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ORIGINAL ARTICLE

Chemical conditioning of aerobically digested sludge using polyelectrolytes with different charge densities

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Abstract

This research was carried out to evaluate the effects of different dosages (1.85–4.44 g kg^{-1} Ts^{-1}) of three cationic polyelectrolytes with charge densities (CD) of 20%, 40%, and 60% on the dewatering properties of an aerobically digested sludge. The sludge was collected from the sludge processing line in a wastewater treatment plant in the city of Mashhad, Iran (MWWTP). To assess the sludge dewatering properties, parameters such as specific resistance to filtration, sludge cluster geometry, filtration rate, and filtrate turbidity and volume were measured. The experimental results were then compared with the effects of a reference polyelectrolyte that was used in the conditioning of the sludge in that treatment plant. The results indicated that the sludge samples treated with the polyelectrolyte of the highest CD matched better dewatering performance than the samples conditioned with the other two polyelectrolytes. This polyelectrolyte (60%CD) presented its best effects at the dosage of 4.07 g kg^{-1} Ts^{-1}. With this dosage, its performance was similar to the performance of the reference polyelectrolyte at the dosage of 4.44 g kg^{-1} Ts^{-1}.

Keywords Aerobically digested sludge · Chemical conditioning · Cationic polyelectrolytes · Sludge dewatering · Sludge cluster

Introduction

Sequencing batch reactor (SBR) technology is more affordable and energy-efficient than alternative biological treatment processes for treating wastewater due to the minimal land and aeration requirements. However, waste-activated sludge (WAS) extracted from this technology is a complex mixture consisting mostly of water, organic matter, microorganisms, and suspended solids. Sludge with high water content leads to a considerable increase in operational costs of sludge treatment (Al-Dawery 2015; Kamizela and Kowalczyk 2021; Baroutian et al. 2013; Xiao et al. 2017; Zhang et al. 2016a). Moreover, due to higher concentration of biodegradable organic matter, more polymer consumption is expected for the conditioning of an activated sludge when a modified version of activated sludge processes (ASP) such as advanced sequencing batch reactors (ASBRs) are applied for biological wastewater treatment (Jafarinejad 2017). Therefore, one of the most critical tasks in decreasing the costs of sludge treatment, transportation, and final disposal is to efficiently remove the sludge water during the dewatering process. Dewatering is usually applied after the sludge is destabilized through the conditioning process. Challenges related to polymer demand needed for chemical conditioning will exacerbate when sludge digestion is simultaneously employed with ASBRs technology. Major studies have been found that aerobic digestion of sludge can negatively affect its dewaterability properties such as flocculability (Zhang et al. 2016b). Murthy and Novak (1999) concluded that

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applying aerobic digestion leads to poor dewatering efficiency and a larger amount of polyelectrolyte consumption. Chen et al. (2021) showed that digestion process has the highest association with the elements affecting dewatered sludge of 32 wastewater treatment plants in Japan.

Because of such impact, it is often necessary to optimize the conditioning process and improve the dewatering efficiency, and it is critical to apply the proper chemical agent as well as proper dosages. Unsuitable chemicals, especially in overdose quantity, lead not only to lower efficiency but also significantly higher operational costs (Langer et al. 1994; Ayol et al. 2005; Abu-Orf and Dentel 1999; Böhm and Kulicke 1997; Ghernaout and Ghernaout 2012).

During the conditioning process, negative surface charge neutralization and bridging cause considerable agglomeration of the sludge particles and generate sludge clusters. This in turn improves sludge dewatering efficiency (Homeyer et al. 1999; Zhang et al. 2022). Thus, using cationic polyelectrolytes with high charge density (CD) is more effective in flocs formation than ionic polyelectrolytes (Homeyer et al. 1999). It has been reported that the cationic polyelectrolytes perform effectively in particle capture and the generation of denser flocs, resulting in better dewaterability while reducing the possibility of overdose (Lee and Liu 2000). To et al. (2020) used cationic polyelectrolyte Zetag8185 for chemical conditioning of mesophilic anaerobic digestion. In a study by Wu et al. (2021), PAM with 70% CD improved anaerobically digested sludge filtration performance. Zhang et al. (2019) indicated that chitosan-based polyelectrolytes performed well in anaerobically digested sludge filtration and result in stronger sludge floc structure. Sun et al. (2014) showed that polyelectrolyte with 40% CD outperformed other polyelectrolytes in the conditioning of activated sludge. Abrahams et al. (2021) used polyelectrolyte FLOPAM with 55–80% CD in conditioning of four activated sludge and in their study lower dosage of high charge density polyelectrolytes was suggested. Shi et al. (2019) evaluate the performance of different polyelectrolytes with 35 to 45% CD in single conditioning of activated sludge. In the study by Shaikh et al. (2017), cationic PAM FO 4800 SH (very high CD, MW) was shown to be the best flocculent among different investigated PAMs.

In general, while the majority of current investigations of PAM are concentrated upon high charge neutralization action and molecular weight (MW) of the amide groups with WAS and anaerobically digested sludge, little focus has been given to the specific impact of charge density on the dewatering properties of aerobically digested sludge after wastewater treated with SBR technology.

The features of conditioned digested sludge and its dewaterability performance are influenced by the floc/aggregate geometrical properties such as their size and compactness (Wei et al. 2018). Various approaches, such as image analysis or light scattering, in association with fractal theory, are used to examine floc/aggregate characteristics (Wei et al. 2009). According to Cao et al. (2016), small flocs with adequate compactness serve as skeleton developers that facilitate the dewatering process. To achieve successful flocculation of sludge particles during the conditioning process, considerable attention should be paid to the applied polyelectrolytes such as their charge density and molecular weight as well as the applied dosage (Wang et al. 2014; Gray and Ritchie 2006). Homeyer et al. (1999) discovered that molecular weight is a crucial element in floc stability. High MW polyelectrolytes generate large, tightly packed flocs that are shear resistant and can remarkably improve filterability performance. Gray and Ritchie investigated the impact of polyelectrolyte MW and CD on floc strength and demonstrated that polyelectrolytes with high MWs generate denser flocs than low molecular weight polyelectrolytes (Shaikh et al. 2017).

Most well-established approaches for sludge dewatering research are limited to the analysis of either generated floc which needs labor-intensive analysis to reveal a strong correlation, this means that our understanding of the interaction between sludge characteristics and PAM is still time-consuming. Therefore, sludge clusters or sludge aggregates should be examined for further investigation. The present study was carried out to investigate the effects of cationic polyelectrolytes with different charge densities and dosages on the conditioning performance and dewaterability characteristics of aerobically digested sludge with an emphasis on sludge clusters.

Materials and methods

Sludge samples and conditioners

The aerobically digested activated sludge (ADAS) used in this study was collected from a holding tank in Khein-Arab WWTP, Mashhad, Iran (KWWTP). The treatment capacity of this treatment plant is approximately 83,000 $m^3\ d^{-1}$ and the treatment technology is an advanced sequencing batch reactor (ASBR). The waste-activated sludge from the SBR reactors is aerobically digested and is conditioned before dewatering with cationic polyacrylamide C-25 (called reference polyelectrolyte) at the dosage 4.44 g kg^{-1} Ts^{-1}. In this research, 40 L of digested sludge from the holding tank was transferred to the WWTP's laboratory periodically and stored at 4 °C. All the experiments and analyses were conducted within a day of collecting the samples. The properties of the unconditioned ADAS are summarized in Table 1. To carry out the necessary experiments and analysis, 450 mL samples of digested sludge were conditioned separately with ultra-high cationic polyelectrolytes having different charge

Table 1 Characteristics of the unconditioned sludge used in this study

Parameters	Unconditioned ADAS
Total solids (g L^{-1})	32
Total suspected solids (g L^{-1})	15
Total volatile solids (g L^{-1})	25
pH	7.2–7.4

densities of 20%, 40%, and 60%. The dosages of each polyelectrolyte were 4.44, 4.07, 3.70, 3.33, 2.96, 2.59, 2.22, and 1.85 g kg^{-1} Ts^{-1}. The polyelectrolytes were purchased from BASF company with the brands Zetag®8167(60%CD), Zetag®8147(40%CD), and Zetag®8127(20%CD), and the main properties of these polyelectrolytes and reference polyelectrolytes are summarized in Table 2.

Sludge conditioning process

For conditioning the ADAS, in the first step, the stock solutions of each polyelectrolyte were prepared by dissolving 2.5 g of the polyelectrolyte in 500 mL of distilled water (0.5% w/v solutions) and using a mechanical stirrer. To achieve the selected dosages of each polyelectrolyte, the proper concentration of the related stock solution was added to 450 mL ADAS followed by stirring the mixture with a mechanical stirrer at 30 rpm.

Sludge dewaterability and properties

The dewaterability performance of the conditioned ADAS samples was evaluated via parameters such as SRF (specific resistance to filtration), filtration rate, and filtrate characteristics, as well as the size of geometrical sludge clusters properties (effective diameter, and two-dimensional fractal). Parameters such as total solids (TS), suspended solids (SS), and volatile solids (VS) were determined based on the standard method (APHA 2005). To evaluate the quality of filtrate water, turbidity was measured by a turbidity meter (HANNA, HI93703). To examine the dewaterability performance (SRF, filtration rate, and filtrate characteristic), the conditioned sludge samples were filtered through a vacuum filtering system consisting of a Büchner funnel (fitted with 9 cm diameter filtrate paper) and a one-stage vacuum pump operating at 0.2 bar. The main components of the filtering system are shown in Fig. 1.

The parameter SRF was calculated based on the following equation proposed by Christensen and Dick (1985).

$$SRF = \frac{2 \times P \times A^2 \times b}{\mu \times w} \quad (1)$$

where SRF is specific resistance to filtration (m kg^{-1}), A is area of filtering paper (m^2), P is hydrostatic pressure (N m^{-2}), b is the slope of "W versus V plot "(s mL^{-2}), μ is filtrate viscosity, (N s m^{-2}), and w is ratio of the dry weight of sludge cake to the volume of sludge before filtration (kg m^{-3}).

Table 2 Characteristics of the polyelectrolytes used in this study

Flocculent	Manufacturer	Charge density (CD) (wt%)	Molecular weight	Ion character
CPAM (C-25)	China	N.A	–	Cationic
Zetag®8167	BASF, Germany	60%	Ultra-high	Cationic
Zetag®8147	BASF, Germany	40%	Ultra-high	Cationic
Zetag®8127	BASF, Germany	20%	Ultra-high	Cationic

N.A not available

Fig. 1 The vacuum pump and the main components of Büchner funnel used in vacuum filtration system

Sludge geometry characteristics

The geometrical characteristics [diameter and two-dimensional fractal (D_2)] of the conditioned sludge clusters were derived from their images captured by a Canon S20 digital camera. To prepare the clusters for taking images, the sludge clusters were placed on microscopic slides with a dimension of 26 mm width and 76 mm length (Saveyn et al. 2005). The images were then transferred to image processing software (Image. J) and were modified to 8-bit being calibrated based on the slide dimension (Jarvis et al. 2005). The diameter of sludge clusters was determined by measuring the effective diameter as the equivalent diameter (Zhao 2003). The two-dimensional fractals (D_2) of sludge clusters were obtained by the regression analysis of the projected area logarithm (A) versus its logarithm of the corresponding maximum diameter (dL) (logA–logdL) (Chen and Wang 2015).

Statistical analysis

Statistical analysis of the resulting data was carried out by establishing a correlation heating map in Python software (V 3.9). The heating map shows a two- dimensional correlation matrix between factors. Based on the results, a significant correlation was observed between the key variables and the performance parameters. The Seaborn library was then used to determine linear-type correlations.

Results and discussions

Effects of polyelectrolyte type and dosage on SRF

The results of the SRF tests with polyelectrolytes at various dosages are shown in Fig. 2. As the figure shows, increasing the dosages of each polyelectrolyte reduces its related SRF value, as found by Zhu et al. (2017). Comparing the values in Fig. 2 indicates that, at all dosages, the best result of SRF was associated with the polyelectrolyte Zetag®8167 (60% CD) with a maximum value of 1.1×10^3 m kg^{-1} at the dosage of 4.44 g kg^{-1} Ts^{-1}. The SRF values for the polyelectrolytes Zetag®8147 and Zetag®8127 at the dosage of 4.44 g kg^{-1} Ts^{-1} were 4.61×10^3 m kg^{-1} and 6×10^3 m kg^{-1}, respectively. However, it should be noted that the values of SRF for Zetag®8167 polyelectrolyte did not change significantly beyond the dosage of 3.70 g kg^{-1} Ts^{-1}. The better performance of polyelectrolyte Zetag®8167, compared to the other polyelectrolytes, was most likely related to its higher charge density and larger bridging capability, which forms denser sludge clusters with better dewaterability. The SRF value for the reference polyelectrolyte (C-25) used as

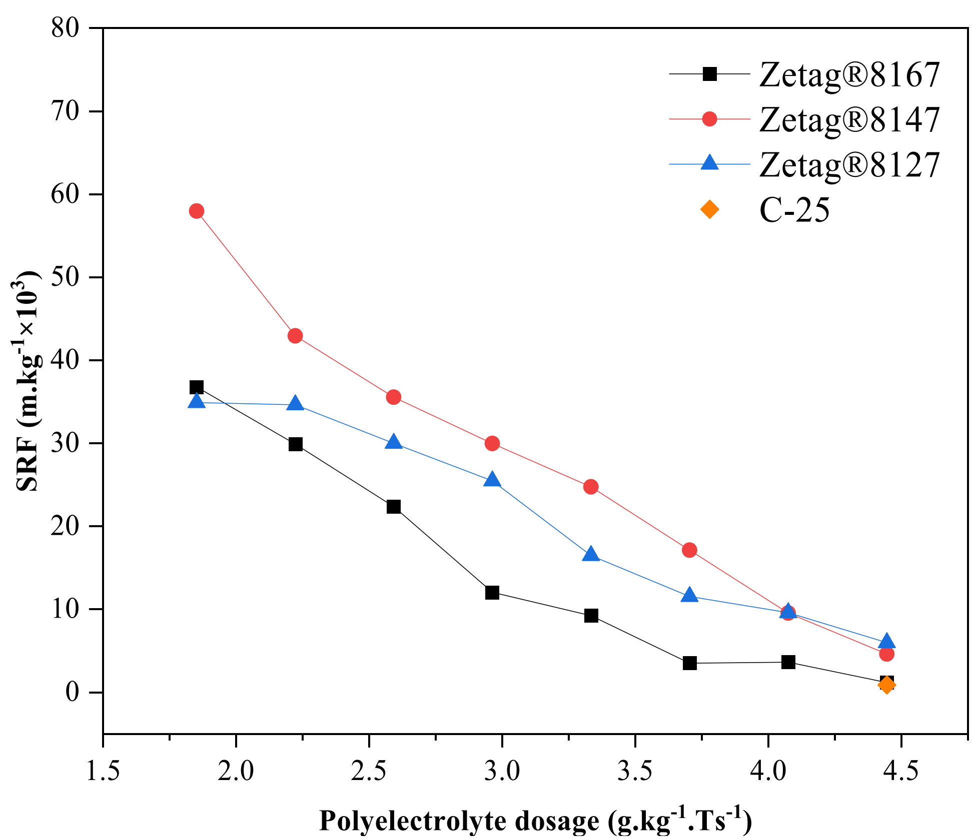


Fig. 2 Effect of polyelectrolyte dosages on SRF

the conditioner agent in the KWWTP was 1.0×10^3 m kg^{-1}, similar to the SRF values obtained for the polyelectrolyte Zetag®8167 dosages in the range of 3.70–4.44 g kg^{-1} Ts^{-1}. Therefore, the C-25 (at the dosage of 4.44 g kg^{-1} Ts^{-1}) could be replaced by Zetag®8167 polyelectrolyte at the dosage of 3.70 g kg^{-1} Ts^{-1}. This is an important point considering the cost-effectiveness of polyelectrolyte Zetag®8167. Based on the results, a dosage greater than 3.70 g kg^{-1} Ts^{-1} is not recommended for any of the polyelectrolytes used in this research due to the frequent filter clogging observed during the filtration process.

Effects of polyelectrolyte type and dosage on filtrate volume and turbidity

The effect of the dosage of polyelectrolytes Zetag®8167, Zetag®8147, and Zetag®8127 on filtrate volume and turbidity are presented in Figs. 3, 4 and 5, respectively. As it is observed, for any polyelectrolyte type of this study, according to the Yousefi study, the filtrate volume increased with an increase in polyelectrolyte dosage, while its filtrate turbidity showed a decreasing trend (Yousefi et al. 2020).

Based on the filtrate volume and turbidity data, the best dewatering performance was related to polyelectrolyte Zetag®8167 during the 7 min filtration of ADAS. This polyelectrolyte at the dosage of 4.44 g kg^{-1} Ts^{-1} resulted in a filtrate volume of 166 mL almost similar to the volume (170 mL) obtained for the reference polyelectrolyte (C-25) at the same dosage. However, the filtrate turbidity for Zetag®8167 was 15.56 NTU, much lower than the value of 34 NTU achieved for C-25. It should be mentioned that at dosages greater than 3.50 g kg^{-1} Ts^{-1}, the performance of Zetag®8167 was excellent. This polyelectrolyte consists of a long chain of monomers with dense positive charges. Thus, it can neutralize the negatively charged sludge particles efficiently (You et al. 2018; Yousefi et al. 2020).

In comparison, as shown in Figs. 4 and 5, for the polyelectrolytes with lower CD (Zetag®8147 and Zetag®8127), no satisfactory results were observed for the filtrate volume and turbidity values even at high dosages in the range of 3.5–4.44 g kg^{-1} Ts^{-1}. To achieve better performance with these polyelectrolytes, their dosage should be increased much more than 4.44 g kg^{-1} Ts^{-1}, which will remarkably raise the operational costs.

In general, the results revealed that the charge density and the molecular weight of polyelectrolytes play an important role in enhancing sludge filtration. In a study by Yousefi et al. (2020), it was also shown that charge density and molecular weight of polyelectrolytes are among the main factors affecting filtration performance and turbidity removal.

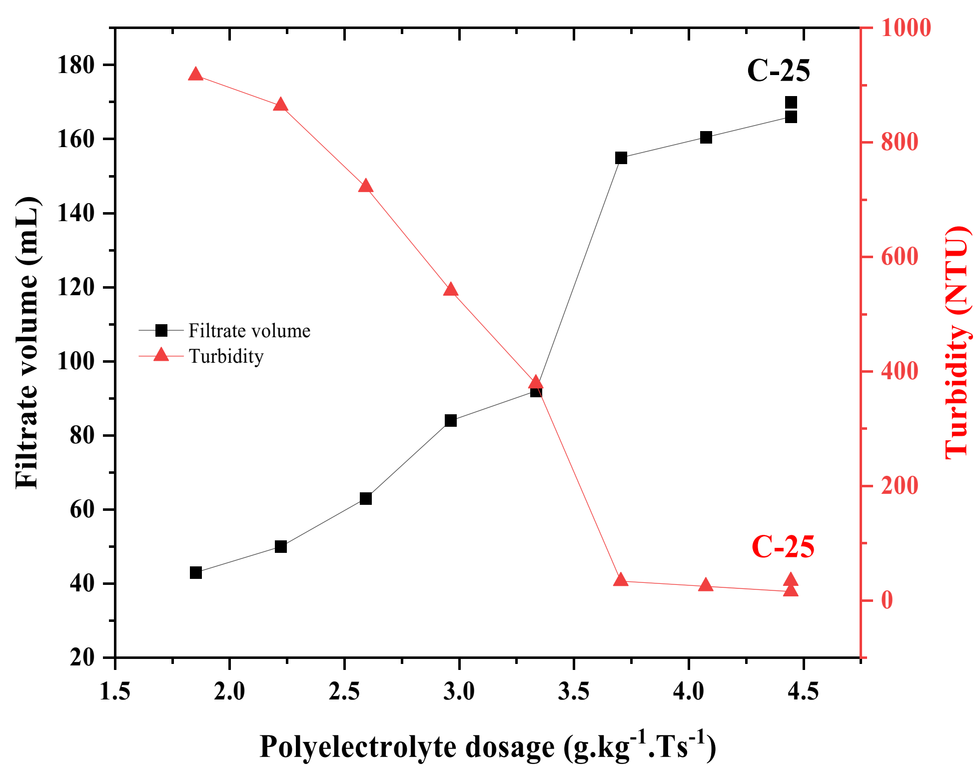


Fig. 3 Effect of the dose of Zetag®8167(60%CD) on turbidity and volume filtrate

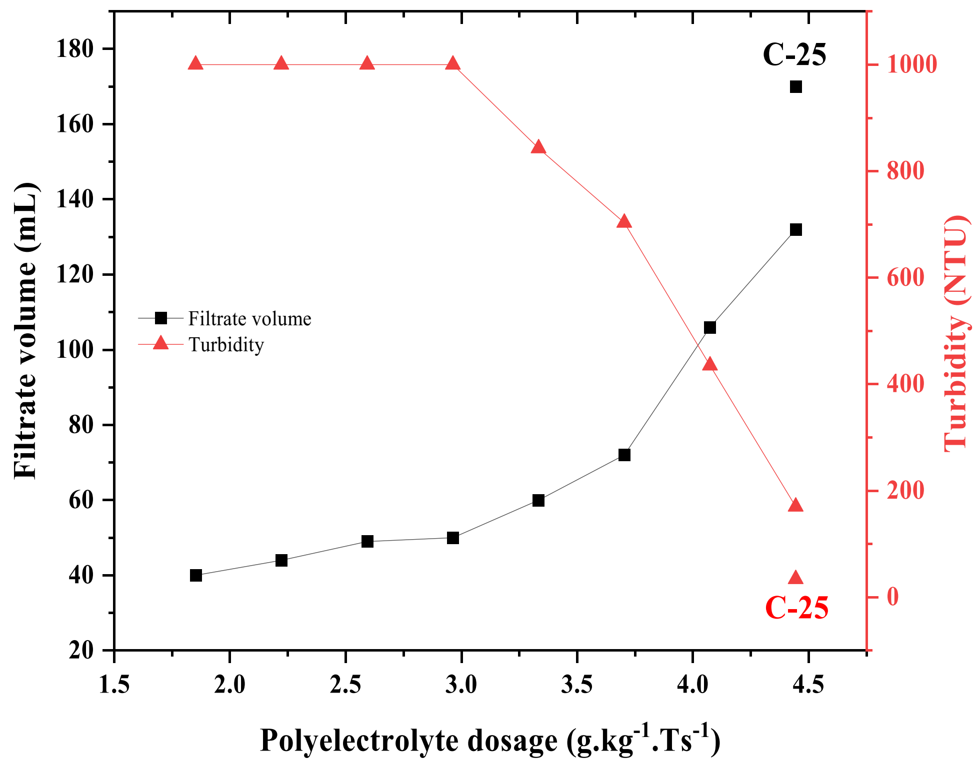


Fig. 4 Effect of the dose of Zetag®8147(40%CD) on turbidity and volume filtrate

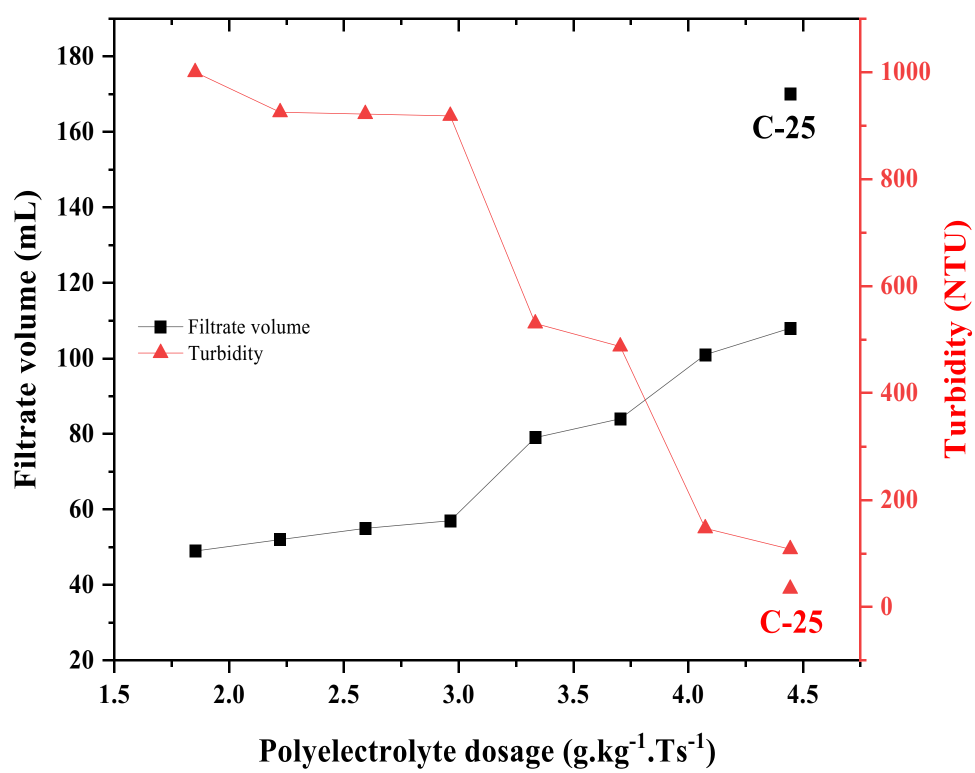


Fig. 5 Effect of the dose of Zetag®8127(20%CD) on turbidity and volume filtrate

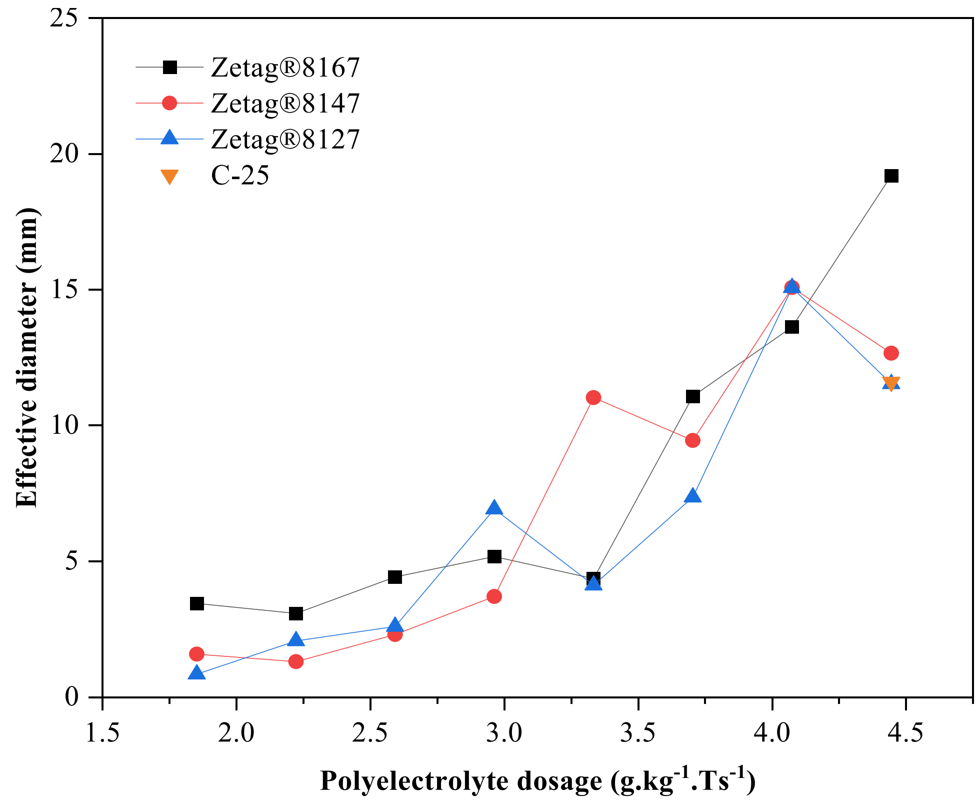


Fig. 6 Effective diameter of sludge cluster with polyelectrolyte dosages

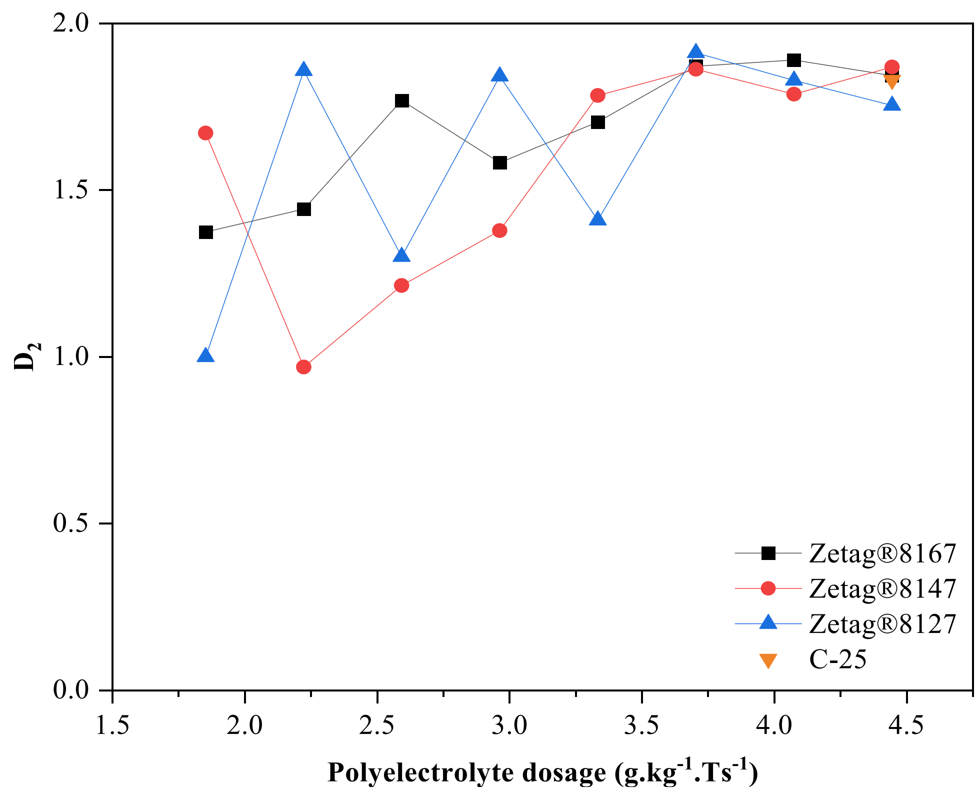


Fig. 7 Two-fractal dimension of sludge cluster with polyelectrolyte dosages

Effects of polyelectrolyte type and dosage on geometry properties of the sludge clusters

The effects of polyelectrolytes' dosages on the geometrical characteristics of sludge clusters are presented in Figs. 6 and 7. Figure 6 shows the effects on the sludge cluster's effective diameter and Fig. 7 presents the effects on the fractal dimension (D_2). From Fig. 6, it can be observed, up to the dosage of 4.07 g kg^{-1} Ts^{-1}, for all the polyelectrolyte types, the effective diameter of the sludge clusters was gradually increased with higher dosages which agreed with Zhao et al. (2011). But at dosages greater than 4.07 g kg^{-1} Ts^{-1}, while the effective diameter of sludge clusters formed by polyelectrolyte Zetag®8167(60%CD) continued to rise, the size of sludge clusters that were conditioned with polyelectrolytes Zetag®8127 and Zetag®8147 showed a sudden fall. These sudden reductions in the size of the sludge clusters at higher dosages could be related to the repulsive force generated by the accumulation of positive charges released by the latter two polyelectrolytes. This repulsive force could lead to the dispersion of sludge clusters. A similar effect could occur for the polyelectrolyte Zetag®8167(60%CD); however, because of its higher molecular weight, the binding effects of the molecular chains kept the sludge particles together and produced larger sludge clusters.

The average sludge cluster size at the dosage of 4.07 g kg^{-1} Ts^{-1} of polyelectrolyte Zetag®8167 was 13.63 mm which was greater than the average cluster size of 11 mm formed by the application of the C-25 polyelectrolyte at the dosage of 4.44 g kg^{-1} Ts^{-1}. In Fig. 7, the effects of polyelectrolyte type and dosage on the tightness of the sludge clusters are shown. The tightness of clusters was determined by measuring the fractal dimension (D_2) of the clusters. As illustrated in Fig. 7, the fractal dimensions of the sludge clusters fluctuated widely at dosages less than 3.70 g kg^{-1} Ts^{-1} of the applied polyelectrolytes. Therefore, no specific trend could be established at such dosages. Wen et al. (1997) also observed similar results in their study. At dosages of 3.70 g kg^{-1} Ts^{-1} and higher, however, the D_2 of the sludge clusters related to different polyelectrolytes were relatively similar and constant, although the highest value (1.89) belonged to the Zetag®8167 at dosage of 4.07 g kg^{-1} Ts^{-1}. The fractal dimension of the sludge clusters generated by the application of 4.44 g kg^{-1} Ts^{-1} of reference polyelectrolyte was 1.83. Regarding the results of D_2, it can be indicated that with polyelectrolyte Zetag®8167(60%CD), the generated clusters were much denser and stronger than the clusters formed by other applied polyelectrolytes including the reference one. The formation of denser and stronger sludge clusters when using high charge density polyelectrolytes was also reported by other authors (Zhao et al. 2011; Wen et al. 1997).

In general, the results of this study showed that the response of the sludge clusters' geometric parameters to different tested polyelectrolytes and dosages was not as sensitive as the responses of other dewatering sludge characteristics. For further illustration, a summary of the sizes and fractal dimensions (D_2) of the sludge clusters formed by the application of different polyelectrolytes at the dosage of 4.07 g kg^{-1} Ts^{-1} is presented in Table 3.

Effects of polyelectrolyte type and dosage on filtrate volume and filtration rate

The results presented in the previous section showed that the three polyelectrolytes Zetag®8127, Zetag®8147, and Zetag®8167 had their best conditioning performance at the dosage of 4.07 g kg^{-1} Ts^{-1}; therefore, the filtration rate for the related sludge samples was determined only at this applied dosage. Each filtration test was performed for a total period of 7 min during which the volumes of the filtrate were collected every 30 s, and based on them, the filtration rate was calculated. The results of filtration volumes and filtration rates versus filtration times are included in Figs. 8 and 9, respectively. As the Figures show, under all the tested conditioners the filtrate volume increased while filtration rates decreased as the process proceeded. These results were expected due to the clogging of the filter media.

According to Fig. 8, after 300 s of the filtration process, there was no filtrate passing through the filter media for the sludge samples conditioned with polyelectrolytes Zetag®8127 and Zetag®8147. The total filtrate volumes collected for these polyelectrolytes were 90 and 95 mL, respectively. In contrast, the passage of filtrate continued

Table 3 The sizes and fractal dimensions of the sludge clusters generated at dosage of 4.07 g kg^{-1} Ts^{-1} of different polyelectrolytes

Polyelectrolyte type	Charge density	Dosage (g kg^{-1} Ts^{-1})	Sludge cluster size (mm)	Fractal dimension (D_2)
C-25 (Reference polyelectrolyte)	N.A	4.44	11.6	1.83
ZETAG® 8167	60%	4.07	13.63	1.89
ZETAG®8147	40%	4.07	15.2	1.80
ZETAG®8127	20%	4.07	15.08	1.83

N.A not available

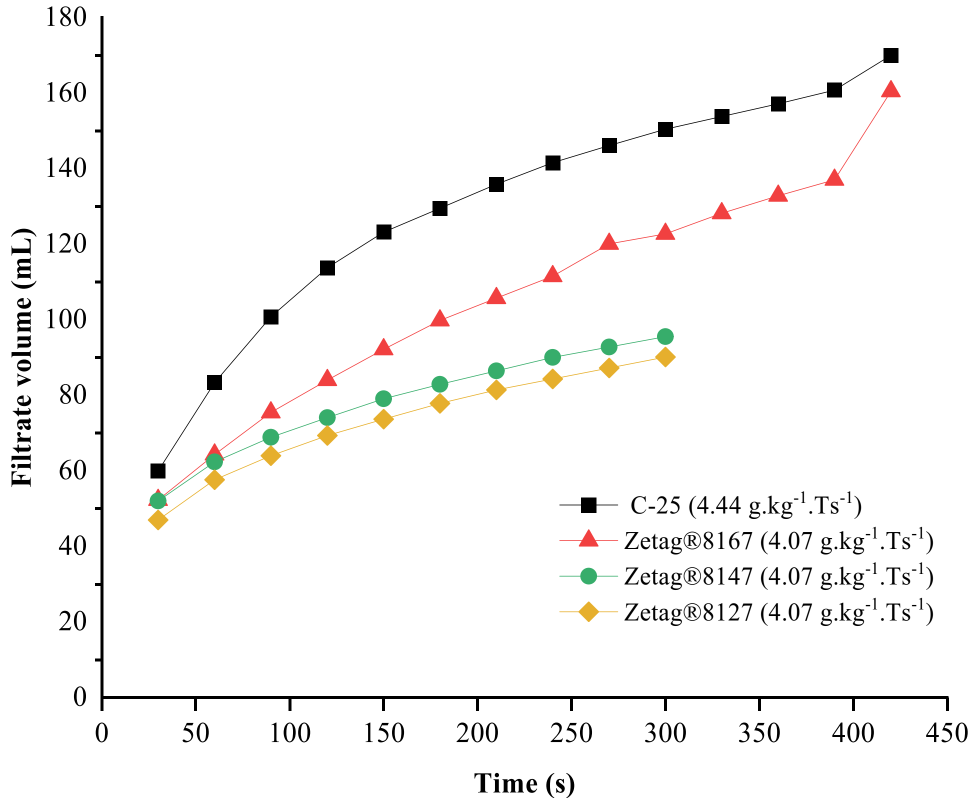


Fig. 8 The filtrate volume collected during filtration process

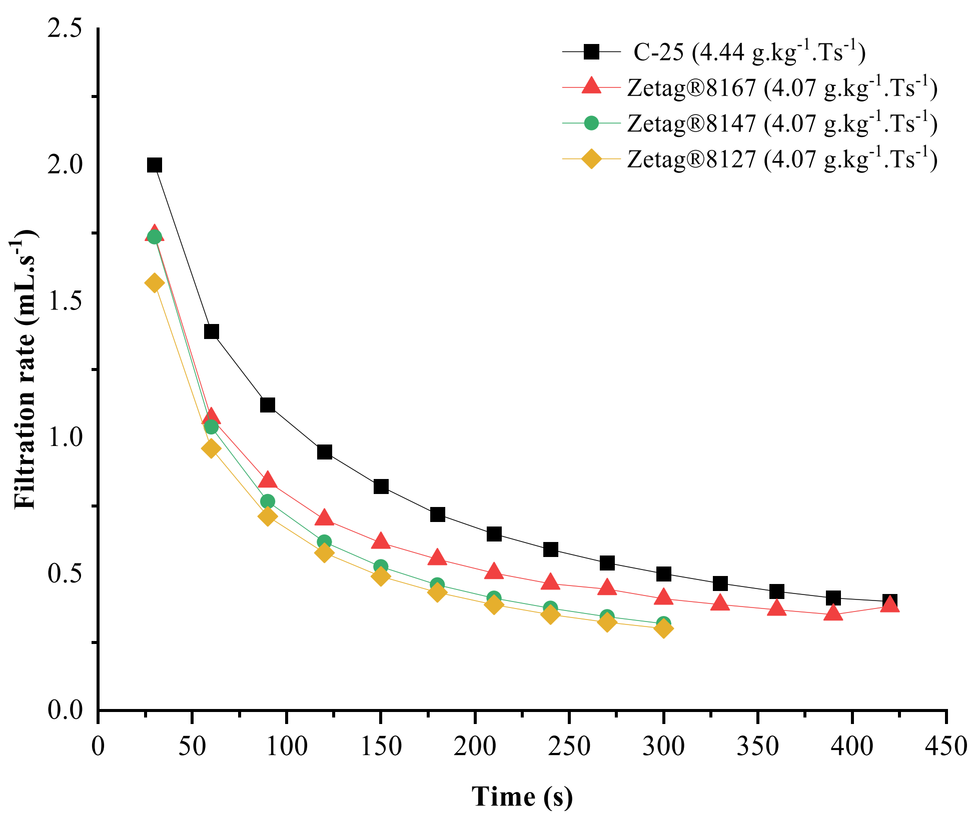
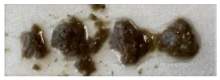


Fig. 9 The trend of filtration rates observed during filtration process

Table 4 Image of sludge clusters generated at the dosage of 4.07 g kg^{-1} Ts^{-1} of different polyelectrolytes

Polyelectrolyte type	Dosage (g kg^{-1} Ts^{-1})	Sludge clusters' image
C-25 (Reference polyelectrolyte)	4.44	
ZETAG® 8167	4.07	
ZETAG®8147	4.07	
ZETAG®8127	4.07	

to the end of the filtration period (420 s) for the polyelectrolytes Zetag®8167 and reference polyelectrolyte (C-25), with the corresponding filtrate volumes of 161 and 170 mL. The faster clogging of filter media associated with polyelectrolytes Zetag®8147 and Zetag®8127 could be attributed to differences between the size of the sludge clusters as the images shown in Table 4. The images demonstrate that the clusters formed under the usage of polyelectrolytes Zetag®8167 and C-25 were much smaller than the sludge clusters generated by the application of other polyelectrolytes.

As shown in Fig. 9, the filtration rate decreased gradually as the filtration process continued. This figure also illustrates that the filtration of the sludge samples conditioned with polyelectrolyte Zetag®8167 outperformed the sludge samples conditioned with Zetag®8147 and Zetag®8127, and was quite compatible with the results obtained for the reference polyelectrolyte. The calculated average filtration rates for the filtration period of 7 min (420 s) can be observed in Fig. 10.

Based on the results shown in this figure as well as the ones demonstrated in Fig. 8, it can be concluded that in the practical sense, due to faster clogging that occurs with the usage of polyelectrolytes Zetag®8127 and Zetag®8147, the number of washing cycles and hence the operational costs will be increased if these polyelectrolytes were to be used.

Data analysis

To evaluate the relative effect of the variables (polyelectrolyte type and dosage) and to determine the correlation between these variables and the sludge dewatering properties (SRF, turbidity, D_2, and filtration rate), a data analysis was performed. The experimental data were compiled as a dataset and analyzed in Python software.

The correlation coefficients between tested variables and parameters are shown in Fig. 11. As illustrated in this figure, the correlation coefficients between the polyelectrolyte type (charge density) and the parameters varied in the range of

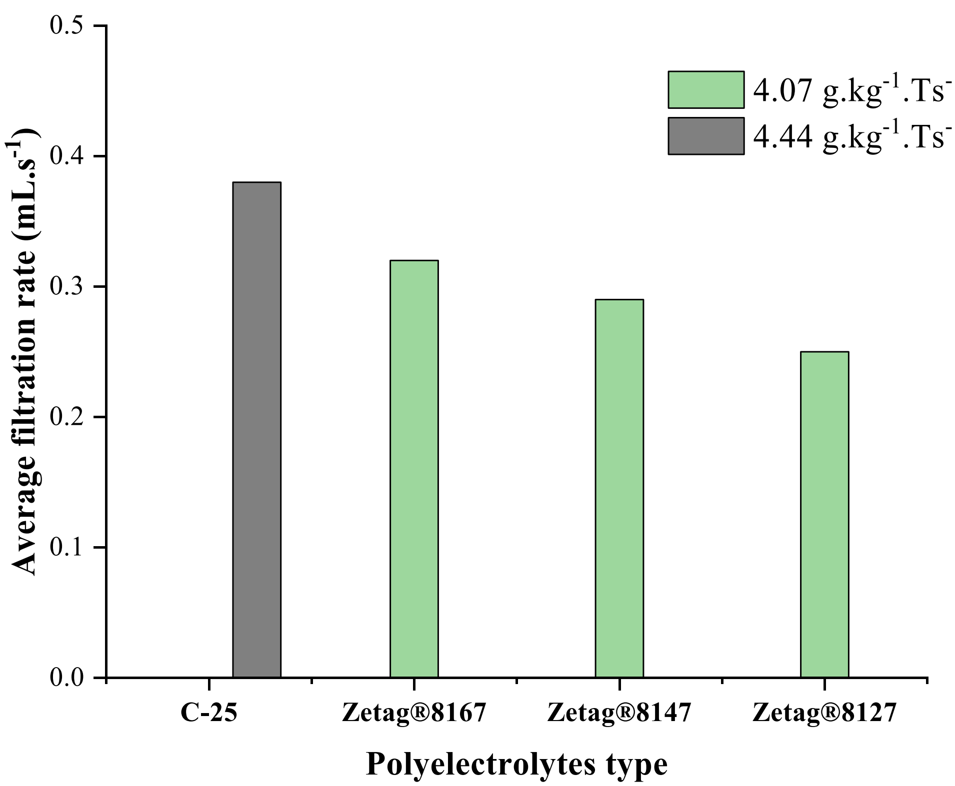


Fig. 10 The average filtration rates obtained during 7 min of filtration process

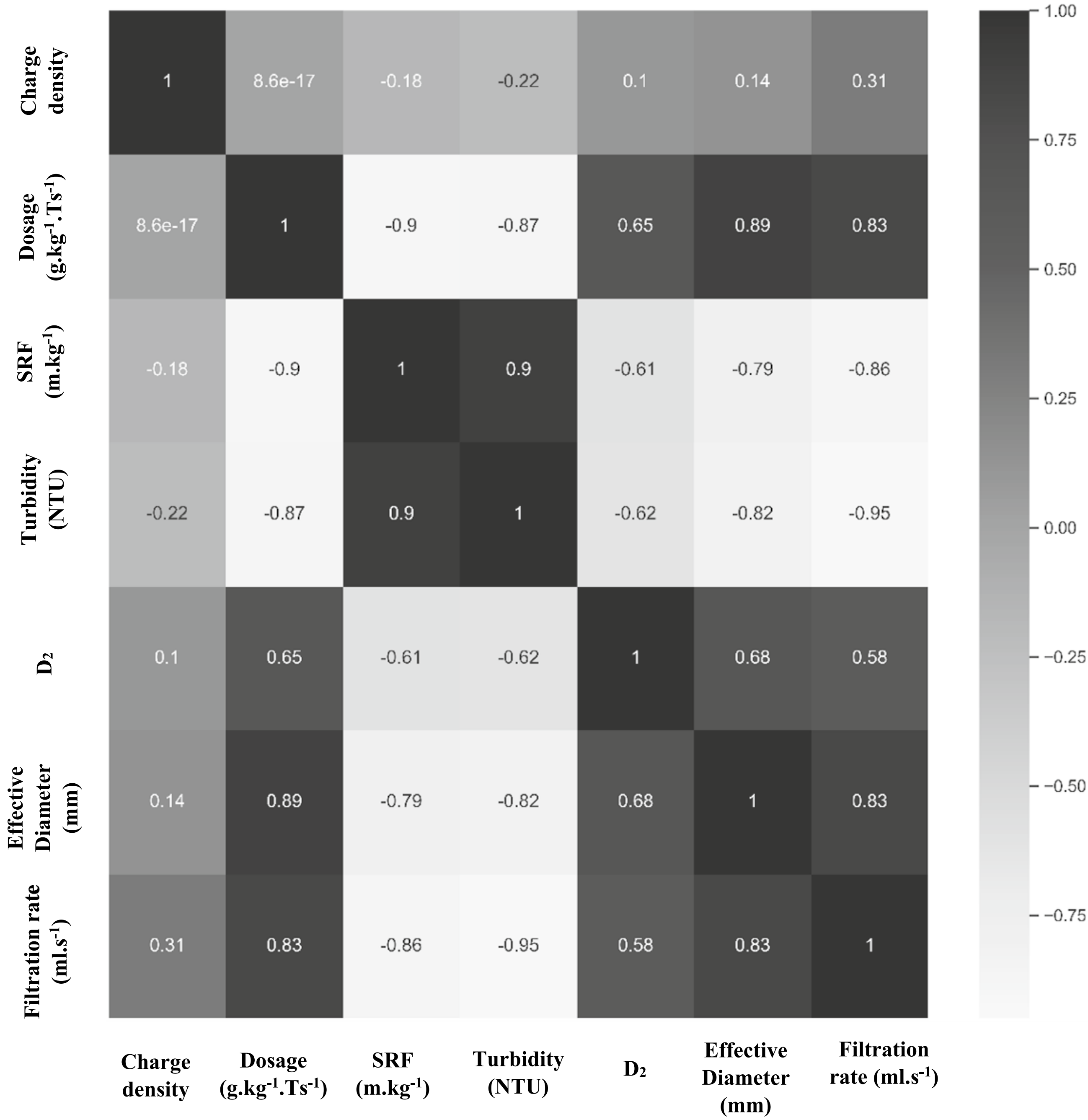


Fig. 11 Seaborn heatmap results on the correlation coefficients between tested variables and parameters

− 0.22 and 0.31, while, for the polyelectrolyte dosage, the related coefficient's values were in the range of − 0.9 and 0.89.

As the higher value of correlation coefficients indicates a higher impact, the polyelectrolyte dosage remarkably affected the dewaterability performance parameters more than the polyelectrolyte type. The figure also indicates that the effect of dosage (positive or negative) on some parameters such as SRF, and turbidity was higher than on other parameters. For example, the negative correlation value of − 0.9 between the dosage and SRF shows a negative stronger effect of the dosage on SRF values, compared to the effects on other parameters. Moreover, Fig. 11 reveals the existing correlation between different parameters. In this regard, the higher coefficient values represent a higher correlation. For instance, the highest

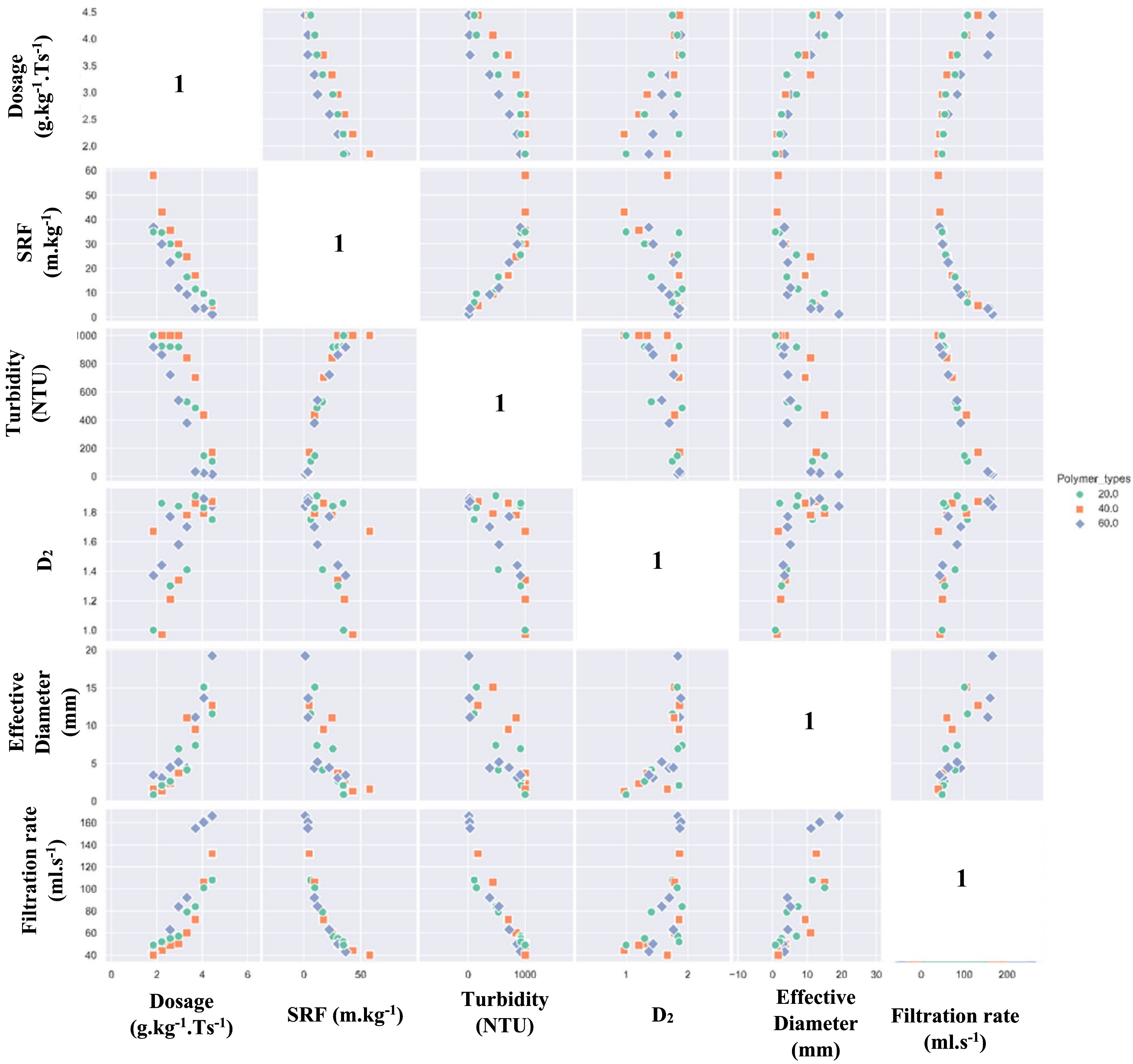


Fig. 12 Seaborn pairplot results on the trend of correlation between variables and parameters as well as among different parameters

positive correlation value (+ 0.9) was associated with turbidity and SRF while the highest negative value (− 0.95) was attributed to the SRF and filtration rate.

The output results of the software on the trend of correlation (linear, logarithmic, and so on) between variables and parameters as well as among different parameters are shown in Fig. 12. It can be observed, for example, that the correlation between polyelectrolyte dosage and most parameters such as SRF, turbidity, and filtrate volume are relatively linear, while the correlation between the dosage and filtration rate is relatively logarithmic.

Techno-economical analysis

A techno-economic analysis was carried out to determine the effect of polyelectrolyte dosage removal on sludge dewatering cost of MWWTP. As shown in Table 5, the dosage of 4.07 g kg^{-1} Ts^{-1} of polyelectrolyte Zetag®8167 was considered as proper dosage which lead to a cost reduction of $4.29 compared to the reference polyelectrolyte with capital price of $4.67 in digested sludge dewatering process. The cost per ton of dry sludge was decreased from 20.73 to $16.24 (i.e., 21%

Table 5 The techno-economic analysis of proper dosages applied in chemical conditioning of ADAS

Polyelectrolyte type	Polyelectrolyte dosage (g/kg.TS)	Polyelectrolyte dosage reduction (%)	Purchase cost ($/g)	Cost per ton of dry sludge ($)	Cost removal per ton of dry sludge ($)	Polymer cost reduction (%)
C-25	4.44	Reference	4.67	20.73	–	–
Zetag®8167	4.07	8.33	3.99	16.24	4.49	21
Zetag®8147	4.07	8.33	3.74	15.22	5.51	27
Zetag®8167	3.70	16.67	3.99	14.76	5.97	29

cost reduction) when polyelectrolyte Zetag®8167 was employed in chemical conditioning of ADAS process.

Conclusion

In this lab-scale study, the conditioning effects of three polyelectrolytes of Zetag®8167(60%CD), Zetag®8147(40%CD), and Zetag®8127(20%CD), each with dosages in the range of (1.85–4.44 g kg^{-1} Ts^{-1}) on dewatering characteristics of an aerobically digested sludge were assessed. Based on the results, the dewatering performance of the sludge samples was enhanced, up to a certain dosage of each polyelectrolyte. The results also indicated that the best performance in terms of the parameters of SRF, filtrate volume and turbidity, filtration rate, and sludge clusters properties belonged to the polyelectrolyte Zetag®8167 at the dosage of 4.07 g kg^{-1} Ts^{-1}. At this dosage, the polyelectrolyte was performed as well as the reference polyelectrolyte (C-25) at the dosage of 4.44 g kg^{-1} Ts^{-1}. The other two polyelectrolytes (Zetag®8127 and Zetag®8147) could also perform satisfactorily at dosages higher than 4.07 g kg^{-1} Ts^{-1}. Considering the performance and the cost associated with each tested polyelectrolyte, the WWTP might replace the reference polyelectrolyte, already in use, with the polyelectrolyte Zetag®8167 during the process of the sludge conditioning.

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Data availability The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Declarations

Conflict of interest The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter discussed in this manuscript.

References

Abrahams M, Aziz M, Kasongo G (2021) Investigating the effects of different cationic charge flocculation polymers on municipal wastewater sludge dewatering. Water Pract Technol 16(3):991–999

Abu-Orf MM, Dentel SK (1999) Rheology as tool for polymer dose assessment and control. J Environ Eng 125(12):1133–1141

Al-Dawery SK (2015) Conditioning process and characterization of fresh activated sludge. Int J Eng Sci Technol 10:692–711

APHA (2005) Standard methods for the examination of water and wastewater, 21st edn. American Public Health Association (APHA), Washington, DC

Ayol A, Dentel SK, Filibeli A (2005) Dual polymer conditioning of water treatment residuals. J Environ Eng ASCE 131(8):1132–1138

Baroutian S, Eshtiaghi N, Gapes DJ (2013) Rheology of a primary and secondary sewage sludge mixture: dependency on temperature and solid concentration. Bioresour Technol 140:227–233

Böhm N, Kulicke WM (1997) Optimization of the use of polyelectrolytes for dewatering industrial sludges of various origins. Colloid Polym Sci 275(1):73–81

Cao B, Zhang W, Wang Q, Huang Y, Meng C, Wang D (2016) Wastewater sludge dewaterability enhancement using hydroxyl aluminum conditioning: role of aluminum speciation. Water Res 105:615–624

Chen Q, Wang Y (2015) Influence of single-and dual-flocculant conditioning on the geometric morphology and internal structure of activated sludge. Powder Technol 270:1–9

Chen M, Oshita K, Mahzoun Y, Takaoka M, Fukutani S, Shiota K (2021) Survey of elemental composition in dewatered sludge in Japan. Sci Total Environ 752:141857

Christensen GL, Dick RI (1985) Specific resistance measurements: methods and procedures. J Environ Eng 111(3):258–271

Ghernaout D, Ghernaout B (2012) Sweep flocculation as a second form of charge neutralisation—a review. Desalin Water Treat 44(1–3):15–28

Gray SR, Ritchie CB (2006) Effect of organic polyelectrolyte characteristics on floc strength. Colloids Surf A Physicochem Eng Asp 273:184–188

Jafarinejad S (2017) Cost estimation and economical evaluation of three configurations of activated sludge process for a wastewater treatment plant (WWTP) using simulation. Appl Water Sci 7:2513–2521

Jarvis P, Jefferson B, Parsons SA (2005) Measuring floc structural characteristics. Rev Environ Sci Bio/technol 4(1):1–18

Kamizela T, Kowalczyk M (2021) Impact of conditioning substances and filtration pressure on dewatering efficiency of sewage sludge. Energies 14(2):361

Langer SJ, Klute R, Hahn HH (1994) Mechanisms of floc formation in sludge conditioning with polymers. Water Sci Technol 30(8):129

Lee CH, Liu JC (2000) Enhanced sludge dewatering by dual polyelectrolytes conditioning. Water Res 34(18):4430–4436

Murthy SN, Novak JT (1999) Factors affecting floc properties during aerobic digestion: implications for dewatering. Water Environ Res 71(2):197–202

Saveyn H, Meersseman S, Thas O, Van der Meeren P (2005) Influence of polyelectrolyte characteristics on pressure-driven activated sludge dewatering. Colloids Surf A Physicochem Eng Asp 262(1–3):40–51

Shaikh SM, Nasser MS, Hussein I, Benamor A, Onaizi SA, Qiblawey H (2017) Influence of polyelectrolytes and other polymer complexes on the flocculation and rheological behaviors of clay minerals: a comprehensive review. Sep Purif Technol 187:137–161

Shi C, Sun W, Sun Y, Chen L, Xu Y, Tang M (2019) Synthesis, characterization, and sludge dewaterability evaluation of the chitosan-based flocculant CCPAD. Polymers 11(1):95

Sun Y, Zheng H, Zhai J, Teng H, Zhao C, Zhao C, Liao Y (2014) Effects of surfactants on the improvement of sludge dewaterability using cationic flocculants. PLoS ONE 9(10):e111036

To VHP, Nguyen TV, Bustamante H, Vigneswaran S (2020) Effects of extracellular polymeric substance fractions on polyacrylamide demand and dewatering performance of digested sludges. Sep Purif Technol 239:116557

Von Homeyer A, Krentz DO, Kulicke WM, Lerche D (1999) Optimization of the polyelectrolyte dosage for dewatering sewage sludge suspensions by means of a new centrifugation analyser with an optoelectronic sensor. Colloid Polym Sci 277(7):637–645

Wang C, Harbottle D, Liu Q, Xu Z (2014) Current state of fine mineral tailings treatment: a critical review on theory and practice. Miner Eng 58:113–131

Wei J, Gao B, Yue Q, Wang Y, Li W, Zhu X (2009) Comparison of coagulation behavior and floc structure characteristic of different polyferric-cationic polymer dual-coagulants in humic acid solution. Water Res 43(3):724–732

Wei H, Gao B, Ren J, Li A, Yang H (2018) Coagulation/flocculation in dewatering of sludge: a review. Water Res 143:608–631

Wen HJ, Liu CI, Lee DJ (1997) Size and density of flocculated sludge flocs. J Environ Sci Health Part A 32(4):1125–1137

Wu W, Ma J, Xu J, Wang Z (2021) Mechanistic insights into chemical conditioning by polyacrylamide with different charge densities and its impacts on sludge dewaterability. Chem Eng J 410:128425

Xiao K, Chen Y, Jiang X, Yang Q, Seow WY, Zhu W, Zhou Y (2017) Variations in physical, chemical and biological properties in relation to sludge dewaterability under Fe (II)–Oxone conditioning. Water Res 109:13–23

You Z, Xu H, Sun Y, Zhang S, Zhang L (2018) Effective treatment of emulsified oil wastewater by the coagulation–flotation process. RSC Adv 8(71):40639–40646

Yousefi SA, Nasser MS, Hussein IA, Benamor A (2020) Enhancement of flocculation and dewaterability of a highly stable activated sludge using a hybrid system of organic coagulants and polyelectrolytes. J Water Process Eng 35:101237

Zhang W, Cao B, Wang D, Ma T, Xia H, Yu D (2016a) Influence of wastewater sludge treatment using combined peroxyacetic acid oxidation and inorganic coagulants re-flocculation on characteristics of extracellular polymeric substances (EPS). Water Res 88:728–739

Zhang Z, Zhou Y, Zhang J, Xia S, Hermanowicz SW (2016b) Effects of short-time aerobic digestion on extracellular polymeric substances and sludge features of waste activated sludge. Chem Eng J 299:177–183

Zhang W, Wang H, Li L, Li D, Wang Q, Xu Q, Wang D (2019) Impact of molecular structure and charge property of chitosan-based polymers on flocculation conditioning of advanced anaerobically digested sludge for dewaterability improvement. Sci Total Environ 670:98–109

Zhang X, Ye P, Wu Y (2022) Enhanced technology for sewage sludge advanced dewatering from an engineering practice perspective: a review. J Environ Manag 321:115938

Zhao YQ (2003) Correlations between floc physical properties and optimum polymer dosage in alum sludge conditioning and dewatering. Chem Eng J 92(1–3):227–235

Zhao YX, Gao BY, Shon HK, Wang Y, Kim JH, Yue QY (2011) The effect of second coagulant dose on the regrowth of flocs formed by charge neutralization and sweep coagulation using titanium tetrachloride ($TiCl_4$). J Hazard Mater 198:70–77

Zhu Y, Tan X, Liu Q (2017) Dual polymer flocculants for mature fine tailings dewatering. Can J Chem Eng 95(1):3–10

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