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Research Paper

Assessment of pressure-driven electro-dewatering as a single-stage treatment for stabilized sewage sludge

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ABSTRACT

The pressure-driven electro-dewatering (EDW) of sewage sludge was assessed using a lab device. The sludge samples were supplied from four different Wastewater Treatment Plants (WWTPs) around the metropolitan area of Milan (Italy), including both aerobically and anaerobically stabilised samples. The test results show that the EDW treatment enabled to dewater the sludge samples to a dry solids content of 18.4–31.1% (wt%), which means 2.0–12.7% improvement as compared to the conventional mechanical dewatering treatment used in these WWTPs. A follow-up test was carried out with the sample giving the best dewatering performance. A dry solids content of 39.3% (wt%) was achieved. Apart from the technological performance, the economic feasibility of EDW was evaluated. The energy consumption and sludge treatment cost associated with the EDW process were compared with the reference case (the corresponding WWTP currently operating with mechanical dewatering line). It was found that for the best performance case, technology upgrade from the conventional mechanical dewatering to the EDW dewatering will enable the WWTP to reduce its sludge management cost up to 35% per year.

1. Introduction

The latest statistics indicates that the sewage sludge produced in the EU has reached 13.25 million ton per year [1]. In the light of the EU's strategy in circular economy, sludge is being regarded as a resource, which can be valorised in various forms, e.g. energy recovery from incineration [2], nutrient recycling in agriculture [3], biopolymer extraction [4] etc. In particular, sludge energy recovery from incineration has drawn considerable attention for its environmental and economic benefits [5]. In this technology route, the incineration efficiency strongly depends on the sludge dewatering and drying. On average, mechanical dewatering enables a dry solids (DS) content of 20–30% (wt%) [6–8], which is not yet enough to achieve a satisfactory incineration efficiency. Therefore, the incineration unit is usually equipped with a heat exchanger to dry the sludge or a thermal drying unit before the incineration process to increase the calorific value of the sludge [9]. However, both solutions can considerably increase the operating cost of the incineration plant.

On the other hand, conventionally, the sludge treatment and disposal account for half of the WWTP operating cost [10]. Therefore, dewatering sludge to a higher DS content for disposal means great saving for the WWTP operators [11]. This is especially true for the case of sludge used for land application [3].

As an alternative dewatering technique, pressure-driven electro-dewatering (EDW) is shown to be efficient in sludge dewatering and is able to increase the DS to 40–45% (wt%) [12–15]. The process has been investigated in many publications, with a focus on the process performance and various operating parameters, such as pressure, electric potential, current, treatment time, delaying the application of the electric field, chemical conditioning dosage and cake thickness in the EDW cell [6,7,12,15–23]. Citeau et al. have shown that the use of a DC power supply at constant electric potential, instead of constant electric current, allows to achieve a higher DS content [20] and a better control of the temperature at the end of the tests, preventing from ohmic heating [17]. The EDW process has also been used as post-treatment to further dewater the sludge samples [8,11,14,24–26]. Visigalli et al. [27] tested sludges from different treatment processes and found that the EDW can achieve higher final DS than the conventional mechanical dewatering processes.

In addition, the EDW process also enables to lower the concentrations of the heavy metals [13] and cations such as Na^+ and K^+ [28] contained within the sludge. As these species tend to migrate towards the cathode, where the water is collected. Furthermore, the EDW leads to the inactivation of pathogenic bacteria such as *Salmonella* spp., faecal

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Table 1
Characteristics of sludge samples taken from the four WWTPs. (DS_i: initial dry solids content). Sample 3-D was used for the follow-up test and was collected from the WWTP in a different batch.

Sample ID	Stabilisation treatment	Polymer dosage g/kg_{DS}	DS_i wt%	VS/DS %	CST s	Conductivity mS/cm	pH	Zeta potential mV
1-A		0	2.0	68.3	32.0	1.34	7.5	−11.9
1-B	Aerobic	4	2.4	68.3	22.5	1.33	7.4	−11.5
1-C		8	2.2	68.3	19.8	1.29	7.4	−11.5
2-A		0	3.3	78.4	103.3	1.84	6.9	−13.1
2-B	Aerobic	4	3.2	78.4	92.7	1.79	6.5	−12.6
2-C		8	3.2	78.4	68.8	1.68	6.6	−11.9
3-A		0	3.2	72.7	35.7	1.28	6.9	−13.4
3-B	Aerobic	4	3.0	72.7	28.3	1.26	6.9	−12.9
3-C		8	2.8	72.7	17.8	1.26	7.0	−12.1
3-D*		0	2.3	71.7	22.9	1.50	6.7	−12.6
4-A		0	4.3	64.8	155.6	4.00	6.7	−11.3
4-B	Anaerobic	4	4.3	64.8	81.6	4.00	6.7	−11.5
4-C		8	4.3	64.8	102.3	4.00	6.7	−11.0

coliforms, total coliforms and *Escherichia coli* [29,30], and this is partly attributed to the local rise of temperature (ohmic heating) [29]. These two effects are particularly interesting in the view of improved sludge quality for agriculture use.

The EDW enables to reach a higher DS at a reasonable energy consumption. It is possible to maintain a superior energy efficiency over thermal drying until reaching the DS of 38–45% (wt%) [19]. The system's efficiency can be further improved with finely designed operating protocols [20]. By taking a life cycle perspective, this part of additional input may be offset either by the reduction of polyelectrolyte in the conditioning stage, by the cost saving in the sludge transport and disposal, by the income from the energy recovery in the incineration, or by any combinations of the above-mentioned items. However, where the break-even point is situated is not known yet. In other words, in order to achieve a net positive economic performance, the energy efficiency of the EDW system needs to be carefully studied.

There are some early attempts to apply economic evaluation to the EDW process. For example, Saveyn [31] calculated the payback period, i.e. the time needed to offset the initial capital investment from the cost saving due to the use of EDW. However, the calculation lacks primary data from the industry (equipment supplier and WWTP). In another study [24] the author considered the EDW cost saving in one aspect only (sludge disposal). Similarly, in a latest research [32], the author only briefly evaluated the economic feasibility by considering the energy consumption and the cost of the conditioner. Therefore, a more comprehensive evaluation that includes all the relevant aspects is needed.

The present work is a follow-on of our last publication [27]. The sludge samples have been supplied from four different WWTPs around the metropolitan area of Milan (Italy), including both aerobically and anaerobically stabilised samples. These samples are dewatered in our "single-stage" EDW lab device, with the aim to provide guidelines for our industrial prototype machine which is currently under development. To this end, several operating parameters will be assessed and optimised, including the polyelectrolyte dosage, cake thickness, and electric potential. More importantly, the energy consumption and operating costs of using EDW will be derived from the tests. These results will be compared with the actual operating cost extracted from the four WWTPs, which are running with conventional mechanical dewatering lines. The objective is to justify the economic feasibility and cost saving potential for these WWTPs when upgrading to the EDW system, with a focus on the costs of polyelectrolyte, electrical energy for dewatering and sludge disposal.

2. Materials and methods

2.1. Sludge characterisation

Sludge samples were taken from four different WWTPs around the metropolitan area of Milan (Italy). WWTP 1, 2 and 3 provided aerobically stabilised sludge, whereas WWTP 4 provided anaerobically digested samples. The thickened sludge samples were collected before the conditioning step.

The conditioning tests were performed in three jar-test beakers, one used as control and the other two, among the typical dosages used in WWTPs [33], operated with two different doses (4 and 8 g/kg_{DS}) of polyamidic and high cationic polyelectrolyte (Tillflock CL-1480). Initial DS (DS_i) amount, volatile solids to dry solids (VS/DS) ratio and capillary suction time (CST) were measured according to Standard Methods (APHA/AWWA/WEF 2012). Electrical conductivity was monitored by a conductivity meter (B&C Electronics-C 125.2) and pH by a pH-meter (Metrohm 827 pH Lab). Sludge samples were filtered under vacuum with a Whatman 42 filter cloth (2.5 μm pores size) and the zeta potential of the filtrate was determined by the instrument Malvern Zetameter ZS90. Prior to use, sludge samples were stored at 4 °C up to a maximum of 1 week in order to keep their properties unaltered.

Table 1 lists the main characteristics of sludge samples collected from the four WWTPs. The A-named samples are related to the unconditioned (control) sludge, whereas samples B and C refer to the sludge conditioned with the two different doses of polyelectrolyte, 4 and 8 g/kg_{DS}, respectively. Sample 3-D refers to an unconditioned sludge sample. It was collected from WWTP 3 at a later time, and used in the follow-up test.

2.2. Mechanical dewatering in the four WWTPs

Table 2 lists some details of the sludge treatment in the four WWTPs: the polymer dosage, the dewatering treatment, the DS content and the VS/DS ratio achieved, the energy consumption and the main routes for sludge disposal are shown. Among the four WWTPs considered in the present work, WWTP 4 serves the highest population equivalent, with a consequently higher amount of sludge produced per year.

2.3. Experimental apparatus

The EDW device used is illustrated in Fig. 1. It is constructed with a cylindrical glass vessel (176 mm high, 80 mm inner diameter) and a pneumatic cylinder (SMC, CP96SDB32-200, 200 mm stroke), of which the piston generates compression pressure and acts as anode (DSA® Ti/MMO, Industrie De Nora, Italy). At the bottom of the cell, a PTT filter

Table 2
Characteristics of the sludge in the four WWTPs.

WWTP No.	Population equivalent served PE	Polymer dosage g/kg_{DS}	Dewatering treatment	DS wt%	VS/DS %	Specific electric energy consumption Wh/kg_{H2O}	Mass of dewatered sludge produced t/year	Disposal routes
1	59,312	11.2 **TILLFLOCK CL1480**	Centrifuge	19.5	72.0	1.7	6041	Agriculture
2	33,722	15.0 **TILLFLOCK CL1480**	Centrifuge	19.0	80.0	3.8	1674	Agriculture
3	47,080	5.3 **PREASTOL 645BC**	Belt-press	18.1	76.0	1.7	2458	Incineration Landfilling Other WWTPs
4	308,646	15.4 **TILLFLOCK CL1480**	Centrifuge	24.1	60.0	0.4	13,808	Agriculture

cloth is mounted above the stainless steel mesh (AISI 304), which works as cathode. The two electrodes are connected to a DC power (GBC, 34121070 bench scale generator).

2.4. Procedure for EDW tests

The EDW testing procedure, adapted from Mahmoud et al. [16], is shown in Fig. 2. To minimise the processing time and avoid leakage of the sample from the cell during the mechanical pressure stage, the sludge samples were preliminarily centrifuged at 4000 rpm (Relative Centrifugal Force ≈1789*g*) for 5 min with a laboratory centrifuge (ThermoFisher Scientific-SL 16). After that, the samples reached a DS content (DS_{CFG}) of 7.5–13.9% (wt%) and then they were fed into the EDW cell. The EDW treatment is composed of two successive phases [16,18]: (i) filtration under mechanical pressure (duration of 10 min), (ii) application of a constant electric potential in the presence of mechanical pressure (duration of 25 min). As already observed by Visigalli et al. [27,34], a polarisation phase of 15 min is enough to reach a DS content higher than that achieved by mechanical dewatering. In this work, the authors tested a 10 min-longer duration.

The EDW tests with samples A, B and C were performed in two replicates using the same operating conditions (see Fig. 2). After the closure of the cell by the cover, the piston started applying pressure (300 kPa) on the sludge. Approximately 90*g* of centrifuged sludge formed a 15-mm thick layer in the cell. The sludge was pressed between the electrodes. After 10 min of pressure application, 15 V electric potential was switched on. The evolution of current densities and filtrate mass were recorded at an interval of 1 min.

The sample 3-D was treated with the same experimental procedure (Fig. 2), in two replicates for each operating condition. Two operating parameters were tested, the cake thickness (15 and 20 mm) and the electric potential (10, 15 and 20 V). The cake thickness of 20 mm was obtained by inserting approximately 120 g of centrifuged sludge in the cell. Moreover, in order to study the effective DS content increase enabled by the EDW process, two control tests were performed by applying only mechanical pressure for 35 min in absence of electric potential on samples with cake thickness of 15 and 20 mm.

2.5. Analysis of the data

During the EDW tests, the electrical currents and the mass of water removed have been recorded manually at an interval of 1 min. These data allowed to plot the experimental results in the diagrams of DS content evolution and current density vs. time.

The dewatering rate was computed as the average dewatering rate in the last 5 min of the polarisation phase.

The specific energy consumption (Wh/kg_{H2O}) was calculated with Eq. (1) [20]:

$$\text{Specific Energy Consumption} = \frac{V\cdot\sum_{j=1}^{n} I_j\cdot\Delta t}{m_{H_2O}} \quad (1)$$

where V is the applied electric potential (V), n is the number of recorded measures, I_j is the measured current (A), Δt is the time interval between two recorded measures (hours) and m_{H2O} is the total mass of water removed (kg) during the polarisation phase.

The accumulated energy consumption was computed with the same formula, while the energy consumption per unit mass of DS was computed with Eq. (2) [20,24]:

$$\text{Energy Consumption} = \frac{V\cdot\sum_{j=1}^{n} I_j\cdot\Delta t}{m_{DS}} \quad (2)$$

Where m_{DS} is the dry mass of sludge (kg).

The sludge treatment costs considered for the economical

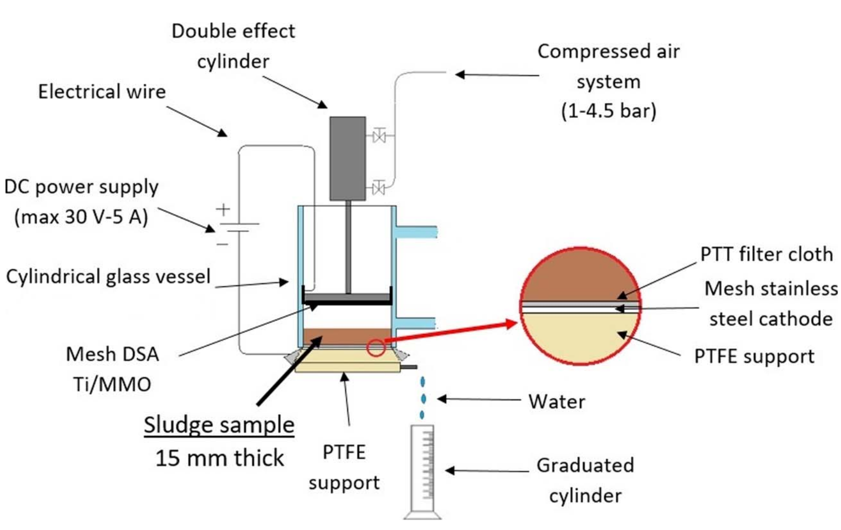

Fig. 1. Schematic representation of the lab scale device for EDW tests [27].

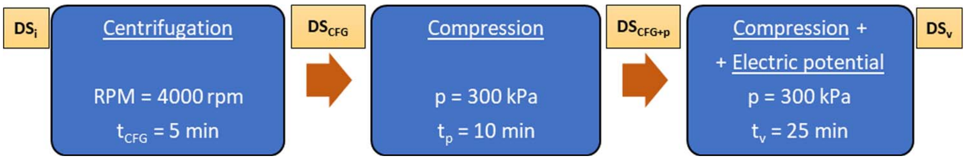

Fig. 2. Flowchart of the pressure-driven EDW testing procedure.

assessment of EDW comprise three major components: conditioning in terms of polymer cost, dewatering in terms of cost of the electrical energy entailed by mechanical dewatering or EDW and sludge disposal. Site-specific data (averaged from yearly basis) have been extracted from the corresponding WWTPs and used as the reference to compare with the EDW cases. The yearly costs (€) of conditioning ($Cost_{COND}$), mechanical dewatering ($Cost_{DW}$), disposal ($Cost_{DISP}$) and EDW ($Cost_{EDW}$) have been computed as follow:

$$Cost_{COND} = \left[\left(\frac{DS_{RAW} \cdot m_{RAW}}{100}\right) \cdot D_{POLY}\right] \cdot Cost_{POLY} \tag{3}$$

$$Cost_{DW} = \frac{E_{DW}}{\left[m_{COND} - \left(\frac{m_{COND} \cdot DS_{COND}}{DS_{DW}}\right)\right]} \cdot Cost_{EE} \tag{4}$$

$$Cost_{EDW} = Cost_{CFG} + Cost_{P} + Cost_{V} \tag{5}$$

$$Cost_{DISP} = m_{DW/EDW} \cdot Cost_{UNIT} \tag{6}$$

Where DS_{RAW}, DS_{COND} and DS_{DW} are the DS contents (wt%) of raw, conditioned and dewatered sludge samples; m_{RAW}, m_{COND}, m_{DW} and m_{EDW} are the masses (tonn) of raw, conditioned, dewatered and electro-dewatered sludge produced per year; D_{POLY} is the dosage of polyelectrolyte (kg/tonn$_{DS}$); $Cost_{POLY}$ is the specific cost of the polyelectrolyte (€/kg$_{POLY}$); E_{DW} is the electric energy consumption (kWh) entailed by mechanical dewatering; $Cost_{EE}$ is the specific cost of electric energy in Italy (≈0.16 €/kWh); $Cost_{UNIT}$ is the unitary cost of disposal (€/tonn) assumed equal to 12.5 €/tonn for transport to other WWTPs, 52.2 €/tonn for agriculture, 78.3 €/tonn for incineration, 104.0 €/tonn for landfilling. The cost of EDW have been computed by summing each contribute of centrifugation ($Cost_{CFG}$), pressure-driven phase ($Cost_{P}$) and EDW itself ($Cost_{V}$).

3. Results and discussion

3.1. Results of EDW tests on DS content

The EDW results are reported in Table 3, which shows (i) the DS content obtained after centrifugation followed by 10 min of pressure (DS_{CFG+p}), (ii) the DS content obtained after 25 min of application of electric potential (DS_V) and (iii) the increase in DS content resulting from the phase in presence of electrical potential ($\Delta DS_{V\text{-}p}$).

Table 3
Results of EDW tests. DS_{CFG+p}: DS content after centrifugation followed by 10 min of pressure. DS_V: DS content after 25 min of application of electric potential. $DS_{V\text{-}p}$: the increase in DS content resulting from the phase in presence of electrical potential. Testing conditions: electric potential was set at 15 V, with an initial cake thickness of 15 mm. Maximum current densities and specific electric energy consumptions are reported. Refer to Table 1 for sample ID explanation.

Sample	DS_{CFG+p} wt%	DS_V wt%	$\Delta DS_{V\text{-}p}$ wt%	Maximum current density mA/cm^2	Specific electric energy consumption Wh/kg$_{H2O}$
1-A	11.3	22.9	11.6	11.8	51.9
1-B	10.6	23.7	13.1	13.0	56.0
1-C	11.7	24.6	12.9	10.7	49.3
2-A	8.5	19.4	10.9	13.9	62.6
2-B	8.8	23.6	14.8	16.9	63.9
2-C	9.1	22.7	13.6	14.8	60.1
3-A	10.6	30.9	20.3	11.2	59.6
3-B	11.4	30.6	19.2	10.6	54.9
3-C	11.1	31.1	20.0	10.0	51.5
4-A	10.9	18.4	7.5	20.6	66.9
4-B	12.9	23.0	10.1	22.6	69.8
4-C	17.2	26.1	8.9	17.9	92.6

The A-named samples from WWTP 1, 2 and 4, referring to the unconditioned sludge, had a lower DS_V content than the conditioned sludge. Indeed, the colloidal and compressible nature of the unconditioned sludge hampers its dewatering and polyelectrolytes addition is needed to induce the formation of flocculated particle networks, resulting in a structure with reduced water retention [35]. However, this behaviour was not shown by sludge from WWTP 3, where DS_V was approximately the same between control and conditioned samples. Generally, a minimum polyelectrolyte dose is necessary to induce fast filtration and reduce the energy requirement in mechanical dewatering [33].

Our study seems to confirm that polyelectrolyte addition does not always exert a positive effect during EDW [36]. The effect of polyelectrolyte is more pronounced for the stage where the dewatering relies on filtration, i.e. the compression dewatering stage, as it flocs the biosolids in the sludge suspension to increase the cake permeability. This can be observed from the development of DS_{CFG+P} – higher polymer dosage higher DS_{CFG+P}. After reaching a certain DS, the cake will become so packed and the permeability drops greatly such that the polymer will lose its effect on enhancing the dewatering. In the following EDW stage, when the electric field is applied, the dewatering mainly relies on the mechanisms of electrophoresis and electro-osmosis, which strongly depends on factors such as particle size and shape, zeta potential, liquid viscosity, dielectric constant rather than the cake permeability [13]. This explains why the polymer dosage has no effects on the DS_v of the samples from WWTP 1, 2 and 3. While for the sample from WWTP 4, it seems that the polymer dosage has an effect, but the truth is that this type of sludge is not very responsive to the EDW so that the DS difference created in the first phase has been maintained to the next phase, i.e. a difference in DS_v. This is also supported by the observation in an earlier publication [16].

Further comments can be derived by looking at the sludge characteristics shown in Table 1. The low value of the zeta potential of sludge from WWTP 3 can be an indicator of a higher electrophoretic rate during EDW. CST is a good indicator of mechanical dewatering but does not give any information on the suitability of EDW [34,37]. On the contrary, high conductivity values can improve the dewatering rate at the beginning of the polarisation phase due to increased measured current densities (Section 3.3).

It can be noticed that for the sludge sample from WWTP 1 and 4 the highest dosage of polyelectrolyte is needed to reach the highest value of DS_V; for the sludge sample from WWTP 2 the dosage of 8 g/kg$_{DS}$ is not justified by the increase in the DS content with respect to the lower dosage; for the sludge sample from WWTP 3 a DS content of 30.9% (wt %) is reached without adding polyelectrolyte.

Generally, for aerobically stabilised sludge, the DS content of the conditioned samples (B-C) obtained after EDW tests was higher than that reached by conventional mechanical dewatering in the four WWTPs. On average, the DS amount is 4.6% higher for sludge from WWTP 1, 4.1% higher for sludge from WWTP 2 and 12.7% higher for sludge from WWTP 3. However, in case of the anaerobically digested sludge, the DS content obtained in the EDW test overtakes the DS content obtained in the WWTP with mechanical dewatering only at the highest polyelectrolyte dosage. This fact is ascribed to the higher dewaterability of anaerobically digested sludge by mechanical methods, which, in turn, is due to the lower organic fraction [38]. However, it must be highlighted that the conditioning stage in the four WWTPs is performed with different polyelectrolytes and dosages with respect to those used in the lab activity.

It is a remarkable fact that EDW tests on sludge from WWTP 1 and 3, without polyelectrolyte addition, always reached a DS content higher than that obtained after mechanical dewatering in the corresponding WWTPs. The reduction of the dosage of polyelectrolyte is one of the most promising outcomes for the application of the EDW process at full scale.

The sludge sample from WWTP 3 turns out to be most suitable for the EDW process: the final DS content is 12% higher than that of the WWTP. Indeed, aerobically stabilised sludge can hardly exceed 25–30% (wt%) DS content, even when dewatered with filter presses which usually operate at higher pressure and produce drier sludge [33]. Moreover, the polyelectrolyte addition does not affect the dewaterability under the EDW and it suggests that the chemical input can be reduced [36].

In the view of identifying the optimal operating conditions, an increase of the duration of the EDW tests or the application of a higher electric potential may lead to a further increase in DS content, which would reduce considerably the disposal costs with respect to conventional mechanical dewatering treatments [24].

3.2. Influence of operating conditions on the EDW process

Because the sludge from WWPT 3 showed the best dewatering performance, a follow-up test was added. The results are reported in Table 4.

As reported in previous studies [8,13–17,19,39], higher potential leads to faster kinetics and thus higher degree of dewatering; while greater cake thickness (or sludge mass) increases the electric resistance, and thus reduces the measured currents and the efficiency of the process. Our test results are in line with this finding.

It is worth noting that a DS content of 39.3% (wt%) was attained without using polyelectrolyte (at 15 mm cake thickness and 15 V of electric potential), that is 21.2% higher than the value achieved by mechanical dewatering in WWTP 3 (see Table 2).

The control samples have been exposed to mechanical pressure for 35 min, which is the same overall duration of the EDW tests. The results on the control samples highlighted the effective increase of the DS content obtained by EDW.

In fact, sample 3-D and 3-A were treated with the same testing parameters. However, sample 3-D gives better dewatering performance, suggesting the effect of sludge variations on the EDW process. On the other hand, this result can be predicted from the dewaterability indicators: sample 3-D gives lower CST value and weaker negative zeta potential as seen in the sludge characterization test (see Table 1) [33,40].

Table 4
Results of EDW tests on sample 3-D (Table 1) at different values of cake thickness (15 and 20 mm) and electric potential (10, 15 and 20 V). Two control tests without the application of the electric potential are reported. DS_{CFG+p}: DS content after centrifugation followed by 10 min of pressure. DS_V: DS content after 25 min of application of electric potential. $DS_{V\text{-}p}$: the increase in DS content resulting from the phase in presence of electrical potential.

Cake thickness mm	Electric potential V	DS_{CFG+p} wt%	DS_V wt%	$\Delta DS_{V\text{-}p}$ wt%	Maximum current density mA/cm^2	Specific electric energy consumption Wh/kg$_{H2O}$
15	–	14.3	(in 35 min)			
15	10	11.7	24.7	13.0	6.9	27.2
15	15	12.4	35.0	22.6	11.2	56.5
15	20	11.3	39.3	28.0	16.6	83.7
20	–	12.7	(in 35 min)			
20	10	10.7	16.4	5.7	5.1	23.8
20	15	10.3	19.8	9.5	7.9	35.4
20	20	10.2	27.0	16.8	11.2	52.5

3.3. Dewatering behaviour of different sludges

Fig. 3 shows the evolution of DS over the treatment time in the EDW process. The current density curve is also integrated in the figure (N.B. The electric potential is applied at the 10 min point).

Firstly, it can be seen that the current densities tend to decrease monotonically after an initial peak. In fact, as the water removal proceeds, the resistance of the sludge cake in close proximity of the anode starts to increase [17]. However, in some cases, as the treatment continues, the current densities may sometimes show a second peak (as seen in Fig. 3b and c). This behaviour may be due to a local rise of temperature in the sludge, which will cause the drop of sludge viscosity and, hence, of its electrical resistance [13,41].

Secondly, it can be noticed that the DS curves of WWTP 2 and 3 have not reached a plateau. This suggests that further increase of the DS_v content is possible by extending the treatment time, and this opportunity may be investigated in future studies.

According to Olivier et al. [19], measured electric current is a good indicator of the filtrate flow rate/dewatering rate, which is the slope of the DS curve. This fact can also be observed in Fig. 4, which shows the plot of the dewatering rate vs current value, both measured at the end of the EDW test. It can be seen that, for samples taken from WWTP 2 and 3, dewatering rates are still relatively high at the end of the EDW test. This also suggest that EDW can remove more water by extending the treatment time.

3.4. Specific energy consumption

The specific energy consumption, as reported in Tables 3 and 4, is calculated as the ratio between the total consumed electric energy (the sum of the products of the developed currents and the electric potential at any time during the polarization phase) and the mass of water additionally removed during the polarization phase [18].

The specific energy consumptions in EDW tests are in the range of 49.3–63.9 Wh/kg$_{H2O}$ for aerobically stabilized sludge (WWTP 1, 2 and 3) and in the range 66.9–92.6 Wh/kg$_{H2O}$ for anaerobically digested sludge (WWTP 4). The electric energy consumption, indeed, is strictly connected to the conductivity of sludge, which contributes to the increase of the maximum developed currents, and to the mass of water removed by the application of the electric potential. For this reason, the sample 4-C, which had the highest conductivity (see Table 1) and the highest DS content after the mechanical pressure phase, entailed the highest energy consumption.

From Tables 2 and 3, one can see that the conventional mechanical dewatering technologies consume one order of magnitude less energy than the EDW process. However, EDW may be able to achieve DS content that would be unachievable by conventional mechanical dewatering, consuming much less specific energy per unit mass of water removed than thermal drying. If we consider the Italian energy conversion efficiency factor (0.469 kWh$_{el}$/kWh$_{th}$, [42]), the estimated total equivalent thermal energy consumption was 104.9–197.0 Wh$_{th}$/kg$_{H2O}$, which is much lower than the that needed for thermal drying (1–1.2 kWh/kg$_{evaporatedwater}$) [16].

The energy consumption of the EDW process can be studied by analysing the evolution of the accumulated energy consumption, expressed as kWh consumed from the beginning of the application of the electric potential per kg of the total mass of removed water, as a function of the DS content of sludge, as shown in left column of Fig. 5. At the beginning of the EDW tests, the measured current values, which mainly depend on the sludge conductivity, and the dewatering rate at the end of the mechanical pressure phase control the peak of

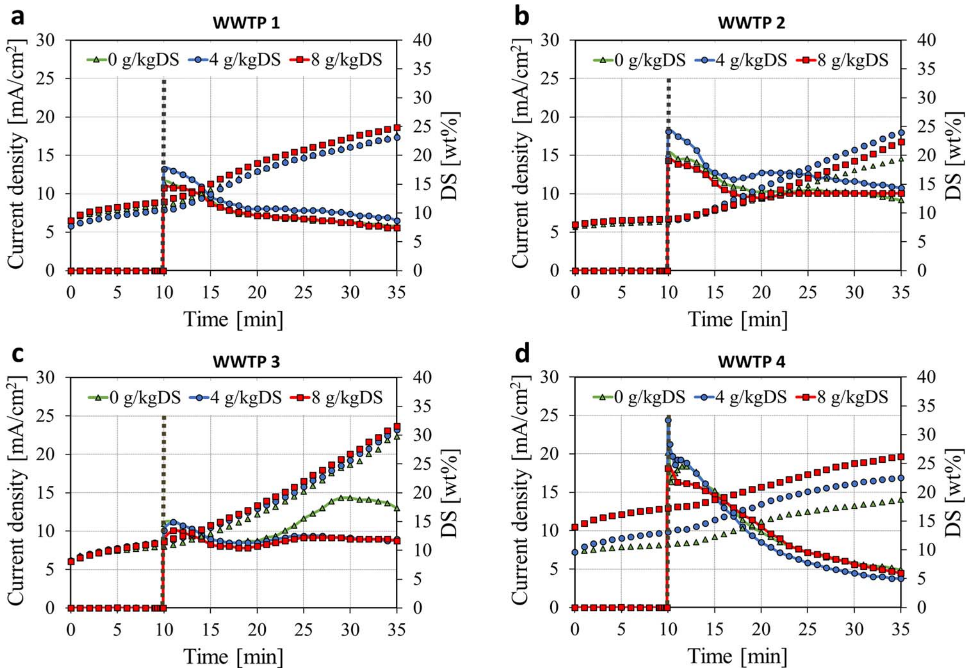

Fig. 3. Results of EDW tests for sludge from WWTP 1 (a), WWTP 2 (b), WWTP 3 (c) and WWPT 4 (d): current density (solid line) and DS content (dotted line) over time. Testing conditions: electric potential 15 V, initial cake thickness 15 mm.

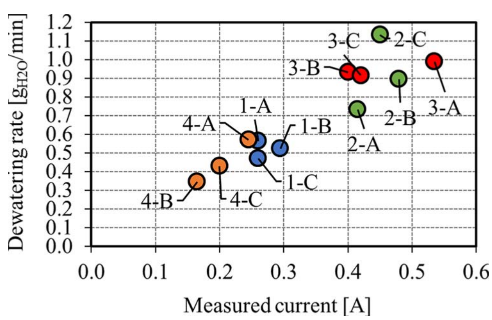

Fig. 4. Dewatering rate vs. electric current measured at the end of EDW tests. Refer to Table 1 for the sample ID explanations.

accumulated energy consumption. In some cases, the mechanical pressure phase after 10 min did not result in a significant dewatering, so that, when electric potential was applied, a high dewatering rate was observed causing a sharp decrease in the accumulated energy consumption values (see Fig. 5b and d) [18].

As already discussed, to demonstrate the feasibility of the EDW process, the study of the specific energy consumption values, expressed in Wh per unit mass of water additionally removed during the polarization phase, allows the comparison of data with thermal drying [16–18]. Aerobically stabilized showed the lowest energy expenditure with the highest increase in DS. However, one can easy understand that the energetic effort to remove water from sludge with a low initial DS is lower than from sludge with an initial higher DS, which means a lower content of free water (the easiest to be removed). Therefore, it is necessary to specify not only the final DS content, but also the initial DS content of the sludge, before the application of the electric potential [18]. The differences in the water content in sludge samples measured at the end of the mechanical pressure phase, when the application of the electric potential starts, strongly affect the energy consumption in Wh per unit mass of the dry solids. Fig. 5 (right column) reports the trend of the specific energy per unit DS mass vs. DS content [20].

Sludge from WWTP 4 had the lowest specific energy consumption values due to the low current values at the end of the EDW tests and, for the conditioned samples, the highest DS_{CFG+p} content. On the contrary, sludge samples from WWTP 2 and 3, which showed an increase of developed current values at the end of the EDW tests (see Fig. 3), required high specific energy consumptions. The electrical current values, as already discussed, determine the efficiency of the EDW process, both in terms of dewatering rate and energy consumption. In conclusion, in order to lower the energy expenditure in EDW, a good control and a longer duration of the mechanical pressure phase are required, with the aim to reach the highest DS_{CFG+p} content and reduce current values at the beginning of the polarization phase. At full scale, the EDW process alone, without a preliminary pressure-driven phase, would entail too high energy consumption.

3.5. Electric energy consumption in the EDW process: effect of operating conditions

Fig. 6 depicts the EDW results of sample 3-D at different cake thicknesses. As observed in the previous test, a higher electric potential gives a higher current value and thus a higher DS content, while a higher cake increases the electric resistance, which will reduce the measured currents and the efficiency of the EDW. Furthermore, there is a possibility to further increase the DS content in the case of 20 mm cake thickness, as indicated by the slope of the DS curve at the end of the test.

The specific electric energy consumption (see Table 4) suggests that there is a need to find a compromise between the electric potential and cake thickness to reduce the costs of the EDW process.

For the case of initial cake thickness of 15 mm, the electric potential of 15 V and 20 V led to a final DS content of 35.0% and 39.3% (wt%), respectively. However, this improvement of 4.3% DS content is based on the increase of energy consumption by 48%. In the meanwhile, these two cases (20 mm – 20 V, 15 mm – 15 V) have a similar energy expenditure but give different final DS contents. The study of the effect of the sludge cake thickness and the electric potential on the DS content and energy consumption needs further research to find the optimal operating parameters and evaluate the costs entailed by EDW. As an example, Citeau et al. [17] found that the energy consumptions at a fixed DS content, for conditioned activated sludge, was not noticeably affected by the initial mass of the sludge sample, while the dewatering rate increased with a lower cake thickness. Mahmoud et al. [16] studied the influence of electric potential and pressure on the EDW and found that the optimum processing conditions were 40 V and 728 kPa, which

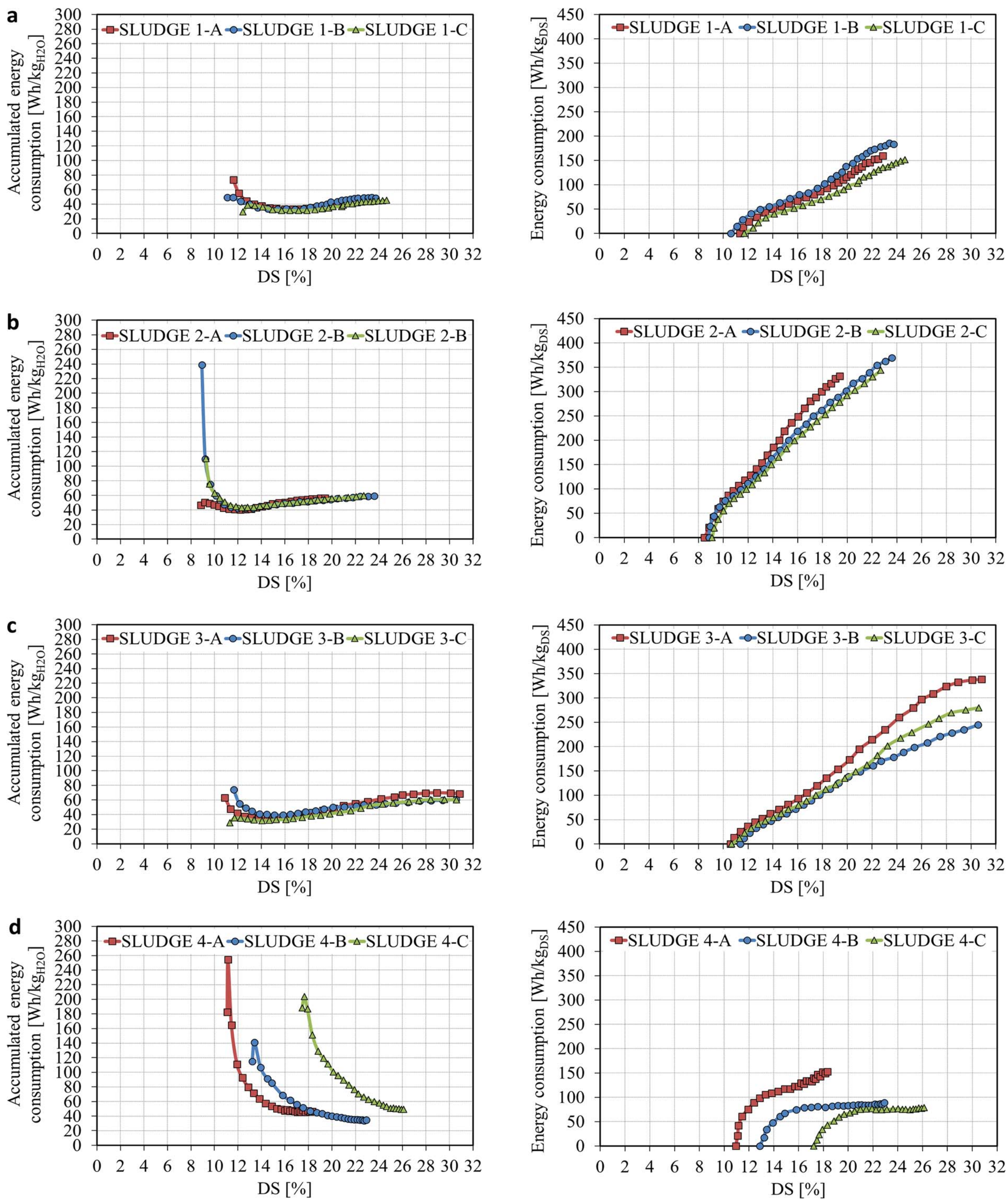

Fig. 5. Accumulated energy consumption (left column) and energy consumption (right column) of the EDW process vs. DS content of sludge samples from WWTP 1 (a), WWTP 2 (b), WWTP 3 (c) and WWTP 4 (d). Testing conditions: electric potential 15 V, initial cake thickness 15 mm. Refer to Table 1 for the sample ID explanations.

gave a final DS content of 51.2% and an energy consumption of 300.0 Wh/kg$_{H_2O}$. Moreover, they found that EDW entailed a specific energy consumption 10–25% lower than thermal drying.

3.6. Economic assessment

The high energy consumption induced by the EDW process, compared to the conventional treatments, may suggest that the use of electric field in a full-scale prototype, as a substitute of mechanical dewatering, would not be feasible. However, as described in the previous sections, the reduction in the polyelectrolyte dosage and the increase of the DS content, with a consequent lower mass of sludge produced, may reduce the cost of conditioning and disposal of sludge. Comparing the data in Tables 2–4, the aerobically stabilised sludges, after the EDW process, showed higher DS content than those achieved by mechanical dewatering. Moreover, these values have been achieved with lower polymer dosage than in case of conventional treatments.

The sludge treatment cost considered here comprises three major components: conditioning, dewatering and sludge disposal. Site-specific data (averaged from a yearly basis) are extracted from the

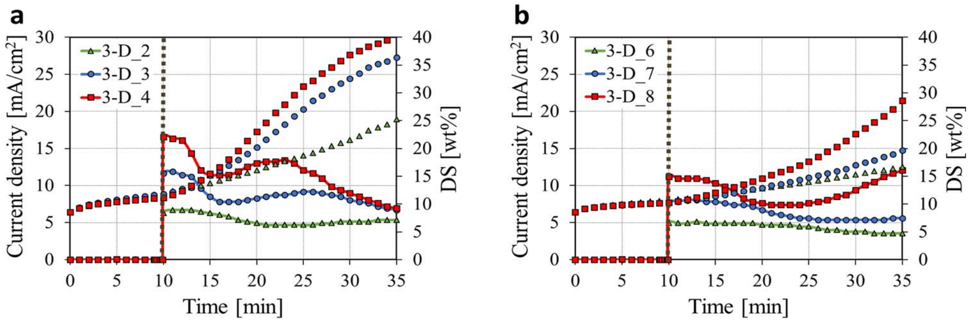

Fig. 6. EDW results of sample 3-D in different cake thicknesses: a) 15 mm and b) 20 mm. Refer to Table 1 for the sample ID explanations.

corresponding WWTPs and used as the reference to compare with the EDW cases.

The dosages of the conditioning polymer in the EDW tests are lower than those used in the four WWTPs, with the only exception of the sample taken from WWTP 3, which was conditioned with a dosage of 8 g/kg_{DS}. Hence, the corresponding estimated costs for conditioning are lower.

Regarding the sludge disposal, WWTP 1, 2 and 4 send their sludge for agriculture use, while WWTP 3 takes a multiple channel approach, including landfilling, incineration and transfer to a thermal drying unit located in another WWTP. For the EDW cases, the disposal routes have been assumed to be the same of those applied in the corresponding four WWTPs.

The personal and maintenance costs are excluded. They are assumed to be the same for the reference and the EDW cases.

Fig. 7 reports the sludge treatment costs derived from the first batch of the EDW tests. The saving percentage is calculated by comparing the EDW cases with the reference case.

Regarding the share of the "dewatering", obviously the EDW cases are higher than the respective reference case that is using mechanical dewatering.

Also, it can be found that the sludge disposal accounts for the biggest share in the sludge treatment cost. Consequently, a higher DS content will greatly reduce the disposal costs and the total costs of sludge management. This is especially true for the EDW cases treating the aerobically stabilised sludge (WWTP 1, 2 and 3), with sample 2-A being an exception. In particular, the best economic performance is from the case of WWTP 3, in which the EDW enables over 30% of cost saving.

On the other hand, the high DS content achieved by mechanical dewatering of anaerobically stabilised sludge, makes untenable the costs of the EDW process (as seen in the case of WWTP 4). Indeed, as already discussed, the lower fraction of volatile solids of the anaerobically digested sludge makes the mechanical dewatering to be more effective (see Table 2) [38]: a high fraction of volatile solids, typical of aerobically stabilised sludge, means that the sludge is rich in organic compounds, which are usually rich in bound water, and requires a great energy expenditure to be drained away by conventional treatments [27].

The aerobic stabilisation is more common in the medium and small WWTPs, where costly equipment such as filter-press is not popular. Thus, the final DS content is relatively low. The EDW machine has a competitive investment cost and improved dewatering performance. It is anticipated that the EDW will find its best application in such like WWTPs.

Above all, it should be noted that sludge type has a very strong influence on the EDW economic performance: for a good-matching type, a break-even point can be achieved and cost saving can be significant; in contrast, for a poor-matching type, the final operating cost will be increased and cost saving is impossible. Based on the present study, a higher zeta potential is beneficial for the EDW process. However, the compatibility between the sludge with the EDW process should be further investigated in the future study.

Fig. 8 depicts the sludge treatment cost derived from the EDW test with sample 3-D. The result indicates that when the sludge type shows good compatibility with the EDW process, and the lab device is running with optimised parameters (in this case, they are 15 mm cake thickness and 15 V electric potential), it is possible to reach a very high DS content (35–40% (wt%)) and at the same time maintain a good economic performance (over 35% saving with respect to the reference case).

Furthermore, if the disposal scenario is set as incineration, sludge of 35–40% (wt%) DS content will enable self-sustain incineration at 850 °C [43]. This will eliminate the thermal drying stage, and thus holds even greater potential in cost saving.

4. Conclusions

In this study, pressure-driven electro-dewatering (EDW) of sewage sludge was assessed using a lab device. The sludge samples were supplied from four WWTPs employing different sludge stabilization processes. Both aerobically and anaerobically stabilised samples were

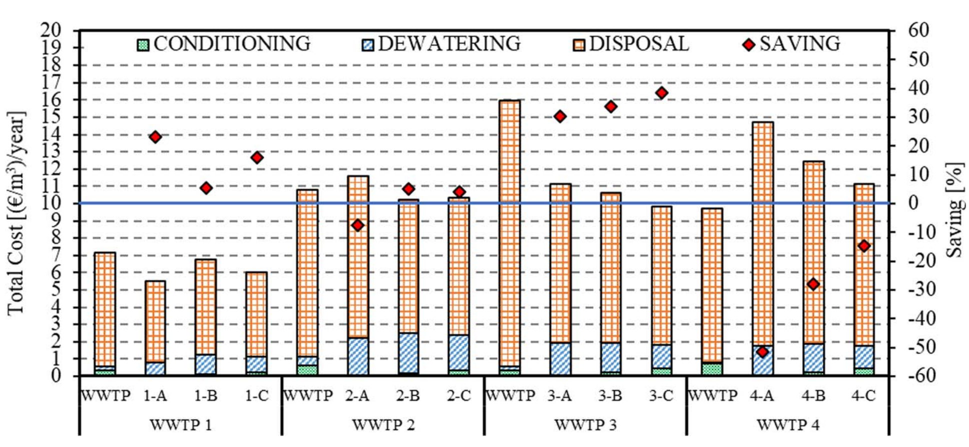

Fig. 7. Total costs of sludge treatment derived from the test. The saving is calculated by comparing the EDW cases with the respective reference cases.

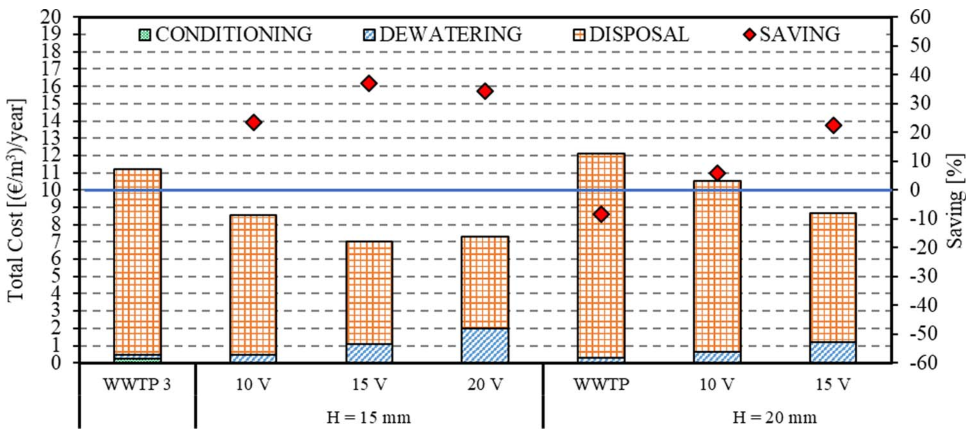

Fig. 8. Total costs of sludge treatment derived from sample 3-D. The saving is calculated by comparing the EDW cases with the reference case WWTP 3.

tested. Therefore, the effect of sludge type on the dewatering performance could be evaluated. For the good-matching sludge, a dry solids content of 39.3% (wt%) was achieved under the optimised operating parameters. In contrast, for the poor-matching sludge, the final DS was in the range of 18–26% (wt%), which also caused higher energy consumption.

In addition, under the current experimental protocol, the dosage of polyelectrolyte had negligible effect on the final DS content, and hence the expense on the chemical could be saved, which is a positive factor for the cost saving.

In a comprehensive economic evaluation, the sludge treatment cost of using EDW was compared with the reference case (the corresponding WWTP that is operating with mechanical dewatering line). A trade-off relationship was established by considering the major contributing components, including the use of conditioning polymers, sludge transport and disposal, and energy consumption induced by the EDW process. Again, sludge type plays an important role in the trade-off relationship. For the poor-matching sludge, the calculation suggests that the use of EDW could increase the operating cost with respect to the reference case. While for the best-matching type, upgrade to EDW dewatering will enable cost saving up to 35% per year.

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