

Wastewater sludge as a resource: sludge disposal strategies and corresponding treatment technologies aimed at sustainable handling of wastewater sludge

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Abstract The paper discusses different strategies for the disposal of wastewater sludge, particularly the “use on land” strategy and the “productification” strategy. In the “use on land” strategy the new regulations in Europe call for stabilization as well as disinfection of sludge to be used on land. The paper discusses the design and operation experiences with stabilization/disinfection methods in Norway where such treatment has been compulsory since 1995. In the “productification” strategy it is differentiated between the production of “bio-soils” and production of specific products (energy, nutrients, coagulants etc) and the “marketability” of these products is evaluated. An example of a sludge treatment concept aimed at recycling – the KREPRO process – is presented.

Keywords Beneficial reuse; disposal alternatives; land application; sludge management

Introduction

There are principally three final disposal strategies for wastewater sludge and sludge components even though there are many “grey zones” between these clear-cut alternatives. Sludge and sludge components may be **deposited** on land (in landfills or special sludge deposits), in the sea (ocean disposal) or to a certain extent in the air (mainly as a consequence of incineration). Sludge and sludge components may also be **used** in different ways. The most obvious one is the direct use of treated sludge on land as a fertilizer and soil conditioner. Treated sludge may also be used on land indirectly after having utilized it as one of the ingredients in constructed “bio-soils”. Finally sludge and sludge components may be **recycled** in a “productification” strategy, i.e. a strategy aimed at making products from sludge intended for sale in the market place. Such components/products may be “bio-soils” (mixture of sludge with other materials), energy (biogas, electricity, oil, heat etc), nutrients (phosphate, nitrogen), metals (coagulants), etc.

Ocean disposal of sludge is nowadays in practice forbidden and sludge deposits in landfills are to be phased out, even though 35–45% of the sludge in Europe is still deposited. Incineration ash will have to be treated like a hazardous waste, a fact that probably will out-phase this solution as well, in favour of use or recycling, because of cost. In reality, therefore, deposition of sludge and its components will not be accepted in the future. It is undoubtedly so that most experts in the field of wastewater sludge handling consider direct use of sludge on land as the most sustainable way. This is also reflected in the working document for a proposed new sewage sludge directive of the EU (Anon., 2000). Nevertheless, use of sludge on farmland for food-production stands under considerable threat as a consequence of concern from the farming sector as well as from consumers regarding the possible long-term health effects of such use.

It is now recognised that sludge must undergo certain treatment steps before use, in par-

ticular disinfection, when it is to be used on farmland. This is now a central requirement in the working document towards a proposed new sludge directive from the EU (Anon., 2000). In Norway we have implemented disinfection of sludge for a ten-year period already and our experiences with the alternative treatment technologies in order to comply with the various regulations will be summarised below.

The “productification” strategy is growing in momentum as a consequence of the concern connected to farmland use. This main strategy may be combined with the other strategies but is different in the way that it considers the sludge as raw material for some marketable products. There are two principally different trends. The first is the production of “bio-soils”, i.e. soil products with treated sludge as a central ingredient to be used on green areas (parks, sporting fields, road embankments, golf courses, etc.) where food is not produced. The treatment required for such products is more or less determined by the same regulations as for use of sludge on farmland. This type of land use is increasing in many countries and may represent a very interesting alternative to use on farmland in the future. The other trend is to go for specific products that can be recycled. One sub-strategy that has been practiced for many years is to use some of these products “on-site”, i.e. at the treatment plants (like heat, electricity made from biogas, coagulants, etc.). A more ambitious sub-strategy is to recover components/products that can be sold in the open marketplace (electricity, heat, coagulants, phosphate, oil, etc.). Below we shall shortly discuss and give examples of treatment technologies used for the recycling/“productification” strategies.

Treatment of sludge in “the use on land” strategy

In the third draft of the Working document on sludge (Anon., 2000) that probably will lead to a new sludge directive in the European Union, it is stated that: “Sludge should be used on land whenever possible and only according to relevant Community or national legislation”. The working document outlines then the framework within which such use on land may take place. It defines what kind of treatment is necessary for different disposal alternatives in order to comply with the regulation.

Generally one differs between conventional treatment and advanced treatment. Conventional treatment includes stabilization (in order to reduce its biodegradability and its potential to cause nuisance) and dewatering (in order to reduce transport cost) while advanced treatment includes sludge disinfection as well (in order to prevent health hazards). Environmental hazards caused by potentially toxic elements (i.e. heavy metals and specific organic compounds) are to be controlled by regulating limit values for concentrations of such compounds in the sludge to be used as well as in the soils where it shall be used.

The Norwegian public health and environmental authorities jointly issued a new regulation for sewage sludge treatment and use on farmland in 1995, with an amendment in 1996. Since it took several years to get them through the bureaucracy, we have in fact practiced these regulations more or less since the beginning of the 1990s. One goal announced by the authorities was to recycle 75% of the total sewage sludge production for beneficial use on land areas within the year 2000. The figure for 1995 was about 66% and in 1999 it was already 79% (69% on farmland and 10% on green areas). In addition to stringent standards for heavy metals content in both sludge and soil and regulations on application rates and the type of crops to be grown on sludge applied areas, the Norwegian regulations include a general requirement for stabilization and disinfection of all sewage sludge before land application. Since there are no good analytical methods available that can be used for determination of a stabilized sludge, the authorities have chosen to approve a set of methods, outlined in Figure 1.

According to the Norwegian regulations, the sludge should meet the following criteria for disinfection:

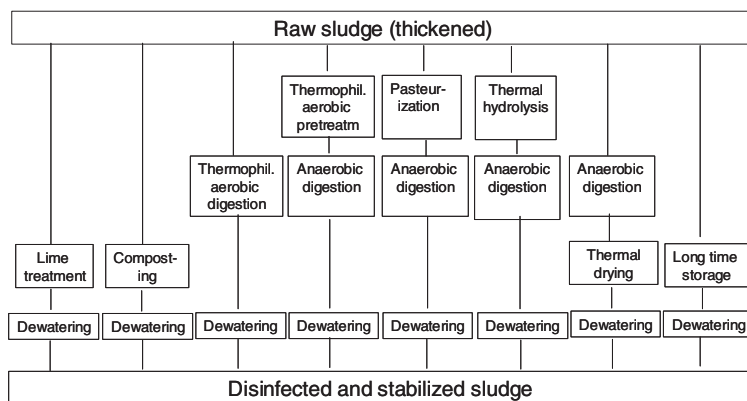


Figure 1 Approved methods for stabilization/disinfection of sludge in Norway

- No *Salmonella* sp. in 50 grams of sludge.
- No viable helminth ova.
- Not more than 2,500 faecal coliforms per gram dry solids.

It is not allowed to spread liquid sludge on land areas and no sludge should be applied on frozen ground. The sludge must, therefore, be stabilized, disinfected and dewatered (min 25% DS). The Norwegian Water and Wastewater Works Association initiated in 1995 a study where the main objective was to collect and summarise operational experiences with the new sludge handling processes in order to recover information for future design and operation of such plants (Paulsrud and Nedland, 1996). A brief summary of the operational experiences from this study is given below as well as some experiences collected later.

Lime treatment

Addition of quicklime to dewatered sludge has become a relatively popular process for disinfection and temporary stabilization at small and medium-sized plants and eight plants. The reaction of quicklime with water increases temperature and pH, which gives the disinfection action. The sludge is only temporarily stabilized, since it may biodegrade later when pH has dropped. The plants have to be designed so as to give:

- Minimum 2 hours at temperature $\geq 55^{\circ}\text{C}$
- Minimum 2 hours at pH ≥ 12

The high lime dosage necessary for complying with the disinfection criteria (typically $> 500 \text{ kg CaO/ton DS}$) is the major problem for this process, involving high operation cost and limitations on land application rate due to the high lime content of the sludge. The investment cost is low, though. The lime treated sludge has, in most cases, a granular consistency, which makes the sludge easy to spread on farmland.

Composting

Windrow – as well as reactor (in vessel) composting is used. Most of the composting plants are small. The plants have to be designed according to the following:

Windrow or aerated static pile:	Reactor (in vessel):
<ul style="list-style-type: none"> • Minimum 3 weeks at $\geq 55^{\circ}\text{C}$ • Minimum 1 turn of windrow in the $\geq 55^{\circ}\text{C}$ period 	<ul style="list-style-type: none"> • Minimum 10 days at $\geq 55^{\circ}\text{C}$ • Minimum 2 days at $\geq 65^{\circ}\text{C}$ • Minimum 2 weeks maturing

Windrow composting is a method that may vary considerably in design and operation. Local conditions (type of bulking agent, dry solids content of sludge and available turning equipment) and operational strategy differ greatly from plant to plant. The process control is often insufficient to achieve high-quality compost that meets the disinfection criteria. Good bacteriological results were achieved for compost produced under favourable conditions (dry and warm summer periods), while the situation is quite different during periods with heavy rain or in cold winters. Under such circumstances plants turning windrows with a standard front-end loader and with a monthly or bi-monthly turning frequency can hardly produce compost that comply with the criteria. Some of the plants are considering changing to a reactor (in-vessel) composting system, as the experiences from such systems in operation are generally more favourable.

Thermophilic aerobic digestion (wet composting)

We have only limited experience with this method as only one municipal wastewater treatment plant in Norway employs this process. However, a few other wet composting plants are handling combinations of septic tank sludge and manure. The plants have to be designed according to the following:

- Minimum 2 reactors in series
- Minimum 23 hours at 50°C or minimum 10 hours at 55°C or minimum 4 hours at 60°C
- Minimum 7 days average residence time

The results from the one plant have been published previously (Paulsrud and Nedland, 1994). Provided a minimum total solids concentration of 3.5–4% in the raw sludge, an average volatile solids reduction of 38–43% was achieved and there has been full compliance with the disinfection criteria.

Thermophilic aerobic pre-treatment + anaerobic digestion

This treatment scheme has become quite popular among medium-sized and large plants in Norway. The plants have to be designed according to the following:

- Minimum 4 hrs at min 60°C in aerobic pre-treatment reactor
- Minimum 12 days at min 35°C in anaerobic digestion reactor

The general opinion among the plant superintendents is that this process combination is a reliable and effective method for complying with the regulations. The microbiological data available support this statement. The limited data on gas production cannot contribute to any clarification of the previous discussions on increased or reduced gas production due to the aerobic pre-treatment stage, but the gas production figures from mixed primary-chemical sludge correspond well with common values for anaerobic digestion of mixed primary-biological sludge ($\sim 1.0 \text{ m}^3 \text{ gas/kg VS}_{\text{reduced}}$). The average polymer consumption in the dewatering downstream stabilization/disinfection is typically around 3 g polymer/kg DS and the VS-reduction typically in the range of 35–45%.

Pre-pasteurisation + anaerobic digestion

This treatment strategy has particularly been used at larger plants in Norway. The plants have to be designed according to the following:

- Minimum 30 min at minimum 70°C in pasteurisation step
- Minimum 15 days at minimum 35°C in anaerobic digestion step

Generally the experiences with this treatment strategy are very good and all the plants comply with the disinfection criteria. The typical values for gas production, polymer consumption and VS-reduction are the same as for thermophilic aerobic pre-treatment + anaerobic digestion.

Thermal hydrolysis + anaerobic digestion

The Norwegian company Cambi AS primarily brings this process to the market. The basic idea behind the process is to increase VS-reduction, biogas-production and dewatered sludge DS-content by pre-treatment through thermal hydrolysis of the sludge that is to be digested anaerobically, while at the same time ensuring good disinfection. As the temperature during hydrolysis goes up to 165°C and the residence time in the hydrolysis is about 30 minutes, there is no doubt that the treated sludge will comply with the disinfection criteria. Steam is used as a heat source added directly to dewatered sludge in a hydrolysis reactor. In the only plant operating in Norway at this time, the hydrolysis takes place in three steps in which the sludge is heated to about 80°C by a heat exchanger as the first step. In the second step flash steam from the reactor is heating the sludge from 80 to 120°C and finally the sludge is heated from 120 to 160°C in the reactor step. In later installations abroad the number of steps have been reduced to two.

Anaerobic digestion + thermal drying

This method is rapidly gaining popularity in Norway especially at medium-sized and large plants. The anaerobic step with subsequent dewatering is designed traditionally. The dryer design results in residence times of about 30 minutes and with a temperature of 80–90°C it is obvious that this method will not have any problems in complying with the disinfection criteria. It is fair to say, however, that plant owners have experienced several operational problems, probably caused by insufficient competence at the suppliers regarding the sludge to be treated (often chemical treatment sludge in Norway). There have also been dust problems of the very dry sludge (90% DS) connected to the handling and spreading of the dried sludge leading to the use of pelletisers in order to produce a user-friendly product.

One may question whether or not sludge drying as such is a sustainable process as it is very energy consuming. Drying can only be defended when full utilization of the energy potential from the biogas-production is utilized. From the point-of-view of energy one may argue that incineration is more sustainable than drying since the heat value of the dry solids itself is utilized in incineration. However, the positive soil conditioning/fertilizing value of the sludge is lost through incineration.

Cost comparisons

A sludge suitability study was carried out for different disposal alternatives for Gardermoen wastewater treatment plant with sludge design load of 3.730 tonnes DS per year (Paulsrud *et al.*, 1999) – see Table 1.

Treatment of sludge in “the productification” strategy

Wastewater sludge contains resources that may be recycled directly (for instance phosphate) and resources that may arise from conversion of compounds in the sludge, for

Table 1 Cost comparisons of sludge treatment methods at Gardermoen WWTP*

Methods for stabilization and disinfection of sludge	Tot. cap. cost (mill. NOK)	O & M cost (mill NOK/year)	Annual cost**	
			mill. NOK/year	NOK/ton DS
Therm. aerobic pre-treatm. + anaer. digest.	36.0	3.15	6.55	1,750
Pre-pasteurization + anaerobic digestion	36.0	3.15	6.55	1,750
Anaerobic digestion + thermal drying	46.5	3.25	7.64	2,050
Reactor composting	48.2	3.95	8.50	2,280
Quicklime treatment of dewatered sludge	25.3	4.95	7.35	1,970

* All figures in 1995 prices, 1 EUR = 8.1 NOK

** The sum of total capital cost (interest rate 7%, average depreciation time 20 years) and operation and maintenance cost

instance electricity. There are different driving forces as to whether a resource or a compound can be recycled from sludge, such as a) the urge to “get rid of” or minimize the sludge, b) the demand versus the general availability of this resource around the globe and c) the cost of the recycled product versus market price. The perfect situation exists when one can solve “the sludge problem” (get rid of the sludge) while at the same time meeting the demands of a product that is limited in the world at a cost that is competitive with the market price of that (or a similar) product in the marketplace at the time. Unfortunately, this is seldom the case because the economic value of the sludge components is low as long as agricultural use is excluded (Kroiss, 2000). There are two main strategies:

- To take the benefit of the mixture of “good things” and make products where several of the compounds can be utilized. This requires that only the “bad things” have to be removed from the sludge
- To extract the “good things” from the sludge and leave the “bad things” in a residue that has to be disposed of outside the marketplace.

The production of “bio-soils” is an example of the first mentioned strategy. In the proposed Norwegian regulation on “Fertilizer products etc. of organic origin” in which sludge as well as “bio-soils” constructed from sludge are included, the treatment requirements are the same for sludge to be used in constructed “bio-soils” as for sludge used directly. There are restrictions on what kind of farming areas such products can be used in. It is not allowed to use them on areas where vegetables, potatoes, berries or fruits are produced. This is stricter than the proposed EU regulation where only use in forests is prohibited when advanced treatment of the sludge is implemented. There is a market for “bio-soil” products to a price that is competitive with other similar products in the marketplace. This means that this strategy has a big potential. The greatest problem is probably that the market is limited and dependent on regional circumstances.

The “sludge factory concept” is an example of the second strategy. In this concept, which is not realized to any extent at this time, the sludge is collected at several treatment plants in a sludge factory in which the sludge is treated and resources extracted from which marketable products are made. Since the sludge is such a dilute “resource” one can not go for recycling of only one compound – at least not at the present time. One will have to make several products. This is not optimal from a production point of view.

The main problem with this strategy is that the products may not be marketable because they cannot compete with similar products on the open market. Some of the products like electricity (made from biogas) are generally marketable, some are locally marketable and some are in-plant recyclable, see Table 2. It is evident that only electricity, heat (only locally) and phosphate seem to be in a good position. Since phosphate is a limited resource, the recycling of phosphate is particularly important and several methods, mainly based on precipitation of iron, calcium or magnesium-ammonium-phosphate precipitation are now being evaluated (Anon., 2001).

Below we shall discuss one treatment scheme based on the “productification strategy” now being considered for implementation at various plants in Scandinavia.

KREPRO – a sludge treatment scheme aimed at recycling

The treatment concept is presented in Figure 2. More details can be found in Cassidy (1998), Eliasson *et al.*, (2000) and Karlsson (2001).

The ambition of this process is to recycle the following “products”/components:

- biofuel for energy production based on incineration
- precipitant to be recycled within the treatment works
- phosphorus to be recycled in agriculture
- carbon source for N-removal recycled within the treatment works

Table 2 Estimate of “marketability” of various sludge products

Resource	Generally marketable	Locally marketable	In plant recyclable	Market potential
Bio-soils	Yes	Yes	No	Good
Energy				
• Electricity	Yes	Yes	Yes	Good
• Heat	No	Yes	Yes	Fair
• Biofuel	Maybe	Yes	Yes/No	Bad
• Oil	Yes	No	No	Bad
Nutrients				
• Phosphate	Yes	Yes	No	Fair
• Nitrogen	No	No	No	Bad
Coagulants	No	No	Yes	Bad
Other metals	No	No	No	Bad
Building material additives	No	May be	No	Bad

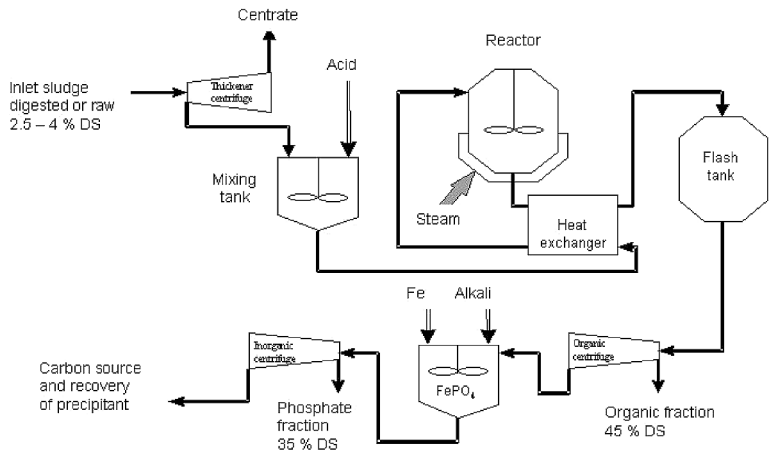


Figure 2 Principle of the KREPRO – Kemwater Recycling Process

In this process the sludge after thickening (5–7% DS) is acidified by addition of sulfuric acid to a pH between 1 and 2. By this most of the inorganic salts dissolve. Then the acidified sludge is hydrolyzed thermally in a pressure vessel at a temperature of 140°C at about 3.5 bars for 30–40 minutes and by this the particulate organic matter in the sludge “solubilises” to a great extent (about 40%). Only inorganic particulate (like sand) and very heavily degradable organic compounds (cellulose-like) remains in particulate form. After this the sludge is cooled down in heat exchangers, where also the incoming sludge is heated up. The sludge now contains dissolved phosphorus, ferrous iron and COD as well as organic, cellulose-like particles (the fiber fraction) separated from the solution in centrifuges (DS ~ 50%). To the liquid phase ferric salts and alkali are added to correct the pH upwards (pH = 3). At this low pH a very pure ferric-phosphate is precipitated and separated by a centrifuge (DS in cake: 35%). After the phosphate precipitation, soluble organic matter and ferrous iron is still in the water phase which is recycled to the wastewater treatment plant where the iron acts as coagulant and where the soluble organic matter may act as carbon source in the biological nitrogen removal processes.

The bio-fuel fraction

This organic fraction is intended for use as bio-fuel since the value for agriculture is minor after having removed phosphates, nitrogen and easily biodegradable organic matter. It has a fibrous structure with a high DS-content (45–55% DS with 30% ash content). It has a heat

value of 6–8 MJ/kg depending on the DS-content, which is equal to that of wood-chips which are otherwise used at bio-energy plants (Cassidy, 1998). The nitrogen content in sludge is higher than in wood fuel, however, which may cause higher NO_x -emissions. A great part of the sulphur in the sludge is present as sulphate and will not contribute to SO_2 -emissions from the boiler. When the sludge is fired in a boiler, the ash composition is of interest. Preliminary findings show that the risk of slagging is lower than for wood chip at furnace temperatures below 1,200°C and somewhat higher at higher temperatures. The risk of fouling is less when sludge is fired compared to wood chip (Karlsson, 2001).

Most of the heavy metal follows the bio-fuel fraction in the first separation step. Most energy plants have cleaning facilities for exhaust fumes. The heavy metals are collected in the ashes and deposited. The results from one of the Swedish plants show, however, that the heavy metal content of the organic sludge fraction (as mg/kg DS) was lower than the maximum values for use on arable land in Sweden (Karlsson, 2001).

The phosphate fraction

The phosphate fraction in the form of ferric-phosphate has a DS content of 35% DS that contains up to 15% as P. At the low precipitation pH the concentrations of heavy metals and organic micro-pollutants are very low, equal to or lower than that in commercial fertilizers. Ferric phosphate produced in the KREPRO-process is not water-soluble but 100% citrate soluble, which should be compared to an artificial fertilizer where the water solubility ranges between 20–60% and the citrate solubility, is 100%. Growth tests have demonstrated this phosphate to be close to equally good as a commercial phosphate fertilizer (4–5% lower yield) (Karlsson, 2001). The liquid phase after ferric-phosphate separation contains now iron (coagulant) and soluble COD (carbon source). It also contains dissolved ammonia that adds somewhat to the nitrogen load if not removed in the recycle stream. If residual metals in the liquid phase have to be removed in order to avoid accumulation in the treatment plant, this is carried out in an extra metal separation step in which the metals are precipitated as metal sulfides after addition of sodium hydrogen sulfide and sodium hydroxide (for pH-adjustment).

The recycled precipitant

The iron content in the liquid phase after phosphate separation is about 6–7 g Fe/l (Eliasson *et al.*, 2000). This iron may be utilized for precipitation of incoming water by recycling the liquid stream to the plant inlet. The amount of recycled iron is sufficient for phosphate precipitation in the wastewater process. This iron will end up in the sludge and once again be recycled through the KREPRO process. Alternatively it may be precipitated as iron-hydroxide and separated and thereafter recovered as iron precipitant.

The carbon source

Table 3 shows characteristics of the recycle stream. Since also the ammonium will be released through hydrolysis, the recycle stream will also add to the nitrogen load.

Table 3 Characteristics of the carbon source based on digested (6% DS) and raw (4% DS) sludge

Parameter	Unit	Digested	Undigested
COD _{filtered}	mg/l	13,000	11,000
VFA	mg/l	1,100	1,800
Tot N _{filtered}	mg/l	1,600	820
COD/N	g/g	8.1	13.4
Direct degradable COD	%	5.5	12.7
Denitrification rate	mg NO_x -N/ g VSS* <i>h</i>	1.9–2.2 (2.8)	1.9–3.4 (3.8)

If the easily biodegradable carbon is not needed for N-removal, it may be co-digested with the raw sludge in a stable process (Eliasson *et al.*, 2000).

Conclusions

The following conclusions may be drawn from this paper.

- Since depositing (land filling) is to be phased out as an alternative sludge disposal method, there are principally two main disposal options left; 1) Use of sludge on land, 2) Productification of sludge.
- Most experts agree that use of sludge on land is the most sustainable alternative. This requires treatment, particularly disinfection and strict regulations with respect to quality of sludge to be used. There are good treatment alternatives available based on stabilization and disinfection.
- Among the “productification” strategies the use of “bio-soils” (i.e. growth soils with sludge a central ingredient) on green areas has a great potential as an alternative to direct use of sludge on farmland.
- Another “productification” strategy is to recycle products from sludge that can either be used in-plant or sold to the open market. The KREPRO process outlined is one example of a treatment/recycle system.

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