From sludge to resources through biosolids

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Abstract The paper gives an overview of the possibilities to achieve a more sustainable sludge management strategy by recovering and reusing valuable products as much as possible. Discussion separately deals with the recovery of products suitable for “material” uses and those for “energy” ones. Discussion on material recoveries includes organic matter, nutrients, carbon source, coagulant, bricks, pumice, slag, artificial lightweight aggregate (ALWA) and Portland cement. Regarding energy recovery, (i) conversion processes, including thermo-chemical conversion of dry sludge to oil, thermo-chemical liquefaction of wet sludge to oil and conversion/combustion processes, (ii) deep shaft wet air oxidation, and (iii) gasification processes, including starved air combustion, are outlined. Only general indications are given because the selection of an appropriate system for sludge management is strongly influenced by many other important factors, such as local economy and geography, climate, land use, regulatory constraints and public acceptance of the various practices. Also, the conventional and more traditional recycling options, like agricultural and other land uses, and incineration with energy recovery, are not dealt with because they are well known and extensively discussed elsewhere.

Keywords Biosolids; energy recovery; material recovery; reuse; sludge management

Introduction

The management of sludge in an economically and environmentally acceptable manner is one of the critical issues facing modern society, due to the very fast increase in sludge production, as a result of extended sewerage, new work installations and up-grading of existing facilities. In addition, during the last decade, there has been a worldwide movement toward a common strategy for any kind of waste with the priorities of reusing waste materials and taking advantage of their material and energy content.

This could be sufficient to recognize the material and energy value of this material, and the need of communities to effectively and beneficially manage it. Extensive research works have been carried out on treatment and disposal of sludge for the past decades, and significant advances in technological and managerial aspects have been achieved.

In this context, it is, however, quite difficult convincing the public that a material with such an ugly name as “sludge” could actually be beneficial, so the use of the name “biosolids” has been introduced in the English language. However, a similar terminology evolution has not found a wide acceptance in other languages, also because often difficult to be translated, so it seems more appropriate to use the word sludge only when speaking of the solids streams within the wastewater treatment plant, and out of it when this material is disposed of without any utilization, and to use the word biosolids only the moment the solids, in whatever form, leave the treatment plant, destined for some form of beneficial use.

Aim of this paper is to give an overview, and discuss the possibilities to achieve a more sustainable sludge management strategy by recovering and reusing valuable products as much as possible. The conventional and more traditional recycling options, like agricultural and other land uses, and incineration with energy recovery, are not dealt with because they are well known and extensively discussed elsewhere.

It seems, also, necessary to stress that any action addressed to recovery of useful
materials or energy from sludge could be positively influenced by a preliminary reduction of the total amount of sludge and/or the improvement, directly or indirectly, of its quality.

Discussion separately deals with the recovery of products suitable for “material” uses and those for “energy” ones. Preventative actions to reduce the sludge mass production and to improve its quality, together with possible changes in treatment scenario of municipal wastewater, are also outlined.

**Preventative actions**

Many sludge components could be valuable for recycling, but it is likely they are more or less contaminated with different dangerous compounds, such as heavy metals, PAHs, and pesticides, pathogens, etc., that should not be part of a recycling process. The fundamental problem is that all these compounds are present in one mixture, while a sustainable treatment involves the recovery and useful reuse of the valuable products and the destruction of the toxic compounds.

It seems, therefore, necessary to stress that any action addressed to recovery of useful materials or energy from sludge could be positively influenced by a preliminary reduction of the total amount of sludge and/or the improvement, directly or indirectly, of its quality.

These actions include biological treatment in combination with ozone treatment, use of higher organisms, such as protozoa and metazoa, aerobic and anaerobic composting, and vermicomposting, advanced dewatering processes, such as electro-osmotic dewatering, advanced drying processes, conditioning by freeze-drying, and Carver Greenfield evaporation, prevention of the discharge of toxic micropollutants into the sewer, removal of colloidal and suspended particles from the influent as a first treatment step, removal of the heavy metals from the sludge by chemical leaching with inorganic and organic acids, complexing agents or by microbiological leaching.

**Material recovery**

**Organic fraction**

The organic fraction of a sludge (the other fractions being water and inorganic one) represents the energy source, but is also suitable for the quality improvement of soils low in humic substances. However, organic sludge contains fewer nutrients than conventional sludge, but also less heavy metals (Hansen, 2001).

Another application for the organic fraction could be as a raw material for activated carbon; trials have shown that the specific surface is 30–40% lower than for a commercial activated carbon, but it works as a conventional activated carbon (Hagström et al., 1997).

**Nutrients**

The nutrients content, mainly nitrogen and phosphorus, is also of interest (Hansen, 2001).

**Nitrogen** is mainly present as ammonium, but also as organic nitrogen. The ammonium can be separated from the sludge in many different ways, but since the main stream of nitrogen in sludge handling is in the reject water from the dewatering, this is best treated.

Ammonium can be separated with stripping or as struvite. Stripping is the most common method: the final product, in liquid form, is normally ammonium sulphate or ammonium nitrate that can be used for agriculture. Struvite, or magnesium ammonium phosphate, is a salt that could be precipitated from the reject water. It is also possible to separate ammonium from the reject water with ion exchange or adsorption techniques, for instance with zeolites.

**Phosphorus** has to be regarded as the most valuable product in the sludge; in addition, it is not an endless resource because in 150 years the apatite mines known today will be empty and we will have no reliable phosphorus sources left, so it is essential to recover the
phosphorus in the sludge since this is one of the major available phosphorus streams in society today. Unfortunately, new regulations and more stringent demands on sludge quality may put a future ban on its agricultural application. This means that the phosphorus has to be cleaned or separated in a non-polluted fraction from the sludge.

There are several techniques to recover phosphorus from sludge available today. In a biological phosphorus removal process parts of the phosphorus can be recovered quite easily. During anaerobic digestion, the bio-P bacteria release parts of the phosphorus; phosphorus will then remain in the reject water when the sludge is dewatered. This phosphorus source is quite pure also because the heavy metals are remaining in the dewatered sludge. The maximum recovery yield with this technique is 50%.

If a higher yield is desired, chemical/physical processes are required. Depending on the sludge quality, it is possible to dissolve more than 90% of the phosphorus in the sludge. If the sludge is merely acidified, the yield is about 70% or more. Unfortunately, when the sludge is treated with acid, not only phosphorus is dissolved but also precipitation chemicals (if present) and all kinds of metals, including heavy metals. The heavy metals have to be separated beforehand or the phosphorus has to be precipitated in an environment where the heavy metals are not precipitated. This product is as pure as a commercial fertiliser and has to be considered as a non-polluted phosphorus source.

It is also possible to recover phosphorus out of the ash from incinerated sludge. Ash is dissolved in an acid and the phosphorus is either separated as mentioned above or with ion-exchangers. Also the precipitant and the heavy metals can be separated in an ion-exchange process.

**Carbon source**

When sludge is hydrolyzed, it is possible to produce a carbon source which can be applied either for biogas production or for improved nitrogen removal (denitrification). Also biological, chemical, mechanical and enzymatic processes do the same (Kristensen and Jørgensen, 1992).

Biological carbon source production normally treats primary sludge which is submitted to fermentation into an anaerobic reactor at a temperature lower than in a digester, and a shorter retention time. The sludge is partly degraded, but no methane gas is produced. The fermentation produces what are intermediate products in the digester, i.e. volatile fatty acids. These will follow the reject water and can be used either to enhance a bio-P process or for improved denitrification. Also enzymes or chemical treatment (low or high pH) can be used for carbon source production.

Another method is mechanical sludge treatment. When the sludge is mechanically disintegrated, dissolved organic substances in the cells release because the cell membranes have been damaged. Mechanical disintegration can also be used to improve biogas production and reduce sludge volumes (Hansen, 2001).

**Coagulant**

On many plants, coagulant, or precipitation chemical, is used to remove phosphorus and/or to increase the capacity of the wastewater plant. This is also a recoverable fraction. Through acidification the coagulant dissolves and can be recycled to the water treatment. Also heavy metals and phosphorus dissolve at a low pH and these will consequently be pumped back to the influent water together with the coagulant. To secure low concentrations of phosphorus and heavy metals, they have to be separated first.

Ion-exchange techniques can also be applied when the coagulant is recovered (Hansen, 2001). Other usable materials which can be recovered from sludge are bricks, pumice, slag, artificial lightweight aggregate (ALWA), and Portland cement (Okuno, 2001).
Bricks
The world’s first full-scale sewage brick plant started operating in 1991 in Tokyo with a capacity of 5,500 bricks a day out of 15,000 kg of incinerated sludge ash. Importantly, no heavy metals leach from the finished bricks, even in adverse environments with pH levels as low as 3.

The molding process is the key to success in making the brick from 100% ash without any additives, so it must be carefully carried out. Also temperature should be carefully controlled. When the kiln temperature reaches 900°C, it is held steady for one hour to prevent “black core”, the phenomenon that occurs when organic substances are poorly oxidised; temperature is then gradually increased to 1,030°C and maintained for 20 minutes to fully heat the molded ash. A slow cooling cycle then follows to avoid breaking from thermal strain, and 4 hours should be taken to cool to air temperature.

The properties of the sewage brick are superior to those of traditional bricks in all respects, including compression strength, water absorption rate, abrasion strength, and bending strength. The sewage brick has been well received and widely applied in public walkways. However, problems of moss growth, ice, and whitening appeared.

Pumice
Pumice is manufactured using the same approach as sewage bricks, with the addition of crushing and sieving processes. Particular attention is paid to reusing the final product for the underlayer of athletic fields. Generally, volcanic gravel is used for this purpose, because it rapidly drains excess water but holds sufficient moisture, thus maintaining the condition of the athletic field. However, volcanic gravel is scarce and sewage pumice is a promising substitute.

Slag
When volume reduction and the immobilization of heavy metals are the primary aims, slag is a possible solution because the volume is reduced to only 4% of the original one. Processing cake slag is fuel efficient, and the calorific value of the organic content of the sludge cake contributes to heat the furnace. However, the process requires an effective drying unit and skilful operation. From operational data, it has been observed that 80% of the metal elements included in the sludge cake remain in the ash, provided that the maximum temperature of the incinerator is maintained below 800°C.

Two different kinds of slag can be manufactured: water-cooled slag and air-cooled slag. Both varieties are vitreous, and meet the standards of the crushed gravel used for concrete, but their compression strength is not comparable to that of natural gravel. Air-cooled slag is used as a substitute for natural coarse aggregate, including concrete aggregate and backfilling material, ready mixed concrete aggregate, roadbed materials, permeable pavement, interlocking tiles and other secondary concrete products.

Artificial lightweight aggregate (ALWA)
A 500 kg/h plant for producing artificial lightweight aggregate (ALWA) began operations in 1996 at the Nambu plant in Tokyo. Incinerated ash is blended with water (23% w/w) and a small amount of alcohol-distillation waste, that acts as a binding reagent. The mixture is then moved to a centrifugal pelletizer, the pellets are dried at 270°C for 7–10 minutes and then conveyed into a fluidized-bed kiln where they are briefly heated at 1,050°C. After heating, the pellets are air-cooled and a hard film forms on their surface, while the inside remains porous. The end product is spherical and has a specific gravity of about 1.5.

Compared with commercial lightweight aggregates, this ALWA has greater sphericity, lower specific gravity, and less compressive strength. Major reuses include fillers for...
clearance between kerosene storage tanks and room walls, planter soils, flower vase additive, thermal insulator panel, substitution of anthracite media of rapid sand filters, water-infiltrating pavement. Because of its elasticity, attractive appearance and avoidance of rainwater pooling, pedestrians appreciate walkways paved with this material.

**Portland cement**

A further potential use for the sludge is as a substitute raw material for Portland cement in replacement of portion of major ingredients, such as CaO, SiO₂, and F₂O₃, traditionally supplied in the form of natural limestone and clay. Manufacturers accept incinerated ash, dried sludge, or dewatered sludge cake, depending on the operation type, being the concentration of P₂O₅ the most important factor in determining whether sludge is suitable for this application. Although no standard exists, the maximum allowable concentration of P₂O₅ seems to be 0.4%. Being the average concentration of P₂O₅ in incinerated ash around 15%, incinerated ash could be blended to comprise up to 2% of the raw material of the concrete volume.

Another related application is in lime blending. In this process, a dewatered sludge cake is blended with an equal amount of lime; moisture is removed from the cake through chemical reactions between which requires a little additional heating, eventually producing a dry powder.

Dried cake is an effective raw material and fuel in Portland cement manufacturing, so technological developments are focussed on drying the dewatered sludge cake. Examples are the “deep frying in waste oil” process, or a drying/pelletizing one.

**Energy recovery**

There are numerous sludge management technologies that fit the classification of thermal processes other than incineration. Established technologies, such as Multiple Hearth Furnace, Fluidised Bed Furnace, Combustion with Solid Waste, are well known and extensively discussed in literature, so only technologies, such as conversion processes, deep shaft wet air oxidation, and gasification processes, including starved air combustion, are reviewed in the following (Bridle, 2001).

**Conversion processes**

There are three principal variants of the conversion processes: thermo-chemical conversion, thermo-chemical liquefaction, conversion/combustion.

The *thermo-chemical conversion* of dry sludges to oil (or low temperature conversion) mimics nature in the way that liquid hydrocarbons are generated from organic substrates, with both thermal cracking and catalytic conversion playing major roles in the process, that is, the process is much more than mere pyrolysis. The conversion takes place at between 400°C and 500°C in the absence of oxygen, essentially at atmospheric pressure.

When processing different sewage sludge, and industrial one, the yields are generally of 15 to 40% for oil, 30 to 70% for char, 7 to 10% for gas, and 10 to 15% for reaction water.

The oil produced by the process has a quality similar to a medium fuel oil and can be used for electricity generation. Unlike biological processes, thermo-chemical conversion is not adversely impacted by inorganic or organic contaminants present in the sludge.

Advantages of this technology include recovery of readily usable and storable liquid fuels, provision of net energy outputs, generation of greenhouse credits, complete control of heavy metals, including mercury, destruction of organochlorine compounds, complete destruction of all pathogens and viruses, odour control, small footprint for plant, minimisation of material requiring trucking off-site, low operating costs. The main disadvantage of the technology is the capital-intensiveness and the relative complexity of the plant.
The direct thermo-chemical liquefaction of wet sludges to oil was initially conducted, at pilot plant scale, at Batelle-Northwest Laboratories in the USA in the mid 1980s, where liquid sludge at about 20% total solids is heated to about 300°C and 10 Mpa pressure for about 90 minutes to effect the liquefaction process, generating a heavy oil, char, gas and reaction water. The technology was then patented as STORS (Sludge-to-Oil Reaction System). Typically oil yields ranged from 10 to 20% and char from 5 to 30% by weight. Oil viscosities are very high, with the oil being a solid at room temperature. Gas yields essentially CO₂, averaged 14%, with the remainder being reaction water (wastewater). The wastewater has a very high BOD, reported to be 30,000 mg/l.

The main advantages of this technology include generation of usable/storable liquid fuels, apparent low operating costs, small footprint for plant, possible destruction of pathogens and viruses, minimisation of materials requiring trucking off-site. The disadvantages include high operating pressures, difficulty in separating products, complex equipment; in addition this process has been only tested at pilot scale.

With the conversion/combustion process the gases are combusted rather than condensed to produce a liquid fuel. Most of the work has been done on organic wastes, such as municipal solid waste (MSW), with or without small quantities of sewage sludge. The MSW is first shredded and then combined with dewatered sewage sludge before being converted at 450°C, in the absence of oxygen, to produce a carbonised solid stream and a gas. The solids are separated to remove the glass, metals and ceramics from the carbonised material, which is entrained into the gas, which is then combusted at 1,300°C, to produce steam and a granulated slag. The steam can be used as a heat source, or be converted to electricity in a steam turbine. Combustion off-gases are cleaned in a complex gas cleaning system incorporating wet scrubbers, electro-static precipitators and fabric filters before being vented to atmosphere. According to available data, the air emission standards can be easily met, and the solid residues recycled, other than the gas cleaning residues, which are classified as hazardous wastes. It has been also reported that the technology will generate 1,050 kWh/t of waste processed.

The conversion/combustion technology involves minimisation of wastes requiring off-site disposal, recovery of energy as gaseous fuels, control of heavy metals and organochlorine compounds. Insufficient data are available on the technology disadvantages.

Deep-shaft wet air oxidation
Deep-shaft wet air oxidation is based on aqueous-phase (wet) oxidation of the organics in sewage sludge, using either air or oxygen as the oxidant. The oxidation takes place at a minimum of 260°C and up to 150 Mpa pressure. A unique feature of the technology is that the pressure is achieved by suspending the reactor in a deep shaft, up to 1,500 m deep.

The aqueous stream contains about 30% of the original organics in the sludge and significant quantities of nitrogen, so it is either returned to the head of WWTP or pre-treated and discharged. The residual solids are inert materials, comprising mainly carbonates, silicates, phosphates and nonleachable heavy metals. Energy can be recovered from the system, as hot water.

Aqueous phase oxidation of sludge offers numerous environmental advantages including complete destruction of all pathogens and viruses, control of heavy metals and odour, relatively simple operation, small plant footprint, minimisation of material requiring trucking off-site. Disadvantages include shut downs required for reactor de-scaling due to inorganic substances and large wastewater stream requiring extensive treatment.

Gasification
Gasification is essentially a variant of starved air combustion, operating at temperatures of 900°C, at least. Sub-stoichiometric quantities of oxygen or air are injected with the sludge,
to allow some combustion of the carbon to CO$_2$, which then reacts with solid carbon, to produce CO. The major constituents of the gas from gasification of sewage sludge are CO, H$_2$, N$_2$, CO$_2$, CH$_4$ and H$_2$S. Conventional gasification of sewage sludge generates a solid residue (char) that still contains some volatile material. The fate of heavy metals in conventional gasification systems has not been clearly defined.

An advanced pressurised entrained flow gasifier has been demonstrated at pilot scale in Germany. Gasification takes place at high temperature (1,400 to 1,700°C) and high pressure (0.6–2.6 Mpa), using pure oxygen as the oxidant. At these high temperatures, the ash from the sludge forms a molten slag, which is quenched, in the bottom of the gasifier, forming fine grained slag particles. The raw gas is cleaned by removing CN, NH$_3$ and H$_2$S to produce a high quality syn-gas. The vitrified slag is completely inert and can be used as an ingredient in concrete mixes. Extensive monitoring of the process has revealed that heavy metals and organochlorine compounds are completely controlled.

Based on pilot testing of this gasification technology it has been demonstrated that the technology can offer complete destruction of all pathogens and viruses, control of heavy metals, including mercury, destruction of organochlorine compounds, odour control, minimisation of material requiring trucking off-site, recovery of energy, potential greenhouse credits. The disadvantages include relatively complex system, and unknown costs; in addition, it has not been proven at full scale.

**Conclusions**

In previous sections it has been shown that sludge, even if contaminated, can be considered a raw material resource for a variety of products and compounds, instead of a waste, so the opportunities represented by sludge should be recognised and investigations on recycling possibilities and applications continued.

The selection of an appropriate system for sludge management should have, as a priority task, the maximization of material and energy recoveries from sludge, and the minimization of the total energy needs and cost of processing. To this end, many technological options are available on the market; however, their selection and application is influenced by many other important factors, such as local economy and geography, climate, land use, regulatory constraints and public acceptance of the various practices, must not be neglected. Due to that, only general indications are given in the paper, just to avoid drawing conclusions not valid in all contexts.

It follows that the correct management of sludge requires the development of a “multiple and diversified options” strategy which is a combined challenge common to city administration, citizens and industry. First, these groups should aim at reducing the amount of sludge produced, second, higher quality sludges should be produced.

Therefore, for optimal sludge management decisions, a case-by-case solution has to be found by determining what is the best solution based on local and site-specific considerations, and then, once the optimal disposal/use practice has been chosen, by defining the treatment/s necessary to optimize the entire system, as a whole.

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**References**
