Sustainable sludge management – what are the challenges for the future?

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Abstract Sewage sludge is a serious problem due to the high treatment costs and the risks to environment and human health. Future sludge treatment will be progressively focused on an improved efficiency and environmental sustainability of the process. In this context a survey is given of the most relevant sludge treatment options and separate treatment steps. Special attention is paid to those processes that are simultaneously focused on the elimination of the risks for environment and human health and on the recovery or beneficial use of the valuable compounds in the sludge such as organic carbon compounds, inorganic non-toxic substances, phosphorus and nitrogen containing compounds. Also, a brief assessment is given of the specific future technological developments regarding the various treatment steps. Furthermore, it is discussed how to assess the various pathways which can lead to the required developments. In such an assessment the technical and economic feasibility, the environmental sustainability, the societal acceptance and the implementation route are important factors. The optimal approach also strongly depends on the local and regional situation of concern and the relevant current and future boundary conditions.

Keywords Assessment; scenarios; sludge; survey; sustainability; treatment

Introduction

During the last twenty years, developments in municipal wastewater treatment strategies are characterised by two aspects. The first aspect is a continuous effort to improve the quality of the effluent by upgrading existing treatment plants and designing and implementation of new more effective treatment plants. This effort simultaneously concurs with an enforcement of the industry and households to reduce or eliminate the discharge of toxic pollutants into the sewer. The second aspect is an increasing awareness of the problems associated with the sewage sludge produced in the wastewater treatment process. These problems are a continuous increase in sludge production, the high costs of sludge treatment and the risks sewage sludge may have to the environment and to human health. This is not surprising because the nature of the present wastewater treatment systems is such that toxic pollutants are concentrated in the sludge, together with a large part of the pathogens. Due to this increasing awareness regarding risks for environment and human health the original application of the sludge as a fertiliser in agricultural systems has become increasingly under pressure (Campbell, 2000). This is also caused by the increasing insight into the possible adverse effect of these toxic pollutants and pathogens. Parallel to this development also the government policy and regulations regarding the application of sludge in agriculture have changed considerably (Spinosa, 2001). However, policy and legislation regarding sludge application and sludge management in general are heavily dependent on local, national and regional circumstances and conditions.

Due to all these developments the current practice of sludge management has considerably changed during the past twenty years. Improved biogas production, advanced sludge dewatering processes, controlled land filling and thermal processes are increasingly applied in practice. This is accompanied with an increase in costs of sludge management. The costs often represent more than fifty per cent of the total wastewater treatment costs.
Due to the high costs, but recently also due to the urgency to develop more sustainable scenarios for sludge treatment, an increasing growth is observed in research into innovative more sustainable sludge treatment processes (Englande and Reimers, 2001; Ødegaard et al., 2002). This research involves a large variety of processes. Most of this research is focused on specific treatment steps of the sludge. Recovery and reuse of valuable products from the sludge is an important criterion in this development. However, with respect to this research, two aspects are very remarkable. The first aspect is that in the research into sludge treatment the waterline of the wastewater treatment process is rarely included, although the waterline processes strongly influence quality and quantity of the sludge. The second aspect is that often research into a specific sludge treatment step is limited to that treatment step only. The sustainability consequences of such a separate treatment step on the total chain of sludge management are rarely assessed.

The aim of this paper is to give a structural approach on how to achieve a more sustainable sludge management strategy in future. Starting points are an integral approach of both the waterline and sludge line and the approach to recover and reuse valuable products as much as possible and to minimise the adverse effect of sludge on the environment. Both current sludge treatment processes that are applied in practice, as well as possible innovative processes are briefly considered and evaluated. The paper is aimed at providing a framework that can be used in the discussion about more efficient and sustainable wastewater treatment systems including sludge treatment as an integral part of it.

Characterisation of sludge
To identify potential scenarios for a more sustainable treatment it is useful to briefly assess the composition of the sludge. As a rough guide this composition is characterised by five groups of components:

- non-toxic organic carbon compounds (approximately 60% on dry basis), Kjeldahl-N, phosphorus containing components,
- toxic pollutants:
  - heavy metals, such as Zn, Pb, Cu, Cr, Ni, Cd, Hg, As (concentrations vary from more than 1,000 ppm to less than 1 ppm)
  - PCBs, PAHs, dioxins, endocrine disrupters, linear-alkyl-sulfonates, nonyl-phenols, etc.,
- pathogens and other microbiological pollutants,
- inorganic compounds such as silicates, aluminates, calcium and magnesium containing compounds,
- water, varying from a few per cent to more than ninety-five per cent.

The fundamental problem of the sludge is in fact that all these compounds are present in one mixture. Organic carbon, phosphorus, and nitrogen containing compounds can be considered as valuable compounds. This often holds for the inorganic compounds as well. Sustainable treatment involves the recovery and useful reuse of the valuable products and the minimisation of the possible adverse impact of sewage sludge on the environment and on human beings. For reasons of transport, disposal or efficient treatment it is also often required to remove the water. With respect to the amount of Kjeldahl-N in the sludge it has to be noted that this amount is small compared with the amount of Kjeldahl-N present in the wastewater. Kjeldahl-N is mostly present as ammonia, a potential fertiliser component. It has to be noted that both the industrial production of ammonia from an energy source, such as natural gas, and the biological destruction in the wastewater treatment requires energy. In modern wastewater treatment systems most of the Kjeldahl-N is destroyed, using also a certain amount of the valuable organic carbon compounds present in the wastewater. The
water in the sludge has in fact no real value, but is very often an obstacle and important cost factor in sludge management.

**Treatment options**
There are six basic approaches to manage the sludge problem in a more sustainable way:
- improvement of the quality of the sludge,
- beneficial use of organic carbon compounds and inorganic compounds,
- reduction of the total amount or volume of sludge,
- recovery of phosphates from sludge for reuse,
- change in treatment scenario of municipal wastewater,
- combination of different approaches.

All these basic approaches are based on molecular and phase separation processes and phase contact processes, microbiological and chemical conversion processes, or combinations of these basic processes. It is further noted that some of these basic approaches or combinations of approaches can still result in a residual amount of sludge that needs a final environmentally sustainable destination, such as a controlled landfill.

**Improvement of the quality of the sludge**
In this approach, three possible routes are identified to improve the sludge quality. With respect to heavy metals these approaches could be as follows.
- Improvement by prevention of the discharge of pollutants to the sewer. Pollutants such as heavy metals, but also pesticides, endocrine disrupters, etc. originate from households, industrial and agricultural activities or from rain water. Over the last twenty years a strong decrease in the discharge of pollutants is observed and it is expected that also in future this decrease will continue (Balmer, 2001). Very helpful is the disconnection of the rainwater. However because of the origin of pollutants, which is often very diffuse and very diverse, and because of the fact that the sewage is often considered as a transport medium for pollutants, it is doubtful that prevention finally leads to a sludge quality far above the quality that can currently be achieved.
- Removal of colloidal and suspended particles from the influent as a first treatment step. It is known that heavy metals in the sewage are mainly bound to the particles present in the wastewater. Furthermore the heavy metals ab(d)sorbed to these particles are more or less equally distributed over all particles. An exception is nickel which is mainly present in soluble form. Removal of the particles results in a primary sludge that is relatively heavily polluted with heavy metals. The next step in this approach could be a precipitation step, for example with sodium sulphide, focused on the removal of nickel and the residual amounts of other dissolved heavy metals. The remaining effluent is free of heavy metals and can be treated biologically. As a result the biological sludge will have a high quality regarding heavy metal concentration.
- Removal of the heavy metals from the sludge by chemical leaching with inorganic and organic acids or complexing agents or by microbiological leaching using Thiobacilli (Marchioretto et al., 2002). With these methods a substantial reduction in heavy metal concentration can be achieved. However, the process requires the use of chemicals and the treatment of leaching liquid containing the heavy metals and is therefore thought to be only applicable in case of very strongly polluted sludges.

The above mentioned methods are primarily focused on quality improvement of sludge with respect to heavy metals. This may be of interest if a further treatment of the sludge requires that the concentration of heavy metals is not too high. These methods are not or are less effective for removal of toxic organics or pathogens, although pathogens are probably also removed for a substantial part. Removal of toxic organics from sludge is possible by
extraction and selective oxidation processes. However, in general these processes are more complicated than the processes for the removal of heavy metals.

**Beneficial use of organic carbon compounds and inorganic compounds**

Within this approach six options are relevant.

- Production of biogas as an energy source, a process that is already applied worldwide on a large scale. A lot of research is currently focused on increasing biogas production by applying hydrothermal heating, microwave heating, ultrasonic heating, use of ozone, use of enzymes, use of liquid jets, pretreatment (hydrolysis) with sodium hydroxide, high performance pulse techniques, wet oxidation and supercritical oxidation as a pretreatment step (Camacho *et al*., 2002; Dohányos *et al*., 2000; Goel *et al*., 2003; Müller, 2002; Neis *et al*., 2000; Weemaes *et al*., 2000). Compared with the standard anaerobic treatment of sludge, biogas production can approximately be doubled, depending on the type of treatment. It is clear that the beneficial effect of a pretreatment step mainly depends on the type of the pretreatment step and the costs of the pretreatment. Furthermore, in all these processes a substantial part of the organic carbon compounds is still not converted into biogas.

- Production of a fuel or feedstock in the form of diesel oil or a gas, for example hydrogen in case of gasification, pyrolysis, or hydrothermal heating at high temperatures (Jaeger and Mayer, 2000; Stolarek and Ledakowicz, 2001). The production of diesel oil from sludge is already applied in practice (Skrypsi-Mäntele *et al*., 2000). The other processes are still in the developing phase. Important aspects in all these processes are the type and quality of the products and their market value.

- Direct use as an energy source (Rulkens, 2003). Examples are the direct incineration of dried sludge in combination with energy recovery and the application of dried sludge as an energy source in coal fired energy power plants, already applied in practice (Luts *et al*., 2000). It is also possible to simultaneously use the organic containing compounds and the valuable inorganic compounds in a useful and beneficial way. Examples of such an application, already applied in practice, are the use of (dried) sludge in the production of Portland cement, and the productions of light weight aggregates, slags and bricks (Okuno *et al*., 1997; Taruya *et al*., 2002).

- Production of volatile acids such as formic acid, acetic acid and propionic acids. This can be achieved either by microbiological processes such as acidification or thermal processes such as wet air oxidation and hydrothermal treatment. Also here the quality of the products and their market value are important factors with respect to the feasibility of these processes (Shanableh and Jomaa, 2001).

- Production of other types of chemicals using microbiological conversion processes or sludge extraction processes. Basically there are various possibilities. However, regarding extraction of valuable compounds from sludge, it is currently doubtful, in view of the large number of toxic pollutants and the strong variation in composition of wastewater and sludge, that this approach will lead to an economically feasible process.

- Supercritical oxidation of sludge. This process occurs in the water phase at temperatures and pressures above the supercritical point of water. Supercritical water shows special properties such as a superior ability to dissolve oxygen and a very high oxidation rate with respect to organic compounds. Energy recovery can occur directly by heat exchange in the reactor or from the exit flow from the reactor. This process is still in the developing phase.

**Reduction of the total amount of sludge**

Many processes are available for this purpose. Some that are focused on the reduction of
organic carbon compounds have already been discussed in the previous paragraph. In addition to these processes there can also be mentioned:

- Use of higher organisms such as protozoa and metazoa. The process is still in the development stage (Rensink and Rulkens, 1997). Recently we found in our laboratory some metazoa that can be used to reduce the amount of sludge produced. Besides this, proteins can be extracted from these organisms, which makes this process even more attractive.
- Ozone treatment of sludge in combination with aerobic microbiological oxidation of the treated sludge in an activated sludge system. This process is already applied in practice. The process reduces the amount of sludge but requires energy (Egemen et al., 2001).
- Aerobic and anaerobic composting, and vermicomposting. In the latter process microbiological conversion takes place by the use of worms (Vigueros and Camperos, 2002). These processes are also applied on a practical scale. Dependent on the quality with respect to toxic compounds such as heavy metals the product can be used as a soil improver.

The amount of sludge can also be considerably reduced by mechanical dewatering of the sludge or by sludge drying. Mechanical dewatering must be preceded by an appropriate sludge conditioning step such as coagulation/flocculation or wet air oxidation. Many modifications of all these processes are already applied worldwide in practice. New, more innovative processes which are already available but which are currently still not applied on a large scale, or which are still partly in a development stage, are electro-osmotic dewatering, advanced drying processes using low caloric waste heat sources, sludge conditioning by freeze-thawing followed by dewatering, application of high frequency heating, and Carver-Greenfield evaporation (Brindley, 1984; Ching Yuan and Chih-Huang Weng, 2002). From a technical-economical point of view there is room for further improvement of sludge dewatering and sludge drying processes. In general the aim of a specific removal process for water is to reduce the final amount of sludge which has to be disposed of in a controlled landfill. However, the aim can also be the increase of the thermal value of the sludge, for example if the sludge is used as a fuel in power plants or in cement production.

**Recovery of phosphates (P) from sludge**

A P-recovery step is often combined with a more general approach on how to recover value products from sludge in combination with the removal of heavy metals from the sludge in order to improve the quality of the sludge and/or the use of sludge as an energy source. Recovery of P is interesting because a lack of P-resources is expected at the end of this century (Levlin et al., 2002; Stark et al., 2002). There are in fact three possibilities to recover phosphorus from the sludge and/or wastewater:

- P-recovery from the sludge by thermal, chemical or microbiological methods or a combination of these methods,
- direct P-recovery from the wastewater in the water line. In this case P is removed by chemical precipitation from the water phase in the anaerobic zone after the sludge has been separated,
- P-recovery from the ashes of sludge incineration plants, for example by means of extraction processes.

Some of these methods can already be applied in practice, others are still in the research stage. It can be expected that the effort to recover phosphorus will strongly increase in the near future.

**Change in treatment strategy of municipal wastewater**

The fifth approach is based on a change in treatment strategy of the municipal wastewater. There are two possibilities. One possibility is an alternative method of centralised
treatment that is primarily based on physical/chemical treatment of the wastewater. This way is schematically shown in Figure 1. In this scenario the first step is a physical/chemical treatment step focused on complete removal and concentration of colloidal and suspended particles by means of flotation or ultrafiltration using organic polymers. The subsequent step is to use a hyperfiltration step in which soluble P, N and organic carbon compounds are concentrated, making it easier to recover P and N by precipitation from the concentrate. The remaining concentrate, containing soluble organic carbon compounds, is digested together with the sludge from the first step. In this way the organic compounds, nitrogen and phosphorus containing compounds are more or less completely available for beneficial use. Furthermore, energy for aeration is not necessary. Calculations at this scenario, which is still in the developing stage, show that 50% more biogas can be produced compared with conventional methods. The second possibility is the decentralised sanitation, an issue which currently is of much interest. A strong point of this scenario is that dilution of wastewater does not occur, making it more easy to recover value products for reuse. Also large transport systems are not necessary. The weakness is that an intensive infrastructure is necessary to collect products and the lack of advantages of large scale treatment, such as costs and availability of expertise. Also the risks for human health are a factor of concern.

Combinations of treatment systems

The mentioned approaches for sludge treatment are often applied in combination with each other, particularly if the treatment process is applied in practice. Examples are the thermal processes in which dried or mechanically dewatered sludge is used. It is of course not always necessary to focus on processes or treatment steps in which sludge is the only waste that has to be treated. It can sometimes be very beneficial or sustainable to treat sludge in combination with other organic or inorganic wastes. Examples are the incineration of sludge in an incinerator for municipal waste, and, as already mentioned, the use of sludge for cement production. Another example is the co-digestion of sludge and another organic waste to increase biogas production.

Assessment and evaluation

It is evident that there are many scenarios and processes to tackle the sludge problem. Which route or process is most optimal mainly depends on the specific circumstances of the region of concern. Factors which have to be assessed in each specific case are:

- technical feasibility and reliability,
- economic feasibility and costs acceptance,
- environmental sustainability, more specifically defined in terms of energy use, prevention of emissions of pollutants and waste, and recovery and reuse of valuable products also including energy and the effluent,
marketing aspects of the valuable products,
infrastructural and logistic aspects,
environmental policy and legislation, national as well as international,
implementation route,
potential risks of residual amounts of sludge for human health,
public acceptance of the chosen scenario,
future technological aspects in other areas of pollution control.

These assessment factors not only heavily depend on the specific local or regional circumstances but also on the environmental policy and legislation, both in a local or national context but also in an international context. To assess all these factors an intensive and difficult path has to be followed. In this path detailed cost calculations have to be made, and studies have to be executed in order to find out which products are required by the market. This is especially the case if a sustainable sludge management route is developed in combination with a treatment process of another waste stream or in combination with an industrial production process. The expected requirements regarding future treatment of wastewater have to be taken into account as well. Also the developments in, for example, energy policy may influence the outcome of this assessment. Environmental impacts can be quantified by Life Cycle Assessments. The general consequence of this assessment approach is that the way to achieve a sustainable development in sludge treatment may not only vary between the highly industrialised western countries and developing countries, but also between individual countries. A tailor made approach is always required.

Discussion and conclusions

A sludge management strategy involves the integrated application of various separate sludge treatment steps or treatment processes. From the previous analysis it is evident that there is a large variety in treatment steps and in the development stage of these treatment steps. Some processes are already applied in practice on a large scale for a long period of time and operate more or less optimally. They have little potential for further improvement. Some processes are already applied in practice but still have potential for further improvement. In this respect mechanical dewatering of sludge, also including the conditioning step with inorganic or organic coagulants and flocculants must be mentioned. Also sludge incineration can substantially be improved with respect to energy recovery.

Other sludge treatment steps are for a large part still in the development stage, such as gasification, pyrolysis, supercritical wet oxidation, application of protozoa and metazoa, recovery processes for phosphate, and sludge pretreatment processes focused on an increase of the biogas production from sludge. As already mentioned, from a more generic technological point of view, all sludge treatment processes and separate sludge treatment steps are based on either phase contact processes and molecular and phase separation processes, chemical and microbiological conversion processes, or combinations of these basic processes. Because these basic processes are also applied in many industrial branches it can be expected that there is a continuous improvement of existing processes and the development of new, innovative processes. This development is also of high importance for future sludge treatment. However, taking into account the very complex composition of sludge and the presence of various types of hazardous substances, it is an illusion to expect that sludge treatment will become substantially less expensive in future. To reduce net costs the focus of sludge treatment has to be more and more on the recovery of potential valuable products from sludge and the development of markets for these products. Also the integration of sludge treatment in other industrial activities, or waste treatment processes, may result in a reduction of the net costs.

The development of more sustainable sludge management strategies requires that the
sludge problem has to be considered in a broader context than has been done in the past. To identify the most sustainable options and the routes to implement these options a broad assessment of the various sludge treatment scenarios and options is necessary. This assessment has to be based on current practice, research results, specific relevant local circumstances, general policy regarding wastewater treatment and sludge treatment, technical and economic feasibility and environmental benefits. Basic aspects in this assessment approach are not only the recovery of valuable products from sludge, the destruction of toxic pollutants and/or pathogens, and the prevention of discharge of toxic pollutants into the sewerage system. Also aspects such as the current national and international policy with respect to sludge, the expected changes in future regarding this, and the public involvement and acceptance, especially regarding treatment location and health aspects, has to be taken into account.

Contrary to the approaches of the past, waterline and sludge line have to be considered simultaneously and in an integral way. In the future this may also lead to a change in water treatment systems. It is evident that there is no such thing as a uniform and unique system which is most sustainable. Each situation basically requires its own tailor-made solution which is most sustainable to the conditions of the specific area in question. This need for a diversification is a characteristic aspect of sludge management. Due to the many factors influencing the sustainability of a sludge treatment system, but also due to progress in insight in the problem and progress in technological tools, sludge management has to be considered as a dynamic activity, always looking for the most efficient sustainable solution at the location of concern and valid within the present and future boundary conditions. To operate a sludge treatment system in a constructive and optimal way within this set of constraints is the challenge for the future.

References


