PRODUCT RECOVERY IN FUTURE SUSTAINABLE URBAN WATER SYSTEMS

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ABSTRACT

Wastewater handling in Sweden has gradually changed from drain off of wastewater and stormwater, successively better treatment of wastewater and handling of stormwater, and to today's trend to recycle resources. These changes have for instance been addressed in a research program "Urban Water" financed by MISTRA. A short summary will be given to projects related to resources recovery in the program. One project in the program performed at the div. of Water Resources Engineering, KTH, has the main focus on product recovery in sludge handling. This recovery may be accomplished by dissolution of different components from sludge followed by recovery of products. Dissolution of components from sludge leads to less remaining sludge, normally to better dewatering properties of the sludge and to possibilities to transfer released toxic components (as heavy metals) in a small stream for further handling. Present state of this concept is summarised for Sweden and examples of dissolution of sludge components and recovery of products are given from recently reported or ongoing master thesis works at the div. of Water Resources Engineering, KTH.

KEYWORDS

MISTRA, products, sludge, sustainable, Sweden, wastewater

INTRODUCTION

The basic requirements imposed for the urban water and wastewater systems are that they should without harming the environment, urban water and wastewater systems (Ministry for Foreign Affairs and SEPA, 1998):

- provide water for a variety of uses to households, factories, offices, schools and so on
- remove wastewater from users in order to prevent unhygienic conditions
- remove stormwater from streets, roofs and other surfaces in order to avoid damage from flooding

These basic requirements are in general fulfilled today in Sweden. Future requirements in addition to the basic ones are related to ecological sustainability as recycling of nutrients, energy savings and recovery, and public participation.

Eco-cycling in sludge handling has some similarities with recycling of wastewater for different purposes including the use as a source for drinking water. Recycling of wastewater is not an important question in Sweden due to good availability of water except for some smaller regions. However, wastewater reuse for different purposes is a question of increasing importance in many countries with water scarcity. In this case it is important to consider and use different barriers to prevent cycling of pollutants. Barriers can for instance be used to prevent supply of toxic substances to the water source, removal of pollutants in wastewater and water treatment facilities, and use of natural treatment by use of for instance artificial infiltration of treated wastewater. By combinations of different barriers a high security is obtained.

If substances in wastewater should be used as resources it is necessary to remove pathogens and toxic materials from the substances that are recycled and for instance are used in agriculture. Eco-cycling of components in wastewater/sludge should also consider the different barriers that can be used to prevent cycling of pathogens and toxic substances. Different barriers to remove these pollutants include:

- Source control of discharges into the sewer net (control of discharges from industries, hospitals etc, use of environmentally friendly household products and construction materials etc)
- Removal of old deposits of toxic substances from sewer net, treatment facilities at dentists, pipes in laboratories etc
- Special treatment methods in wastewater treatment plants
- Special precautionary measures in application of sludge or sludge products on for instance agricultural land (restrictions on supplied amounts, maximum concentrations of different pollutants, spreading time, type of crops etc)

MISTRA - PROGRAMME URBAN WATER

The Sustainable Urban Water Management programme, which started 1999 and encompasses 15 research projects dealing with drinking water, waste water and storm water has the main objectives:

1. Towards a non-toxic environment
2. Improved health and hygiene
3. Saving human resources
4. Conserving financial resources
5. Saving financial resources
6. Increasing Sweden's competitiveness

Supplementary requirements for a sustainable urban water system are:
- The system should have high functional security
- The system should be adapted to local conditions
- The system should be easy to understand and thus promote responsible behaviour by users

Three new future urban water systems are studied for their sustainability and compared with the fourth – a typical centralized system of today:

- The centralized "end-of-pipe" system is based on the existing system transformed in to a sustainable direction. Methods will be developed for wastewater and sludge treatment that are able to extract nutrients, heavy metals and energy to a large extent.

- A future centralized system, where the biological cycle is kept apart from the technical cycle requires the reconstruction of the wastewater collection system, with new pipelines and reconstruction of wastewater treatment plant.

- In the third studied future system the cycles are closed locally. In the technical system, industrial wastewater system should be handled and recycled as much as possible within industries, which is already largely the case. The storm water pollutant sources should be reduced and the water used in the cities. In the biological system, local separating methods could be applied. Decentralized, local system for collecting and handling urine and other fractions, or black water and grey water should be studied. If the biological cycles are closed on a local scale, the option to use the existing sewerage system for transportation and treating storm water and industrial wastewater will emerge.

In the centralized systems the requirements listed above for a sustainable water system will be met, but in the third system this is uncertain, especially the requirement relating to health and hygiene.

The are many ways of usage the sludge as resource in the future urban water systems and these even can be combined. Choice of treatment method gives different conditions for recovery of resources from wastewater and sludge. In Urban Water three ways are represented (Figure 1):

- 1. Better source control during water and wastewater treatment
- 2. Separation of different streams during water and wastewater treatment in such way that partly streams having low content of pollutants can be used for example in agriculture.
- 3. Sludge fractionation for product recovery and separation or removal of harmful substances from products.

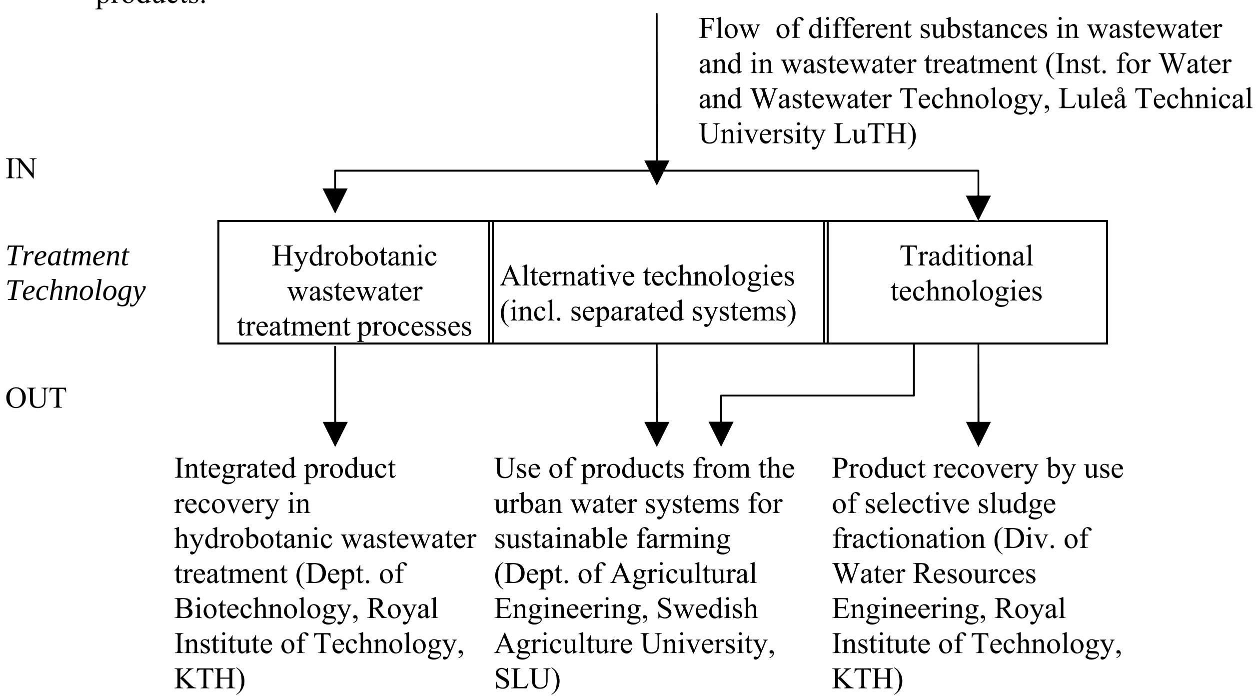


Figure 1. Flow of substances and product recovery studies within the MISTRA-programme.

Three research projects are dealing with product recovery from wastewater and sludge:
1. Product recovery by use of selective sludge fractionation
2. Integrated product recovery and wastewater treatment
3. Influence of sewage fertilizer products on sustainability of farming

Sludge fractionation in general may be performed at different stages of the sludge treatment process:
- handling of separate streams as anaerobic treatment of primary sludge and secondary sludge to decrease sludge production and recovery of post-precipitated sludges
- treatment of combined sludges before anaerobic digestion
- treatment of digested sludge for recirculation to the digester to increase gas production and decrease sludge volume

- treatment of digested sludge for product recovery and removal of heavy metals

CHARACTERISATION OF SLUDGE AS A RAW MATERIAL FOR PHOSPHORUS RECOVERY AND BIOGAS PRODUCTION

Characterisation of wastewater is necessary for efficient design and operation of treatment plants with biological nitrogen and phosphorus removal. Main characterisation for sludges has been directed towards sludge thickening and dewatering properties and on stabilisation degree of the sludge. If product recovery from sludges is an important goal, emphasis must be laid on characterisation of sludges in relation to the product that should be recovered. The products mostly studied are phosphorus containing compounds and biogas (methane).

Phosphorus fractionation is a way to better understand how phosphorus is bound to sludge and has earlier been used in studies of sediments (Löwén and Piirtola, 1998) and may be performed in different modified ways. A typical example is shown in Table 1.

Table 1. Phosphorus speciation method according to Uhlmann (1990)

Extractant	Soluble reactive phosphorus (orthophosphate)
Deionised water	Easily extractable (washable) phosphorus
Bicarbonate dithionite	Phosphate bound to ferric hydroxide
NaOH	Phosphate bound to metal oxides and exchangeable against OH^-; P compounds soluble in bases
HCl	Phosphate bound to $CaCO_3$, $MgCO_3$, in apatite and possibly in struvite

The anaerobic biological decomposition is generally considered to be a four step process: hydrolysis, fermentation, acetogenesis and methanogenesis. The methanogenic reaction is usually considered as the rate-limiting step, although in considering particulate substrates as sludges, hydrolysis may be the slower step. Hydrolysis means the breakdown of long-chain biomolecules to short-chain hydrolysis products, which are water soluble. Only in a water-soluble state they can penetrate the cells of bacteria to become degraded further. The composition of the sludge influences the optimal handling of sewage sludge handling.

A hydrolysis model for organic wastes is illustrated in Figure 2. The organic sludge fractions were divided into particulate lipids, particulate proteins and particulate carbohydrates. Studies, however, showed that it may be suitable to differentiate carbohydrates into glucose, starch and cellulose and proteins into fractions of animal and plant origin (Christ et al., 2000).

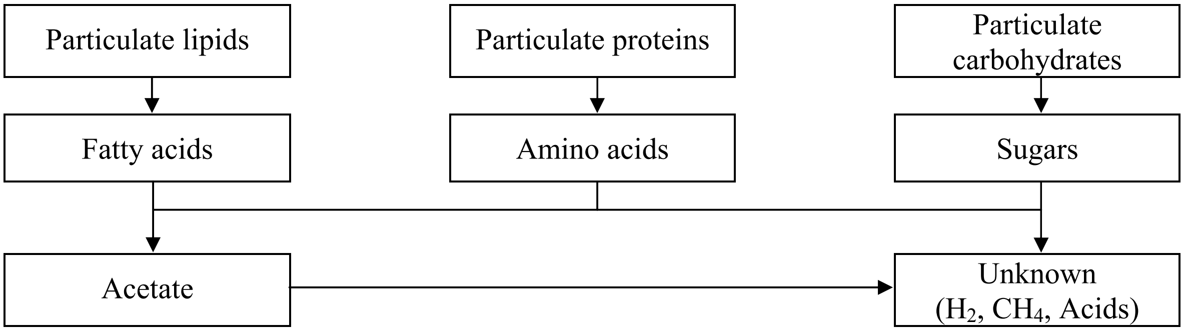


Figure 2. Hydrolysis model of organic waste (Christ et al., 2000).

Hydrolysis of sludges may be done by use of mechanical, chemical, thermal and enzymatic means. Each method hydrolyses sludges in different ways. It may therefore be suitable to combine different methods in one or several steps. Pre-treatment of sludges before anaerobic digestion may have the following effects:

- An increased rate of biogas production if hydrolysis is the rate determining step
- An increased production of biogas due to solubilisation of an increased amount of biodegradable materials
- Less sludge production due to the increased biogas production and release of certain sludge components
- Increased concentration of soluble compounds as phosphate and ammonium. This gives the possibilities of product recovery but may also cause operational disturbances as precipitation of magnesium ammonium phosphate or ammonia inhibition of methane production.

HYDROLYSIS OF SLUDGES AND DISSOLUTION OF SLUDGE COMPONENTS

Different sludges or ashes

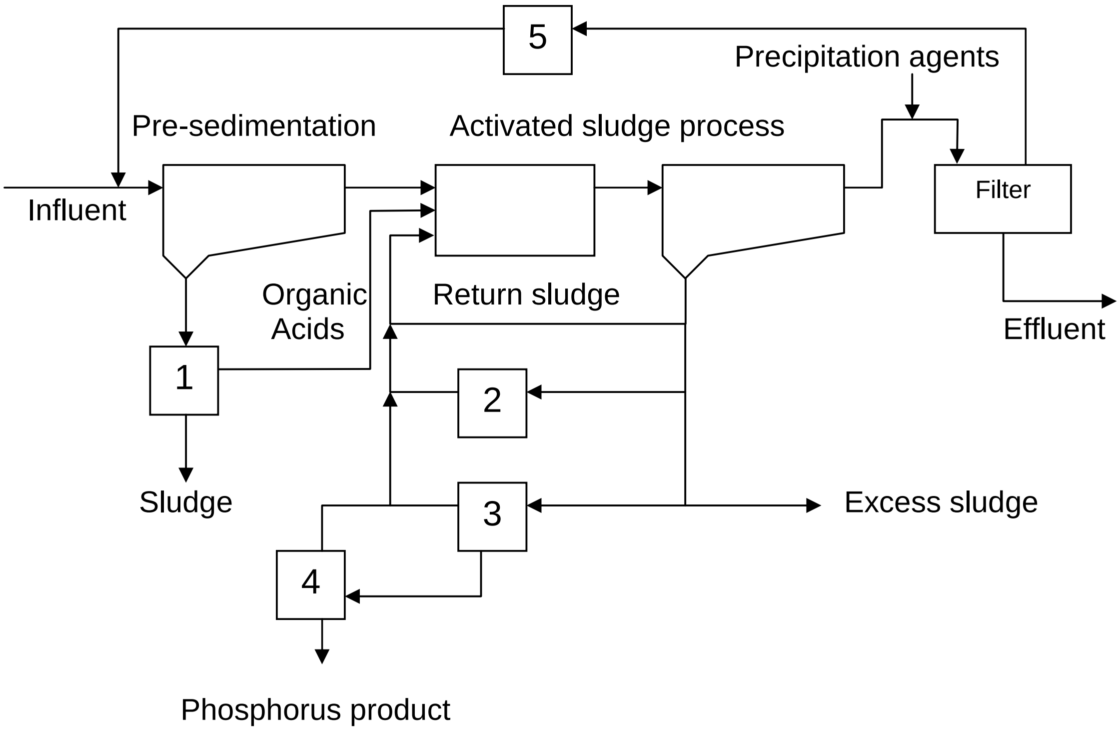
Hydrolysis or dissolution of different components from sludges can be done at different places in the process scheme for wastewater or sludges:

- Separate treatment of different sludges from the wastewater treatment processes (primary sludge, biological sludge, post-precipitated sludge)
- Pre-treatment before the digester and recycling of digested sludges
- Treatment of digested sludge
- Treatment of ashes from incineration of sludges

Sewage sludges may also be treated together with solid wastes. Sometimes other wastes are added to the digester and sewage sludge may be co-incinerated with solid wastes.

Separate treatment of sludges from wastewater treatment

In a wastewater treatment plant with primary sedimentation, biological treatment followed by a post-precipitation step it may be advantageous to treat the sludges separately in order to reduce the sludge production and/or recover resources. Different examples are shown in Figure 3.



(1) Hydrolysis of primary sludge for production of organic acids
(2) Treatment of a fraction of return sludge for reduction of excess sludge production
(3) Anaerobic treatment of a fraction of the return sludge for phosphate release
(4) Precipitation of phosphate
(5) Dissolution of post-precipitated sludge

Figure 3. Examples of modified operation of wastewater treatment plants for sludge reduction and production of organic acids, precipitation agents and phosphorus products.

Much attention has been given to treat primary sludges anaerobically in order to produce organic acids. These acids may be used for improvements of the biological phosphorus removal (Zeglin, 1999), denitrification or as a first step in anaerobic digestion.

Two different types of treatment of return sludge has got much attention. The first type of treatment is related to biological phosphorus removal by use of the Pho-Strip method. In this case a part of the return sludge is diverted to the anaerobic phosphorus stripper tank at a ratio of about 10-30 % of the influent flow. This tank also plays the role of a thickener. The solids retention time in the stripper tank varies between 5 and 20 hours. Released soluble phosphate in the supernatant from the stripper tank is removed by use of chemical precipitation with for instance lime or by crystallisation (Rybicki, 1997).

The second application of treatment of a fraction of the return sludge has the purpose to decrease the produced amount of excess sludge. By use of physical (as heat), mechanical, chemical (as addition of acids, alkali or ozone) or biological (as use of enzymes) cell walls are destroyed and the sludge is more easily degraded, thus giving a lower sludge production. This application has been reviewed by Low and Chase (1999).

An example of recovery of phosphorus and precipitation chemicals from post-precipated sludge has been reported by Ripl et al. (1988). The sludge produced by post-precipitation with ferric iron was treated with hydrogen sulphide to produce iron sulphide. Thereby 99 % of the phosphorus was redissolved by the transformation of iron phosphate to iron sulphide. The released phosphate was treated with lime to precipitate apatite. By treatment of the iron sulphide with hydrochloric acid hydrogen sulphide was released and used for dissolving phosphate and about 80 % of the iron was recovered. The remaining sludge contained most of the heavy metals.

In Sweden Lee and Welander (1996) have studied possibilities to decrease the excess sludge production by dispersing bacteria and increasing the grazing capacity of protozoa. Fujii (1997) reviewed in his master thesis work waste activated sludge reduction by chemical hydrolysis, endogeneous respiration and predatation. Introductory studies were performed to hydrolyse sludge by addition of sodium hydroxide. In one experiment activated sludge was treated 24 hours with sodium hydroxide at pH 12. The concentration of volatile suspended solids (VSS) decreased by about 30 % and the soluble COD concentration increased from 45 to 405 mg/l. Then the sludge, after neutralisation and seeding with activated sludge, was aerated 53 days the reduction of VSS was 77 %.

In another master thesis work Ostojic and Jillehed (2000) studied the release of COD and reduction of VSS of sludges treated by heat between 60 and 100 ^{o}C. In one experiment the soluble COD increased from 46 to 780 g/m^3, then sludge with a concentration of 5060 g VSS/m^3 was heated at 100 ^{o}C during 90 minutes. Then the sludge was aerated 13 days the VSS decreased by 38 % and the soluble COD to about 180 g COD/m^3.

Two ways of product recovery from post-precipitated sludge with ferrous sulphate as coagulant in deep-bed filters were studied by Zoppoth (1998). The first way considered recovery of the precipitation agent and thereby a reduction will be obtained of the sludge amount. The sludge was treated by hydrochloric acid at pH-values between 1.6 and 3.4. After mixing for half an hour total suspended solids (TSS), inorganic solids and volatile suspended solids (VSS) were measured. The inorganic solids dissolved almost completely already at pH 3.4, while the removal of VSS was below about 20 % (see Table 2).

Table 2. Suspended solids before and after addition of HCl

Before addition of HCl

Suspended solids SS mg/l	Inorganic solids mg/l	Organic solids VSS mg/l
96	20	76

After addition of HCl

pH	Suspended solids SS mg/l	Inorganic solids mg/l	Organic solids VSS mg/l
3.4	76	3	73
2.3	70	2	68
2.1	60	0	60
1.7	60	0	60

The dissolved inorganic material consists both of iron salts and phosphate. The molar ratio of Fe/P before the filter is high and the removed phosphorus normally less than about 1 mg/l due to addition of ferrous sulphate also to the pre-precipitation step. If the dissolved inorganic material from the post-precipitated sludge is transferred to the inlet a somewhat higher phosphate concentration will be obtained in the influent. Although a certain fraction of the recycled iron salts will be used to re-precipitate phosphate most of the recycled iron salts can be used for precipitation of phosphate in the wastewater from the sewer net.

Another investigation by Zoppoth (1998) was to study possibilities to selectively remove phosphate from the post-precipitated sludge by use of addition of sulphides. The intention was to transfer iron phosphate in the sludge into iron sulphide and thereby dissolve phosphate from the sludge.

Post-precipitated iron containing sludge was used. The phosphorus concentration in sludge on unfiltrated and filtrated samples and after addition of 120 mg/l sodium sulphide after 1 and 4 hours is shown in Table 3. The used pH value was 5. The release of phosphorus was about 27 % after 4 hours.

Table 3. Release of phosphorus

	Total phosphorus µg/l-P
Sludge ~ 100 mg/l SS	4965
Sludge ~ 100 mg/l SS filtered	48.5
Na_2S 120 mg/l 1h filtered	924
Na_2S 120 mg/l 4h filtered	1336

In order to improve the release of phosphate the pH value was lowered to 4 and experiments were performed during 6 days. The sludge concentration was about 100 mg/l and 120 mg/l of sodium sulphide was added and an additional amount of 120 mg/l was added after 4 days. The total soluble phosphorus concentration as a function of time is shown in Fig. 4. About 80 % of the phosphorus in the sludge could be released by the sulphide addition at pH 4.

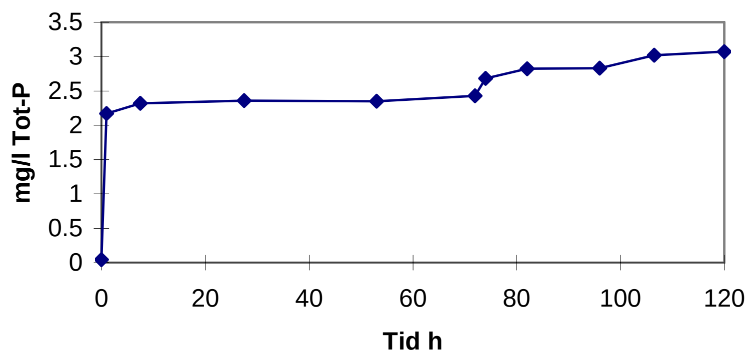


Figure 4. Release of phosphorus at pH4 and addition of sodium sulphide 120 mg/l + 120 mg/l

Sludge reduction and product recovery in connection with anaerobic digestion

Anaerobic digestion gives a reduction of sludge mass and possibilities to recover biogas. By different methods the reduction of sludge mass and production of biogas can be significantly increased and the supernatant from the digestion can be treated to recover dissolved phosphate and ammonium. Some possibilities for improved sludge reduction and product recovery is shown in Fig. 5.

The sludge from wastewater may be pre-treated before the digester to increase the release of sludge components and to increase the sludge biodegradability. The methods suggested are similar to those used to decrease excess sludge production and include:

- Mechanical treatment for disintegration of the sludge (Muller et al., 1998)
- Thermal hydrolysis (Schieder et al., 2000)
- Use of chemicals as acids, bases and oxidising agents as ozone (Weemaes et al., 2000)
- Use of enzymes (cell lysate) from disintegrated sludge (Dohanyos et al., 1997)

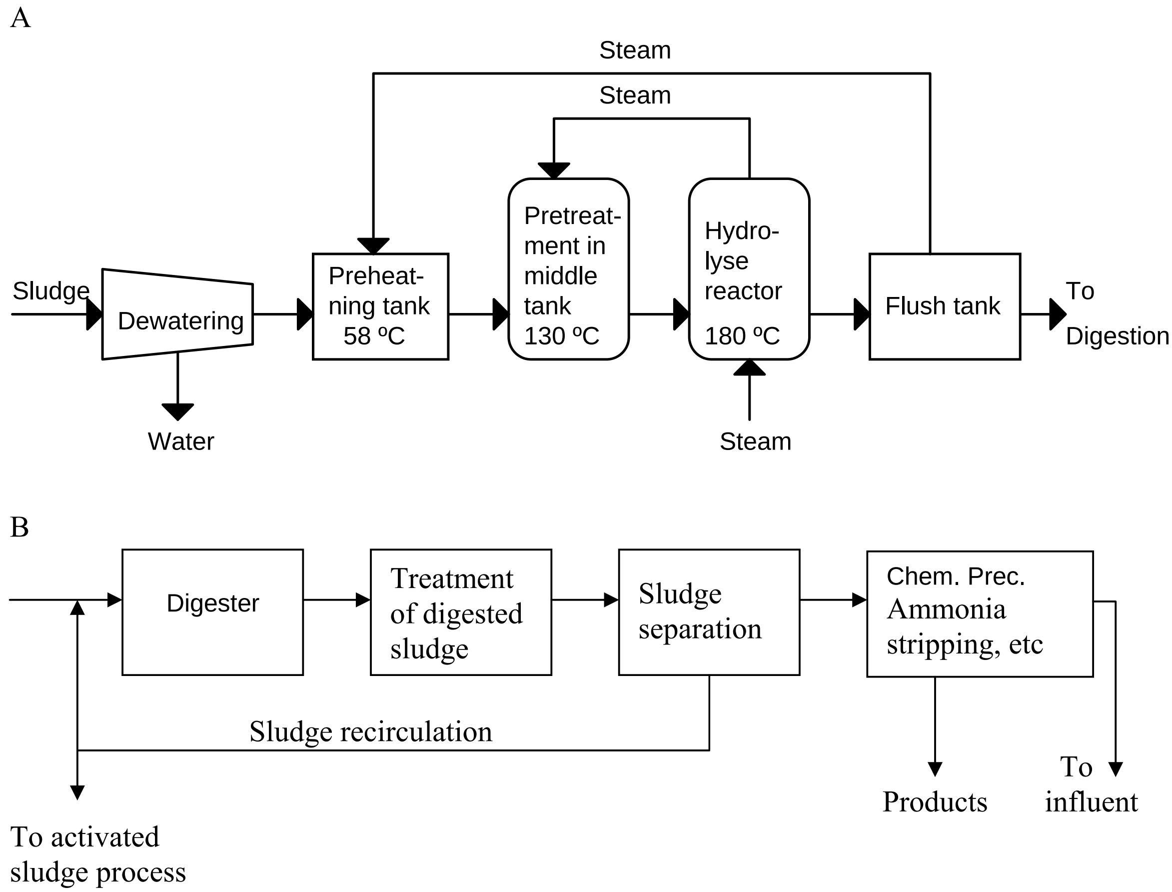


Figure 5. Thermal hydrolysis with the Cambi process (Gotthardsson, 1997) (A) and with further possibilities to increase digested sludge biodegradability and with product recovery (B).

Technologies for pre-treatment of sludges before digestion has not been studied to any larger extent in Sweden. However, recent problems for disposal of sludges has increased this interest and full-scale plans exist to pre-treat sludges by ultrasonic or to use the Norwegian process Cambi.

Ultrasound has many possible applications in environmental engineering (potable water, wastewater and sludge) and is one of many options for disintegration of sewage sludges (Neis, 2000). At high acoustic intensities gas bubbles are generated which will grow by taking in gas and vapour from the liquid. The bubbles change in size in relation to the acoustic wave and can collapse in the compression cycle (implosion). At sudden implosion of the bubbles, dramatic conditions exist in the gaseous phase with extreme temperatures and high pressures. The implosion causes rupture and disintegration of flocs and single cells (Neis, 2000).

A Swedish company (UltraSonus) has developed and patented ultrasonic equipment and is planning to use this equipment at Östhammar wastewater treatment plant about 100 km north of Stockholm. The ultrasonic equipment will treat sludge before anaerobic digestion and the intention is to show that the treatment will reduce the sludge amount and increase the biogas production.

The Norwegian process Cambi has also raised a large interest in Sweden (Gotthardsson, 1998). In the process, steam is used to disintegrate sludge before digestion. The HIAS plant (80,000 p.e.) in Hamar Norway have operated the system for more than three years and a full-scale system has also been installed at Thames's Chertsey works in England (Anonymous, 1999).

In the Cambi process dewatered sludge is thermally hydrolysed before the digestion. The hydrolysis starts with a thermal pre-treatment step, where sludge is homogenised and treated with steam (Fig. 5). Afterwards the sludge is pumped into the hydrolysis reactor, where the temperature and pressure are increased in steps. In a flush tank the steam is flushed off and the sludge cooled before pumping to the digester (Gotthardsson, 1997).

The result is that 30% of total COD is being dissolved. Thermal hydrolysis also improves digestibility of the sludge. The reduction of organic material by the digestion is increased from 45-50% to 65-70%, the biogas production is increased with 50% and the volume of dried residue is less than 50% of the dried residue from conventional digestion. Digested sludge after dewatering is treated by acids to allow recovery of precipitation chemicals and then dried to get stabilised, final product with 90-95% of total solids (Water Quality International, 1996a).

It is also possible to hydrolyse obtained digested sludge to make it biodegradable and to recirculate the treated sludge back to the digester or to the activated sludge process. Takashima et al. (1996) have found in laboratory studies that combined treatment of digested sludge with heat (175 ^{o}C) and sodium hydroxide and recirculation of the treated sludge back to the digester gave a nearly total digestion of the supplied activated sludge.

The supernatant from digestion contains a high concentration of ammonium and depending on conditions also sometimes of phosphate. The concentrations increase if pre- or post-treatment (with recycle) is used. Phosphorus may be recovered as apatite (by precipitation with lime) or as magnesium ammonium phosphate (by addition of magnesium salts and adjusting the pH-value) and nitrogen as magnesium ammonium phosphate or ammonium sulphate by use of ammonia stripping followed by absorption in sulphuric acid. The last process is used in Sweden in the city of Eslöv (Mossakowska et al., 1997).

Treatment of digested sludge

The digested sludge may be biodegradable by use of many methods. The mainly studied process in Sweden is the KREPRO process, which uses thermophilic hydrolysis followed by product recovery. The KREPRO system has been tested in the city Helsingborg and there are plans to install the system at the largest treatment plant (Sjölunda) in the city Malmö. It is expected that future costs for sludge handling will not exceed the present costs (Winnfors, 1999).

In thermal hydrolysis used in the KREPRO process digested sludge is treated in a reactor with sulphuric acid (pH of 1) at a temperature of 160ºC and pressure of 6 bar (Fig. 6). As the result of the process the sludge is fractionated and heavy metals and phosphorus are dissolved. The hydrolysed sludge is dewatered and the acid solution is neutralised and an inorganic hydroxide sludge is precipitated. The organic sludge residue has a too high content of mercury and copper and too low content of nutrients to be used as fertiliser. The inorganic sludge is used for recovery of phosphorus and precipitation chemicals. The sludge is dissolved in sulphuric acid and oxidised to get an iron phosphate precipitation which can be separated from an acid solution with the heavy metals. These are precipitated as hydroxides.

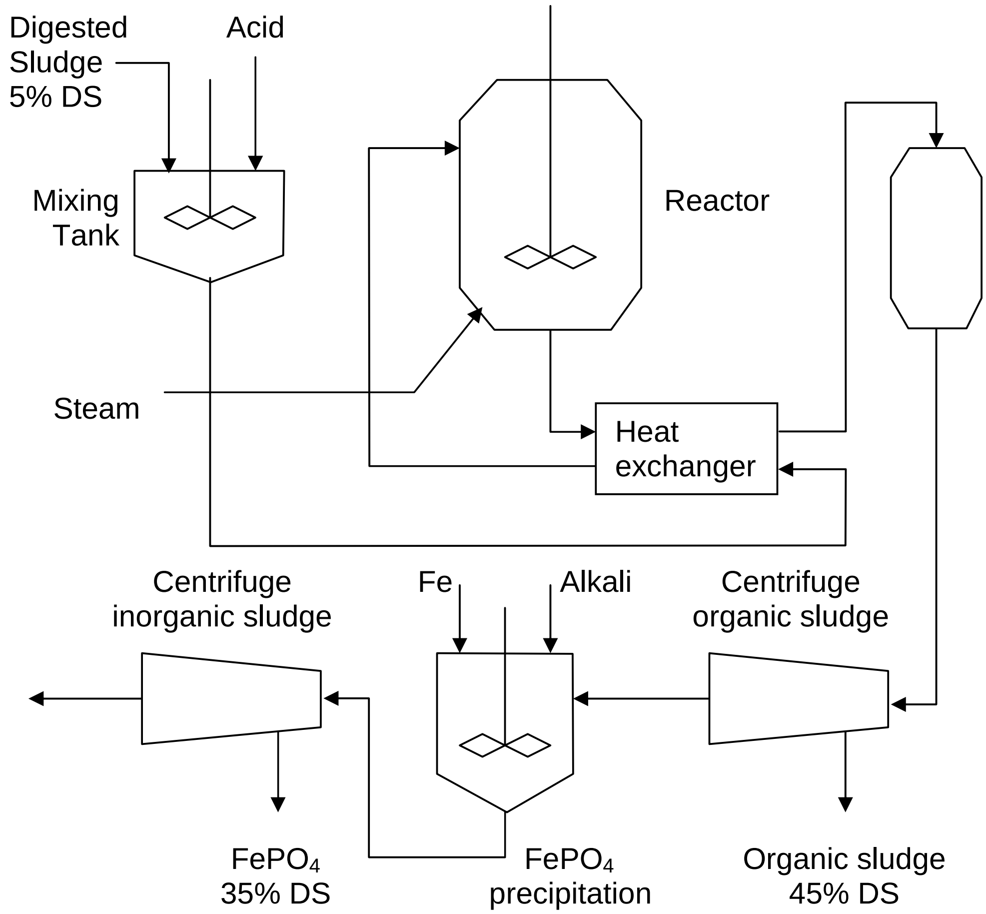


Figure 6. Thermal hydrolysis with KREPRO.

The KREPRO process gives sludge with high dewaterability. After hydrolysis all inorganic salts and about 40% of the organic matter are dissolved. The remaining organic matter is dewatered to about 50% dry solids. Following further precipitation inorganic sludge (containing the phosphorus, precipitation chemicals and heavy metals) can be dewatered to about 30%.

Treatment of ashes

Full-scale experiments with co-incineration of sludges with solid wastes or biofuels have been performed in Stockholm. The ashes were treated with acids to evaluate possibilities for phosphorus recovery. A complicating factor is the simultaneous release of phosphates and different metal ions (Levlin, 1997).

Treatment of ashes from mono-incineration of sewage sludge with sulphuric acid has been done by the Danish company BioCon (Fig. 7). The obtained liquor is treated by a system of four different ion exchangers to recover ferric ions (as precipitation agent), phosphoric acid, potassium hydrogen sulphate and metal ions, respectively. The system is planned to be installed in the city of Falun in Sweden (Widén, 2000).

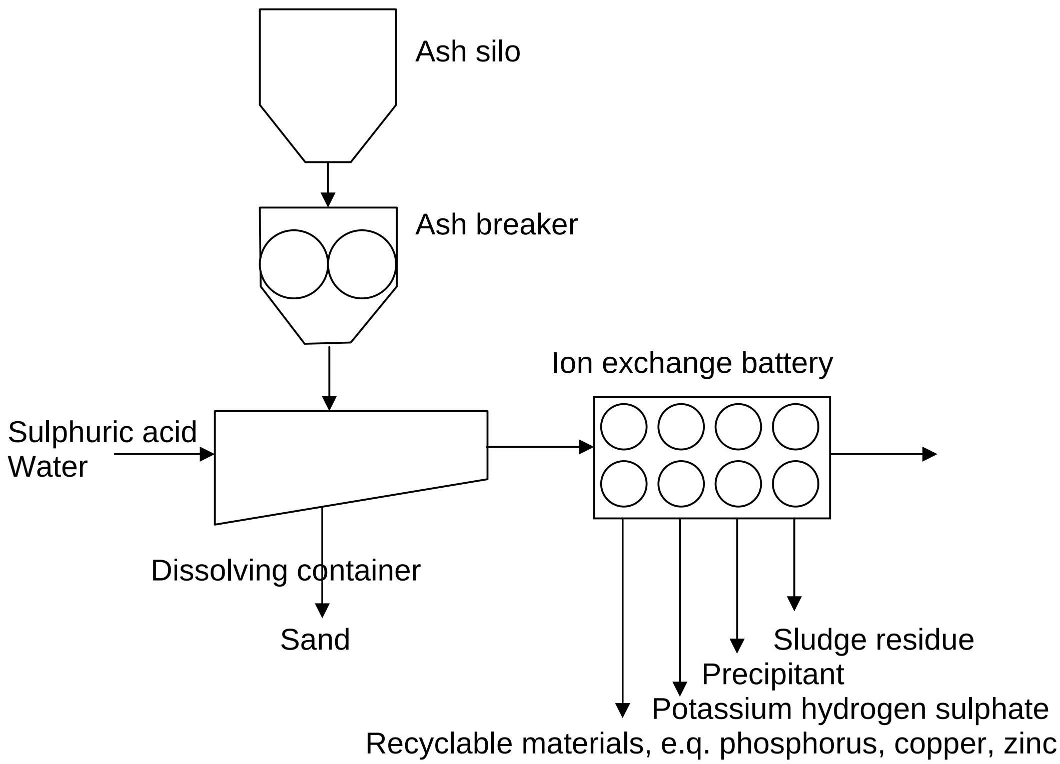


Figure 7. Resources recovery from ashes by the BioCon system.

DISCUSSION

Product recovery in wastewater treatment normally involves dissolution of different sludge components and/or making the sludge more easily biodegradable. Dissolution of sludge components and more efficient sludge biodegradation means that the sludge mass will be significantly reduced and different treatment methods of the sludge often improves the sludge dewatering properties. The released sludge components may be separated into different products or to small flows of harmful substances as heavy metals.

There are many methods both for dissolution of sludge components or increase of sludge biodegradability (physical, mechanical, biological and chemical) and to concentrate and recover dissolved sludge components (ion exchange, chemical precipitation, transfer to gas phase etc). The dissolution of components from sludges or ashes, increase of sludge biodegradability and recovery of products may be done at several places in the wastewater treatment plant as illustrated for different sludges from the wastewater treatment (Figure 3), sludges treated by anaerobic digestion (Figure 5), digested sludge (Figure 6) and ashes (Figure 7).

A systems approach should be used due to the many methods for treatment of the sludges, recovery of products and places for the treatment and recovery. It is possible that sludge reduction and product recovery should be seen as a multi-step process instead of one major step. Rather simple methods as dissolving post-precipitated sludge, anaerobic handling of a fraction of the return sludge for phosphorus recovery and mechanical disintegration of a fraction of the return sludge could significantly decrease the sludge amount for further handling and recover part of the phosphorus. Some pre-treatment of sludge supplied to the digester (as heat treatment or use of cell lysates) could again significantly reduce the sludge amount and increase the possibilities for product recovery as biogas and from the digester supernatant. The remaining sludge could then be treated by stronger agents as bases, acids and ozone in order to further decrease the sludge amount and increase the product recovery efficiency.

One product that is produced may be combined with another product. If, for instance, phosphoric acid is produced this acid may be used to absorb ammonia produced in an ammonia stripping system and ammonium phosphate will be the final product. A sustainable sludge handling system should not be dependent on external energy supply. The extra energy that may be obtained from biogas (electricity and heat) due to modified sludge treatment should for instance be sufficient for heat treatment of sludge and supply electricity needed for mechanical sludge disintegration or production of ozone.

CONCLUSIONS

(1) In order to obtain a safe eco-cycling of sludges or sludge products different barriers should be considered to prevent negative effects of harmful substances. Such barriers include effective source control, removal of old leaching deposits for instance in the sewer net, special methods to separate or destruct harmful substances and use of suitable spreading techniques and crops if sludge is used on land.

(2) A multi-disciplinary project "Urban Water" has started in Sweden with several universities involved to evaluate different methods to reach sustainable development. As a part of the program, research on different ways to recover resources in wastewater handling has been initiated.

(3) The focus at the div. of Water Resources Engineering, KTH, is directed towards sludge fractionation with the purpose to decrease the produced amount of sludge, recover valuable products and to separate harmful substances into a small waste stream.

(4) The technologies for increased sludge reduction and release of sludge components into a concentrated liquid are based on different physical, mechanical, biological and chemical methods.

(5) Treatment of excess sludge by heat or sodium hydroxide followed by aeration of the sludge leads to high reductions of the volatile suspended solids, about 35-40 % if the sludge is boiled and more than 70 % if the sludge was treated by sodium hydroxide at pH 12.

(6) The inorganic fraction of post-precipitated sludge with ferrous sulphate as the coagulant was almost completely dissolved at pH-values below 3.4.

(7) About 80 % of the phosphorus content in post-precipitated sludge with ferrous sulphate as the coagulant was released in experiments during six days with the addition of sodium sulphide and pH adjustment to a value of 4.

(8) Full-scale experiments are performed or planned in the near future in the Nordic countries to improve sludge reduction and to recover products. Such methods include the use of thermal hydrolysis of sludge before the digester (Cambi), product recovery from digested sludge by thermal hydrolysis in combination with the addition of acids (KREPRO), the use of ultrasonic (Ultrasonus) and the recovery of different products from ashes by use of ion exchange technology (BioCon).

(9) A system analysis approach is recommended for finding of suitable solutions for reduction of sludge mass and product recovery.

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