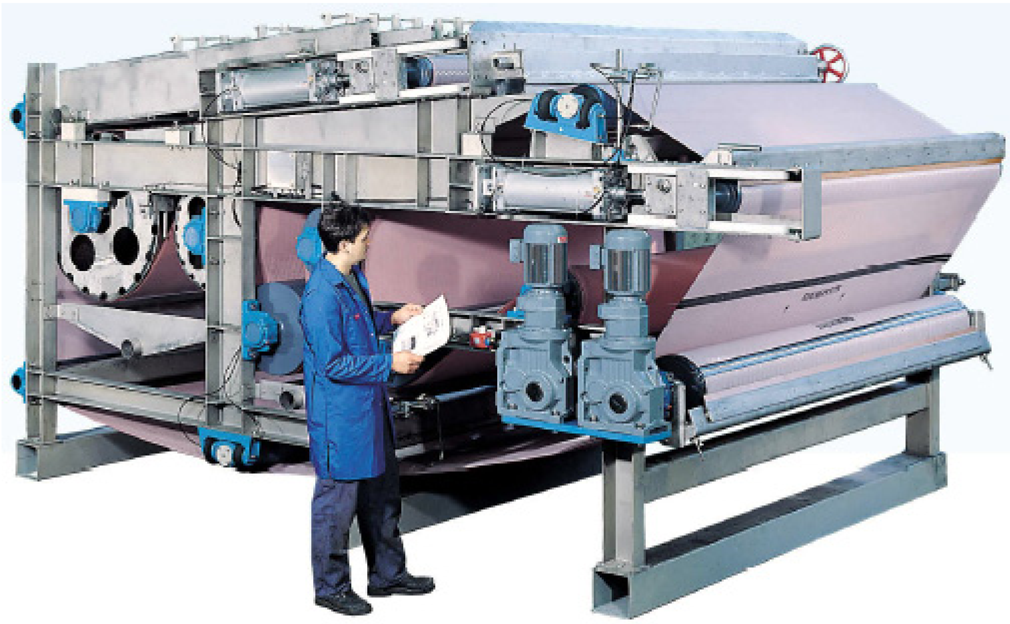


Figure 21. A typical belt filter for dewatering of sludge (http://www.andritz.com/ep-mechanical-sludge-treatment-belt-filter-presses-001-big.jpg)

4.3.2 Centrifuges

Centrifuges make use of the specific gravity to rotate away the water content in sludge. A typical principle can be illustrated in Fig 22 below. When the sludge containing water comes into the middle of the centrifuges, it is thrown away to the radial direction, and the water is pressed out from sludge particles.

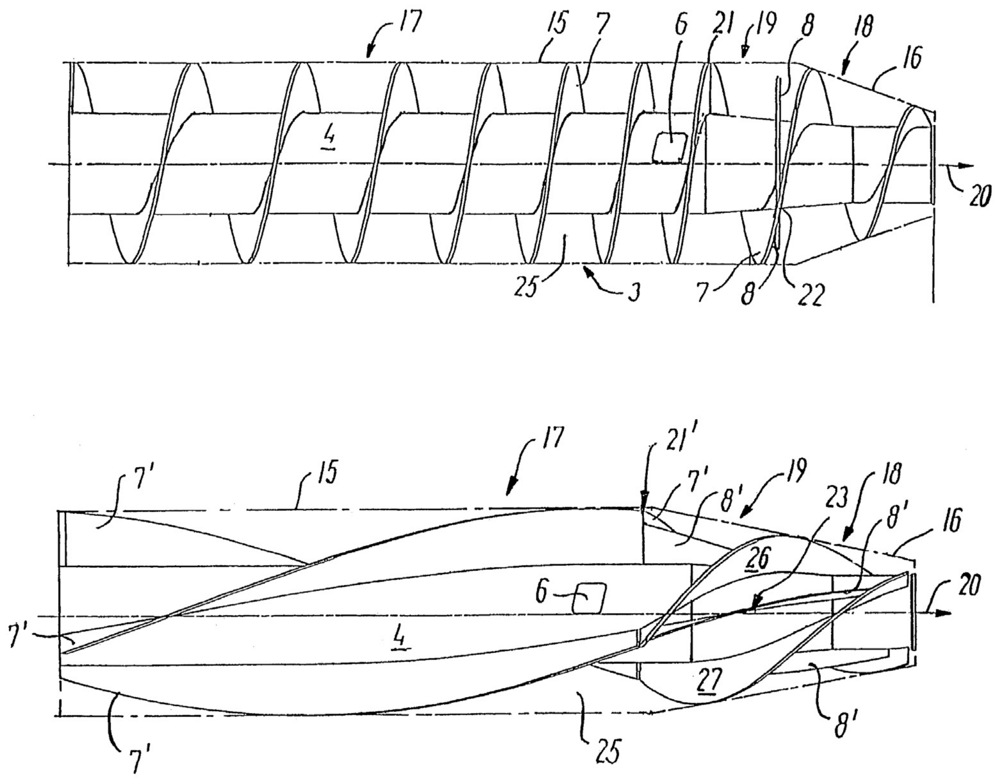


Figure 22. A principle description of centrifuges (http://www.freepatentsonline.com/7156801-0-large.jpg)

The high-solid centrifuges represent the development recently due to its advantages on meeting the criteria of high DS% for further disposal.

The dewatering step is one of the key steps for optimal management of sludge for beneficial disposal, although it is one of expensive steps.

4.4 Stabilisation for degradation of volatile organic solids

Vesilind (2001) claimed that it is very difficult to define the concept of stabilisation. The main reasons are that there are so many aspects involved into the stable state of sludge, such as health risk, smell, potential of produce further problems in soil, etc. Here a simplification of the concept is to define as: Degradation of the volatile organic solids in sludge to such an extent that there will be relatively low impacts on health risk.

Therefore a series of processes can be included for this purpose: aerobic digestion, composting, lime stabilisation, anaerobic digestion, thermal drying, and chemical stabilisation.

4.4.1 Aerobic digestion for stabilisation

Aerobic stabilisation has long been used to treat sludge by purging into air or oxygen in order to degrade the organic matters through heterogenic bacteria.

Due to the need to control during the aerobic digestion, it is then required to increase the water temperature to 45-65% degree. Under such circumstances the aerobic digestion is called Autothermal aerobic digestion process (ATAD) (Stentiford 2001) (Fig 23).

Typical operating characteristics for ATAD process can be defined as

Influent solids	4-6%
Volatile solids	60% of dry solids
Hydraulic retention time	5-9 days
Air supply	2-4 m^3/m^3tank/h
Volatile solids reduction	25-65% depending on different type of sludge

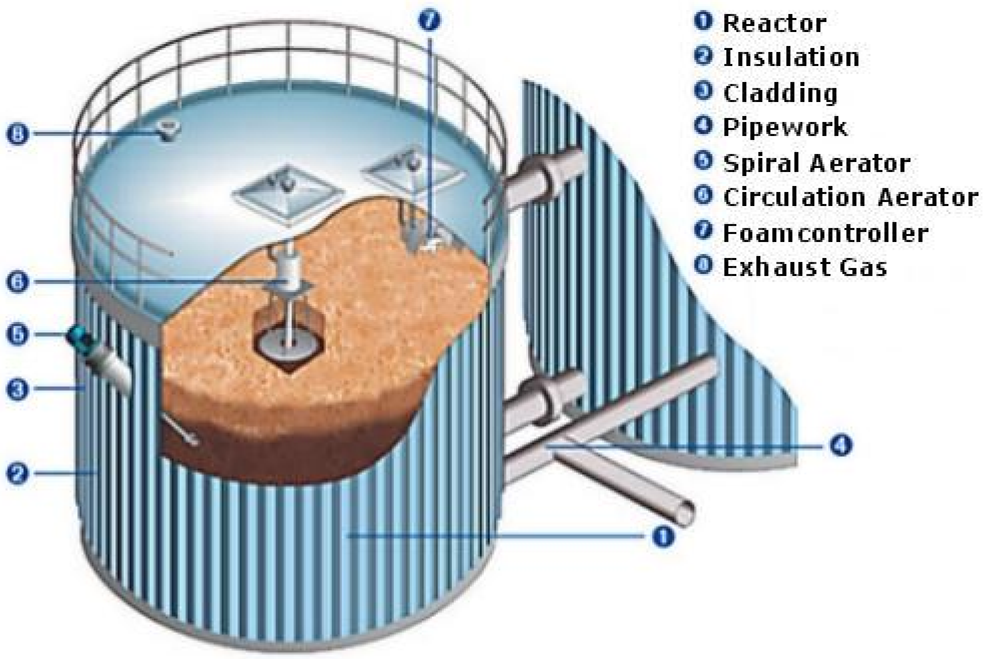


Figure 23. An example of ATAD using spiral aerator (http://pagesperso-orange.fr/isma/images/an_sat/photo2.jpg)

The ATAD is an energy demanding process, so it comes to be an expensive process for sludge stabilisation and hygenisation.

Additionally, due to open tank for ATAD, there is some extent of odour emission out.

4.4.2 Lime stabilisation

Lime is widely used in sludge treatment (around 4% of sludge in European WWTPs using lime). Either salked lime ($Ca(OH)_2$) or quicklime (CaO) are used to considerably increase the pH value in sludge over 11-12. The addition of quicklime at the same time produces a lot of heat to increase the temperature in sludge to help killing pathogens. Consequently lime is also added to the sludge total DS concentration. The crystallisation process may occur in sludge to form a hard surface to prevent water coming into sludge complex. The dewaterbility of sludge is improved.

There is a significant effect on pathogen control using lime stabilisation, and the biosolids treated by lime complies with the Class B requirement in USA. It is also helpful for depression of potential regrowth of bacteria as long as pH is over 12.

The fertilizing effects of lime stabilised sludge depend on the forms of organic and nutrient components and also the soil properties. Due to its high pH value, it is better suitable for acidic soil for remediation and at the same time the fertilizing effect.

The operational condition for lime stabilisation may bring with health impact on the working personnel. Therefore better protection should be implemented.

4.4.3 Composting

Composting is the purposeful biodegradation of organic matter, such as yard and food waste. The decomposition is performed by micro-organisms, mostly bacteria, but also yeasts and fungi. In low temperature phases a number of macro-organisms, such as springtails, ants, nematodes, isopods and red wigglers also contribute to the process, as well as soldier fly, fruit flies and fungus gnats. There are a wide range of organisms in the decomposer community.

Composting technologies vary from simple open windrow (Fig 24) to in-vessel reactor system (Fig 25).

Figure 24. Statile windrow composting

Figure 25. In-vessel composting

A biodegradable material is capable of being broken down under the action of microorganisms into carbon dioxide, water and biomass. It may take a very long time for some material to biodegrade depending on its environment (e.g. wood in an arid area versus paper in water). Many contaminating materials not dealt with in common composting are in fact "biodegradable", and may be dealt with via bioremediation, or other special composting approaches.

There are a series of requirement for optimal composting, including moisture content varying from 55-60% in the beginning to 40-45% at the end. Aeration is required to provide oxygen for metabolism, with the air demand from 2.5 L/g dry solids up to 27 L/g dry solids for drying. The temperature is required to control to be around 55 ^{o}C in most of time. At last but not the least, the proper C/N ratio is required to 20:1 to 30:1 in the beginning and often it is required to add (mixed) with fibre rich material especially for sludge composting.

The advantages of composting include storable and saleable end product, combination with biowaste composting and low costs compared to incineration. But the disadvantages are often significant in area requirement, sludge DS% higher than 18-30%, potential odour, and complicated in control of the composting system during low temperature environment. The end product is able to meet Class B biosolids.

4.5 Sterilisation /disinfection

Application of sludge on land is by far the most economic way to dispose the sludge because the sludge contains beneficial nutrients. But at the same time the pathogens existing in sludge are a health risk for land application when pathogens may be transferred to animals and finally back to human beings. Therefore in USA there is a Class A pathogen requirements set up be US EPA (40 Code of Federal Regulations part 503 dated 1993). The objective of Class A requirements is to reduce pathogen densities to be below the following detectable limits:

Fecal Coliform	less than 1000 MPN/4 g-dry weight
Salmonella sp.	Less than 3 MPN/4 g-dry weight
Enteric viruses	less than ¼ g-dry weight
Viable helminth ova.	Less than ¼ g-dry weight

There are six alternative requirements to demonstrate Class A pathogen reduction. They are

1. Thermally treated sewage sludge
2. sewage sludge treated by a high pH-high temperature
3. Sewage treated by other processes
4. Sewage treated by unknown processes
5. the use of process to further reduce pathogens (PFRP)
6. the use of processes equivalent to PFRP

The processes that have been certified as being equivalent to PFRP in US include

Two stage sludge stabilisation like heat treatment
Modified thermophilic aerobic digestion
Modified composting processes
Modified sludge drying processes
Modified alkaline stabilisation process
Ozonation process.

Comparatively, the lower requirements for Class B biosolids are only defined for less than 2 million fecal coliforms per gram of dry solids. There is no requirement for viable helminth ova counts.

4.5.1 Pasteurization

Pasteurization is simply put as heating the sludge up to 70 ^{o}C and retention time at minimum 30 minutes. If lower temperature is as low as 55 ^{0}C then the retention time is kept longer (3 hours) as practiced in the UK (Spinosa and Vesilind 2001). Pasteurization only may not ensure the pathogen disinfection, therefore often requires stabilisation afterward.

Havelaar (1983) summarised the effect of different disinfection techniques and find out the pasteurization is good against bacteria, viruses, parasite egg, but poor against spores.

Other methods and the effects can be listed up the table 5.

Table 5. The effectiveness of various disinfection techniques for sludge

Processes	Lethal factors	Bacteria	Viruses	Parasite eggs	Spores	Stability
Pasteurization	Heat 30 min 70 °C	good	good	good	poor	Variable
Irradiation	Ionising 300 krad	good	poor	good	poor	Variable
ATAD	Heat 60-80 °C	good	good	good	poor	variable
Composting	Heat 40-60 or 50-80 °C	good	variable	good	good	Good
Lime treatment	pH up to 12 + temp up to 80 °C	good	good	variable	NA	Good

4.6 Utilisation of resources and bio-energy

4.6.1 Resources utilisation

Despite the potential problems of using sludge as biosolids back to land in terms of heavy metals, the sludge contains rich resources for natural recycling, among them the most import is Phosphorous, together with organic matters and nitrogen. According to pilot study, the fertiliser effects of biosolids (Class A and Class B) have at least equivalent or better for normal crops.

Elliott and O'Connor (2007) analysed the sustainable management of phosphorous from biosolids. A P-index was introduced that how much P should be used for different land describing the phosphorous loss rate (kg/ha). If this rate is higher, the addition of biosolids to land should be lower, in order to keep the P in proper content in the soils.

Cordell et al (2008) addressed the food security with respect to phosphorous. The non-renewable P reserves will probably be depleted within 50-100 years. But P demanding is increasing to secure the food supply in the world. The figure 26 indicated that the fast increasing in P consumption for food production has been dramatically during the last 40-50 years, and the trends in increase will continue.

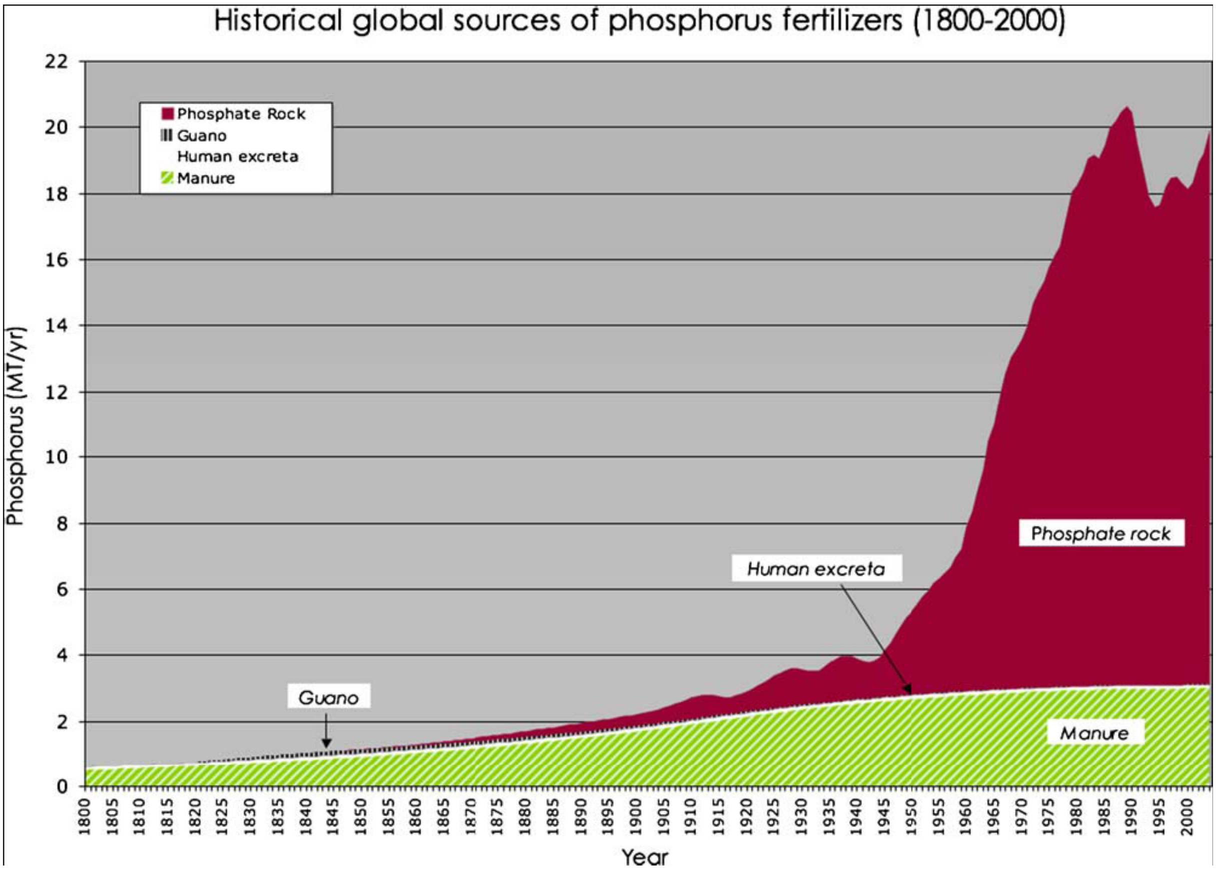


Figure 26. Global P consumption for fertilisers (Cordell et al 2008)

An analysis of P flow in the natural environment shows that P gets loss to non-arable land, landfill, and water (Fig 27). Therefore the minimization of the P loss in treatment and disposal P rich wastes like manures and sludge together organic waste comes to be more important than before.

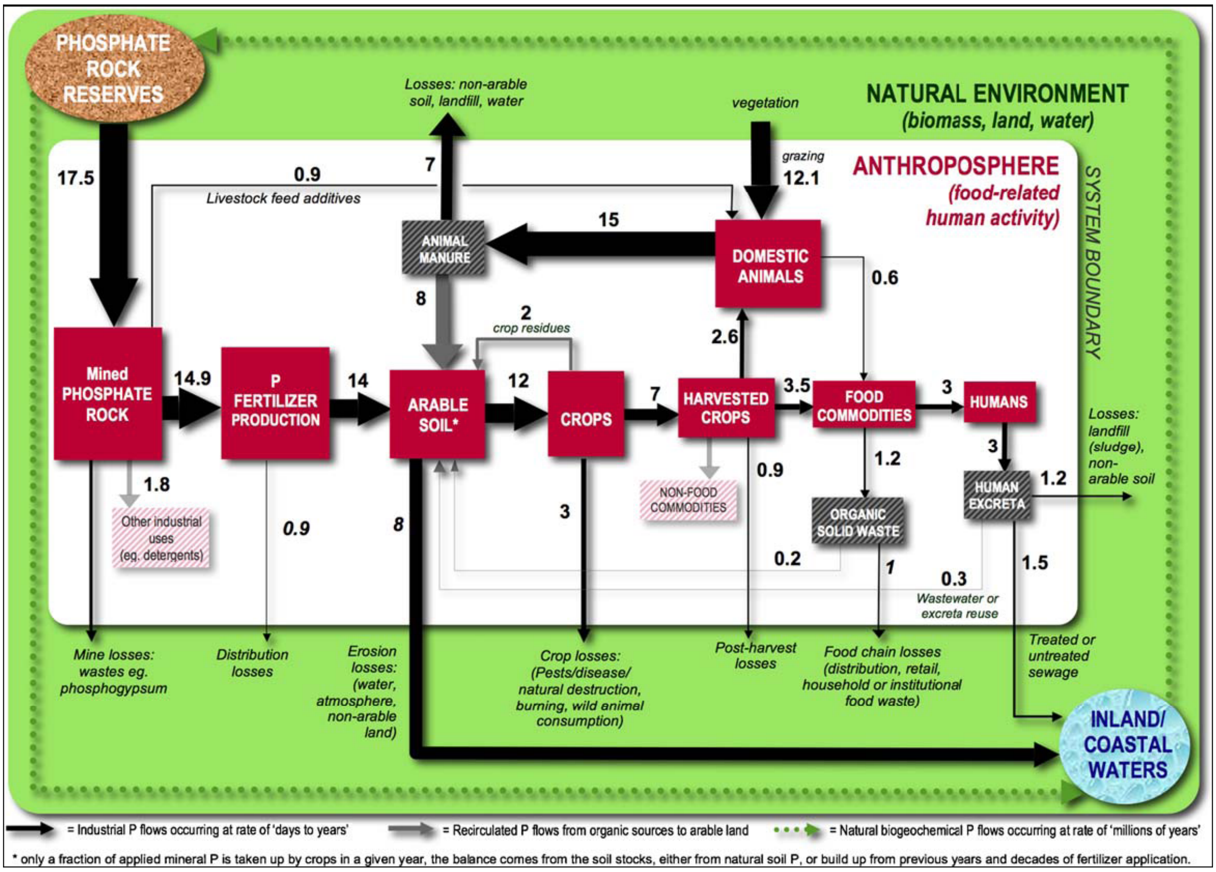


Figure 27. Key phosphorus flows through the global food production and consumption system, indicating phosphorus usage, losses and recovery at each key stage of the process. Units are in Million Tonnes per year (Only significant flows are shown here, relevant to modern food production and consumption systems.). Calculations based on data in IFA (2006) and Smil (2000a,b).

So an integrated and sustainable P management is called for globally and nationally in every country.

An analysis of P content in the biosolids from three sludge treatment plants in Norway (Vogelsang et al 2010) is illustrated in Table 6.

Table 6. P utilisation from treated sludge (biosolids) from three plants in Norway

	Units	VEAS	BRA	NFR
P in sludge	g P/kg TS	16-19	26,3	22,4
	tons P/year	266	132	17
	% P reused	71	93	92
Agriculture use	%	70	90	63
Green area	%	0	0,4	0
Storage	%	30	9,3	37
Other uses	%	0	0	0

The use of P in sludge back to land can replace the mining of P rocks and therefore make the reserves lasting longer time than expected.

4.6.2 Bioenergy utilisation from sludge

Mininni (2001) described the gross calorific value (GCV) in sludge can be estimated by the formula below:

GCV (kJ/kg-VS)=32810*C+142246*(H-O/8)+9273*S

Where C, H, O, and S represent the weight fraction of the elements in the VS (volatile solids).

Typical calorific value of municipal sludge is between 23300-27900 kJ/kg-VS for raw primary sludge, 20700-24400 kJ/kg-VS for activated sludge and 22100-24400 kJ/kg-VS for primary digested sludge.

The lower calorific value (LCV, kJ/kg-sludge) is used to consider the real heat value in sludge with moisture. LCV of VS can be calculated by taking into account the DS% content and the heat need to evaporate water moisture.

LCV= GCV*DS%*VS-2440*(9*H*VS*(1-DS%))

Assuming GCV of 23000 kJ/kg VS, and VS as 70%, then the relationship between LCV and DS% can be estimated as in figure 28.

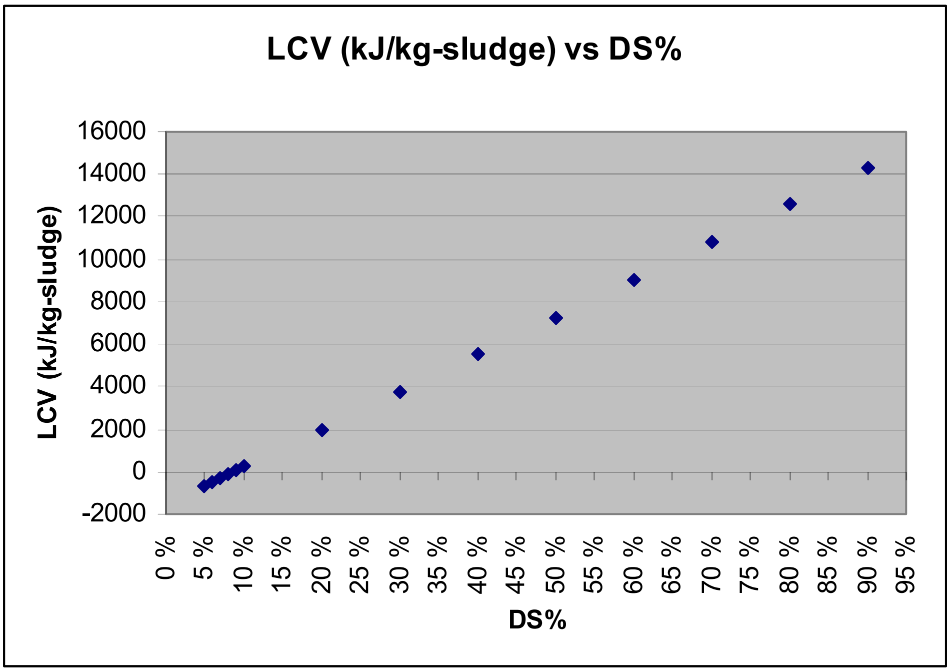


Figure 28. An estimate of LCV (kJ/kg-sludge) versus DS% in sludge

So the higher the DS% is, the higher the LCV for wet sludge has. In incineration, there is a need for minimum DS% into the system to keep the balance of energy.

There is a potential to utilise the calorific value in sludge either by direct combustion or indirect digestion for biogas production.

Incineration of sludge with energy recovery is increasingly used in sludge treatment and disposal since European Landfill Directive has been in force since 1995. The advantages in sludge minimisation and avoidance of landfill of raw sludge can be the driving force of incineration, and at the same time incineration fulfils the pathogen requirement for health impact due to its high temperature during combustion (over 850 ^oC). But the existence of heavy metals and organic micropollutants (e.g. PAH, PCDDs, PCDFs) in sludge may restrict the application especially the most potential evaporation of Hg into air and dioxins. The potential of emissions of hazardous gas depends on the element components in sludge.

There are several types of incineration systems, like multiple hearth furnaces (MHF), fluidised bed furnaces (FBFs), rotary kiln furnaces (RKFs) are widely used (Mininni 2001). Additional pre-treatment and post treatment are required to prepare the feeds and the flue gas and ash treatment. The total incineration systems are complicated and a big investment for many cities to deal with sludge and biowaste treatment and disposal.

The energy recovery from incineration is carried out through boilers to produce steam, and further to produce electricity by steam turbines.

In general, the raw sludge incineration (from DS% around 20% after dewatering) is energy demanding due to the very low LCV. Therefore additional energy is often required to facilitate optimal combustion. There is some comparison about the pre-treatment of sludge to improve energy efficiency, with thermal drying with the waste heat from incinerators, and utilisation of biogas produced in digestion prior to incineration, make the system more sustainable (Murray et al 2008).

Anaerobic digestion is from almost all aspects the best alternative for energy utilisation, economic effectiveness of sludge treatment, and nutrient recycling back to land application. In the next section, a detailed description of anaerobic digestion and the optimisation is presented.

4.6.3 Anaerobic digestion

Demirel et al (2010) reviewed the anaerobic digestion processes. Anaerobic digestion is widely used for digestion of organic solid and liquid waste, sludge, manures, etc. Biogas production increased over 20% in last years in Europe. The production of biogas accounted for 12 Mtoe (million ton oil equivalent) among the total 87 Mtoe by biomass in Europe in 2007 as shown in figure 29 and figure 30.

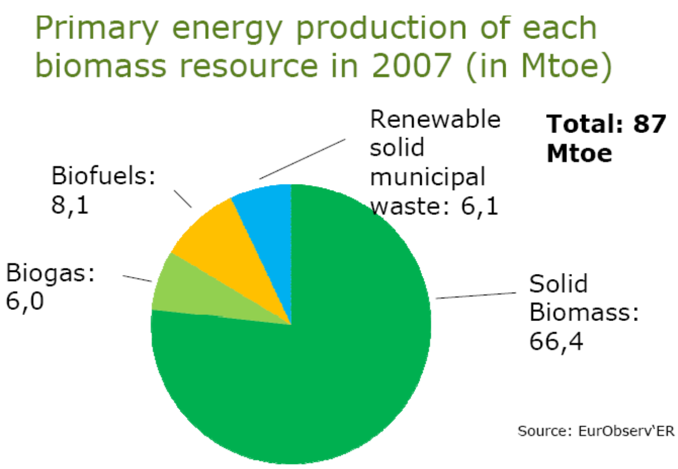


Figure 29. Biomass resources for Bioenergy production in Europe (2007) (EBA 2009)

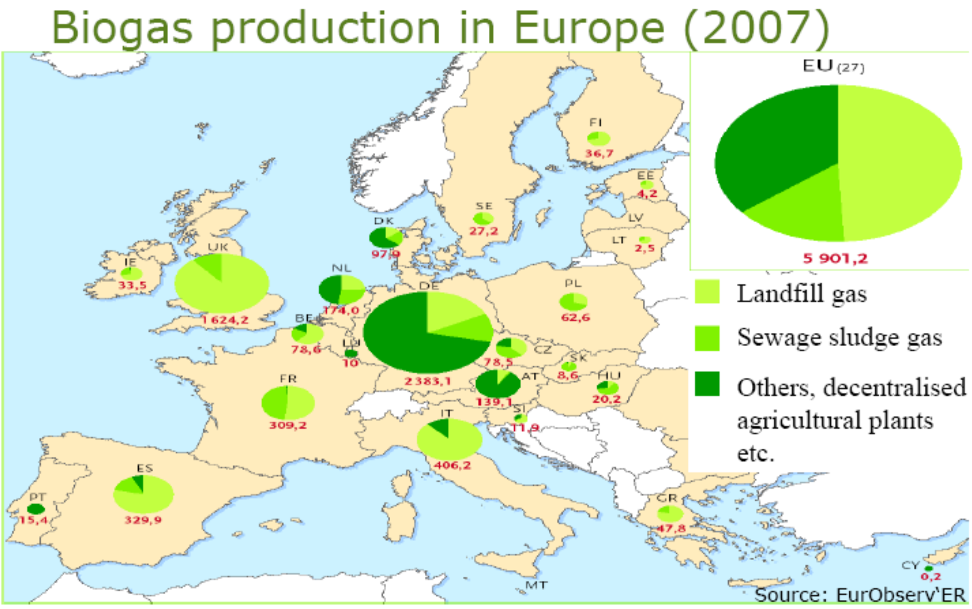


Figure 30. The distribution of biogas production in Europe (EBA 2009)—the highest production of biogas is in Germany and UK.

Sewage sludge for biogas production accounts for significant fraction especially in UK.

Traditional biogas production via anaerobic digestion is often low in efficiency, in that there is a need foe long retention time and low conversion rate of volatile solids (Demirel 2010). Often used digestion is mesophilic digestion in one stage. There is also two stage digestion (also called two phase digestion) with the first phase as pre-digestion at thermophilic state in order to improve biogas production.

4.6.4 The basic principle of anaerobic digestion

The basic principle of anaerobic digestion can be illustrated in figure 31. The limiting step of hydrolysis is critical for optimisation of digestion process.

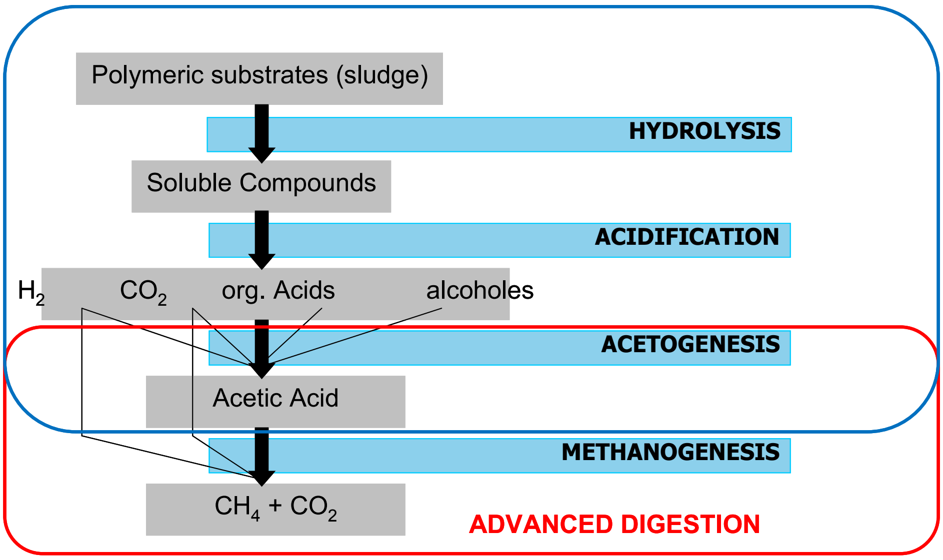


Figure 31. Anaerobic digestion with pre-treatment (hydrolysis as often a limiting step), acidification, acetogensis, and methanogensis (Cambi 2010).

4.6.5 Enhancement of biogas production via pre-treatment

State of Science Report: Energy and Resource Recovery from Sludge (edited by Kalogo and Monteith 2008) is a profound report on how to improve the biogas production through various pre-treatment of enhancement. Several processes have been developed to break down the raw sludge solids to promote easier biotransformation to methane. Thermal, mechanical and chemical cell destruction processes have been developed, including hydrothermal heating, ultrasonic cell disintegration, use of ozone and electrical pulses.

Thermal hydrolysis

Thermal hydrolysis is a process used to increase sludge digestibility for better biogas production, and to decrease the quantity of residue for disposal. During thermal treatment, sludge is heated at high temperature and high pressure for several minutes. Microbial cell walls in the sludge are destroyed, releasing more easily digestible organic compounds contained within the cells. The advantages of combining thermal hydrolysis and anaerobic digestion are high volatile solids (VS) destruction and increased biogas production. Currently, the most known commercial thermal hydrolysis technologies are Cambi® and BioThelys®.

The experimental study showed that the COD conversion under temperature 175 ^{o}C is able to increase to over 60%, which is much higher than normal condition without thermal hydrolysis (Fig 32).

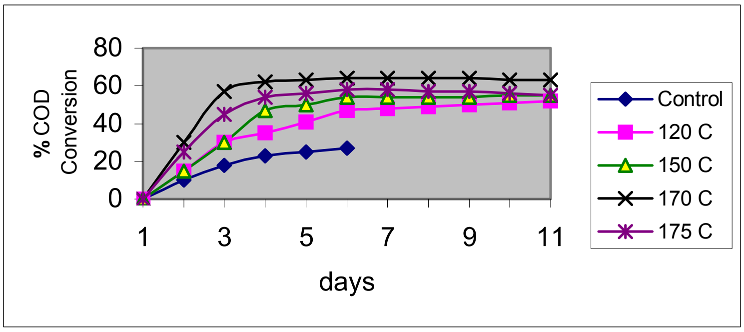


Figure 32. Influence of temperature on COD conversion for sludge digestion (Novak 2009)

Cambi ® installations have been widely established in Norway, Denmark, UK, Australia etc for more 14 million p.e. According to independent researches and investigation, the Cambi® process is able to increase biogas production by 50%, to double the digester capacity by reducing the retention time and high solids feed to digestion, and persistent high quality if biofertilizer fulfilling with Class A requirement with high DS% between 30-35% due to better dewaterability after pre-treatment. Therefore the overall economic benefit using Cambi ® process has been proven by large scale sludge treatment plants in UK (Panter, 2009). Figure 33 and figure 34 show plants using Cambi® THP process.

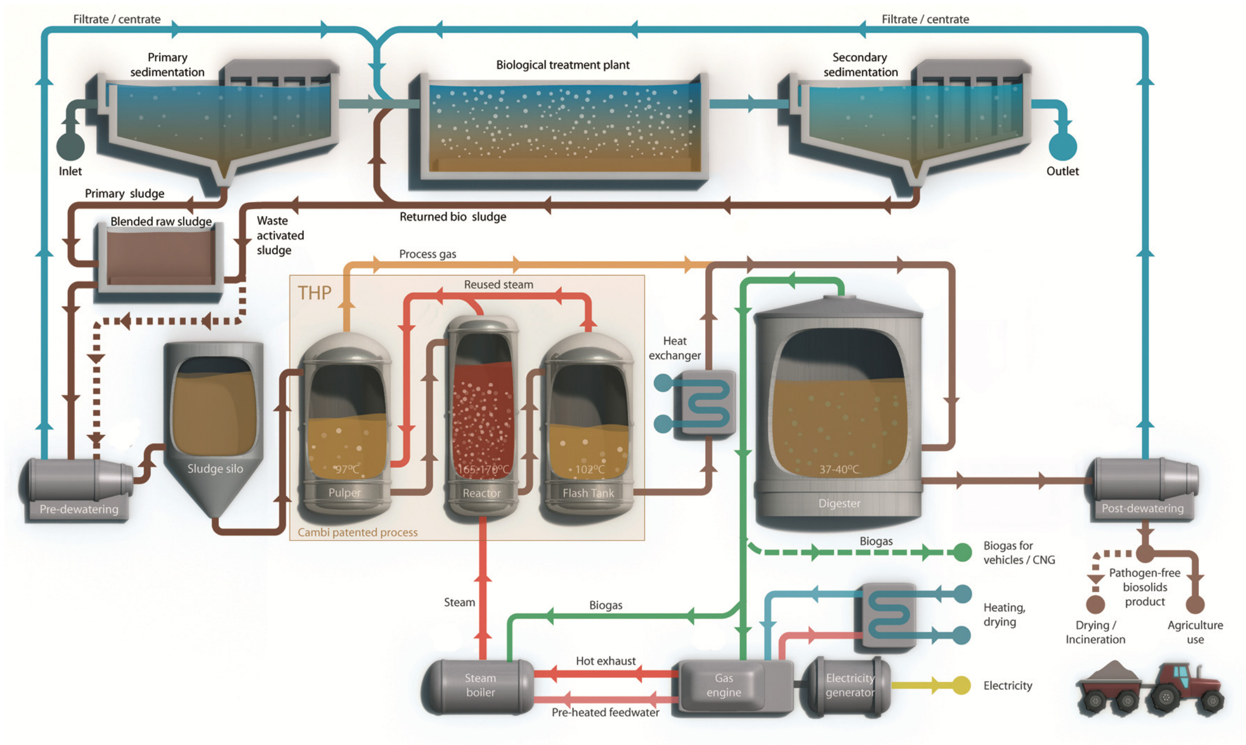


Figure 33. A typical flow sheet for wastewater treatment and sludge treatment using Cambi ® installation (Cambi AS, 2010)

Figure 34. A photo of Bran Sands sludge treatment plant in UK (Aker Solutions 2009) using Cambi ® THP process (in the middle of photo) for pre-treatment to enhance biogas production (in commissioning 2009)

Other promising processes for pre-treatment include ultrasonic treatment (heating), Ozonation, thermophilic short time digestion, and pulsive electric field.

4.7 Final disposal

There are several ways of disposing the sludge in the end, e.g., land application to integrate into the natural cycle, landfill to fix within the confined area, manufacture of bricks, cements, incineration and co-combustion with coals.

4.7.1 Land application

Sludge is treated to biosolids and use in agriculture either as fertiliser, soil conditioner, land cover, horticulture, etc to beneficially use the fertilising effects especially the P content. Figure 35 shows how the dewatered digested sludge (with DS% 30-35%) can be easily distributed to grassland.

Figure 35. Dewatered digested biosolids from Aberdeen sludge treatment plant are spreading over the grassland in UK (Panter 2009)

There is a limit of how much biosolids can be applied on the land based on the nutrient contents and the sensitivity of potential threat of pathogens to crops.

4.7.2 Landfill

Landfill Directive in EU has set up a goal of reducing the landfill of sludge and other biodegradable organic waste. Therefore, pre-treatment is required if the sludge should be landfill, especially in the total VS fraction and the DS%. Typical environmental threat from landfill is first the land area requirement to disposal, second the emission of odour and GHGs to adjacent air, third the troublesome leachate to be handled, and the great potential to pollute the underground water which is rather vulnerable to management.

Landfill itself is also a complicated system. It is often now difficult to find out the correct sites for landfill, and in most of big cities there is running out the landfill capacity. Careful management of landfill is often required to meet the environmental requirement. Complains from people living and working nearby become the headache for local governments. A profile of landfill site is shown in figure 36.

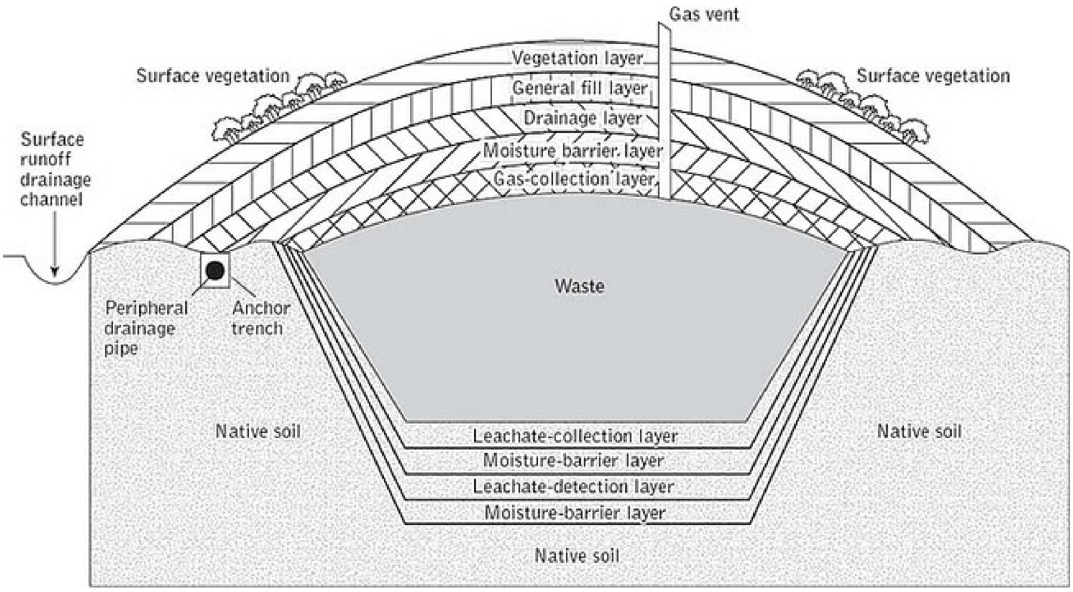


Figure 36. The profile of landfill site (http://science.jrank.org/article_images/science.jrank.org/landfill-techniques.1.jpg)

It is now taking into force of collecting the landfill gas both for reduction of GHG emission and the utilisation of bioenergy, while the methane content in landfill is often low (Fig 37).

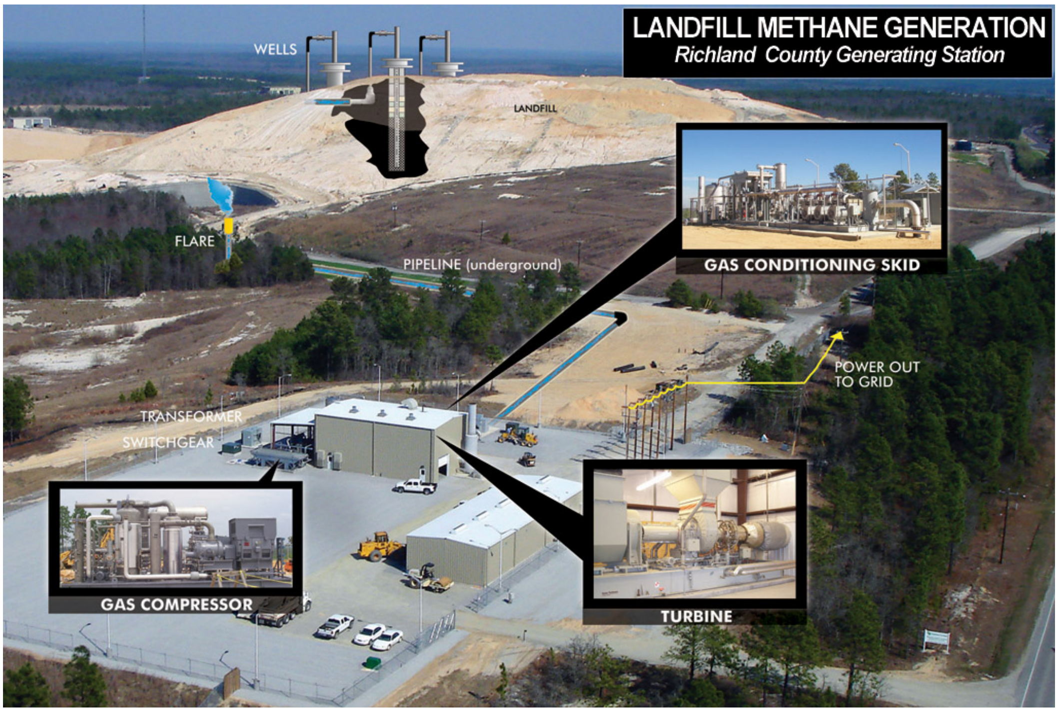


Figure 37. Landfill gas recovery (http://www.scgreenpower.com/portal/page/portal/SCGreenpower/Images-Flash/gp_process.jpg)

5. Norwegian Experiences in Sewage Sludge Treatment and Disposal

5.1 Norwegian Sewage Sludge Politics

Norway has established a sludge politics with the vision of quality controlled sludge (biosolids) to contribute to a more sustainable development in accordance with Water Frame Directive in Europe, REACH, and non-toxic environment (Norsk Vann 2008).

Norsk Vann (Norwegian Water Association) recognised that
1. Sewage sludge produced from wastewater treatment plants is the product of the local society, and the recirculation of the treated sludge (biosolids) back to the nature is the responsibility of local society.
2. Treatment and application of quality controlled sludge brings better chance to reduce the emissions of GHGs by increased use of GHG-neutral biogas and increased CO_2 capture.
3. Phosphorous is a limited resource in the world, so it is important to recycle the Phosphorous, and it is necessary to develop technologies to make phosphorous easily accessible for crops.
4. Among all the biofertilizer, the treated sludge (biosolids) is the most investigated and controlled one. Precaution principle is established for strict requirement of quality and application.
5. With effective treatment and quality control according to the defined regulations, the use of biosolids poses minimal risk to health and environment.

5.2 Quality control of treated sludge (biosolids)

Quality control of treated sludge (biosolids) follows up the Fertilizer Regulations in Norway. Norsk Vann will:
1. All sludge treatment methods should be validated to follow up the Fertilizer Regulations. Validation of sludge treatment methods includes that the methods should be tested by independent professional institutes in order to document whether the method meets the function requirement of inactivation of parasite pathogens.
2. Reception of external fractions does not reduce the quality and security of sludge treatment. Norsk Vann works out to quality control and dialogue with external organisation.
3. Norsk Vann works actively the analysis methods and improvement and the understanding and explanation of results.
4. Norsk Vann contributes to assist the development of sludge based products to meet the market needs. In addition, the sludge treatment should at minimum meet the quality class and hygenisation.

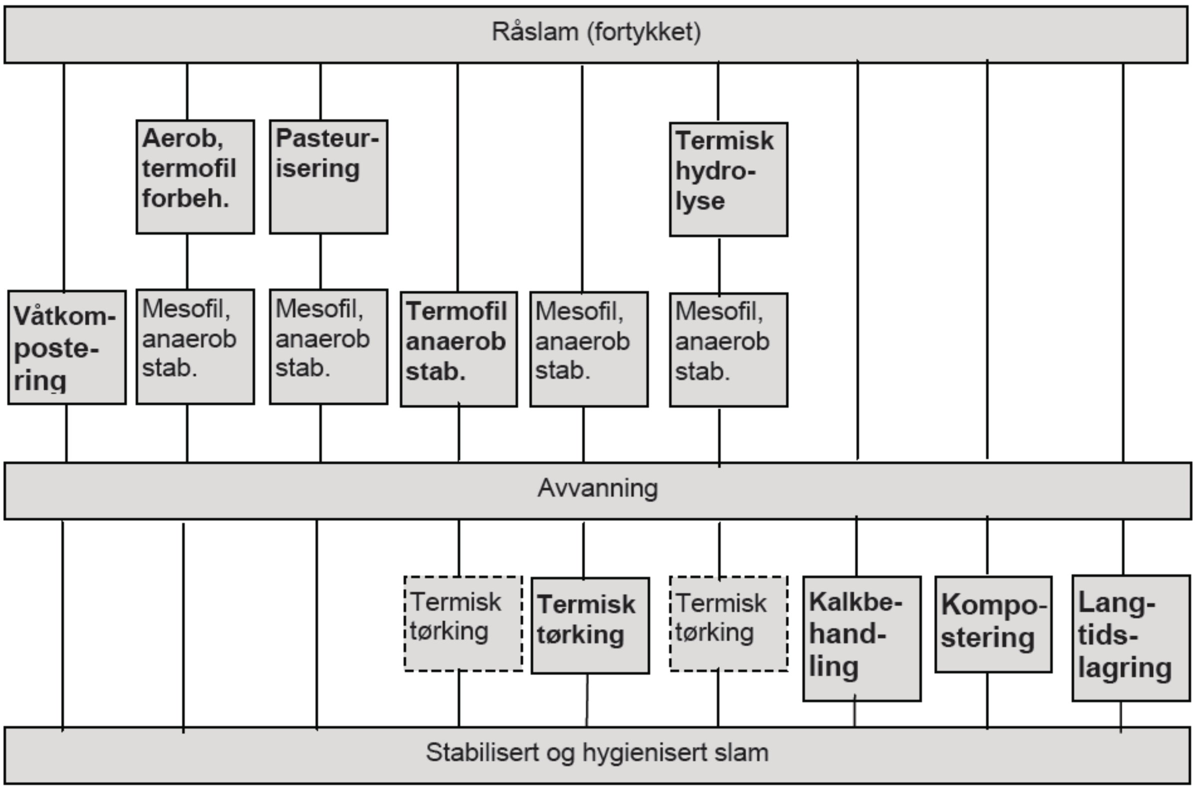
It is required in Fertilizer Regulations that products should be stabilised such that it will not result into smell or odour and other environmental problems when they are stored and applied for. It regulates that the products should not contain *Salmonella* bacteria and other infective parasites eggs, and the thermo tolerant coliforms bacteria should not exceed over 2500 per gram of dry solids.

5.3 Sludge treatment methods used in Norway that meet the hygenisation requirement

Various methods are used in Norway to treat sludge to meet the hygenisation requirement. They include

1) wet composting (aerobic thermophilic stabilisation),
2) aerobic thermophilic pre-treatment together with mesophilic anaerobic digestion,
3) pasteurisation together with mesophilic anaerobic digestion
4) thermophilic anaerobic digestion
5) anaerobic stabilisation with thermal drying
6) thermal hydrolysis and anaerobic stabilisation
7) lime stabilisation of dewatered sludge
8) Windrow composting
9) Reactor composting
10) Lang time storage and simple composting

The combination of different methods is illustrated in figure 38.



(Notes: Råslam—raw sludge, fortykket—thickened, aerob—aerobic, thermofil—thermophilic, forbeh.—pre-treatment, pasteurisering—pasteurisation, thermisk—thermal, hydrolyse—hydrolysis, våtkompostering—wet composting, mesofil—mesophilic, anaerob—anaerobic, stab.—stabilisation, avvanning—dewatering, tørking—drying, kalkbehandling—lime treatment, kompostering—composting, langtidslagring—lang time storage)

Figure 38. Combinations of different methods for sludge stabilisation and hygenisation (Norsk Vann 2008)

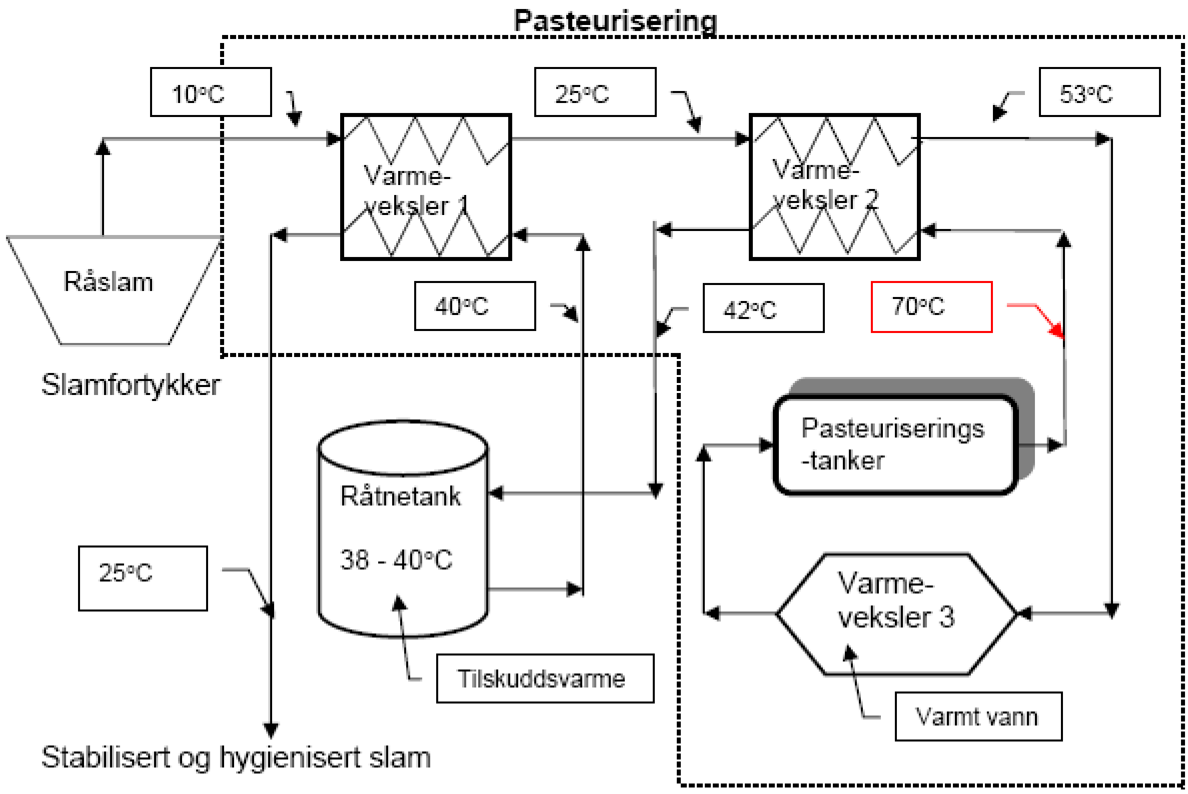
Composting (including wet type, windrow type, and reactor type) is used for those plants near available land. Due to the variation in environmental temperature and potential problems in control, this type of method comes to be not popular.

Anaerobic digestion (either mesophilic or thermophilic) is widely used in combination with energy utilisation.

Thermal drying is used for those require landfill of sludge.

5.3.1 Pasteurisation and mesophilic anaerobic digestion

A flow sheet of pasteurisation and mesophilic digestion used in several plants is shown in fig 39.



(notes: råslam—raw sludge, slamfortykker—sludge thickener, pasteurisering—pasteurisation, varmeveksler—heat exchanger, råtnetanker—digesters, varmt vann—hot water, tilskudsvarme—supplied heat)

Figure 39. Flow sheet of pasteurisation and mesophilic digestion

It is required that pasteurisation should ensure 70 °C and 30 minutes to ensure the effect of hygenisation. The stabilisation of sludge is conducted in mesophilic digestion with HRT of 15-20 days. Class B biosolids are produced, however, the Class A quality can not be ensured.

5.3.2 Thermal hydrolysis and mesophilic anaerobic digestion

The thermal hydrolysis developed by Cambi AS has widely used for high quality sludge treatment (Class A biosolids) with enhanced biogas production. The total flow sheet using thermal hydrolysis and mesophilic anaerobic digestion is shown in figure 40 for the HIAS plant in Norway.

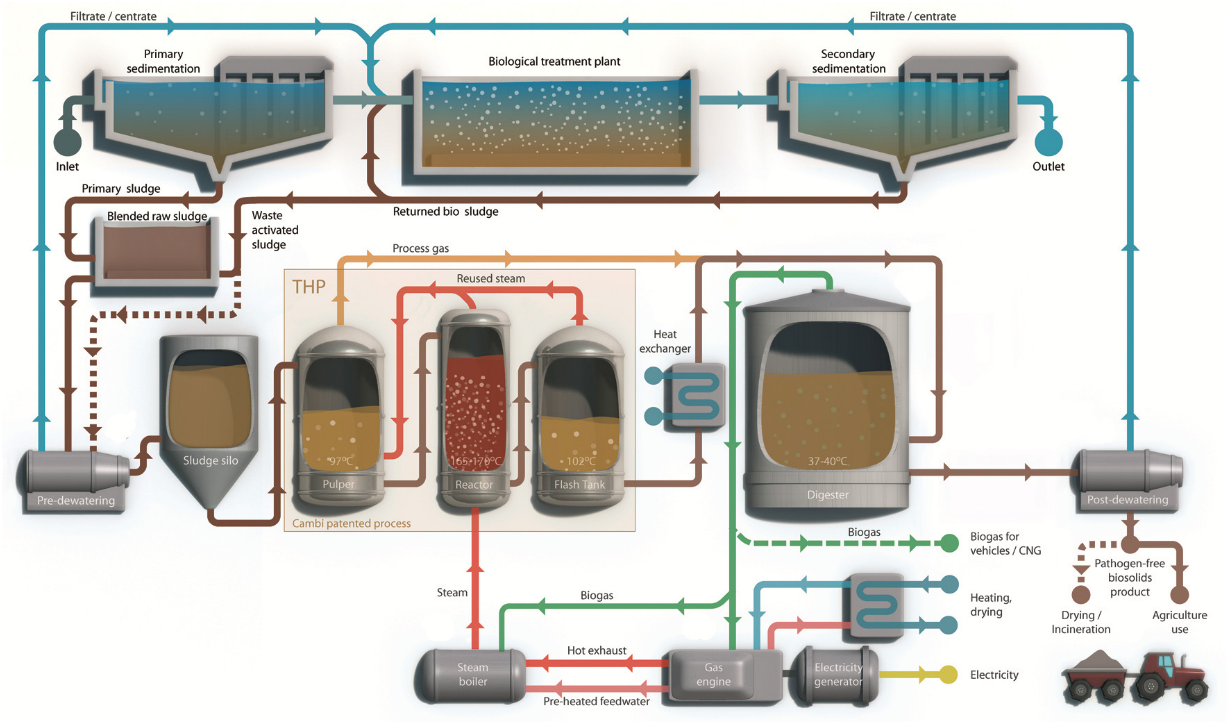


Figure 40. Flow sheet of thermal hydrolysis (THP) and mesophilic digestion in the HIAS plant (Norway).

The sludge after dewatering is feeded into the THP process in which high pressure steam is added first into the pulper for complete pre-heating and mixing, then flow to THP reactor for 30 min under pressure of 8 MPa and 175 ^{o}C. Then the thermal hydrolysed sludge is released to lower pressure and explosion with steam occurred to disrupt the cells of organic matters (bacteria, etc) for much better dissolution of particulate organic matters and deactivate all pathogens. Then the sludge is digested under mesophilic condition, to produce much more biogas (50% increases) within shorter retention time (10-15 days). The biogas produced is used for cogeneration of heat and electricity, and the heat is recovered to supply the need in THP process.

5.3.3 Sludge treatment in VEAS plant using thermophilic digestion and thermal drying

VEAS plant, the biggest wastewater treatment plant in Norway, is an inter-community wastewater treatment plant for Oslo, Asker and Bærum, is located on the western side of the Oslofjord as shown in figure 41.

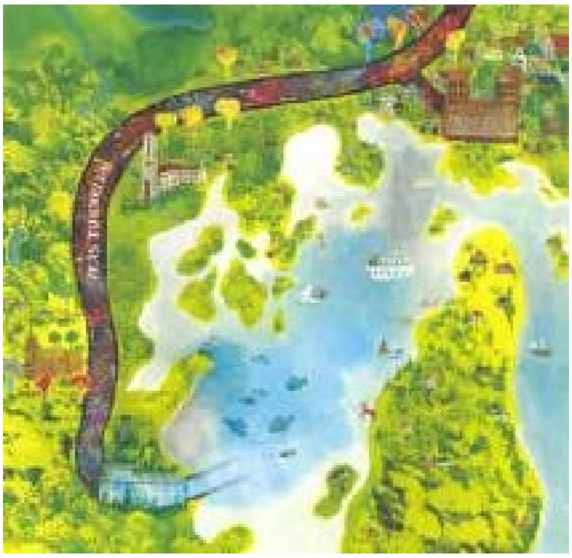


Figure 41. The wastewater tunnel leading to VEAS plant on the western shore of Oslofjord.

The wastewater treatment and sludge treatment processes at VEAS are shown in figure 42.

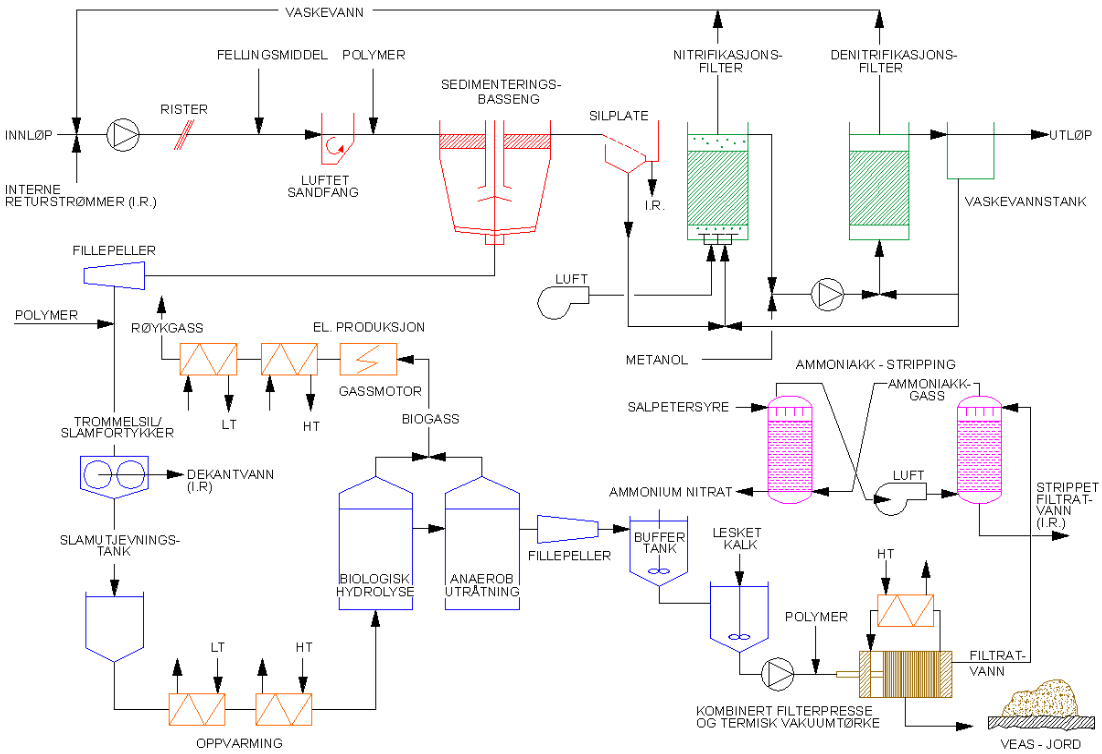


Figure 42. The wastewater and sludge treatment processes in VEAS (www.veas.nu)

It is noted that the sludge from sedimentation tank (sedimenteringsbasseng) flow to two-stage thermophilic digestion and further thermal vacuum drying to a dry solid content of about 50% before used on land as biosolid.

6. Suggestions on how to combine Sewage Sludge and Marine Algae to a Biosolid Composite

An important part of the Norway Grant project is to investigate possibilities of combining sewage sludge with marine algae to form a valuable bio-composite. The aim is to combine these waste products in an innovative manner to avoid the negative aspects of sewage sludge and solve the existing problems with stranded marine algae along the Romanian coastal line of Black Sea.

Some earlier work has been conducted on the combination of sewage sludge with marine algae to produce biofertilizer (Davidson 2008). The stranded marine algae is a problem all over the coastal lines shown in figure 43.

Figure 43. Marine algae on the coastal line of Romanian Black Sea

It has been showed that codigestion of seaweed and sewage sludge (50:50) has better methane production than seaweed alone (Fig 44).

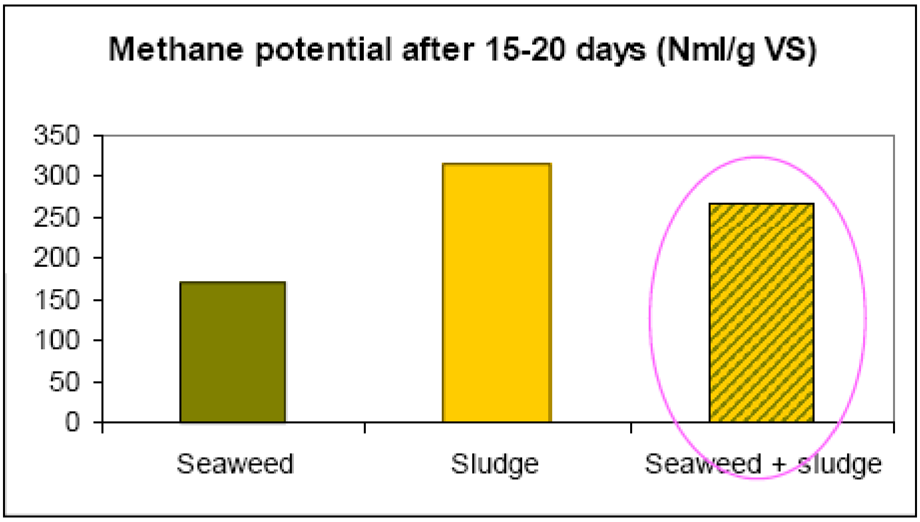


Figure 44. Codigestion of seaweed and sewage sludge (50:50) has better methane production than seaweed alone (Davidson 2008).

Pre-treatment by thermal hydrolysis produces the highest biogas yield compared to chemical (the second highest), coarse and fine disintegration.

The salt content in the seaweed reduced the methane production by 5-10%. As described in another report by NIVA for this project, heavy metals are able to accumulate in marine algae, therefore it might be required to reduce the heavy metal content if the content is high. Extraction of cadmium by acid can remove 75% of total cadmium.

It seems feasible to combine sewage sludge with marine algae to produce biosolids if there is no problem with heavy metals. However, more fundamental study is required.

An optimal flow sheet for the combination of sewage sludge and marine algae to biosolids should be based on the following points:

1. The minimum requirement for stabilisation and hygenisation—Anaerobic digestion and thermal hydrolysis as pre-treatment to produce Class A biosolids
2. The combination of proven technologies used in sewage sludge treatment and seaweed utilisation –anaerobic digestion and thermal hydrolysis are proven technologies
3. The combination of alternative technological routes should be based on optimal economic considerations. The thermal hydrolysis before mesophilic digestion maximise the biogas production.
4. The combination of different technologies should also be based on the traditional and existing systems Romania have in Black Sea (Constanta) area—anaerobic digestion has been used in the largest wastewater treatment plant in Constanta. (see figure 45)

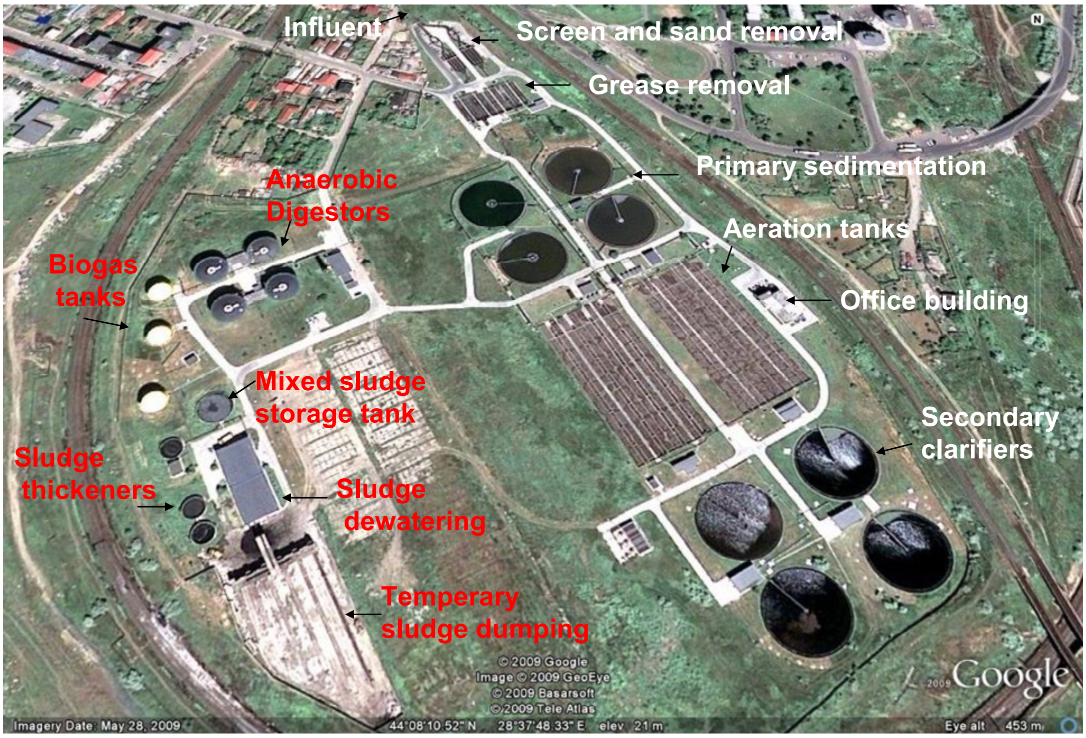


Figure 45. Constanta South Wastewater Treatment Plant (4 units of anaerobic digestors and three biogas tanks are used today)

Therefore a suggested flow sheet for bio-composite (biosolids) from sewage sludge and marine algae is illustrated in figure 46.

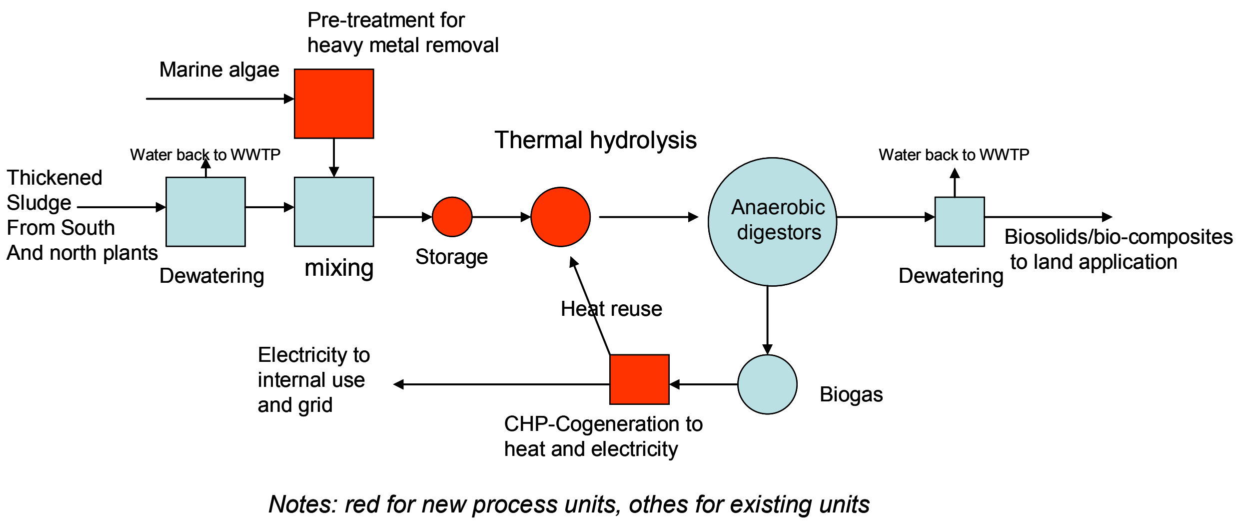


Figure 46. A suggestion to innovative bio-composite production from sewage sludge and marine algae in Constanta. Red color indicates new process units to be included.

The sludge from South and North plants in Constanta can be treated together. The marine algae can be transported to the plant via pre-treatment by heavy metal removal if necessary. Then the sewage sludge is mixed with algae before the new thermal hydrolysis process to enhance the bioconversion and biogas production. The existing anaerobic digestors should be big enough to deal with the increased load. The biogas production is used to co-generate heat and electricity, and the heat is further reused for thermal hydrolysis and heating. The end product is Class A biosolids, heat and electricity.

Pilot study is however required to facilitate the basis for successful application.

7. Literature

Alberto Vergara-Fernandez, Gisela Vargas, Nelson Alarcon, Antonio Velasco, 2008, Evaluation of marine algae as a source of biogas in a two-stage anaerobic reactor system. BIOMASS AND BIOENERGY 32 (2008) 338 – 344.

Barber W P F, (2009), From raw incineration to advanced digestion—influence of sustainability on meeting a sludge strategy, WEFTEC 2009.

Cambi AS, Introduction to Cambi thermal hydrolysis pre-treatment for advanced anaerobic digestion of sewage sludge, communication with Cambi AS, 2010.

Carrington E G, 2001, Evaluation of sludge treatments for pathogen reduction, ISBN 92-894-1734-X, © European Communities, 2001

Davidson Åsa, 2008, Biogas production from seaweed and waste. Presented Nordic Biogas Conference 2008 by Detox Company.

Demirel, Burak; Sheder, Paul; Yenigun, Orhan and Onay, Turgut T. (2010), Production of methane and hydrogen from biomass through conventional and high-rate anaerobic digestion processes, Critical Reviews in Environmental Science and Technology, 40:2, 116-146.

EBA (European Biogas Association) 2009, Current state and potentials of the biogas market in Europe. Presented at COGEN Europe Annual Conference 22 April 09.

Elliott H.A., O'Connor G.A., 2007, Phosphorus management for sustainable Biosolids recycling in the United States. Soil Biology & Biochemistry 39 (2007) 1318–1327

Harrison Ellen Z., Oakes Summer Rayne, Hysell Matthew, Hay Anthony, 2006, Organic chemicals in sewage sludges: Reviews. Science of the Total Environment 367 (2006) 481–497.

Institute for European Environmental Policy, 2009, Report on the Implementation of the Sewage Sludge Directive 86/278/EEC. Pp40.

Kalogo,Youssouf and Monteith, Hugh, 2008, STATE OF SCIENCE REPORT: ENERGY AND RESOURCE RECOVERY FROM SLUDGE. Global Water Research Coalition,

Kim, Jinkyung & Marion W. Shepherd Jr. & Xiuping Jiang (2009), Evaluating the Effect of Environmental Factors on Pathogen Regrowth in Compost Extract, Microb Ecol (2009) 58:498–508.

Lund H., Mathiesen B.V., 2009, Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 34(2009)524–531

Maria Cristina Nitoiu, 2009, Romanian Water and Wastewater Sectors, Embassy of the United States.

McClellan Kristin, Halden Rolf U., 2010, Pharmaceuticals and personal care products in archived U.S. biosolids from the 2001 EPA national sewage sludge survey. Water Research 44 (2010) 658 – 668.

Mininni G, 2001, Incineration with energy recovery, in Part II Options for Biosolids utilisation and sludge disposal, in *Sludge into Biosolids, processing, Disposal, Utilization.* Edited by Spinosa L and Vesilind P A, IWA Publishing, ISBN 1 900222 08 6.

Norsk Vann, 2008a, Stabilisering og hygienisering av avløpsslam – metoder i bruk i Norge, pp 23.

National Research Council, 2002, BIOSOLIDS APPLIED TO LAND: ADVANCING STANDARDS AND PRACTICES. National Academy Press, 2101 Constitution Ave., NW
Box 285, Washington, DC 20055, 800-624-6242, 202-334-3313 (in the Washington metropolitan area), http://www.nap.edu, Copyright 2002 by the National Academy of Sciences.

Norsk Vann, 2008b, Norsk Vann sin politikk for bruk av kvalitetssikret avløpsslam, pp 3.

Norsk Vann, 2008c, Hygienisering av avløpsslam – Norsk Vann sin anbefaling for kontrollopplegg, pp 10.

Novak J T 2001, Dewatering, in Part III Treatment options, in *Sludge into Biosolids, processing, Disposal, Utilization.* Edited by Spinosa L and Vesilind P A, IWA Publishing, ISBN 1 900222 08 6.

Novak J T, 2009. The advantages of thermal hydrolysis in sludge treatment, Water 21, Dec 2009. pp26.

Panter K and Auty D, 2009, Thermal hydrolysis, anaerobic digestion and dewatering of sewage sludge as a best first step in sludge strategy: full scale examples in large projects in the UK and strategic study including cost and carbon footprint. Presented at IWA Sludge Conference in Harbin China, 2009.

Pathak, Ashish, Dastidar M.G., Sreekrishnan T.R. 2009 ,Bioleaching of heavy metals from sewage sludge: A review. Journal of Environmental Management 90 (2009) 2343–2353

Pevere A, G. Guibaud, E. van Hullebusch, P. Lens, and M. Baudu, (2010), Viscosity evolution of anaerobic granular sludge, Biochemical Engineering Journal, Volume 27, Issue 3, January 2006, Pages 315-322.

Sidhu Jatinder P.S., Toze Simon G. 2009, Human pathogens and their indicators in biosolids: A literature review, Environment International 35 (2009) 187–201

Smith, Stephen R. 2009, A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge, Environment International 35 (2009) 142–156

Spinosa L., 2001, Evolution of sewage sludge regulations in Europe, Water Science and Technology, Vol 44, No 10, pp 1-8

Spinosa L and Vesilind P A, 2001, Sludge into Biosolids, processing, Disposal, Utilization. Edited by Spinosa L and Vesilind P A, IWA Publishing, ISBN 1 900222 08 6.

Stentiford E I, 2001, Aerobic digestion, in Part III Treatment options, in *Sludge into Biosolids, processing, Disposal, Utilization.* Edited by Spinosa L and Vesilind P A, IWA Publishing, ISBN 1 900222 08 6.

U. S. EPA, 2009, Targeted National Sewage Sludge Survey Overview Report. EPA-822-R-08-014, US EPA 2009.

Vesilind P A, 2001, Introduction to stabilisation, in Part III Treatment options, in *Sludge into Biosolids, processing, Disposal, and Utilization.* Edited by Spinosa L and Vesilind P A, IWA Publishing, ISBN 1 900222 08 6.

Vogelsang C., Liao, Z., and Tryland I., 2010, Resursutnyttelse ved RA—Leveranse No 12, Fagrådet.

Wang, Wei, and Qiao, Wei, (2009), Improve Sludge Dewatering and Anaerobic Digestion Performance by Hydrothermal Technology, IWA Sludge conference in Harbin, August 2009.

http://www.salsnes-filter.no

http://www.innovasjonnorge.no/TP_fs/Design/107-0730_IMG.JPG

http://www.evergreenengineering.ie/images/salsnes_dia_side.jpg

http://water.dhv.com/NL/waterbehandeling/afvalwater/Documents/Leaflet_Carrousel.pdf

http://www.enviroenergysystems.co.in/images/sbr1.jpg

www.anoxkaldnes.com

http://www.hrsd.state.va.us/images/ATP/Secondary%20Clarifier%20Equipment.jpg

http://www.mindfully.org/Water/UV-Disinfection-Wastewater.jpg

http://www.dcwasa.com/wastewater/wwt_process.jpg

http://media-2.web.britannica.com/eb-media/34/1534-004-5BBDA0CA.gif

http://www.princeton-indiana.com/wastewater/Media/wastewater/biosolids/gravity-belt-thickner-2.jpg

http://www.andritz.com/ep-mechanical-sludge-treatment-belt-filter-presses-001-big.jpg

http://www.freepatentsonline.com/7156801-0-large.jpg

http://pagesperso-orange.fr/isma/images/an_sat/photo2.jpg

http://science.jrank.org/article_images/science.jrank.org/landfill-techniques.1.jpg

http://www.scgreenpower.com/portal/page/portal/SCGreenpower/Images-Flash/gp_process.jpg

http://www.veas.nu

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