Investigation and assessment of sludge pre-treatment processes

J.A. Müller*, A. Winter* and G. Strünkmann*

* Institute of Sanitary and Environmental Engineering
** Institute of Mechanical Process Engineering, Post Box 3329, Technical University of Braunschweig, D-38023 Braunschweig, Germany (E-mail: jo.mueller@tu-bs.de)

Abstract The pre-treatment of sludges by disintegration will result in a number of changes in sludge properties. Floc destruction as well as cell disintegration will occur. This leads to an increase of soluble substances and fine particles. Furthermore, biochemical reactions may appear during or immediately after disintegration. The influence of disintegration of excess sludge on anaerobic digestion was studied in full scale. A stirred ball mill, an ultrasound disintegrator, a lysate centrifuge and ozone treatment were used. The results of the degradation process were compared to a reference system without pre-treatment. An enhancement of the degree of degradation of 7.4% to 20% was observed. The pollution of sludge water as well as the dewatering properties of the digested sludge were investigated. COD and ammonia in the sludge water were increased and a higher polymer demand was observed while the solid content after dewatering stayed almost unchanged. Based on these results the cost effectiveness has been assessed taking into account different conditions (size of WWTP, cost for disposal, etc.). Capital and energy costs are the main factors while the decrease in disposal costs due to the reduced amount of sludge is the main profit factor.

Keywords Disintegration; economic efficiency; pre-treatment; sewage sludge

Mechanisms of sewage sludge disintegration

Sewage sludge disintegration can be defined as the destruction of sludge by external forces. These forces can be of physical, chemical or biological nature.

A result of the disintegration process is numerous changes of sludge properties, which can be grouped in three main categories:

- destruction of floc structures and disruption of cells
- release of soluble substances and fine particles
- biochemical processes

The first two categories are demonstrated in Figure 1, which shows the mechanical disintegration as a function of the specific energy input.

Floc destruction and cell disintegration

The applied stress during the disintegration causes the destruction of floc structures within the sludge and/or leads to the break-up of micro-organisms. If the energy input is increased, the first result is a drastic decrease in particle size within the sludge (Figure 1). The destruction of floc structures is the main reason for this behavior. The disruption of micro-organisms is not as easily determined by the analysis of particle size because disrupted cell walls and the original cells are of similar size. Floc destruction and cell disruption will lead to the following changes in sludge characteristics:

- Hydrolysis: Disintegrated micro-organisms are much more easily hydrolyzed than undisrupted ones. The reduction in particle size generally allows an easier hydrolysis of solids within the sludge due to larger surface areas in relation to the particle volumes. The result is an accelerated and enhanced degradation of the organic fraction of the solid phase.
Disinfection: All micro-organisms are affected by the disintegration process. Higher organisms are disrupted easiest because of their size and gram-positive bacteria are the most difficult organisms to be disrupted due to their strong cell wall. Depending upon the treatment a partial up to a complete disinfection of the sludge is possible since pathogenic micro-organisms are also disintegrated.

Settling and dewatering: In case of a strong disintegration a large amount of organic solid material is transferred into the liquid phase (see later paragraph). The remaining solid sludge particles contain a higher percentage of inorganic substance. The result is a higher content of dry substance after dewatering (Müller, 2003). In case of a less intense disintegration combined with a partial disruption of floc structures the results in settling of a well sedimenting sludge are worse. But the settling properties of filamentous sludges (bulking sludge) can be improved due to the destruction of voluminous floc structures.

Flocculation: The reduction of particle size and therefore the increase of the specific surface causes a higher amount of surface charges that need to be neutralized when the sludge is conditioned. Consequently, disintegrated sludges use more flocculant.

Viscosity, foaming: Disintegration has an effect on other sludge parameters as well. The viscosity is severely decreased which simplifies mixing and pumping of sludge. Foaming problems can be controlled in case of sludge with a high content of filamentous micro-organisms. The production of scum as well as the foaming within digesters is reduced.

**Release of soluble substances and small particles**

The destruction of floc structures and disruption of cells result in the release of organic sludge components into the liquid phase (Figure 1). These components exist in a dissolved phase already, e.g. components of the intracellular water, or can be liquefied. Particle size or colloidal components may still be present within the solution because they cannot be separated from the liquid phase. Their minute particle size and only a slight difference in density of particle and surrounding water are the cause. But the components are easily biodegradable on the other hand. Since they are already liquefied or offer a large surface in comparison to their volume, the hydrolyzing process is simple. The influence of the released amounts of carbon, nitrogen and phosphorus compounds on sludge characteristics are:

Degradation: Carbon compounds are easily accessible and can be digested much faster in later biological processes than sludge in a particular phase. The results are shorter degradation times and higher degrees of degradation during the aerobic and anaerobic stabilization.

![Figure 1](https://iwaponline.com/wst/article-pdf/49/10/97/420353/97.pdf)
Carbon source: Easily accessible compounds can further be used for carbon limited process steps within the wastewater treatment such as denitrification or the biologically enhanced phosphorus elimination.

Return-Flow-Pollution: The wastewater has to be cleaned from released nitrogen and phosphorus compounds before leaving the treatment plant. If this happens by returning the water into the WAS-process, additional capacities have to be taken into account.

Recycling: A separate treatment and recycling is possible as well, e.g. through ammonia stripping or phosphor crystallization. Disintegration within the sludge pre-treatment has advantages in combination with selective recycling processes due to the increased nitrogen and phosphorus concentrations.

Biochemical reactions

During or immediately after the disintegration, biochemical reactions may appear. The influence of these reactions on the degradability of the sludge is contrary:

- Continuing formation or release of easily degradable compounds
- Formation of hardly degradable compounds

The formation of problematically biodegradable, humic-like reaction products if sludges are disintegrated at higher temperatures can be explained by the “Maillard-reaction”. At lower temperature ranges this effect is less strong, but it is suspected that problematically biodegradable compounds are produced in any thermal disintegration process.

Many times proven is the transformation of problematic compounds to easily degradable compounds by partial oxidation. This effect has been found especially in the treatment of industrial wastewaters, but it is not fully verified in sludge treatment through ozone or other oxidation partners. The formation of hardly degradable compounds was found as well and degradation processes only performed well after an adaptation of the micro-organisms (Scheminski et al., 1999).

Biochemical reactions following the disintegration that is catalyzed by released enzymes are seen controversially by experts. While some authors see great potential, others have not been able to prove any kind of effect (ATV, 2003).

Influence of disintegration on the anaerobic digestion process

Sewage sludge disintegration has been studied for the past ten years by many researchers and with the help of results of a few full-scale investigations. The effects and properties that have been described in this article were confirmed in other works of research (Lee and Müller, 2001). The size of the attained effects varies a lot. The diversity of results is mainly caused by the lack of a parallel running reference system operated without disintegration when full-scale tests are carried out. Instead the results are compared to past plant data. The obtained outcome can therefore not entirely be explained by disintegration effects, but is influenced by other changes, such as the amount of sludge, sludge properties or the operating schedule of the plant. Anyone has to be aware of the limited validity of such results.

The application of disintegration processes generates investment and operational costs. It is frequently asked, if the use of disintegration methods decreases the costs of a sludge treatment. A truthful answer is only possible, if reliable basis data about the expected changes exists. For this reason the TU Braunschweig in cooperation with the Emschergenossenschaft carried out a research project, which investigated the effects of disintegration on the digestion process in large scale experiments. The full-scale investigations were carried out at a municipal WWTP of 17,000 PE of the Emschergenossenschaft/Lippeverband, Germany. A stirred ball mill was compared to a lysate centrifuge, an ultrasonic disintegrator and a chemical disintegration by partial oxidation with ozone.
The thickened surplus sludge was disintegrated and in combination with primary sludge digested. In a second, parallel operating digester, the untreated raw sludge was stabilized. While all processes disintegrated the total amount of surplus sludge, only the ultrasonic disintegrator used one third of the amount. The results of the disintegration were quantified by the degree of disintegration. This parameter is determined by the rate of oxygen demand (DDO) and the COD release (DDCOD). Both methods are described elsewhere (Müller, 2000).

The disintegration process carried out with ozone shows the highest specific energy demand (Figure 2). Fifty per cent of the energy demand is used up for the provision of pure oxygen as an input element. The achieved degree of disintegration is the highest in this process as well. The lysate centrifuge only showed little increase of the degree of degradation, but therefore has a lower energy demand. The ultrasonic disintegrator shows similar results to the lysate centrifuge concerning the degradation. The energy demand is comparable as well, if it is taken into account that only one third of the sludge was treated.

The pollution of process water after dewatering of the digested sludge is increased due to the disintegration (Figure 3). Especially the ozone treatment leads to a remarkable increase. The enhancement of the phosphorus content (not indicated in the Figure) was lower than five per cent in just about all cases.

The increase in the demand of flocculant is less than 10% except for the ozone treatment. The dry substance content after dewatering in a pilot-scale chamber filter press showed little influence due to the disintegration.

**Economic evaluation**

The use of disintegration in order to enhance the digestion process is the best-researched full-scale application today. The following paragraph contains a model calculation for the costs of a disintegration process step before the digestion on a fictitious plant for 250,000 population equivalents (PE). The basis data is taken from the above-described investigations, other research results and the work of the ATV-DVWK working group “sewage sludge disintegration” (ATV, 2001). Assuming a relatively high increase of the degree of degradation of 20% and a relatively low energy demand of 0.3 kWh/Mg TS for the disintegration, positive values are used within the span of results.

Data of the model plant:
- Size: 250,000 PE, with 200 l wastewater/PE.d = 50,000 m³/d

![Figure 2](https://iwaponline.com/wst/article-pdf/49/10/97/420353/97.pdf)
Surplus sludge: 40 g DS/PE*d = 10 Mg DS/d = 3,650 Mg DS/a, mech. thickened to 5% TS

Primary sludge: also 3,650 Mg DS/a

Loss on ignition of excess sludge: 75%

Increased degree of degradation of organic substance of the raw sludge from 40% to 48%, which equals 8% absolutely and 20% relatively. The increase is the result of a better degradation of the surplus sludge from 31% to 46%, which equals 15% absolutely and 48% relatively. The organic content of primary sludge (loss of ignition = 65%) is decreased by 50%. Now the amount of completely digested sludge only adds up to 4,847 Mg DS/a instead of 5,256 Mg DS/a without disintegration. The amount of sludge that needs to be disposed of went down by about 409 Mg DS/a.

The following hypotheses regarding plant parameters are made:

A mechanical excess sludge thickening process is offered. The excess sludge can be separately treated this way and is brought into the disintegration process with a relatively high solid content. The space necessary for a disintegration apparatus is available. Capacities for the higher return flow of nitrogen and for the utilization of increased amounts of digester gas are accessible. This way the investment costs are limited to the purchase and integration of the disintegration device.

**Investment costs.** An amount of surplus sludge of 10 Mg DS/d with a solid content of 5% produces 200 m³ sludge daily, which needs to be treated. Depending upon the process, the costs for a mechanical disintegration unit and the costs for integration of the unit amount to €400,000 to 900,000. In case of an existing thickening centrifuge being retrofitted with a lysate unit, the costs are much lower. For further calculations of the example, the investment costs will be estimated as €650,000. At an interest rate of 5% and a depreciation span of 10 years the yearly costs will add up to roughly €84,000/a.

**Personnel costs for operating the disintegration unit.** The operation of the unit is done automatically to a great extent. The approximate time effort, including upkeep and minor repairs, is about 5 hours/week. The hourly wages of a technician are calculated as €30/h and add up to yearly personnel costs of around €8,000/a.
Costs of wearing parts for heavily stressed unit components. These costs can be a major factor in the calculation of operational costs. Only a rough estimate can be given so far. €2 to 25/Mg DS have to be put into account depending on the method and operational conditions. Since sufficient experience regarding unit technology has been gathered and technical improvements in wear-resistance are expected, an approximation of costs of around €5/Mg DS is acceptable. The yearly costs would come to around €18,300/a.

Costs for unit servicing. Aside from simple reparations (as mentioned earlier) a yearly unit servicing by the producer is included and the costs would be approximately €3,000/a.

Energy costs of disintegration process. The specific energy necessary for the disintegration is estimated as 15 kWh/m³ or 0.3 kWh/kg DS (at 5% TS), because sufficient degrees of disintegration can be achieved at this energy level (Winter et al., 2002). Costs for power are put in at €0.08/kWh. The yearly energy costs are €87,600/a.

Operational costs of additional cogeneration capacities. An increasing amount of digester gas requires additional capacities for the cogeneration of heat and power and therefore costs for operation, upkeep and servicing of about €30/MW el. The extra costs for the power production of 809 MWh/a are approximately €24,300/a.

Costs and savings influenced by dewatering behaviour. If the specific sludge disposal costs are related on wet sludge mass, the dewatering result will be of influence. In most research conducted so far there was a slight deterioration of the dewatering behaviour found (ATV, 2001). In single cases an improvement was achieved. In this example the influence of the dewatering on the disintegration is being neglected and the specific sludge disposal costs are calculated on the basis of the sludge dry mass.

Increase in flocculant demand. Although in some applications a decrease in polymer demand was observed, a larger demand of flocculant caused by the disintegration is estimated at 10% of the starting value according to own experience. A flocculant demand of 8 kg/Mg DS for untreated sludge and costs of flocculant at €4/kg were used for the example calculation. Because of the reduction of sludge mass to be flocculated the costs for flocculant will increase by only €2,400/a.

Costs through additional return flow from sludge treatment. The most important parameter in sludge water pollution is nitrogen. Research results show that phosphorus is only found in slightly increased amounts in most cases. The increase in COD return flow is small in comparison to the overall COD load of the WWTP, which allows one to neglect any cost factors. This example is based on sufficient volume of the aeration basin for an elimination of nitrogen and the existence of free aeration capacities. Costs can be estimated in this case as cost for power supply of the aeration and costs for an additional carbon source (methanol) with €0.75/kg N elim. Due to the increased degree of degradation it was possible to reduce the residual sludge amount by 409 Mg DS/a. This degraded surplus sludge mass contains approximately 8% nitrogen corresponding to 32.7 Mg N/a, which is resubmitted to the plant with the sludge water. The yearly cost amounts to about €24,500/a.

All cost factors for the use of a disintegration treatment have been estimated. The total sum is €252,000/a. The different cost percentages are portrayed in Figure 4.
Reduction of costs due to electricity production from additional digester gas. The example calculation assumes an increase of the degree of degradation of absolutely 10%, which results in 809 MWh/a out of electricity production and can be included in the cost figuration as €0.08/kWh. Yearly savings are amounting to €64,800/a.

Reduction of costs in sludge disposal. Disposal costs are regionally and temporally inconsistent. If costs for sludge disposal without costs for dewatering are assessed at €150 to 400/Mg DS then the reduction of residue sludge of 409 Mg DS/a allows savings between €61,000 and 164,000/a. The break-even-point will be reached for this example calculation at disposal costs of €458/Mg DS.

The costs of disintegration are strongly influenced by three factors:
- level of achieved increase of degree of degradation
- costs for disposal of residue sludge
- size of wastewater treatment plant, influencing the investment costs

The importance of these three factors upon the costs is shown in Figure 5. The cross indicates the example calculated in detail from above. Using the diagram one has to keep in mind, that it is based on the assumptions given above.
Conclusions
Disintegration of sewage sludge results in disruption of floc structure and cells, release of diluted and small particle substances and possibly in following reaction chains. Therefore, the properties of the sludge change drastically after disintegration. Positive effects, e.g. better degradability, for the whole sludge treatment process as well as negative effects, e.g. a higher pollution of the return flow, are the result.

Full-scale investigations have shown that disintegration technology as an instrument of digestion improvement is only efficient if the total sludge disposal costs are high. Because the investment and energy costs are the largest sums within the cost calculation, it seems to be beneficial to increase the efficiency of disintegration units. This would not only reduce energy costs, but lower investment costs as well, because more compact disintegration units would be used.

The specific conditions of each treatment plant may provide further arguments for or against an application of disintegration. Especially operational problems are important factors, e.g. difficult digestion properties of the sludge, poor dewatering characteristics, overload of digesters, foaming problems due to filamentous micro-organisms in excess sludge and others.

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