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Performance of electro-osmotic dewatering on different types of sewage sludge

Simone Visigalli[a], Andrea Turolla[a], Paolo Gronchi[b], Roberto Canziani[a,*]

[a] Department of Civil and Environmental Engineering – Environmental Section, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I 20133 Milano, Italy
[b] Department of Chemistry, Materials and Chemical Engineering, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I 20133 Milano, Italy

The feasibility of pressure-driven electro-dewatering (EDW) on sludge samples taken after different biological processes, stabilisation methods or mechanical dewatering techniques was assessed. First, the influence of potential values on EDW of anaerobically and aerobically stabilised, mechanically dewatered, sludge samples was investigated. Preliminary tests carried out by applying a constant potential (10, 15 and 20 V) in a lab-scale device confirmed the possibility to reach a dry solid (DS) content of up to 42.9%, which corresponds to an increase of 15% of the dry content in dewatered sludge without the application of the electrical field. Dewatering increased with the applied potential but at the expense of a higher energy consumption. A potential equal to 15 V was chosen as the best compromise for EDW performance, in terms of DS content and energy consumption. Then, the influence of the mechanical dewatering was studied on aerobically stabilised sludge samples with a lower initial DS content: the higher initial water content led to a lower final DS content but with a considerable reduction of energy consumption. Finally, the biological process, studied by comparing sludge samples from conventional activated sludge and membrane bioreactor processes, didn't evidence any influence on EDW. Experimental results shown that DS obtained after mechanical dewatering, volatile solids and conductivity are the main factors influencing EDW. Anaerobically digested sludge reached the highest DS content, thanks to lower organic fraction.

Keywords: Electro-osmosis, Electro-dewatering, Sewage sludge, Electric field

1. Introduction

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, called "excess biological sludge" or "waste sludge". 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 2–5%, rich in organic substances, mostly biodegradable. Therefore, it needs further processes to reduce (i) its volume, by decreasing its water content, and (ii) its polluting potential, due to its high content of biodegradable organic matter. Mechanical dewatering (belt pressing, filter pressing, centrifuging, etc.) of sludge produced by wastewater treatment plants (WWTPs) hardly gets more than 20–25% DS content (Lee et al., 2002; Yang et al., 2011; Zhan et al., 2016). Therefore, the high dryness demanded for thermal valorisation of sludge cannot be achieved by mechanical techniques. Conventionally, thermal drying removes water from sludge to significantly higher degree than the best mechanical dewatering processes and sometimes it is considered a necessary step to reduce volumes of sludge to be transported and to increase its calorific value for incineration (Flaga, 2006).

Seeking new and efficient methods for dewatering, many authors (Yoshida, 1993; Barton et al., 1999; Gingerich et al., 1999) exploited electro-osmosis in order to improve water removal from sludge, being the resulting process usually defined as electro-dewatering (EDW). The application of an electric field, sometimes in combination with pressure, seems capable to increase the DS content in sludge up to 45%, much higher than the values commonly achievable by mechanical methods (Mahmoud et al., 2010; Weng et al., 2013; Feng et al., 2014). The high sludge dryness that is reached by the EDW process is a promising alternative to the thermal drying technique, thanks to the

Abbreviations: AS, Activated sludge; DC, direct current; DS, dry solids; DS_i, dry solids at beginning of the test; DS_f, dry solids at the end of the test; DSA®, Dimensionally Stable Anode, a registered trade mark of Industrie De Nora Milan; E, electric field (V/cm); EDW, electro-dewatering; MBR, Membrane bioreactor; P, pressure (kPa); PTFE, polytetrafluoroethylene; PTT, poly(trymethylene terephtalate); t_P, duration of pressure application (min); t_V, duration of potential application (min); TiMMO, titanium coated with mixed metal oxides; V, potential (V); VS, volatile solids; VS/DS, organic fraction of DS; WWTPs, wastewater treatment plants

* Corresponding author.
E-mail address: roberto.canziani@polimi.it (R. Canziani).

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lower energy consumption involved. Sludge thermal drying indeed requires, at industrial scale, energies ranging from 617 $Wh/kg_{evaporated\ water}$ (the enthalpy of water vaporization) to as high as 1200 $Wh/kg_{evaporated\ water}$ (Olivier et al., 2014). On the contrary, depending on the potential and pressure values applied, EDW process is capable to reduce the energy consumption by 10–25% of the theoretical thermal drying energy (Mahmoud et al., 2011).

Although chemical-physical phenomena involved in pressure-driven EDW are not fully understood yet, many authors suggest that water is removed from sludge according to the following processes (Barton et al., 1999; Mahmoud et al., 2010; Mok, 2006):

(1) Applied pressure reduces the volume of the pores and squeezes out free water (if any);
(2) The charged particles (usually negative colloids) are still free to move in the fluid suspension. They tend to migrate towards the electrode carrying the opposite charge (usually the anode);
(3) When the cake has formed, the particles are locked in their position and hence unable to move; water is transported through the porous medium by electro-osmosis towards the cathode;
(4) Electrochemical reactions at the electrodes are essential to restore charge equilibrium;
(5) Finally, water ceases to be the continuous phase in the cake, and the electrical resistance rises, leading to ohmic heating; we should keep this effect at the lowest possible level, as it would lead to higher energy consumption, with very little increase in final DS content.

As a side effect, electro-migration may reduce the concentration of heavy metals in the sludge, as they tend to migrate towards the cathode, where water is collected (Mahmoud et al., 2010). As shown by Tuan and Sillanpää (Tuan and Sillanpää, 2010), EDW can also reduce the concentration of ions like Na^+ and K^+, which migrate towards the cathode, and organic matter (fatty acids and humus), which migrate towards the anode, in the sludge cake. Moreover, inactivation mechanisms of bacteria such as *Salmonella* spp., faecal coliforms, total coliforms and *Escherichia coli* have been investigated (Daneshmand et al., 2012; Huang et al., 2008). EDW seems to be efficient in inactivating bacteria thanks to the rise of temperature due to Joule effect, while the low pH plays a secondary role (Daneshmand et al., 2012). These effects may improve sludge quality for its use in agriculture.

Many experimental factors can influence the reduction of water content and, consequently, the process yield. The main critical processing factors affecting pressure-driven EDW are (i) the properties of the sludge, such as the ratio between volatile and dry solids (VS/DS), particle size distribution, zeta potential; (ii) process parameters, such as applied voltage (or current), temperature, pressure, process duration; (iii) chemical conditioning (Mahmoud et al., 2010, 2011).

Many authors (Feng et al., 2014; Mahmoud et al., 2011; Yuan and Weng, 2003; Tuan et al., 2008; Pham et al., 2010) investigated the influence of process parameters such as pressure, potential (or current) values, tests duration and cake thickness. Citeau et al. (2011) also studied the influence of polyelectrolyte type and dosing on EDW efficiency. However, so far the high variability of sludge samples produced by different WWTPs (in terms of DS, VS/DS, conductivity) prevented from building a general model capable of predicting EDW efficiency for all the sludge types. Therefore, further investigations are strongly required, especially in the view of developing prototypes for full-scale application.

In the present work, the parameters affecting pressure-driven EDW were investigated by means of a lab-scale device, using several types of sewage sludge, differing in biological processes, stabilisation methods or mechanical dewatering techniques. In preliminary tests, the EDW of anaerobically and aerobically stabilised, mechanically dewatered, sludges with similar initial DS content (DS_i) was studied. In detail, EDW performance on different sludge samples was compared, in terms of DS increase and energy consumption, at different potential values (10, 15 and 20 V), by keeping constant pressure and cake thickness. Later, the influence on EDW performance of the mechanical dewatering method, resulting in different DS_i values, was assessed. Finally, the influence of biological process was investigated by considering sludges from different WWTPs, comparing conventional activated sludge and membrane bioreactor (MBR) processes.

2. Material and methods

2.1. Sludge samples

Four different WWTPs around the metropolitan area of Milan were selected for this research. A preliminary sampling campaign was performed on these WWTPs to determine the average characteristics of produced sludges and to design the experimental activities.

Subsequently, preliminary pressure-driven EDW tests were performed by studying two different sludges: an anaerobically digested sludge, dewatered by centrifuge (sludge A), and an aerobically stabilised sludge, dewatered by filter press (sludge B), both originated by conventional activated sludge processes. The influence of stabilisation method on EDW was studied by treating sludge samples with similar DS content.

Later, two other sludges were selected in order to study the influence of wastewater treatment processes on EDW: sludge C originated from a conventional activated sludge process and sludge D from a WWTP equipped with MBR process. Both samples were mechanically dewatered by a belt press and had similar DS_i.

Prior to use, sludge samples were stored at 4 °C up to a maximum of 1 week in order to keep their properties constant. DS and VS were measured according to Standard Methods (APHA and WEF, 2012). pH was measured by a pH-meter Metrohm 827 pH Lab and electrical conductivity by a conductivity meter (B & C Electronics-C 125.2). pH and conductivity were measured in the liquid sludge before dewatering.

The main characteristics of sludge samples are listed in Table 1.

2.2. Lab-scale device

Experiments were performed by means of a lab-scale device able to produce both a mechanical pressure and an electric field (Fig. 1). The reactor is composed of a cylindrical glass vessel 176 mm high, with a diameter of 80 mm, equipped with a double effect cylinder with a 200 mm stroke (SMC-CP96SDB32-200). The reactor was also provided of a cooling water jacket to keep the temperature constant during the

Table 1
Characteristics of sludge samples used for pressure-driven EDW tests.

Sludge samples		Biological process + Stabilisation	Mechanical dewatering	DS [%]	VS/DS [%]	pH	Conductivity [mS/cm]
WWTP	No.						
A	7	AS + Anaerobic	Centrifuge	22.2 ± 3.43	61.6 ± 3.84	7.0 ± 0.19	4.6 ± 0.54
B	7	AS + Aerobic	Filter press	23.6 ± 2.78	71.9 ± 2.26	5.9 ± 0.74	1.3 ± 0.17
C	6	AS + Aerobic	Belt press	17.5 ± 1.81	70.1 ± 3.25	6.6 ± 0.39	1.5 ± 0.26
D	4	MBR + Aerobic	Belt press	14.9 ± 1.33	73.6 ± 1.52	6.9 ± 0.17	1.2 ± 0.67

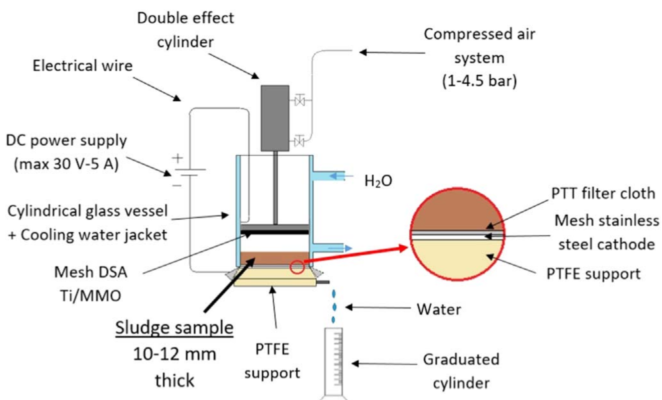

Fig. 1. Schematics of the lab-scale pressure-driven EDW device.

experiments. The upper electrode is a dimensionally stable anode DSA® (manufactured by Industrie De Nora, Milan, Italy) made of titanium coated with mixed metal oxide (Ti/MMO) and it is attached to the piston, on a support made of polytetrafluoroethylene (PTFE). The cathode is made of stainless steel mesh (AISI 304) and it is covered by a polytrimethyleneterephthalate (PTT) filter cloth. The cathode and the anode, both disc shaped, are connected to the negative and the positive pole of the direct current (DC) power supply (GBC-34121070 bench scale generator, maximum 30 V /5A). The piston is connected to the laboratory pressurised air system, equipped with manometer and valve to set pressure values (300 kPa). Discharged water is collected in a graduated cylinder put on a precision scale balance. The weight of the collected liquid is recorded at regular intervals to calculate the dewatering rate. To control the temperature during tests, a thermocouple (Data logger thermometer OMEGA-HH306A) is inserted into the glass cell.

2.3. Pressure-driven EDW tests

Pressure-driven EDW procedure consisted of two successive stages: a preliminary filtration by applying pressure (t_P = 5 min) followed by the additional application of a potential at the selected operating voltage (t_V = 15 min), according to a procedure similar to that detailed by Citeau et al. (2012).

Initially, the glass cell is filled with the sludge sample: 1.0–1.2 cm thick cake corresponds to about 35–45 g of wet sludge, depending on DS_i (35 g for sludges A and B, and 45 g for sludges C and D). Then, the cell is closed with the cover and the piston is activated for applying pressure (300 kPa) on the sludge. Sludge is pressed between the upper anode and the lower PTT filtering cloth. Usually, during the initial 5 min, no water is extracted, as the sludge has been already mechanically dewatered. Then, the power supply is switched on and the potential is applied. Three different voltages were tested, namely 10, 15 or 20 V. Values of current density vs. time are recorded. At the same time, recording of extracted water weight and temperature of the cell takes place at a pace of one per minute. Pressure-driven EDW tests on each type of sludge were repeated at least three times.

3. Results and discussion

The main aim of this research was to evaluate the feasibility of EDW process on different types of sludge. First, anaerobically and aerobically digested sludge samples, with similar DS content, were tested by applying constant potential (10, 15 and 20 V) to assess the best compromise between final DS content (DS_f) and energy consumption (Section 3.1), which was found in correspondence to 15 V. Then, the influence of mechanical dewatering and DS_i on EDW was studied (Section 3.2). Subsequently, the biological process was investigated by comparing sludges A, B and C, originated from the conventional activated process, with sludge D, derived from a MBR process (Section 3.3). Finally, dewatering rate and electric energy consumption obtained in experimental tests have been discussed (Sections 3.4 and 3.5).

3.1. Influence of sludge digestion

DS_f as well as total and specific energy consumptions are presented in Table 2. The increase in dry solid content (ΔDS) is calculated as DS_f - DS_i. Two sludges have been treated: *anaerobically digested sludge* (sludge A), dewatered by a centrifuge and with DS_i = 27.2%, and *aerobically digested sludge* (sludge B), dewatered by a filter press and with DS_i = 26.8%, comparable to the value of sludge A. Three constant potentials were applied: 10, 15 and 20 V.

Anaerobically digested sludge (sludge A). On average, DS_f increased of 5.6% at 10 V, 10.8% at 15 V and 15.7% at 20 V. Potential values up to maximum 20 V and the cooling system (water jacket) have allowed keeping temperature below 30 °C in the reactor at any process time, hindering the effect of joule heating on sludge viscosity and EDW results (Citeau et al., 2016).

Under constant potential application, the voltage and the developed currents affect significantly the dewatering kinetics and the final cake dryness: an increase of the potential leads to faster kinetics, and to a higher degree of dewatering. Moreover, water removal starts earlier at an applied voltage of at least 15 V (Fig. 2a) (Feng et al., 2014; Olivier et al., 2015).

In Fig. 2b one can see that current densities tend to decrease monotonically over time, due to the increase of sludge cake resistance next to the anode, with the progress of water removal (Citeau et al., 2012). This occurs more rapidly during the tests run with higher values of the electric potential and the current densities reach approximately the same values at the end of the tests, independently of the potential applied. However, electric energy consumption and specific energy consumption values increase along with the potential applied, due to the higher maximum currents that develop during the tests. Indeed, the application of higher electric potentials allow obtaining higher DS_f values at the expense of a higher electric energy consumption. This aspect must be taken into account when choosing the best set of process parameters. On the other hand, the higher electric energy consumption

Table 2
Pressure-driven EDW results obtained on sludges A, B, C and D.

Sample no.	Electric potential (V)	DS_i	DS_f (%)	ΔDS (%)	Electric energy consumption during t_V (Wh)	Specific electric energy consumption during t_V (Wh/kg_{H2O})
A-10	10	27.2	32.8 ± 1.81	5.6	1.2 ± 0.10	205.9 ± 32.88
A-15	15	27.2	38.0 ± 4.66	10.8	2.6 ± 0.25	289.7 ± 82.62
A-20	20	27.2	42.9 ± 1.47	15.7	3.9 ± 0.11	308.5 ± 10.81
B-10	10	26.8	27.9 ± 0.04	1.1	1.4 ± 0.04	953.0 ± 41.49
B-15	15	26.8	34.0 ± 1.55	7.2	2.9 ± 0.07	409.7 ± 74.91
B-20	20	26.8	37.5 ± 3.79	10.7	4.8 ± 0.19	514.9 ± 150.15
C-15	15	16.3	28.7 ± 1.26	12.4	1.6 ± 0.13	83.4 ± 6.32
D-15	15	15.8	25.7 ± 0.79	9.9	1.6 ± 0.16	92.6 ± 4.38

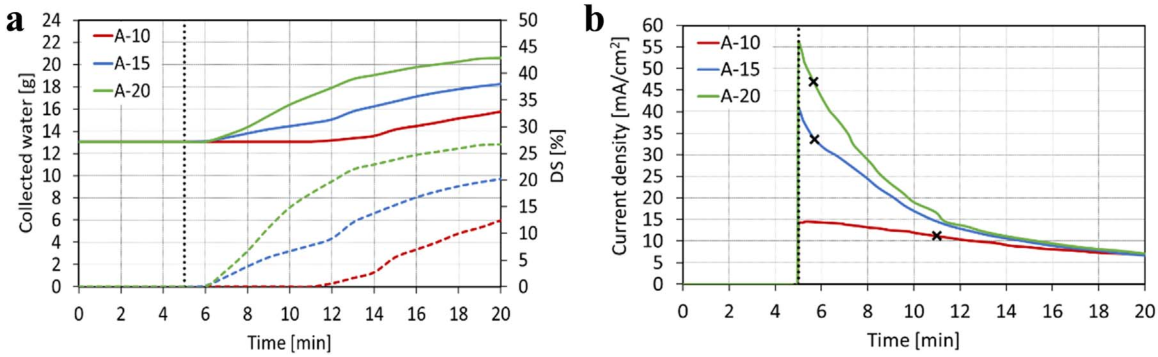

Fig. 2. Diagrams of pressure-driven EDW tests on sludge A for samples A-10 (10 V), A-15 (15 V) and A-20 (20 V) showing: (a) collected water mass (dotted lines) and dry solids (solid lines) vs. time; (b) current density vs. time. Crosses point out the first filtrate drop.

is counterbalanced by the increase of water amount removed when a greater DS_f is obtained.

These preliminary results show the effectiveness of EDW on anaerobically digested sludge, as it allowed increasing DS of mechanically dewatered sludge in the range 5.6–15.7%, depending on the potential applied. These results confirmed the feasibility of EDW in reducing the mass of raw sludge to be disposed of and may be promising in the use of a self-sustainable sludge when incinerated. However, these considerations must take into account the cost of EDW process, considerably higher than conventional mechanical techniques.

Aerobically digested sludge (sludge B). On average, DS increased of 1.1%, 7.2% and 10.7% at 10, 15 and 20 V, respectively. As reported for sludge A, Fig. 3a shows that by increasing the electric potential, the dewatering rates increase. Moreover, the same DS_f is reached in shorter times at higher applied potential values.

Even though the DS_i of sludges A and B are similar, pressure-driven EDW looks less effective if applied to aerobically stabilised sludge, since DS_f values were always lower than the corresponding values obtained with anaerobically digested sludge. This fact could be ascribed to the different fraction of organic matter (expressed in term of VS) of the two sludges, and to the different stabilisation process: the lower VS/DS ratio of anaerobically digested sludge may be a consequence of a lower presence of extracellular polymeric substances (EPS), which hinder water removal from sludge (Skinner et al., 2015).

Furthermore, comparing Fig. 2b and Fig. 3b, the main difference is the presence of a peak of current density after some minutes in case of aerobically digested sludge (sludge B), unlike for anaerobically digested sludge (sludge A), in which it occurs when the potential is applied. As reported by Olivier et al. (2015), it is possible to divide the EDW process into two main distinct steps. In step (I) current density varies unevenly, and reach a maximum due to electrode reactions and diffusion of charged species through the sludge cake. In step (II) the current density decreases monotonically over time. The early occurrence of the peak in case of sludge A may be ascribed to a faster diffusion of charged species. In addition, Fig. 3b shows that a higher potential (Sample B-20) leads to a higher peak. The peak of current densities causes an increase of the electric energy consumption. Tests with aerobically digested sludge showed lower amounts of removed water (kg) and higher total electric energy consumption (Wh), leading to a much higher specific energy consumption (Wh/kg).

The higher conductivity of sludge A with respect to sludge B is the main cause of the increase in the maximum developed current densities. With the application of a constant potential, the filtrate flow rate during step (II) increases with the measured current values (Olivier et al., 2015), so that the resulting dewatering rate is higher for anaerobically digested sludge, especially in the first stages of the tests. Fig. 3b shows that water was not removed during step (I) in the tests run with sludge B: the electrode reactions and the diffusion of charged species seem to hinder the removal of water in the first stages of the tests.

The results shown in Table 2 prove that EDW may effectively increase the DS content much further than what can be achieved with conventional mechanical dewatering techniques, which usually reach average values up to 25%. At equal durations of the tests and at the same initial conditions, water removal increases at increasing electric potential values. However, this is obtained at the expense of a higher electric energy consumption. In the view of making EDW competitive with mechanical dewatering, in terms of DS_f, and with thermal drying, in terms of energy consumption, 15 V was chosen as the best compromise. Indeed, at 10 V, the increase of DS was relatively low with respect to mechanical dewatering (especially for aerobically stabilised sludge), while at 20 V the specific energy consumption exceeded the threshold obtained by thermal drying, as shown in Section 3.5.

3.2. *Influence of mechanical dewatering methods*

A third series of tests have been carried out on samples of aerobically digested and belt pressed sludge (sludge C) at $DS_i = 16.3\%$, much lower than the two previously tested sludges. The

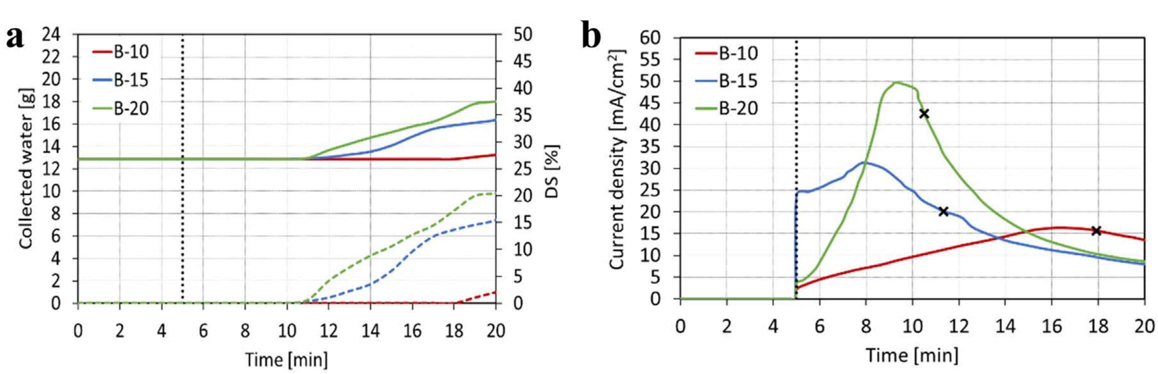

Fig. 3. Diagrams of pressure-driven EDW tests on sludge B for samples B-10 (10 V), B-15 (15 V) and B-20 (20 V) showing: (a) collected water mass (dotted lines) and dry solids (solid lines) vs. time; (b) current density vs. time. Crosses point out the first filtrate drop.

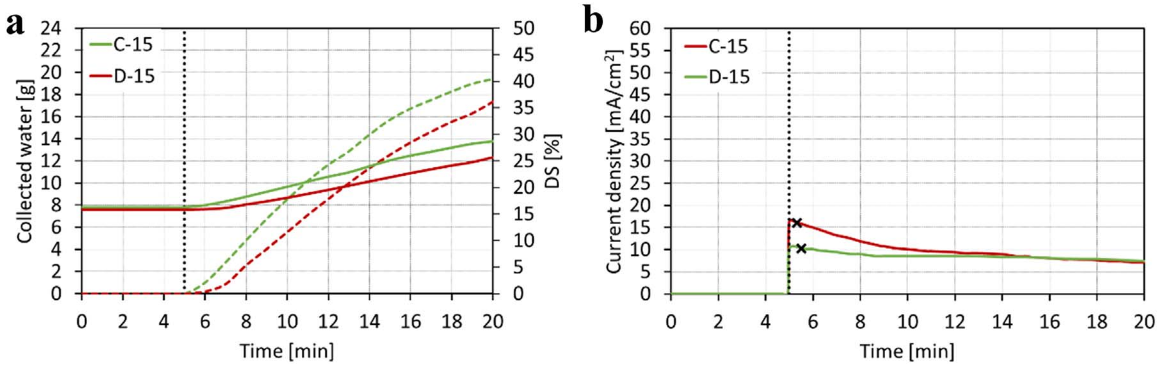

Fig. 4. Diagrams of pressure-driven EDW tests on sludge C and D for samples C-15 and D-15 (15 V) showing: (a) collected water mass (dotted lines) and dry solids (solid lines) vs. time; (b) current density vs. time. Crosses point out the first filtrate drop.

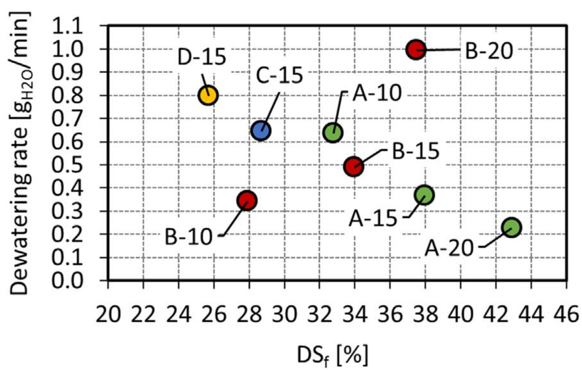

Fig. 5. Dewatering rate measured for samples A, B, C and D in the last minutes of EDW tests.

aim was the study of pressure-driven EDW on sludge types which have reached a low dry-solid content after mechanical dewatering in the WWTP. As stated in previous section, an electric potential of 15 V was applied, while pressure was kept constant. The mass of raw sludge was increased to 45 g in order to test DS_i more comparable with sludge A and B and study similar cake thicknesses. Experimental results obtained are shown in Table 2.

Differently from previous tests, DS_f increased up to maximum 28.7% (Fig. 4a), 5.3% lower than aerobically digested sludge B and 9.3% lower than anaerobically digested sludge A. However, DS_i was more than 10% lower and, thanks to pressure-driven EDW process, it increased by 12.4%, which was higher than the ΔDS of sludge A and B at 15 V.

Moreover, energy consumption values have been drastically reduced with respect to preliminary tests. Indeed, a higher amount of water was removed and, due to the higher mass of sludge and the consequent increase of the cake resistance, lower current densities have been measured.

These results highlight the feasibility of pressure-driven EDW, especially for sludge with a DS_i lower than 20%. The DS_f content reached higher values than those achievable by conventional filter press, which are usually considered to be more efficient than belt press or centrifuge, with a relatively low energy consumption. The dewatering rate seems to remain high after 15 min of electric potential application, suggesting that sludge C may reach DS_f similar to values obtained in tests on sludge A and B. The potential to further dewater the sludge can be estimated by quantifying the dewatering rate at the end of test, as shown later.

3.3. Influence of the biological process

By keeping constant the pressure at 300 kPa and the potential at 15 V, pressure-driven EDW was tested on sludge D in order to study the efficiency of the process on sludge taken from a WWTP equipped with a MBR. Experimental results are shown in Table 2.

Results show that DS values increased of 9.9% at 15 V, slightly lower than the cases with sludge C, in spite of their similar DS_i. However, the worse efficiency in terms of DS_f with respect to sludge C was not ascribed to the biological process involved in the WWTP. Indeed, the lower maximum current density values were caused by the lower sludge conductivity and led to longer times for water removal (Fig. 4). For this reason, energy consumptions were similar to sludge C and much lower than sludge A and B. The biological process seems not to be a discriminating factor for the EDW efficiency, which is more conditioned by conductivity, DS_i, VS/DS and mass of raw sludge.

3.4. Considerations on the dewatering rate

DS_f and ΔDS are usually different among the sludge samples, since they have different properties and characteristics (zeta potential, conductivity, filterability, etc.), even at similar DS_i. Fig. 5 shows the dewatering rate of samples A, B, C and D at the end of the tests, expressed as the slope of the best-fit line of the mass of water collected in the last four minutes.

It is expected that higher the dewatering rate, higher is the potential for further dewatering at increased test duration. Considering tests performed at 15 V, sludge C and D, which started with a low DS_i, show the highest values, pointing out that we may achieve higher DS_f and ΔDS by increasing the test duration. These results highlight the fact that dewatering rate is decreasing monotonically over time with the increasing of DS values.

The dewatering rates of sludge A and B change with the electric potential in a different way. For sludge A, at the end of the EDW tests, water is removed faster at lower values of electric potential due to the considerable lower amount of water in the sludge cake. The high conductivity of sludge A leads to a fast dewatering in the first stages of the tests (higher at higher values of potential) and to a reduction of the dewatering rate with the increasing of DS_f values. On the contrary, during the tests with sludge B, the presence of peak (I) in the measured current densities leads to a delayed removal of water and the dewatering rate at the end of the tests is conditioned by the higher electric potential values.

3.5. Considerations on energy consumption

Table 2 has shown that DS values increase with increasing potential values, but this implies a higher electric energy consumption. The initial conditions of the sludge samples play a fundamental role in electric energy consumption. In particular, a high DS_i value (DS_i > 20%) means that free water is present in a much lower amount than intracellular and bound water, which needs a great energy consumption for its removal from sludge. This fact is evident in the

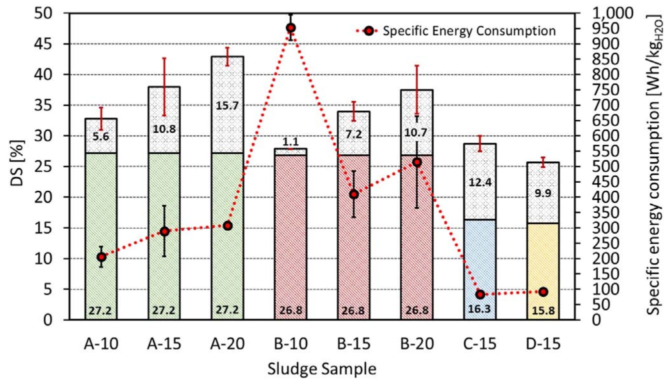

Fig. 6. Diagrams of pressure-driven EDW tests on sludge samples A, B, C and D showing DS_i obtained after mechanical dewatering, ΔDS obtained by EDW and specific energy consumption.

first 5 min of tests that have been carried out on sludge A and B, when a pressure of 300 kPa is applied and no water is collected. Therefore, only by the application of electric field, the interstitial and surface water can be drained from sludge.

Better results were observed for anaerobically digested sludge (sludge A) than for aerobically stabilised sludge (sludge B). This seems to be related to the lower fraction of volatile solids of the anaerobically digested sludge. A higher fraction of volatile solids means that the sludge is rich in organic compounds. These are usually rich in bound water, which, in turn, requires a great energy expenditure to be drained away. The comparison of energy consumption between the two samples highlights this difference. The effect of the lower fraction of volatile solids in reducing the performance of mechanical dewatering has been observed in two surveys, covering more than 120 WWTP in Italy (Cristoforetti, 2016; Canziani et al., 2015). The aerobic stabilisation is more common in medium and small WWTPs, where costly equipment such as filter presses are less commonly applied, as in WWTP where sludges C and D were collected, in which the DS amount obtained after belt pressing is relatively low. Therefore, pressure-driven EDW may find its best application in such plants, improving DS_f up to 40%, after optimization of process parameters. This value is compatible with monoincineration without pre-drying for most sewage sludges.

All the results obtained by pressure-driven EDW process are summarised in Fig. 6.

Energy consumption of tests A-15 and B-15 were in the range 289.7–409.7 Wh/kg_{H2O} due to the high DS_i, gained after mechanical dewatering (centrifuge and filter press respectively) and the high currents developed during the tests. Considering that the Italian energy conversion efficiency is equal to 0.47 (Caputo and Sarti, 2015), the total equivalent thermal energy consumption is 616–871 Wh/kg_{H2O}, lower than the maximum energy needed for thermal drying (1200 Wh/$kg_{evaporated\ water}$) (Olivier et al., 2014), but not economically feasible with respect to conventional mechanical methods.

On the other hand, pressure-driven EDW of sludge with low DS_i after mechanical dewatering in the WWTPs, such as sludge C and D, entailed a lower specific energy consumption, due to the presence of a higher amount of free water. According to Olivier et al. Caputo and Sarti (2015), the instantaneous specific energy consumption required to remove a given amount of filtrate at constant applied voltage is strongly correlated to the cake dryness (DS) at that time. This fact implies that EDW of sludge is economically viable for poorly dewatered sludge (e.g., sludges C and D).

As shown in the previous sections, the DS_i and the mass of raw sludge samples are key factors for this process: the higher DS_i entails a lower removal of water, while a slight increase of the cake thickness lowers the developed currents. The high variability of sludge samples explains the difficulties in predicting EDW efficiency. The sludge characteristics (DS_i, VS/DS and conductivity) must be deeply investigated in order to optimize process parameters, such as pressure, potential, cake thickness and duration of EDW tests.

In conclusion, pressure-driven EDW may have a great potential for practical applications in most cases. If sludge is disposed of at 40% dry matter instead of 25%, the total mass to be disposed (and the inherent costs) will be reduced by a factor of 1.6 and the lower disposal costs widely compensate the cost of energy for the electro-osmotic dewatering. Furthermore, if sludge is incinerated, electro-dewatered sludge at 40% DS can self-sustain combustion at 850 °C, avoiding a thermal drying step, which would consume more energy.

4. Conclusions

In this work, pressure driven EDW has been carried out with the aim to evaluate the feasibility of this process and determine the dewatering efficiency in terms of DS_f and energy consumption. By using the lab-scale device, potential values were set at 10, 15 and 20 V with a pressure of 300 kPa. The main results are the following:

- Dewatering improves at increasing applied potential;
- Pressure-driven EDW is more efficient for anaerobically digested sludge: at 20 V DS values increased up to 37.5% and 42.9% for aerobically and anaerobically digested sludge, respectively;
- Pressure-driven EDW tests at 15 V have shown the best compromise between DS_f and energy consumption;
- Pressure-driven EDW entails lower energy consumption for sludge that is more difficult to dewater with conventional methods in the WWTPs;
- The main parameters that control electro-osmosis process are applied potential value, initial DS, VS/DS ratio, conductivity and mass of raw sludge.

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