Eco-friendly and energy efficient sewage SLUDGE deWaTeRing through novElnanomAterials and elecTro-osmotic process

SLUDGEtreat

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1. INTRODUCTION

1.1 Background

1.1.1 Sludge management in Europe

The so-called “activated sludge process” is adopted by almost the totality of urban and industrial wastewater treatment plants to achieve the concentration limits of biodegradable pollutants stated by the law to allow the discharge of treated effluents to natural water bodies (rivers, lakes and the sea). About half of the organic pollution load treated by the activated sludge process is oxidised and converted into water and carbon dioxide, while the remaining is converted into biomass. In order to keep a constant concentration of active biomass, called “excess biological sludge” or “waste sludge”, as it is due to bacterial growth. At present, this technique is the cheapest way to remove colloidal and soluble organic pollutants from sewage, but it produces a huge amount of liquid waste sludge, with a dry solid (DS) content of less than 2%, rich in organic substances, mostly biodegradable. Therefore, it needs further processes to reduce its volume, by reducing its water content, and to reduce its polluting potential, due to its high content of biodegradable organic matter. As a matter of fact, the dry matter of sewage sludge contains up to 80% volatile solids (at 600°C), made of active biomass, organic debris and residual of cellular decay. The organic fraction (or volatile solids, VS) of the dry solid content of sewage sludge can be reduced down to about 60% after biodegradation through further aerobic or anaerobic biological processes, often called “stabilisation” or “digestion” processes, as they aim at reducing the content of biodegradable matter and “stabilise” the biodegradation processes.

The annual production of sewage sludge in 2010 was about 11.5 million tonnes of DS in 27 member states of the European Union (Table 1): Germany is the largest producer, followed by United Kingdom, Italy, Spain and France. About 70% of the annual European sewage sludge production is obtained by these five countries. All over the world, an increase in sludge production is expected.

Table 1- Sewage sludge production in EU countries in the period 2010.

<table>
<thead>
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<th>Member State</th>
<th>Sewage sludge production [tDS/year]</th>
<th>Proportion of total EU [%]</th>
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<tr>
<td>Austria</td>
<td>273,000</td>
<td>2.4</td>
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<tr>
<td>Belgium</td>
<td>170,000</td>
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<td>Bulgaria</td>
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<td>Cyprus</td>
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<td>Czech Republic</td>
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<td>Denmark</td>
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<td>Estonia</td>
<td>33,000</td>
<td>0.3</td>
</tr>
<tr>
<td>Finland</td>
<td>155,000</td>
<td>1.3</td>
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<tr>
<td>France</td>
<td>1,300,000</td>
<td>11.3</td>
</tr>
<tr>
<td>Germany</td>
<td>2,000,000</td>
<td>17.4</td>
</tr>
</tbody>
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### Member State | Sewage sludge production [tDS/year] | Proportion of total EU [%]
--- | --- | ---
Greece | 260,000 | 2.3
Hungary | 175,000 | 1.5
Ireland | 135,000 | 1.2
Italy | 1,500,000 | 13
Latvia | 30,000 | 0.3
Lithuania | 80,000 | 0.7
Luxembourg | 10,000 | 0.1
Malta | 10,000 | 0.1
Netherlands | 560,000 | 4.9
Poland | 520,000 | 4.5
Portugal | 420,000 | 3.7
Romania | 165,000 | 1.4
Slovakia | 55,000 | 0.5
Slovenia | 25,000 | 0.2
Spain | 1,280,000 | 11.1
Sweden | 250,000 | 2.2
United Kingdom | 1,640,000 | 14.3
**Total** | **11,503,800** | **100**

After reducing the content of biodegradable matter through biological stabilization processes (aerobically or anaerobically) and after reducing the water content through mechanical dewatering or thermal drying, the sludge is suitable for its final disposal. The most commonly applied routes are:

- direct land application in agriculture or forestry;
- indirect use in agriculture, as a soil-amending material (compost) obtained through further processing with other organic wastes;
- incineration, with or without energy recovery;
- sanitary landfilling.

![Figure 1 - Disposal routes of sewage sludge in EU (year 2000)](image-url)
The dry content of stabilised sewage sludge is rich in nutrients such as nitrogen (1 to 6%)⁴, phosphorus (0.05 to 3%) and potassium (<1%)³ and contains valuable organic matter (humus) that is useful for application to soils that are depleted or subject to erosion. Organic matter and nutrient content in sludge are key elements that make agricultural use of sludge a widespread method of sludge disposal. About 36% of the total amount of sewage sludge in EU is used in agriculture in year 2000 (Figure 1)⁴, while in 2006 this fraction increased to 39%. At European Community level, the use of sewage sludge in agriculture is regulated by the Sewage Sludge Directive 86/278/EEC and the Urban Water Treatment Directive 91/271/EEC. The Sewage Sludge Directive 86/278/EEC encourages the use of sewage sludge in agriculture and regulates its use to prevent harmful effects on both environment and human health. Therefore, environmental issues that may be associated with the use of sewage sludge in agriculture are mainly related to heavy metals, harmful organic compounds, nitrogen if present as nitrate ion (NO₃⁻) and pathogenic microorganisms.⁶ However, the presence of high content of harmful substances, organic contaminants, heavy metals such as cadmium, copper, nickel, lead, zinc, mercury and chromium limits its use and leads to a decrease in soil applications (as stated in Waste Framework Directive 2008/98/EC, and Directive 99/31 on landfill of waste).

It may be worth noticing that Switzerland has banned sludge landfilling (since 1996) and also its use in agriculture, as stated in the Ordinance on Fertilisers (“Ordonnance sur la miseen circulation des engrais”, as modified on November 14th, 2007). Therefore, the only residual option remaining for the disposal of sewage sludge is incineration, according to the Technical Ordnance on Wastes, dated 10th December 1990, updated on July 1st 2011.

Sludge must be dewatered before composting, incinerating, landfilling or reusing as fertilizer, in order to decrease transport and treatment costs (sludge disposal costs are about 280-470 €/t_DW in EU and 150-250 €/t_DW in Italy)⁷. Different techniques, such as thermal, mechanical or electromechanical are investigated in order to reach the highest DScontent and the lowest economic impact. The aims of dewatering include: recovery of the product for sale in a dry form, more practicable for further treatments; recovery of water for recycling; transformation into forms that are easily handled and can be safely disposed of.⁸

1.1.2 Sludge management in Italy

Italian legislation on sludge is basically developed as an enforcement of EU Directives, and generally is included in those regarding wastes and wastewaters. In particular, environmental matters are mainly regulated by the Legislative Decree (DL) 152 of April 3, 2006 (where wastewater sludge is classified as “special waste”), recently completed and integrated by the DL 4 of January 16, 2008.

Other important regulations regarding wastes, including sludge, are those relevant to incineration processes, and the DL 36 of January 13, 2003, as enforcement of European Directive 1999/31/CE on waste landfilling, followed by the Ministry of Environment Decrees (DM) of March 13, 2003, and August 3, 2005, defining criteria for waste admittance in landfill.

In Italy, sludge utilisation in agriculture is regulated by the DL 99 issued in 1992 in application of the European Directive 86/278/EEC which states general conditions for sludge application and
utilisation on land, including limits on heavy metals and Salmonellae, but not on organic contaminants. Each of the 20 Italian Regions may issue and enforce Regional Directives aimed at adapting general requirements to local situations, including introduction of more stringent limits.

In Lombardy, a production of around one million tonnes of sewage sludge was documented (IRER, 2010).\(^9\) Over half of the sludge, after appropriate treatment, is designed to agricultural reuse; the remaining half is sent, in roughly equal parts, to landfill or for incineration. Sludge production in Lombardy is going to increase due to the growing consumption and population. Moreover, the tens of millions of Euros allocated in Lombardy for large interventions in response to EC infringement procedure 2034/09, which imposes heavy penalties for purification and sewage systems that will not be in accordance with limits within 2015, will lead to an improvement in the quality of rivers and the environment, but simultaneously to an increase in the quantity of sludge.\(^4\)

Taking into account this trend, management of sewage sludge is becoming a fundamental factor in order to satisfy environmental rules and decrease disposal costs.

Figure 2 shows the sludge final use in Italy according to a research of 2006.\(^10\)

![Figure 2- Sewage sludge final use in Italy (2006).](image)

1.1.3 Aim of the work

The aim of this work is to establish the feasibility of electro-osmotic dewatering under constant voltage for different sludge types and improve the dewatering efficiency in terms of final DS content, dewatering rate and energy consumption.

Today’s sludge average DS content after mechanical dewatering lies in the range of 20-30% of dry solids, with average values around 24-25%.\(^1^1\)

The minimum legislative requirements for thermo-valorisation require that the sewage sludge is dried up to about 30-45% of DS in order to self-sustain combustion at 850°C. At lower DS content, pre-heating the combustion air by adding additional fossil fuel (such as methane) is necessary to remove the water content from the sludge. Sewage sludge can be also dried up to 90% of DS...
content in drying ovens, which are heated by fossil fuels and then used in cement kilns or brick furnaces as both additional fuel (for its combustible volatile fraction) and inert filler (for its inert fraction).

When compared with thermal (evaporative) processes for water reduction, mechanical dewatering is often selected due to its low energy requirement. The processes of mechanical dewatering are largely developed on the industrial scale and, thanks to the pressure application, can produce sludge with 20-25% of DS content, and, in some cases, up to 30%. In general, the highest DS content can be achieved for primary sludge, while the lowest DS content is achieved for aerobically digested biological sludge.\(^\text{12}\)

However, the high DS values demanded for thermal valorisation of sludge cannot be achieved by mechanical dewatering techniques. In the case of aerobically digested biological sludge, the goal of 25% dry solids can be hardly achieved, even with high pressure filter-presses.

Seeking new and efficient methods for dewatering, many authors (Yoshida in 1993\(^\text{13}\), Barton et al. in 1999\(^\text{14}\), Gingerich et al. in 1999\(^\text{15}\)) exploited electro-osmosis in order to remove water from sludge: the application of an electric field, sometimes in combination with pressure, seems capable to increase the DS content well beyond the values that can be achieved by mechanical means. Among electro-kinetic phenomena, electro-osmosis rules this process and leads to a transport of water molecules to the negative electrode (cathode), increasing the dry matter significantly and lowering the energy consumption with respect to conventional techniques. However the high efficiency of this method is in contrast with its applicability due to the high sludge volumes involved, oxygen and hydrogen evolution at the electrodes (their amount must be lower than a fixed threshold ruled by ATEX), Joule effect caused by the application of electrical field and the increase in resistance due to water removal. Since electro-osmosis dewatering has been studied mainly at bench-scale, and industrial applications have been limited to very few full scale plants. Therefore, these critical aspects must be taken into account in order to develop an effective, reliable, and economically feasible sludge electro-dewatering process.
2. LITERATURE REVIEW

2.1 Introduction

Starting from the studies on soils made by Casagrande in 1939, electro-osmotic dewatering has been studied for other particulate materials such as sludge. However, the sludge electro-dewatering is not fully understood until now, since the electro-osmotic phenomenon encounters many critical aspects (high temperature, high resistance of the sludge with the proceeding of the process, hydrogen and oxygen evolution at the electrodes, and so on) that limit its development to the full industrial scale.

2.2 Need of sludge dewatering

Sludge is produced by wastewater treatments and is in the form of a liquid slurry, with a water content of 95-99%. After thickening and digestion sludge has still a water content of 95-97% and needs dewatering. The main objective of dewatering is to produce a waste (European code 19 02 05) that can be safely handled and disposed of.

2.3 Sludge liquid phase

2.3.1 Types of sludge

Sludge produced by Wastewater Treatment Plants (WWTPs) vary according to the processes and methods of operation. Figure 3 shows a schematic view of the main processes in a Wastewater Treatment Plant and consequent sludge production, that has to be disposed of to agriculture, incineration and landfill or water for discharge.

![Figure 3-Wastewater treatment process](image-url)
Sludge can be classified according to its origin: **primary**, from primary settling tanks; **secondary**, from biological processes; **tertiary**, from finishing processes such as flocculation sedimentation and filtration; **anaerobically digested**, after being processed by anaerobic digestion; **aerobically stabilised**, if their content in volatile solids has been reduced through aerobic processes. All are different in physical, chemical and biological characteristics, which have an influence onto sludge dewaterability.

**Primary sludge**

Primary wastewater treatment usually involves gravity sedimentation to remove settleable solids and organics, usually by a primary clarifier. In general, about half of the solids suspended in wastewater are removed through primary treatment. The material collected in the bottom trough of primary settlers is a concentrated suspension, 3 to 5% dry solids (i.e.: 95-97% water content) called primary sludge, made up of organic components, mainly made of human excreta, ranging from 70-75% of volatile solid\(^1\). If they are going to be disposed of to agriculture they need further processing to reduce their content in easily biodegradable organics (i.e. putrescible organics) and their content in pathogens. In USA and UK biologically stabilised sludge is called “biosolids”.\(^2\)

**Secondary sludge (also named “excess, biological sludge” or “waste activated sludge”)**

In the secondary treatment process called activated sludge process, microorganisms oxidise organic substrates to get the energy they need to grow. More precisely,\(^2, 3\)

- heterotrophic biomass consumes dissolved oxygen to degrade dissolved and suspended organic matter;
- autotrophic biomass consumes oxygen to oxidise ammonium nitrogen to nitrates;
- both kind of microorganisms take up ammonium and phosphate from the wastewater to fulfil their metabolic needs and to grow;
- produce oxidises inert products (carbon dioxide, water, nitrates) and other microbial products.

The organic content of biological sludge varies between 60% and 80%. In general, dewaterability of secondary sludge depends on numerous factors. Excessive growth of filamentous bacteria, due to low dissolved oxygen, nutrients deficiency and high temperature, is a common problem in activated sludge process: the bulking sludge causes poor settling and dewatering. In order to control the bulking sludge, oxidant chemicals such as chlorine and hydrogen peroxide are added into the aeration tank.\(^2\)

Usually, sludge with a low content of volatile solids (i.e. the solids lost after 2 hours in an oven at 600°C), is more easily dewaterable than a sludge with a higher volatile solid content.

**Tertiary sludge**

Tertiary treatment is used when high-quality effluent is required, such as direct discharge to a drinking water source or to reclaim water for unrestricted agricultural irrigation or to improve the quality of rivers that receive heavy pollution loads. It is produced by flocculation/precipitation downstream of the biological treatment and final filtration. In the presence of simple filtration, without the addition of inorganic reagents, the nature of the sludge is similar to that of secondary sludge. Otherwise chemical precipitates are present in a variable percentage depending on the
type of the process applied. Tertiary sludge is usually recycled back to primary settling tanks or sent to thickening units.

**Digested sludge**

Raw sludge cannot be disposed of directly as it is rich in easily biodegradable compounds, that lead to uncontrolled biological reactions which release fermentation products, due to volatile fatty acids, mono and di-ethylamines, indole, skatole (3-methylindole), mercaptans, etc., and gases (H₂, CO₂, H₂S, CH₄). These compounds cause either bad odours or potential hazards to human health and environment. Bio-stabilization can be performed by biological digestion under aerobic or anaerobic conditions, and reduces the organic content in sludge from 75% to as low as 50%.\(^{21}\)

**Anaerobic digestion** is a biological process that is carried out in the absence of oxygen. The process can either be thermophilic, in which sludge is fermented in tanks at a temperature of 55 °C, at a retention time of about 15 days, or mesophilic, at a temperature of around 36 °C, at a retention time of about 30 days. The process is performed in a way that the biological reactions occur under a controlled environment (the digester) and convert biodegradable substrates into biogas (a mixture of methane, carbon dioxide, hydrogen sulphide and other minor components), producing stabilized sludge. As a rough approximation, biological reactions can be grouped into four main steps:

- hydrolysis of particulates into colloids, of colloids into soluble compounds;
- acidogenesis, that is the conversion of soluble organic compounds into volatile fatty acids (VFAs);
- acetogenesis, that is the conversion of VFAs into acetic acid;
- and heterotrophic methanogenesis, that is the conversion of acetic acid into methane and carbon dioxide; autotrophic methane production from carbon dioxide and hydrogen may contribute to biogas formation, but to a very limited extent.

Methane is usually 65 to 70% of the total biogas produced. Part of the biogas is used to feed a boiler to heat the incoming sludge up to the required process temperature and to compensate heat dispersions from the digestion reactor. The excess biogas can feed endothermic engines or gas turbines, but it requires a preliminary treatment to remove humidity (by condensation), hydrogen sulphide (by alkaline scrubbing) and siloxanes (by adsorption on activated carbon granules). However, the large reactor volumes, the sludge heating system, the biogas treatment and the operation of the energy recovery systems entails high capital costs that can be recovered within the useful lifespan of the plant only if the energy obtained from the combined heat and power (CHP) units is subsidised.\(^{24}\)

**Aerobic digestion** is a biological process that is performed by adding air or oxygen, and where organic matter is oxidised into carbon dioxide, water and stabilised organic debris (humus). Once there is a lack of organic matter, bacteria die and are used as food by other bacteria (endogenous respiration): solids reduction occurs in this phase. Aerobic digestion takes 10 to 15 days under ambient temperature and needs no insulation. Therefore the capital costs of aerobic digestion are lower, but the operating costs are greater because of the energy used by the air blowers or to buy oxygen.\(^{25}\)

After aerobic and anaerobic digestion, the dewaterability of the digested biological sludge is decreased in comparison to raw, undigested excess sludge due to the increase of fine
particles. However, after a proper conditioning process (see paragraph 2.5), the lower content of volatile solids in digested sludge digested sludge dewater better than undigested. 21

2.3.2 Water distribution in sludge

Water contained in sludge can be of four types26,27:

- Free water: water not bound to the particles, which represents the largest part of sewage sludge (70-75%). Mechanical dewatering technique such as filtration/compression, gravitational settling and centrifugation can easily remove this kind of water.
- Interstitial or capillary water: water bound by capillary forces between the sludge flocs or water trapped in crevices and interstitial spaces. This water can be released by mechanical dewatering with a breaking of the floc.
- Surface or vicinal water: water associated with the solid particles. Multiple layers of water molecules hold tightly to the particle surface by hydrogen bonding. This water is held on particle surfaces thanks to the molecular structure of the water molecules and cannot be removed by mechanical methods.
- Intracellular water, water of hydration or chemically bound: water bound within the particle structure that can be released only by thermo-chemical destruction of the particles.

The most popular definition is that the free water freezes at freezing point, while bound water remains unfrozen (it freezes at -20 °C, or at -8 °C).21

The different kinds of water are shown in Figure 4.

![Figure 4: Distribution of water in sludge.](image)

Large and dense flocs are always preferable for good settling and dewatering: the poorer dewaterability of sludge is related to a larger amount of fine flocs in sludge because they not only clog the pore structure in the sludge cake, but also increase the amount of bound water.28
The dewatering methods in relation to sludge-liquid phase are shown in Figure 5, where Stern layer and Helmholtz plane are drawn (see chapter 2.7.2 Electro-osmosis).

Figure 5- Dewatering methods in relation to water distribution in sludge.

2.4 Parameters affecting dewaterability

Sludge dewaterability is affected by many parameters as shown in the following list:

- Time to filter (TTF)
- Capillary suction time (CST)
- Specific resistance to filtration (SRF)
- Water content at 105°C
- Total and suspended solids
- Inert solids (residue at 600°C)
- Granulometry, or particle size distribution
- Temperature
- Extracellular polymeric substances (EPSs)
- Microbial soluble products (MSPs)
- Bacterial species (floc formers or filamentous; hydrophobic or hydrophilic)
2.4.1 TTF, CST and SRF

Sludge dewatering properties can be described by three parameters: capillary suction time (CST), time to filter (TTF) and specific resistance to filtration (SRF). The CST test (UNI-EN 14701-1) determines the rate of release of water from the sludge: it is performed placing a sludge sample in a small cylinder on a sheet of chromatography paper (Whatman rectangular filter), which extracts water by capillary suction. The time required to move in a specified distance is monitored measuring the conductivity change between two points appropriately spaced and in contact with the paper. The TTF and SRF (UNI-EN 14701-2) are similar if the viscosity and the content of the sludge do not vary among the compared samples. Both tests are performed by using the same system: a sludge sample is placed in a Buchner funnel with a paper support filter and vacuum is applied, the funnel is connected to a graduated cylinder and the amount of filtrate is measured as a function of time. The time required (seconds) for 50% reduction in sample volume is TTF, while SRF parameter can be calculated as:

$$SRF = \frac{2 \times A^2 \times \Delta P \times b}{\eta \times DS}$$

Where:

- SRF [m/kg]: specific resistance to filtration
- A [m^2]: filtration area
- ΔP [N/m^2]: pressure drop across the filter cake
- b [s/cm^6]: slope of the curve obtained by plotting the time of filtration to volume of filtrate ration (t/V) versus V itself
- η [kg/m/s]: dynamic viscosity
- DS [kg/m^3]: solid content of sludge sample

CST is a rapid and simple measurement, but may yield unrealistic results because of no pressure application. SRF is considered a realizable dewatering measurement but the coefficient b is difficult to calculate and large errors appear when dealing with low DS of content sludge samples. Time to filter (TTF) and CST can be used to compare different types of sludge, but not to obtain reliable estimates of full-scale dewatering performances.

2.4.2 Extracellular polymeric substances

Extracellular Polymeric Substances (EPSs) are high molecular weight compounds accumulating on the surface of bacterial cells. They contain a variety of organic substances (EPS constitutes 50% to 90% of a biofilm total organic matter) such as carbohydrates, exopolysaccharides, exoproteins, DNA, humic acid, uronic acid, etc. EPSs form a protective layer for the cells against the harsh external environments (high toxicity, sudden change of pH) absorbing exogenous nutrients and organic molecules, and aggregate bacterial cells in flocs (Figure 6). Thus, EPSs play an important
role in flocculation, settling and dewatering of sludge: an increase of EPSs results in a decrease in sludge dewaterability.\textsuperscript{21,32}

2.5 Sludge conditioning

Sludge conditioning is a process where sludge solids are treated with chemicals or various other means to prepare the sludge for dewatering processes. Both chemical conditioning and physical conditioning change the structure of the sludge in order to make the solid and liquid portions become more easily separable. The most widely used methods are chemical conditioning and physical conditioning.

a) Chemical conditioning

The use of appropriate dosage of organic, usually cationic, polymers (such as polyethylene imines epichlorohydrin/dimethylamine, diallyldimethyl ammonium chloride, acrylamine) at appropriate pH eliminate electrostatic repulsion, allowing short-range attractive forces to make zeta potential approaching zero and promote aggregation (charge neutralization model) or they react as cationic sites to bind more than one sludge particle, thus bridging the system of solid particles (bridging model). As a result, flocculation and dewaterability with the use of a high molecular weight polymers increase.

Iron and aluminium salts and lime are commonly used as inorganic flocculants. However, mechanical dewatering methods do not perform well using sludge samples conditioned with inorganic flocculants. To achieve high sludge dewatering, doses of 20-40\% of the original dry weight of sludge are usually required, causing a significant increase of sludge volume, which raises transport and disposal costs. Therefore, the use of inorganic flocculants is limited.\textsuperscript{21}

Another chemical technique for sludge pre-treatment is Fenton oxidation by hydrogen peroxide/ferrous ions.

Oxidation by H\textsubscript{2}O\textsubscript{2} and transition metal salts (such as Cu(II), Fe(II), Co(II), Ru(III), Ni(II)) or ozone, followed by an activation by UV-light, results in formation of hydrogen radicals and in a significant decrease in the water content of the final sludge cake. Advanced oxidation can help to improve sludge dewatering by degradation of EPSs, which reduces their water retention properties releasing EPSs-bound water, increasing the size of sludge flocs.

In Fenton oxidation, dewaterability of sludge is strongly dependent on the reaction temperature, H\textsubscript{2}O\textsubscript{2} concentration and pH (the optimal pH is around 3 where EPSs are released from sludge.

\textsuperscript{21,32} Figure 6- Biofilm formation.
particle surfaces and ζ value increases reducing the electrostatic repulsion between particles).  

b) **Physical conditioning**

Freezing and thawing convert the jellylike consistency of the wastewater to a granular-type that drains readily. During sludge freezing (at least 30 minutes at temperatures ranging from -10 to -200 °C), the free water begins to freeze and pushes the floc particles to the ice front. Once free water is frozen, the interstitial water is extracted by diffusion and added to the growing crystalline structure. All other impurities and solid particles are forced to the boundaries of the ice crystal where they become compressed or dehydrated. Freeze-thaw treatment transforms sludge into a compacted form and reduces the sludge bound water content. Thus, it makes sludge easier for settling and filtration: after thawing and dewatering, dewatered sludge cake can range from 25 to 40% of solids.

Another physical conditioning method is thermal treatment. Sludge heat treatment in temperature ranging from 40 to 180 °C: experiments performed at temperatures of 120 °C for 60 min showed that thermal treatment reduces the residual sludge amounts and enhances the dewaterability thanks to EPSs degradation and their natural properties are changed. Hydrolysis of the exocellular organic fractions (130-180 °C) leads to the destruction of the colloidal structure resulting in release of the bound water from the sludge particles.

### 2.6 Conventional dewatering techniques

Mechanical dewatering of sludge is conventionally integrated in WWTPs in order to lower the cost of transportation and disposal. Filtration by vacuum, by plate filter presses, by belt filter presses and centrifugation are the most used processes which exploit mechanical forces to remove water.

#### 2.6.1 Vacuum filtration

Vacuum filters are widely used to dewater low solid slurries, wherein the solid constituent in a sludge is separated by a porous filter cloth rotated through the slurry, with vacuum applied to the inner surface to cause the solids to accumulate on the surface as a cake.

The apparatus (Figure 7) consists of a rotary drum filter, vacuum pump, filtrate tank and scraper blade. In the vacuum filtration process, the sludge is drawn to the surface of the drum, which is covered with the filter material, holding the solids and allowing the liquid to enter the drum. The liquid is pulled by the vacuum flow to a filtrate tank. A vacuum is applied to the drum as the drum rotates, drawing air through the solids on the drum face and further reducing their moisture content. Just prior to discharge, a blast of compressed air is used to push the solids away from the drum surface, thereby allowing the scraper blade to operate effectively without tearing the filter material on the drum surface.

Nowadays they are very seldom used for dewatering sewage sludge.
2.6.2 Plate filter press

A filter press (Figure 8) includes a plurality of plates arranged in a horizontal stack, where a pressure piece is hydraulically pushed towards a headpiece. The plates and headpieces have a central sludge feed port, while filtrate outlet ports are usually located at the corner of the plates. Each plate has a cloth on both sides with appropriate holes for the feed and filtrate ports, thus creating a series of chambers when the plates are held together. The sludge is pumped into the chambers allowing solids to build up in the filter, letting the filtrate to flow through the cloth and along the ribbed plate surface to their filtrate outlets. The press is fed under pressure until the set pressure is reached or until the filtrate flow drops below a minimum value. In the conventional plate filter press, after a press cycle, the feed ports are blown out with air and the plates are separated from each other, allowing cake to drop out of the bottom of the press. After discharge of all cakes, the press is closed again for the next cycle.
2.6.3 Belt filter press

Belt filter presses are commonly used to dewater sewage sludge. They consist of two endless filter cloths belts, which encapsulate the sludge. Drainage is achieved by causing the belts to move closer together thereby applying mechanical pressure to the sludge. This is done by passing the belts over a number of closely spaced rollers (Figure 9).

There are three distinct phases in the process:

- Pre-conditioning
- Preliminary drainage
- Secondary dewatering

In the pre-conditioning phase, the sludge is pumped into a mixer where it is conditioned by adding flocculants. The pre-conditioned sludge is then discharged into the preliminary drainage zone where the free water is drained by gravity through a porous belt. The sludge then passes to the secondary dewatering phase where it is compressed between the belts with increasing high pressure.8

![Belt filter press](image)

**Figure 9- Belt filter press.**

2.6.4 Centrifuge

Centrifuge dewatering processes use centrifugal force to promote solid/liquid separation. The sludge is fed into a rotating basket assembly and accelerated. Solids are pulled out of the slurry by centrifugal force and are collected on the basket wall. The separated liquid flows out of the basket and is collected in the centrifuge housing, before being discharged (Figure 10).8

![Centrifuge](image)

**Figure 10- Centrifuge.**
Centrifugation represents one of the most used dewatering technologies. Current commercial centrifuges can reach up to around 30% of DS content when treating anaerobically digested municipal sewage sludge, but this value generally reduces to 23-24% for aerobically stabilised sludge, especially for sludge deriving from the combined treatment of industrial wastewater with domestic sewage.

2.6.5 Advantages and disadvantages of conventional dewatering techniques

The main advantages and disadvantages of conventional dewatering processes, including natural processes such as drying beds and drying lagoon, are shown in Table 2. Because of a large area requirement and odour potential, natural dewatering processes are applied at small Wastewater Treatment Plants only.

Table 2- Advantages and disadvantages of mechanical dewatering methods.42

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
</table>
| PLATE FILTER PRESS | • High cake solid concentration  
• Low suspended solids in filtrate  
• Good dewatering process for hard-to-handle sludge  
• Plates can be added to increase capacity without significant increase in floor area | • Batch operation  
• High capital and labour costs  
• Requires maintenance and skilled personnel  
• Requires inorganic chemical conditioning that produces additional solids |
| BELT FILTER PRESS | • Relatively low capital, operating and power costs  
• Easy to shut down the system  
• Easy to maintain | • Very sensitive to fed sludge characteristics  
• Sensitive to polymer type and dosage rate  
• Requires large quantity of belt wash water |
| CENTRIFUGE | • Relatively less space required  
• Fast start up and shutdown capabilities  
• Does not require continuous operator monitoring  
• Clean appearance and good odour containment | • Relatively high capital cost  
• High consuming of direct power per unit of product  
• Requires grit removal from feed sludge  
• Requires periodic repair of scroll, resulting in long downtime |
| DRYING BEDS AND DRYING LAGOON | • Low capital cost when land is readily available  
• Low energy consumption  
• Low chemical consumption  
• Least operator attention and skill required | • Large area requirement  
• Requires sludge stabilization  
• Design requires consideration of climatic effect  
• Sludge cake removal is labour intensive  
• Potential odour |
The main drawback of mechanical dewatering is that the dewatering rate depends on many sludge characteristics, mainly its porosity and hydraulic permeability. In the case of filter presses (both plate and belt presses) the layer of sludge near the filter medium is compressed during the process, thus reducing the porosity in that layer and decreasing the dewatering rate due to a blocking of the filter medium. As a result, conventional dewatering techniques based on filtration are not efficient methods to dewater sludge with low hydraulic permeability values.

In the case of centrifugation, dewatering depends more on sludge density and on the contents of colloidal matter. As volatile solids are lighter and colloidal, a lower content of volatile solids generally favours the separation efficiency in centrifuges.

2.7 Electrochemical dewatering: process principles

2.7.1 Electro-kinetic phenomena

Six different physical processes are usually grouped under the term electrokinetic phenomena:

- **Electrophoresis** is the movement of charged particles relative to a stationary liquid.
- **Electromigration** is the transport of ions in solution with respect to the solution itself. Each species moves according to its own ionic mobility, which is a function of the electrical charge, the diffusion coefficient and temperature.
- **Electro-osmosis** takes place at the solid/liquid interface of the medium and induces a displacement of the bulk water molecules.
- **Sedimentation** (Dorn effect) occurs when dispersed particles move under the influence of either gravity or centrifugation in an electrolyte solution. This motion disrupts the equilibrium symmetry of the particle's double layer. While the particle moves, the ions in the electric double layer lag behind due to the liquid flow: this causes a slight displacement between the surface charge and the electric charge of the diffuse layer. As a result, the moving particle creates a dipole moment and the sum of all of the dipoles generates an electric field which is called sedimentation potential. This situation is the opposite of electrophoresis as the particle movement creates the electrical field.
- **Streaming** occurs when an electric field is created by an electrolyte solution being forced to flow (by applying a pressure) through a charged surface (e.g. the surface of a capillary tube or through a porous plug). The counter-ions from the diffuse layer are dragged away due to the hydraulic displacement of the liquid over the surface: the ion accumulation in the direction of the liquid flow generates a potential difference. This situation is the opposite of electro-osmosis.
- **Electrochemical reactions** at the electrodes guarantee the continuity of the electrical transportation. When an electric field is applied across electrodes in an aqueous solution, electrolysis of water occurs in order to maintain charge equilibrium. The electrolysis of water produces oxygen gas and protons, H\(^+\), at the anode, while hydrogen gas and hydroxyl anion, OH\(^-\), are formed at the cathode: as a result, the pH near the cathode increases while the pH near the anode decreases.
A brief description of the above-mentioned electrokinetic phenomena is given in Table 3. All electrokinetic phenomena are related to the development of the electrical double layer (EDL), at the particle/electrolyte interface.

<table>
<thead>
<tr>
<th>ELECTROKINETIC PHENOMENA</th>
<th>DRIVING FORCE</th>
<th>RESULTING PHENOMENA</th>
<th>MOVING PHASE</th>
<th>STATIONARY PHASE</th>
<th>QUANTITY MEASURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrophoresis</td>
<td>Electric field</td>
<td>Particles movement</td>
<td>Particles</td>
<td>Liquid</td>
<td>Electrophoretic mobility</td>
</tr>
<tr>
<td>Electromigration</td>
<td>Electric field</td>
<td>Ions transport</td>
<td>Ions/particles</td>
<td></td>
<td>Ionic mobility</td>
</tr>
<tr>
<td>Electroosmosis</td>
<td>Electric field</td>
<td>Pressure gradient</td>
<td>Liquid</td>
<td>Plug or capillary</td>
<td>Electro-osmotic volume flow per unit current</td>
</tr>
<tr>
<td>Sedimentation potential</td>
<td>Particle movement</td>
<td>Electric field</td>
<td>Particles</td>
<td>Liquid</td>
<td>Potential difference per unit of length</td>
</tr>
<tr>
<td>Streaming potential</td>
<td>Pressure gradient</td>
<td>Electric field</td>
<td>Liquid</td>
<td>Plug or capillary</td>
<td>Streaming potential (or current) per unit of applied pressure</td>
</tr>
</tbody>
</table>

The most involved events in electro-dewatering are: electro-osmosis, electrophoresis and electromigration. A description of these phenomena is given in the following chapters.

### 2.7.2 Electro-osmosis

Electro-osmosis balances the electrical and viscous forces in the double layer. Several theories have been proposed to explain and to predict electro-osmotic behaviour. The Helmholtz–Smoluchowski theory for the electro-osmotic rate in a capillary is one of the most widely followed.

Electro-osmotic transport can be induced by an external electric field in capillary or porous plug systems where the electric polarization (charging) of solid surfaces occurs. Due to the fixed surface charge at the solid interface, an oppositely charged region of counterions develops in the liquid to maintain the electroneutrality of the solid/liquid interface: this screening region is denoted as the electrical double layer (EDL). The typical situation is depicted in Figure 11.

The first layer is at the inner Helmholtz plane and bears the potential $\psi_i$, where co-ions and counterions are not hydrated and are specifically adsorbed to the surface. The second layer is defined by the outer Helmholtz plane with potential $\psi_d$, consisting of a layer of bound, hydrated, and partially hydrated counterions. The outermost and third layer is the diffuse layer, composed of mobile co-ions and counterions, in which resides the slip plane bearing the zeta potential, $\zeta$. In most cases, the outer Helmholtz plane and the slip plane are situated close to each other, allowing
the approximation of $\psi_d$ with the $\zeta$ potential for practical purposes. The slip plane, or shear surface, is an imaginary plane separating ions that are immobile at the surface from those that are mobile in solution.\(^{29}\)

![Electric Double Layer Diagram](image)

**Figure 11- Structure of electric double layer, with the corresponding potential distribution with distance from a charged wall.**\(^{29,44}\)

According to the theory, the electro-osmotic velocity can be derived based on the balance of the electrical and frictional forces between water and the wall of the capillary and is described by the following equation\(^{42}\):

$$v_{eo} = \frac{\varepsilon_r \zeta \Delta V}{\eta \Delta L}$$

$v_{eo}$ [m/s]: electro-osmotic velocity  
$\zeta$ [V]: zeta potential  
$\varepsilon_r$[F/m]: dielectric permittivity of the liquid; note that F units are [kg m$^2$ V$^{-2}$ s$^{-2}$]  
$\eta$ [kg m$^{-1}$ s$^{-1}$]: viscosity of the liquid medium  
$\Delta V$ [V]: electric potential  
$\Delta L$ [m]: length of the capillary between the electrodes

The flow rate is instead described by\(^{21}\):
During electro-dewatering, electro-osmosis is considered to play the most important role to gain extra water removal from sludge. The zeta potential of sludge usually has a negative value, therefore, the direction of electro-osmotic flow is from the anode to the cathode.

2.7.3 Electrophoresis

Electrophoresis refers to the movement of solid particles suspended in a liquid under the influence of an electrical field. The solid particles acquire a surface charge either from their own intrinsic surface ionization such as in the case of clays or sludge, or by the adsorption of polyelectrolytes, surfactants or ions onto their surface. In the case of colloids, the surface area of the particles is large relative to the volume of the particles and therefore electrostatic repulsions dominate over the Van der Waals interaction. The electrostatic repulsion force arises from the electrical double layer, which prevents the particles coagulating or agglomerating. When an electric field is applied across a colloidal suspension, the charge on the particle (negative) interacts with the field and the particles move towards the electrode of opposite charge (anode).

\[ v_{ep} = \gamma \frac{\varepsilon_0 \varepsilon_r E \zeta}{\eta} \]

\( v_{ep} \): electrophoresis velocity
\( \varepsilon_0 [8.854 \times 10^{-12} \text{ F/m}] \): dielectric permittivity of vacuum
\( \varepsilon_r \): dielectric permittivity of the liquid
\( \gamma \): coefficient for particle shape (for spherical particles \( \gamma = 2/3 \))

Barton et al.\textsuperscript{14} described the influence of electrophoresis on enhanced water removal. During the initial stages of electro-dewatering, the sludge particles are still free to move in the fluid suspension. Because of negative charge of particles, they tend to migrate towards the anode, thus delaying the onset of cake formation on the lower filter medium and hence leading to enhanced water flow. When DS content in sludge segment becomes higher, sludge particles will be locked in position and are hence unable to move, so only electro-osmosis plays an important role in transporting water from anode towards the cathode.\textsuperscript{21}
2.7.4 Electromigration

Transport by electromigration is only possible if the electroneutrality balance, which is imposed when a system is at equilibrium, is broken by the exchange of the electrons at the electrodes, as a result of electrochemical reactions. The electron transfer at the electrodes produces electromigration, which acts to restore electroneutrality. A general description of the flux of charged species in an electrochemical system is developed from the Nernst–Planck equation.\(^{29}\)

\[
J_j = u_j^* c_j \nabla (-E) \\
u_j^* = \frac{D_j z_j F}{RT} \tau n
\]

- \(J_j\) [mol/(m\(^2\)s)]: flux of the species j
- \(u_j^*\) [m\(^2\)/Vs]: effective ionic mobility
- \(c_j\) [M]: molar concentration of the species j
- \(E\) [V/m]: electrical potential gradient
- \(D_j\) [m\(^2\)/s]: diffusion coefficient of species j in the dilute solution
- \(z_j\): charge of chemical species
- \(F\) [96,487 C/mol]: Faraday’s constant
- \(R\) [8.314 J/(molK)]: universal gas constant
- \(T\) [K]: absolute temperature
- \(\tau\): porosity of medium
- \(n\): tortuous factor

During electro-dewatering, electromigration could occur, but the phenomenon which rules the removing of water from sludge is electro-osmosis.
2.8 Electro-osmotic dewatering of sludge

Electro-osmotic dewatering is an attractive technique to dewater sludge since it can remove water trapped between fine solid particles when it cannot be removed by the application of pressure or vacuum. This is because electro-osmotic flow is based on the surface and colloidal characteristics of particles in suspension and is independent on pore size. As a result, the low hydraulic conductivity of sludge and the resultant blocking of filter medium do not significantly affect the dewatering rate when applying electro-osmotic dewatering. Therefore, electro-osmotic dewatering is an efficient method to dewater low permeability sludge having hydraulic conductivity values less than $10^{-6}$ cm/s. Usually it is combined with mechanical methods to improve the rate and efficiency of dewatering.\(^{19}\)

\[
\text{Figure 12- Processes occurring in sludge electro-dewatering.4}
\]

2.8.1 Electro-mechanical dewatering process

The application of an electric field, combined with a pressure, tends to increase sludge dewaterability: the phenomenon of electro-osmosis rules the flow in charged particle matrix. Electro-osmosis reduces the interstitial water and some extent of the vicinal water, thus resulting in a dryer sludge cake: it appears an energy efficient alternative solution to current technologies to bring sewage sludge from 20-25% up to 45-50% of dry-solid content.
Furthermore, electro-dewatering reduces the concentration of heavy metals in the sludge (by separating them in the osmotic process) and this will lead to a high fraction of the sludge that satisfies regulation and can hence be used as not pollutant fertilizer in agriculture.

Many experimental factors can influence the reduction of water content and, consequently, the process yield. The critical processing factors are voltage (or current), pressure, time, floc size distribution, conditioning parameters, polyelectrolyte characteristics, temperature etc. A study of the influence of certain of these factors should indicate the optimum experimental conditions.

Although electro-mechanical dewatering is still not fully understood, the mechanical and electrical effects, resulting in the reduction of water content, are usually thought to satisfy the following steps\textsuperscript{19,29,45}:

- The mechanical dewatering reduces the volume of the pores and squeezes the water out of the product.
- The charged particles (usually negative) are still free to move in the fluid suspension. They tend to migrate towards the electrode carrying the opposite charge, where the filter medium is located.
- When the cake has formed, the particles are locked in their position and hence unable to move. Water containing ions is transported by viscous or molecular interactions and as a hydration sheath: it is transported through the porous medium by electro-osmosis.
- Electrochemical reactions at the electrodes are essential to restore charge equilibrium that enables electro-dewatering to proceed beyond the transient stage.
- Finally, water ceases to be the continuous phase in the cake, and the electrical resistance rise leading to ohmic heating. The resulting reduction in viscosity facilitates the removal of some of the remaining water.

In principle, the achievement of complete water removal within the sludge is not possible since, when the liquid phase in the sludge is no longer continuous as a result of dewatering, the sludge does not conduct electricity and, then, electro-osmosis ceases.\textsuperscript{8,13}
2.8.2 Electrochemical reactions effects

In typical electro-dewatering operations, the applied DC voltages are in the range of 5-30 V (some authors applied higher voltages but obtained too high resistive sludge cake). These systems are essentially electrochemical cells, where the application of an electric field produces electrochemical reactions, which affect the performance of the electro-dewatering process. The possible cathode and anode reactions are:

**CATHODE:**

\[
\begin{align*}
2H_2O + 2e^- & \rightarrow H_2(g) + 2OH^- & E_0 = -0.83 \text{ V} \\
2H_3O^+ + 2e^- & \rightarrow 2H_2O + H_2(g) & E_0 = 0 \text{ V} \\
M^{n+} + ne^- & \rightarrow M & (c)
\end{align*}
\]

Where \( M^{n+} \) represents cationic species that can be reduced and \( E_0 \) is the standard electrode potential at a temperature of 298 K.

**ANODE:**

\[
\begin{align*}
M^{n+} + ne^- & \rightarrow M & (d) \\
2H_2O & \rightarrow O_2(g) + 4H^+ + 4e^- & E_0 = 1.23 \text{ V}
\end{align*}
\]
These electrode reactions are affected not only by the materials of the electrode, but also by the ions in the electrolyte: they may cause some hindering during electro-dewatering.

Reaction (a) produces hydroxide ions and reaction (e) produces protons, this may result in a pH gradient across the filter cake. Tuan et al. (2008) reported that the pH drop relates to the reduction of the absolute value of the zeta potential, thus the decrease in pH (specifically at the anode) reduced the electro-osmotic flow during direct current application.

Hydrogen and oxygen evolution at cathode and anode respectively leads to an increase in the electrical resistance of the system, with the formation of an electrically insulating layer. On the other hand, it may lead to an explosive mixture, causing a potential safety risk, which in batch devices is usually avoided by venting systems.

The oxidation of the anode material, due to oxygen evolution, reduces the process efficiency and can cause in some applications the contamination of the filter cake or filtrate, increasing the operating cost. Anodes such as stainless steel will be subject to corrosion, thus the use of dimensionally stable anode materials is necessary. As reported in Table 5, the anodes used in experiments are made of conventional metallic plates (or meshes) such as stainless steel or nickel steel (which have sufficient strength but are easily corroded), graphite (which is cheap but fragile and cannot undergo to pressure conditions) and copper. Raats et al. (2002) and Saveyn et al. (2006) documented that the use of titanium coated with mixed metal oxide (MMO) plates, such as Ir$_2$O$_3$-coated titanium, as anode, prevents corrosion. Anodes made of conducting ceramic materials (e.g. iridium oxide or ruthenium oxide) coated on titanium seem to be highly effective due to their excellent strength, flexibility and corrosion resistance.

The choice of materials for the cathode electrode presents far less problems in terms of corrosion resistance: stainless steel, copper and nickel in the form of plates or meshes can be used.

The electrical field used in electro-dewatering applications usually exceeds the decomposition voltage of water, leading to a considerable ohmic loss that causes heating in the dewatering device and thus a decreasing liquid viscosity. This heating effect increases together with the duration of the electro-dewatering operation.

2.8.3 Features of electro-osmotic dewatering

Yoshida (1993) has identified the main features of electro-osmotic dewatering as follows:

- The filter medium is not damaged and blocked as in conventional belt or plate filter presses, so the effect of blocking on dewatering rate is very small.
- The rate of dewatering and its efficiency are easily controlled by regulating the voltage applied to the sludge and electric current passing through the sludge.
- Effective dewatering can be achieved in sludge which are not amenable to mechanical dewatering processes.
Electro-osmotic dewatering can be easily combined with mechanical methods, leading to additional improvement in the rate and efficiency of dewatering.

Corrosion of the electrodes as a result of electrolysis can occur, resulting in subsequent contamination of the sludge.

When the electric conductivity of the sludge is very large, electric power efficiency becomes low because of the generation of heat. When conductivity is very low, a very large voltage is required to drive the flow. Therefore, the application of electro-osmotic dewatering is restricted by the electrical properties of the sludge.

**Table 4- Advantages and disadvantages of sludge electro-dewatering.**

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High dewatering capacity for hard-to-dewater liquid</td>
<td>• Corrosion of electrodes due to electrochemical reaction and pH change</td>
</tr>
<tr>
<td>• Significant reduction in polyelectrolyte amount</td>
<td>• Possible Joule effect</td>
</tr>
<tr>
<td>• Lower energy requirement than filter press</td>
<td></td>
</tr>
<tr>
<td>• Low mechanical support demand</td>
<td></td>
</tr>
<tr>
<td>• Long life service</td>
<td></td>
</tr>
<tr>
<td>• No damaging and blocking of filter medium</td>
<td></td>
</tr>
</tbody>
</table>

2.8.4 Efficiency of electro-osmotic dewatering

According to many studies, an increase in electrical field and pressure application results in an increase of sludge dewatering rate. The former improves electroosmosis, while the latter, together with the squeezing of the sludge, let a better contact between the electrodes and the sludge itself. However this kind of behaviour is hindered at voltages higher than a threshold value, in approximation around 40 V. A high electrical field implies high currents, so faster electrolysis reactions: oxygen and hydrogen evolution (which are ruled by ATEX) are produced and pH near electrodes changes together with zeta potential. Removal of these gases is a critical aspect of the process, in order to avoid explosions during experiments. At the same time, sludge resistance becomes too high due to the lower water amount and, because of Joule effect, temperature raises too much.  

According to Mahmoud et al. (2010)\(^{29}\), current increases with voltage in the early period and, after reaching a maximum, it decreases with time. Indeed, in the early period, the electric resistance of the sludge bed decreases with the lowering of distance between anode and cathode with the proceeding of dewatering. Thereafter resistance increases under the influence of the unsaturated sludge layer formed in the dewatered sludge. On the other hand, oxygen and hydrogen evolution leads to the appearance of voids within the bed and increases the electrical resistance of the system: an electrically insulating layer is produced if the process last for a long time. Finally, the electrical resistance of the cake formed is too high, the electrical current reduces and eventually ceases causing the interruption of electro-dewatering.\(^{29}\)
These behaviours affect considerably dewatering efficiency and must be considered before designing the apparatus.

In general, power consumption is an important parameter in operating an electro-osmotic dewatering system. Energy expenditure per unit weight of sludge processed can be formulated as:\(^{52}\):

\[
E_u = \frac{P}{W} = \frac{1}{W} \int V I dt
\]

\(E_u\) [Wh/kg]: energy consumption per unit weight of sludge  
\(P\) [Wh]: energy expenditure  
\(W\) [kg]: weight of sludge  
\(V\) [V]: voltage  
\(I\) [A]: current  
\(t\) [h]: processing time

As a rule of thumb, it can be considered that much less total energy is required for electro-dewatering of filter cakes that contain less liquid, as the water that can be separated is lower; however the specific energy consumption per unit weight of water will be higher.\(^{53}\)

Comparing power consumptions of sludge electro-dewatering with those of thermal drying, we should assess that the former involves lower costs, so electro-osmosis as a promising sludge dewatering process. The minimal drying energy requirement refers to the latent heat of water evaporation of about 0.617 kWh/kg, while in industrial devices the total energy consumption can be up to 0.9 to 1.2 kWh/kg.

However, the data on power consumption reported in the literature are difficult to compare and analyse: several authors employed the additionally electrical energy consumed per unit mass of the dry solids (kWh/kg\(_{DS}\)) and therefore it is difficult to compare with the data reported for a drying process. Moreover, the electro-dewatering energy expressed as kWh/kg\(_{DS}\) strongly depends on the initial cake dryness which is different in each study.\(^{29}\)

One of the best ways to compare the power consumption is to calculate the energy per the additional mass of water removed (in comparison to dewatering without electrical field).

Figure 14 gives an overview of the different specific electric energy consumptions at different pressures and electrical fields, in comparison with thermal drying consumptions: it was found that the electro-dewatering technique requires much less energy than thermal drying. These findings confirm that the application of a voltage is an interesting technique to enhance wastewater sludge dewatering.\(^{54}\)
However, one important consideration is that drying uses heat, electro-dewatering uses electricity. Therefore, the thermodynamic efficiency of the electrical network must be considered when comparing the energy consumption of the two methods. As the thermal efficiency of conventional power stations in Italy is 0.444\(^5\), this means that a kWh of energy used in an electro-dewatering device should be compared with \(1/0.444 = 2.25\) kWh of thermal energy, unless the electricity is produced from a photovoltaic or eolic device. Therefore, to be energetically efficient if compared to thermal drying, the electro-dewatering must consume less than \(0.9 - 1.2 \times 0.444 = 0.4 - 0.5\) kWh/kg of water removed. Figure 14 shows that electro-dewatering with applied voltages of up to 50 V and pressure of up to 1200 kPa consume less than 0.4 kWh/kg of water, making electro-dewatering always competitive with thermal drying.

\[\text{Figure 14- Energy consumption of conditioned activated sludge as a function of applied voltage for three different pressures.}\]
2.9 Review of electro-osmotic dewatering of sludge

The earliest studies on electrokinetic dewatering made by Casagrande\textsuperscript{16} focused on the stabilization of soil. In the last decades, the use of electro-dewatering to remove water from different materials such as clay\textsuperscript{56,57,58,59}, tomato paste suspension\textsuperscript{60}, food\textsuperscript{61}, vegetable sludge and sewage sludge started to be developed. The main difference between sludge and other materials is that sewage sludge is composed of a mixture of organic compounds and microorganisms (dead and living biomass such as helminths, helminth eggs, protozoans, bacteria, etc.).

Most of the set up for electro-dewatering studies have been performed with lab scale devices: they vary in size, have horizontal or vertical set up, non-pressure, pressure, and vacuum application etc. Electro-dewatering is commonly carried out in cylindrical cell with pressure application: electro-osmosis is combined with conventional mechanical dewatering methods to improve the rate and efficiency of water removal. Electro-osmotic devices can be used in conjunction with conventional dewatering devices such as belt filter press\textsuperscript{18,26} and pressure filter press.\textsuperscript{62}

Typically, direct electrical field has been used in electro-dewatering process, but also interrupted DC electro-dewatering has been studied\textsuperscript{56,57,63,64,65}: the authors reported that a short interruption of power application enhances electro-osmotic flow. Yoshida tried the use of AC electric field with periodic reversals of electrode polarity.\textsuperscript{66} A constant voltage from 5 V to over 60 V has been used in most studies. Some researchers have reported electric field strength as V/cm in their studies.\textsuperscript{46,51,57,58,60,67,68,69,70}

Yoshida proposed also the multi-stage electrode dewatering method\textsuperscript{71} in which three perforated electrodes are vertically arranged at regular intervals within the sludge bed and are sequentially switched on. This method could improve the efficiency of dewatering and reduce power consumption and it has been further investigated in Vijh's studies\textsuperscript{72} by the use of a “gate” electrode. This configuration can lead to a better control of both current and particles flux, thanks to the intermediate electrode activation, and to an increase of liquid capacity with respect to normal electro-dewatering.

Ho and Chen designed a lab scale device with a flat plate rotated anode\textsuperscript{58}. The anode was able to rotate at different speeds, improving contact between the electrode and sludge and increasing its conductivity to get a dryer cake. A higher rotating speed of the anode has been related to a decrease in water content of the cake, with maximum efficiency at 240 rpm.

In some non-pressure electro-dewatering tests, electrical field was applied directly to the original waste sludge or clay.\textsuperscript{56,57,26,68} In other experiments, sludge was pre-dewatered by mechanical dewatering process, in which some of the water content was removed.\textsuperscript{46,73} In pressure electro-dewatering, the process lasts from several minutes to several hours. An increase in the applied pressure resulted in a dryer sludge cake.\textsuperscript{27,74} During electro-dewatering, sludge at the anode becomes dry: this may deteriorate the electrical contact between the sludge and the electrodes and the increasing in contact resistance causes a drop in the electrical field. Thus, higher pressure application improves the electrical contact leading to more efficient electro-osmotic flow and dryer sludge cake. Sludge electro-dewatering at different voltages has been presented in many studies.\textsuperscript{27,74} Increase in voltage leads to higher water removal rates and dryer sludge cake. However, higher electrical field application cause higher energy consumption.
Also the influence of addition of polyelectrolytes and polymers, in order to get a higher DS content, has been studied by different authors.\textsuperscript{69,75,76}

The use of filter cloth between electrodes and sludge cake to hinder the loss of solids has been investigated by Yu et al.\textsuperscript{70}: they suggested the use of a cathode mesh with small holes size instead of a polypropylene cloth, due to its water removal hindering. Citeau et al. studied the best arrangement of filter cloths and electrodes.\textsuperscript{77}

The energy consumption of electro-dewatering has been calculated in several studies. However, the power consumption of sludge electro-dewatering among the different papers is difficult to compare and analyse: it depends on the initial DS content of the sludge (it is expressed as kWh/kg\textsubscript{DS}). In order to get a comparable value, Gazbar et al. (1994)\textsuperscript{78} and Saveyn et al. (2006)\textsuperscript{51} calculated the energy per the additional amount of water removal in comparison to normal dewatering without electrical field application (kWh/m\textsuperscript{3}): they found electrical consumption between 46 to 445 kWh/m\textsuperscript{3}, depending on voltage application. As it has been already noticed, this consumption is lower than conventional thermal evaporation methods, where the energy requirement must be higher than pure latent heat (617 kWh/m\textsuperscript{3})\textsuperscript{79}, up to 1200 kWh/m\textsuperscript{3} in industrial applications.\textsuperscript{78} On the other hand, one must consider that electricity requires heat to be generated, as it has been already shown in Chapter 2.8. According to Tuan et al.\textsuperscript{73}, high voltage applications are not economical from the perspective of energy consumption because the residual water content in the final sludge cake was independent on voltage from 10 to 30 V. However, higher voltages resulted in much shorter dewatering times. In this study, the application of 30 V consumed 150 kWh/m\textsuperscript{3}: energy consumption in this study, depending on the applied voltage, was four to six times less than the theoretical thermal evaporation of water. Gingerich et al. (1999)\textsuperscript{80} showed that the energy consumption is not uniform during electro-dewatering process, but it increases with the increasing of cake DS content, because the last water fractions become increasingly difficult to remove due to its high binding strength. Saveyn et al. (2006)\textsuperscript{51} highlighted a linear relationship between the energy consumption and the amount of additional water removal. Gingerich et al.\textsuperscript{80} and Yuan and Weng\textsuperscript{46} made an economic analysis of the electro-dewatering process, taking into account of the additional energy costs and possible savings by transport and disposal, and came to the conclusion that electro-dewatering to intermediate moisture contents is the most cost-efficient.

In Table 5, some examples of studies about dewatering found in literature are shown.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Material</th>
<th>Initial dry solids</th>
<th>Apparatus</th>
<th>Electrodes</th>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friehmel t et al(^1)</td>
<td>Harbour sludge, sewage sludge, or industrial sludge</td>
<td>15% (h=14.4 mm)</td>
<td>Vertical cylinder Piston</td>
<td>NA</td>
<td>2 A</td>
<td>1140 s</td>
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<td></td>
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<td>0.5 A</td>
<td>840 s</td>
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<td>1 A</td>
<td>420 s</td>
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<td>1.5 A</td>
<td>360 s</td>
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<td></td>
<td></td>
<td></td>
<td>2 A</td>
<td>180 s</td>
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<tr>
<td>1996 Gopalakrishnan et al(^7)</td>
<td>Bentonite clay</td>
<td>10%</td>
<td>Vertical acrylic cylinder (Ø=5 cm)</td>
<td>NA</td>
<td>6 V/cm DC IS(30/0.1)</td>
<td>4200 s</td>
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<td>IS(30/0.05)</td>
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<td>IS(30/2)</td>
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<tr>
<td>1997 Shang et al(^8)</td>
<td>Phosphatic clay, sedimented by gravity</td>
<td>13.2%</td>
<td>Vertical plexiglass cylinder (Ø=9 cm, H=20 cm)</td>
<td>Stainless steel mesh electrodes</td>
<td>DC 16-10 V IS(15/16) 20-19.5 V IS(15/17) 3-6-17-8 V IS(15/20) 15 V</td>
<td>24 h</td>
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<td></td>
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<td>19.5%</td>
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<td>25.7%</td>
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<td></td>
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<td>15.7%</td>
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<td>33.5%</td>
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<td></td>
<td></td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
<td>26.3%</td>
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<tr>
<td>2001 Lee et al(^7)</td>
<td>Digested sludge</td>
<td>3%</td>
<td>Vertical teflon cylinder (Ø=7 cm, H=50 cm) Piston</td>
<td>Anode: copper plate 80 V/cm (bar) 0.981 1.926 2.943 3.924 3.924 3.924 3.924 3.924</td>
<td>900 s</td>
<td></td>
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<td></td>
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<td></td>
<td>Cathode: copper plate with 3 mm holes 80 V/cm 0 V/cm 40 V/cm 80 V/cm 120 V/cm</td>
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<tr>
<td>2001 Ho(^8)</td>
<td>Bentonite slurry</td>
<td>9.1%</td>
<td>Vertical cylinder (Ø=9 cm, H=25 cm) Rotational anode</td>
<td>Anode: titanium plates coated with Sn and Sb oxides 6 V/cm 0 rpm</td>
<td>240 rpm ND</td>
<td>14.4% 23%</td>
</tr>
<tr>
<td>Authors</td>
<td>Material</td>
<td>Initial dry solids</td>
<td>Apparatus</td>
<td>Electrodes</td>
<td>Parameters</td>
<td>Results</td>
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<tr>
<td>2002 Raats</td>
<td>Flocculated WMO-Al sludge</td>
<td>5%</td>
<td>Gravity-driven thickening belt</td>
<td>Stainless steel (or titanium coated with iridium oxide)</td>
<td>0 V, 15 V, 30 V</td>
<td>0.05 bar</td>
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<td></td>
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<td></td>
<td>Conventional belt press (filter belt W=1 m)</td>
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<td>WMO iron-ion-coagulated sludge, floculated and pre-dewatered gravimetrically</td>
<td>15%</td>
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<tr>
<td></td>
<td>Anaerobically digested sewage sludge, floculated and pre-dewatered gravimetrically</td>
<td>9%</td>
<td>Vertical PVC cylinder (Ø=5.5 cm, H=20 cm)</td>
<td>Stainless steel electrodes</td>
<td>30 V</td>
<td>2.5 bar</td>
</tr>
<tr>
<td></td>
<td>Fresh water dredging sludge, floculated and pre-dewatered gravimetrically</td>
<td>9%</td>
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<tr>
<td>2003 Yuan et al</td>
<td>Belt pressed mixed sludge</td>
<td>15.9%</td>
<td>Horizontal acrylic cylindrical cells (Ø=4 cm): Sludge specimen chamber (L=6 cm) Cathode reservoir (L=4 cm)</td>
<td>Graphite rod electrodes</td>
<td>2.5 V/cm, 2.5 V/cm, 5 V/cm, 5 V/cm, 5 V/cm</td>
<td>-</td>
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<tr>
<td>2003 Weber</td>
<td>Quartz sand SF800</td>
<td>5%</td>
<td>Filter press: Filter plates (47 cm X 47 cm) Filter chamber (H=6 cm)</td>
<td>Outer electrodes 0 V, 120 V Middle electrode 60 V, 120 V</td>
<td>4 bar</td>
<td>1500 s</td>
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<tr>
<td></td>
<td>Amberger kaolin</td>
<td></td>
<td></td>
<td></td>
<td>0 V, 80 V</td>
<td>1200 s</td>
</tr>
<tr>
<td>2004 Al Asheh et al</td>
<td>Tomato paste suspension</td>
<td>5%</td>
<td>Vertical acrylic cylinder (Ø=9.1 cm, H=25 cm)</td>
<td>Circular stainless steel mesh (AISI 316) discs</td>
<td>100 mA</td>
<td>9000 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.5 V/cm, 3.75 V/cm, 5 V/cm</td>
<td></td>
</tr>
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### Authors, Material, Initial dry solids, Apparatus, Electrodes, Parameters, Results

<table>
<thead>
<tr>
<th>Authors</th>
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<th>Initial dry solids</th>
<th>Apparatus</th>
<th>Electrodes</th>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang et al (2005)</td>
<td>Pet food industry wastewater sludge</td>
<td>3-7%</td>
<td>Horizontal PVC cell (L=14 cm, W=10 cm, H=10 cm)</td>
<td>Anode: graphite sheet, Cathode: stainless steel mesh</td>
<td>H= 4 cm 2.5 V/cm, 5 V/cm, 7.5 V/cm</td>
<td>42.7% 44.6% 48.4%</td>
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<tr>
<td></td>
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<td></td>
<td>Vertical cylinder (Ø=15 cm, H=22 cm)</td>
<td>Anode: graphite, Cathode: porous stainless steel</td>
<td>IS(60/30) 60 V + IS(10/30) 30 V + 40 V</td>
<td>ND 54.2%</td>
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<tr>
<td>Saveyn (2005)</td>
<td>Thickened activated, conditioned sludge</td>
<td>3.63%</td>
<td>Vertical plexiglass cylinder (Ø=7 cm) Piston</td>
<td>Stainless steel electrodes</td>
<td>0 V/cm + 25 V/cm</td>
<td>4 bar 1800 s + 1800 s 40%</td>
</tr>
<tr>
<td>Reddy et al (2006)</td>
<td>India harbour sediments</td>
<td>No polymer, Polycryllic acid: 0.5% 1% 2%, Polyaclrylamide: 0.5% 1% 2%</td>
<td>Vertical acrylic cylinder</td>
<td>Graphite electrodes</td>
<td>0 V/cm 1 V/cm 1 V/cm 1 V/cm</td>
<td>145 h 145 h 211 h 210 h 212 h 212 h 290 h 290 h 32% 35% 29%</td>
</tr>
<tr>
<td>Shin et al (2006)</td>
<td>Sludge without electrocoagulation</td>
<td>2.4%</td>
<td>Vertical teflon cylinder (Ø=7 cm, H=50 cm) Piston</td>
<td>Anode: nickel plate, Cathode: nickel plate with 3 mm holes</td>
<td>0 V/cm 0 V/cm 40 V/cm 80 V/cm 120 V/cm</td>
<td>3.924 bar 1500 s 11% 24% 34% 37% 45%</td>
</tr>
<tr>
<td>Authors</td>
<td>Material</td>
<td>Initial dry solids</td>
<td>Apparatus</td>
<td>Electrodes</td>
<td>Parameters</td>
<td>Results</td>
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<tr>
<td>2006 Larue et al&lt;sup&gt;59&lt;/sup&gt;</td>
<td>Gelatinous bentonite suspension</td>
<td>8.5%</td>
<td>Vertical polypropylene cylinder (Ø=5.2 cm, Ø&lt;sub&gt;e&lt;/sub&gt;=10 cm)</td>
<td>Stainless steel electrodes</td>
<td>100 mA</td>
<td>1530 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Piston (Ø=5.1 cm) Filter base (Ø&lt;sub&gt;e&lt;/sub&gt;=13.6 cm) with a cylindrical cavity (1 cm)</td>
<td></td>
<td>10 bar</td>
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<td>2007 Glendinning et al&lt;sup&gt;26&lt;/sup&gt;</td>
<td>Digested, conditioned sludge</td>
<td>13.9%</td>
<td>Vertical perspex cylinder Piston</td>
<td>Copper discs</td>
<td>1 V/cm</td>
<td>0.5 bar</td>
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<td></td>
<td></td>
<td>14.8%</td>
<td></td>
<td></td>
<td>0.25 bar</td>
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<tr>
<td></td>
<td>Activated, thickened, conditioned sludge</td>
<td>7.6%</td>
<td>Belt press</td>
<td>Woven polyester electrified with carbon fibre strips</td>
<td>15 V</td>
<td>0.25 bar</td>
</tr>
<tr>
<td>2008 Tuan et al&lt;sup&gt;49&lt;/sup&gt;</td>
<td>Primary and secondary mixture, predewatered sludge</td>
<td>8.6%</td>
<td>Vertical acrylic cell (H=55 cm, W=17 cm, L=31 cm): 10 cm gravel bed and 10 cm sand bed</td>
<td>Anode: titanium plate Cathode: stainless steel mesh</td>
<td>15 V</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>6.7%</td>
<td>Vertical polyvinyl chloride cylinder (Ø=9.8 cm, L=30 cm)</td>
<td></td>
<td>4 bar</td>
<td>ND</td>
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<tr>
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<td>Primary and secondary mixture, predewatered sludge + alkalinity (NaH&lt;sub&gt;2&lt;/sub&gt;O)</td>
<td>8.3%</td>
<td>Vertical acrylic cell (H=55 cm, W=17 cm, L=31 cm): 10 cm gravel bed and 10 cm sand bed</td>
<td>Anode: titanium plate Cathode: stainless steel mesh</td>
<td>15 V</td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Material</td>
<td>Initial dry solids</td>
<td>Apparatus</td>
<td>Electrodes</td>
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<td></td>
<td>Vertical polyvinyl chloride cylinder (Ø=9.8 cm, L=30 cm)</td>
<td>4 bar</td>
<td></td>
<td>34.9%</td>
</tr>
<tr>
<td></td>
<td>Anaerobically digested, pre-dewatered sludge</td>
<td>7.5%</td>
<td>Vertical acrylic cell (H=55 cm, W=17 cm, L=31 cm): 10 cm gravel bed and 10 cm sand bed</td>
<td>Anode: titanium plate Cathode: stainless steel mesh</td>
<td>15 V</td>
<td>-</td>
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<td></td>
<td></td>
<td></td>
<td>40.6%</td>
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<tr>
<td></td>
<td></td>
<td>6.9%</td>
<td>Vertical polyvinyl chloride cylinder (Ø=9.8 cm, L=30 cm)</td>
<td>4 bar</td>
<td></td>
<td>40.2%</td>
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<tr>
<td>2010 Yu et al.</td>
<td>Activated, thickened, conditioned and centrifuged sludge</td>
<td>21%</td>
<td>Vertical acrylic cylindrical cell (Ø=7 cm)</td>
<td>Stainless steel electrodes (no filter cloth)</td>
<td>16 V/cm 20 V/cm 24 V/cm</td>
<td>0.07 bar 300 s</td>
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<tr>
<td>2010 Tuan et al.</td>
<td>Anaerobically digested, pre-dewatered (in a natural sand-drying bed) sludge</td>
<td>7.8%</td>
<td>Vertical acrylic cell (H=55 cm, W=17 cm, L=31 cm): 10 cm gravel bed and 10 cm sand bed</td>
<td>Anode: titanium plate Cathode: stainless steel mesh</td>
<td>0 V 3 V 5 V 10 V 15 V 20 V 30 V</td>
<td>- 4 days</td>
</tr>
<tr>
<td>2010 Tuan et al.</td>
<td>Anaerobically digested, pre-dewatered (in a natural sand-drying bed) sludge</td>
<td>7.8%</td>
<td>Vertical polyvinyl chloride cylinder (Ø=9.8 cm, L=30 cm)</td>
<td>Anode: titanium plate Cathode: stainless steel mesh</td>
<td>40 V DC IS(45/15) IS(30/30) IS(15/45)</td>
<td>5 bar ND</td>
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<tr>
<td>2011 Citeau et al.</td>
<td>Activated and conditioned sludge</td>
<td>8.3%</td>
<td>Horizontal cylinder (V=69.5 cm³) Peristaltic pump</td>
<td>Titanium coated by ruthenium discs (DSA)</td>
<td>80 A/m² 5 bar 30000 s</td>
<td>45-53%</td>
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<tr>
<td>2011</td>
<td>Activated</td>
<td>2.8%</td>
<td>Vertical</td>
<td>Anode: 0 V + 50 V 4 bar 2 h+2</td>
<td>11-13% +</td>
<td></td>
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<tr>
<td>Authors</td>
<td>Material</td>
<td>Initial dry solids</td>
<td>Apparatus</td>
<td>Electrodes</td>
<td>Parameters</td>
<td>Results</td>
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<tr>
<td>Mahmood et al[5]</td>
<td>conditioned sludge</td>
<td>8.2%</td>
<td>teflon cylinder (Ø=7 cm, H=14.5 cm) Teflon piston (stroke: 14.5 cm)</td>
<td>titanium coated MMO (DSA) Cathode: Titan</td>
<td>2 bar</td>
<td>56%</td>
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<td></td>
<td></td>
<td>2 h+2 h</td>
<td>11.8% 14.8% 26.8% 28.8%</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>6 bar</td>
<td>16.8% 25.3% 26.8% 28.8%</td>
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<td></td>
<td></td>
<td>12 bar</td>
<td>23.3% 26.8% 25.3% 26%</td>
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<tr>
<td>Citeau et al[77]</td>
<td>Activated and conditioned sludge</td>
<td>9.1%</td>
<td>Horizontal polypropylene cylinder (V=69.5 cm³) Peristaltic pump</td>
<td>Anode: titanium coated MMO (AO2023) Cathode: stainless steel disc</td>
<td>5 bar</td>
<td>30.1% 31.7% 31.3% 26.3% 33.1% 37.5%</td>
</tr>
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<td></td>
<td>Digested and conditioned sludge</td>
<td>10.3%</td>
<td></td>
<td></td>
<td>7200 s</td>
<td>47% 28.7% 46% 50.3% 53%</td>
</tr>
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<td>Weng et al[83]</td>
<td>Activated sludge, conditioned</td>
<td>31.1%</td>
<td>Horizontal acrylic cylindrical cells (Ø=4 cm): Sludge specimen chamber (L=6 cm) Cathode reservoir (L=4 cm)</td>
<td>Graphite rod electrodes</td>
<td>4 h</td>
<td>36.4% 42.6% 51.2%</td>
</tr>
<tr>
<td>Loginov et al[76]</td>
<td>Bentonite drilling sludge</td>
<td>23.4%</td>
<td>Horizontal polypropylene cylinder (cross-section=26 cm³)</td>
<td>NA</td>
<td>0.05 bar</td>
<td>66.4% 65% 66% 67% 66.4% 67.2% 66% 66.2% 66.2%</td>
</tr>
</tbody>
</table>

Dissemination level: PU
### Authors: Feng et al. (2014)
- **Material:** Activated, conditioned sludge
- **Initial dry solids:** 6%
- **Apparatus:** Vertical plexiglass cylinder (Ø=7 cm, V=2 L) Teflon piston
- **Electrodes:** Titanium coated mixed metal oxide (DSA) electrodes
- **Parameters:**
  - 0 V+10 V
  - 0 V+30 V
  - 0 V+50 V
  - 2 bar
  - 2 h+2 h
- **Results:**
  - 11%
  - 13%
  - 20%

### Authors: Olivier et al. (2014)
- **Material:** Activated, conditioned sludge
  - 2.5-3.2%
- **Apparatus:** Vertical teflon cylinder (Ø=7 cm, H=14.5 cm) Teflon piston (stroke: 14.5 cm)
- **Electrodes:**
  - Anode: titanium MMO (DSA)
  - Cathode: Titan
- **Parameters:**
  - 0 V + 50 V
  - 4 bar
  - 2 h+2 h
- **Results:**
  - 11-13% + 56%

### Authors: Olivier et al. (2014)
- **Material:** Anaerobically digested, conditioned sludge
  - 2.5-3.2%
- **Apparatus:**
  - Vertical teflon cylinder (Ø=7 cm, H=14.5 cm) Teflon piston (stroke: 14.5 cm)
- **Electrodes:**
  - Anode: titanium MMO (DSA)
  - Cathode: Titan
- **Parameters:**
  - 0 V + 30 V
  - 4 bar
  - 2 h+2 h
- **Results:**
  - 15-18% + 63%
2.10 Industrial applications of sludge electro-osmosis dewatering

Among the patents related to electro-osmotic dewatering, like U.S. 5034111 (December 27, 1989), the energy consumption is considered too high compared to the benefits in term of increased DS content, for a commercial use. However, some commercial full-scale equipment are currently on the market, such as CINETIK™ Linear Electro-Dewatering (Eimco Water Technologies, Canada), ELODE® electro-osmosis dehydrator (ACE Korea Incorporation), EDW (Water Technologies of Australia), and Electrokinetic (Electrokinetic Limited, UK).

A picture of the two systems is reported in Figure 15.

Elode-SELO (patent: WO 2008/140175 A1) is a compact second stage dehydrator which uses electro-osmosis to further dehydrate the treated sludge cake from conventional dehydrators, in order to obtain an higher dryness and a significant reduction in sludge weight. Sludge is transported on belts and run through rollers, which press the sludge reducing moisture content. It can be integrated into any of the existing conventional dewatering machines such as belt-press, filter press, or centrifuge. The sludge shall be treated to or above 5% dry solids by conventional thickening devices before it can be treated by SELO.

Elode-BELO is a dehydrator that combined first stage of mechanical dehydration by belt press and second stage by electro-osmosis method. This equipment brings the sludge cake to much higher dryness, reducing the DS content to 60% (at the dehydration ratio of 40%). It also reduces volume of the sludge to or less than 10% of input liquid sludge or at least 50% compared to conventional dehydrator.

BELO is a compact and robust machine, suitable for plants run by less skilled personnel, where low noise and ease of operation, flexibility and low maintenance are critical. However, this kind of machines are not particularly efficient because sludge dries at the anode and as soon as its dry content increases, its conductivity decreases and it acts as a dielectric, preventing further drying of the sludge layers that is behind it, which is not in contact with the anode surface. Part of the sludge dries much more slowly and remains wet, reducing the overall efficiency of the process. Furthermore, operators must pay attention on the possibility of noxious vapours (ammonia, toxic organic compounds) outflow that can arise from the driest sludgecake which is in contact with the anode.
Elcotech’s Cinetik™ is a batch press which extracts water from sludge upon the combined action of a controlled mechanical pressure and electro-osmosis, where an electrical field generated inside the sludge liberates and carries away the water bonded to hydrophilic particles. As shown in Figure 16, Elcotech’s CINETIK™ incorporates the electro-dewatering process in a metallic structure (2) housing a linear filter belt (4) arrangement which moves the sludge cake along multiple serviceable power blocks (3) that apply pressure and DC current via modular rectifiers (1) to the sludge, hence dewatering it. When applied to a sludge of about 10-15% dryness, the CINETIK™ process can yield dryness levels of 30 to 50% or greater.

However, this process is long and time consuming because only a limited and predetermined quantity of sludge can be treated in each cycle: there are various interruptions of the dehydrating process, which enables only a small quantity of sludge material to be treated per unit of time. The efficiency of this process is not ideal since it produces dehydrated sludge with a percentage of dry matter which is still low (around 30-33%), because its ineffective mixing decreases sludge conductivity.
Electrokinetic geosynthetic (EKG) belt filter presses have increased the solids contents of sewage cake from 20% to 31% and diamond mine tailings from 62% to 75%.  

In Table 6 cost savings referred to EKG belt press with respect conventional belt press are shown.

![Figure 17- Electrokinetic geosynthetic belt press.](image)

**Table 6- Economic and cost savings of EKG belt press.**

<table>
<thead>
<tr>
<th></th>
<th>Conventional belt press</th>
<th>EKG belt press</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading dry solids [kg/h]</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>Operating hours</td>
<td>8000</td>
<td>8000</td>
</tr>
<tr>
<td>Cake dry solids [%]</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td>Disposal cost [£/m³]</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Disposal cost [£/year]</td>
<td>340500</td>
<td>208500</td>
</tr>
<tr>
<td>EKG saving per machine[£/year]</td>
<td></td>
<td>132000</td>
</tr>
</tbody>
</table>
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http://www.electrokinetic.co.uk/