NOVEL METHODOLOGIES FOR DETERMINING A SUITABLE POLYMER FOR EFFECTIVE SLUDGE DEWATERING

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Abstract

Understanding the interactions between sludge particles and polymers during sludge dewatering is necessary to: firstly, maximize dewatered cake solids content; and secondly, minimize polymer demand. In this study, two scientific methodologies, namely the 'y–intercept' concept and Higgins modified centrifugal technique (Higgins MCT) were used to identify the optimum polymer demand and type for effective conditioning and dewatering. Results from the 'y–intercept' concept show that a large amount of polymer required during conditioning of anaerobically digested sludge (ADS) is mainly due to neutralization of soluble biopolymers. In contrast, conditioning of aerobically digested sludge (AEDS) and waste activated sludge (WAS) is mostly controlled by a polymer bridging mechanism. The results indicated that, in order to achieve maximum dewatering performance with minimum conditioning polymer requirement, high charge density polymers are suitable for ADS while branched (or cross–linked) polymers can be used for AEDS and WAS. The new lab–scale technique, Higgins MCT, was successfully implemented for measuring cake solids content achievable by centrifuge and determining the optimum polymer demand (OPD). The Higgins MCT also helped to understand the relationship between digestion, conditioning and dewatering.

KEYWORDS: *Sludge Characteristics, Polymer Characteristics, Flocculation Mechanisms, Optimal Polymer Demand, Sludge Dewaterability Indicators.*

1. Introduction

Low cake solids content and high polymer demand for conditioning in sludge dewatering are two major issues that lead to high chemical and transportation costs in wastewater treatment plants (WWTPs). The selection of appropriate polymer types and optimal polymer demand (OPD) for conditioning could help to minimize chemical costs and maximize dewatering performance. However, it is challenging to have a proper selection strategy due to the limited understanding of factors that control OPD for various sludge and polymer types [1,2]. Consequently, plant operators have difficulty in choosing the best polymer type and dose for conditioning of a given sludge without comprehensive laboratory or field testing. The influential factors of sludge conditioning and dewatering can be classified into three categories, i.e. sludge characteristics, polymer characteristics and dewatering equipment.

Sewage biological sludge particles are often considered to be hydrophilic colloids which explain their great affinity for water [3] as well as its poor dewaterability. The complicated and variable nature of sewage sludge can significantly affect conditioning and dewatering performance [4]. There is consequently a need to identify the most significant parameters that affect these processes.

Higgins et al. [2] defined extracellular polymeric substances (EPS) or biopolymers in sewage sludge as mainly protein and polysaccharides with particle size ranging from 2.4µm to 6µm. A number of studies have demonstrated that soluble EPS particles smaller than 4.2µm create a major proportion of the polymer demand and result in high chemical requirement for conditioning [2,5,6,7]. Higgins et al. [2] stated that various sludge types typically had different soluble biopolymer concentrations with waste activated sludge (WAS) and aerobically digested sludge (AEDS) typically having the least. Anaerobically digested sludge (ADS) had the highest concentration of soluble EPS among three sludge types (WAS=AEDS<ADS). It has been proved that soluble biopolymers are released in significant amounts into supernatant solution

during digestion, especially anaerobic digestion [6]. Therefore, investigation of the inter–relationships among sludge treatment processes is vitally important to identify pathways for improving biosolids dewaterability and reducing chemical demand.

Conditioning polymers interact differently with sludge particles during flocculation due to their different charge densities, molecular weights and structures. It has been known that flocculation of sludge particles by polymers mainly follows two mechanisms: charge neutralization and polymer bridging [9]. However, the governing mechanism depends on both sludge types and polymer characteristics. Vaxelaire and Olivier [1] stated that the flocculation was mainly controlled by bridging formation when high molecular weight or structured (branched or cross–linked) polymers are used for conditioning. In contrast, charge neutralization is predominant when using low molecular weight or high charge density or linear polymers. However, this study was limited to only two polymer types, one sludge type and belt press dewatering. Thus, further investigation is required to confirm the aforementioned mechanisms.

Another important and influential element of conditioning and dewatering is dewatering shear. The high shear during mechanical dewatering can help to increase the cake solids content. However, it is also considered as one of major causes of high polymer demand for conditioning. Novak and Lynch [10] noted that polymer demand is required to flocculate sludge particles as well as to overcome effects of shear on sludge flocs. In the WWTPs, different dewatering devices impart different shear stress on sludge cake. Centrifuges generate the highest shear intensity and belt filter presses establish the lowest during dewatering [2]. Novak et al. [11] and Spinosa and Mininni [12] also observed that belt filter presses and centrifuges require different chemical demands, leading to distinctive dewaterability indicator for each equipment types.

It is believed that a reliable dewatering index should be established to simulate real water extraction process and estimate the maximum solids content of sludge cake achievable by that process [13]. Most traditional dewaterability measuring techniques, including Capillary Suction

Time (CST) and Specific Resistance to Filtration (SRF), often measure the rate of filtration/water removal only. CST is a quick and easy technique, but it does not give a measurement of cake solids content. Furthermore, it does not represent the full–scale dewatering process. The SRF test, which is quite similar to pressure filters and vacuum filters, can provide cake solids content, but it is time–consuming and complex [13]. Various attempts have been made to identify reliable indicators for sludge dewatering by centrifuge. Spinosa and Mininni [12] reported that sludge settleability, scrollability and floc strength were the major sludge characteristics influencing centrifugability. Unfortunately, there was no established method that can include all the above properties in the dewaterability measurement. Chu and Lee [14] introduced an arm–suspended centrifuge to investigate the centrifugal separation of moisture from conditioned activated sludge and determine the optimal rotational speed for maximum moisture removal. However, this method cannot predict the final achievable cake solids content because the centrifuged cake remained in contact with the supernatant solution. More details concerning the difficulties in assessing sludge dewatering performance and the main techniques used to evaluate dewatering performance were recently presented in the review paper by To et al. [13].

Higgins et al. [15] proposed a modified lab–scale centrifuge device that enables the separation of the dewatered cake from the suspending liquid. This has shown to be a suitable small scale dewatering test that overcomes the limitations of the conventional dewaterability indicators described above. The Higgins modified centrifugal technique (Higgins MCT) was initially introduced and investigated in our earlier work [7]. The technique was originally designed for estimating relative polymer demand and cake solids content achievable by centrifugal dewatering. In our previous study, we confirmed that the Higgins MCT test can: firstly, simulate the real centrifuge process; secondly, predict maximum cake solids content achievable by centrifuge; and thirdly, determine the OPD for sludge conditioning [7]. However, in that particular study, the Higgins MCT was solely utilized to evaluate the dewatering of anaerobically digested sludge (ADS), which is not sufficient to prove the universality of this technique. In the present study, the Higgins MCT was implemented on another sludge type, the waste activated sludge (WAS) in order to elucidate the applicability of this method. In addition, more samples of ADS were analysed. The Higgins MCT was also applied in this study to better comprehend the effects of sludge pre–treatment methods, particularly digestion, on sludge dewatering efficiency.

The main purpose of this study was to evaluate the ability of the new laboratory methodology in selecting appropriate polymer types and doses for conditioning of different sludge types. The specific tasks were to:

(i) identify the relationships between OPD and sludge characteristics to determine the most influential factors of OPD based on the observed relationships;

(ii) clarify the interaction mechanisms of conditioning polymers and sludge particles;

(iii) investigate the application of the laboratory–scale Higgins MCT in estimating the maximum cake solids content achievable by centrifuge and determining the OPD for a given sludge.

2. Materials and methods

2.1. Materials

2.1.1. Sludge samples

Three different sludge types were collected from three WWTPs run by Sydney Water, Australia. They were ADS from Wollongong WWTP (seven sampling times covering the period May 2013 to March 2014), AEDS from St. Marys WWTP (seven sampling times lasting from October 2013 to June 2014) and WAS from Quakers Hill WWTP (seven sampling times for the period October 2013 to June 2014). General information on sludge treatment of the three

WWTPs, in terms of upstream sludge treatment processes, conditioning and dewatering, is summarized in Table 1.

Table 1

As–received sludge samples were collected from a sampling point before being conditioned and dewatered at these WWTPs. The sludge samples were then immediately transferred to the laboratory for characterizing their physical and chemical parameters (pH, zeta potential (ZP), total solids (TS) content, soluble COD (sCOD), soluble protein (sP) and soluble polysaccharides (sPS)) on the same day. Samples used for conditioning tests were stored at 4^{o}C (in order to minimize the microbial activity). Dewatered cake samples were also collected at outlets of centrifuges at the three WWTPs to compare the full–scale dewatering performance with the laboratory–scale dewatering.

2.1.2. Conditioning polymers

This study used two cationic polymers which were Zetag 8165 (used in Wollongong and Quakers Hill WWTPs) and Zetag 8180 (used in St. Marys WWTP) for conditioning and dewatering experiments. Characteristics of these two polymer types are presented in Table 2. Polymer solutions were prepared by dissolving the powdered polymer in de-ionized water at the same concentrations used at the three WWTPs (as shown in Table 2). The polymer manufacturing companies recommended to use de-ionized water for polymer dissolution in order to maximize the performance of conditioning polymers although it may not be practical for large WWTPs (using treated water or tap water). Both mixing time and aging time were 30 minutes each. For maximum effect, the polymer solution was used within two days of the experiments. In this study, polymer dose was expressed as kg of powdered polymer per tonne of dry solids or kg/DT.

Table 2

2.2. Experimental studies

Each experiment and analysis were conducted in duplicate and the average values were reported.

2.2.1. Sludge characterization

Preparation for analysing soluble biopolymers and soluble COD

The purpose here is to extract soluble biopolymers and soluble COD from sludge. As–received sludge samples were centrifuged at 3000 rpm for 15 minutes and then supernatant was filtered using Whatman filter paper No. 542 (pore size 2.7μm). The selection of the filter paper pore size was based on the study of Higgins et al. [2]. The filtrate was then used to measure soluble COD and soluble EPS.

Analytical methods

Soluble COD was analysed using Hatch COD vials. Soluble protein and polysaccharides were measured using the modified Lowry [18] and Phenol–Sulphuric [19] methods, respectively. TS and VS were measured following Standard Methods 2540B and 2540E [20], respectively. Temperature and pH of sludge before conditioning were measured by pH meter (Hana, model HI 9025C). Zeta potential (ZP) of the sludge particles was measured using Malvern Instrument (ZetaSizer Nano ZS–90).

2.2.2. Conditioning test

Only five out seven sampling times in each plant were used for this experiment. Experiments were carried out by transferring 500 mL of the as–received sludge samples into 1L cylindrical beakers. Different pre–determined amounts of the stock polymer solution were mixed with the sludge at optimized mixing regimes (presented in the next section) using a bench–scale agitator (3 blade impeller, Heidolph RZR 2020). CST test was used with the conditioned sludge samples to determine OPD_{CST} and optimal mixing intensity. The maximum cake solids content achievable by centrifuge was determined by Higgins MCT.

2.2.3. CST test

OPD determination

CST values of conditioned sludge with different polymer doses were measured and the dose that resulted in the lowest value of CST (sec) was defined as optimal polymer demand (OPD_{CST}) for conditioning. OPD_{CST} was correlated with sludge characteristics in order to identify the most influencing factors of sludge conditioning and dewatering.

Optimal mixing intensity determination

After mixing at a pre–determined mixing time (30s; 60s; 120s; 180s; 300s) at a mixing speed (100rpm; 200rpm; 400rpm; 500 rpm), conditioned sludge samples were used for the CST test to identify the mixing condition that led to the shortest CST. Optimized mixing speed and mixing time were 200rpm and 60s, respectively.

CST was determined using 304B Portable CST Unit, Triton Electronics Ltd., UK using Whatman paper No. 17 (which is a standard grade of chromatography paper). Details for this procedure are documented elsewhere [21]. In this study, CST test was utilized together with the Higgins MCT so that shortcomings in the CST test could be overcome.

2.2.4. Higgins modified centrifugal technique (Higgins MCT)

A lab–scale centrifuge device was modified to ensure that the dewatered cake is kept separate from the centrate. A support was provided to hold the filter paper (Whatman paper No. 4, 20 µm pore size) about half way from the bottom of the centrifuge tube, ensuring that the cake formed is always above the liquid level (as shown in Figure 1). This modified centrifuge apparatus served to determine cake solids content achievable by centrifuge at different centrifugal intensity values. This method was first proposed by Higgins et al. [15] and investigated by To et al. [7] in their study. The centrifugal intensity or shear applied on sludge flocs during dewatering was quantified by both relative centrifugal force (RCF) or gravitational force and centrifugal residence time, CRT [22]. Thus, a multiplication of RCF and CRT was used to represent the centrifugal shear in this study.

Figure 1.

RCF is often expressed in units of gravity (times gravity or xg). Since most centrifuges only have a setting for centrifugal rotating speed which is in revolutions per minute, RPM, the relative centrifugal force was converted from RPM and radius of rotor, R (in cm), by the following formula [23]:

$$\mathrm{RCF} = (1.118\times10^{-5}) \times \mathrm{R} \times \mathrm{RPM}^2 \quad (1)$$

Table 3 presents the conversion between RPM and RCF for 7 cm of rotor radius of the lab–scale centrifuge and different values of centrifugal intensity used in the study. Here CRT is the centrifugal residence time in minutes.

Table 3

Procedure

The study used only ADS and WAS for the Higgins MCT experiment. The reason was, among the three WWTPs studied, both Wollongong (ADS) and Quakers Hill (WAS) WWTPs have utilized centrifuges for dewatering while St. Marys WWTP has employed belt filter presses. Since different dewatering devices vary in their efficiency, as a result only the two WWTPs using centrifuges were selected for comparison. Conditioned sludge samples after free drainage (in order to remove free water) were placed directly on the filter paper inside the modified centrifuge tubes and then the lab–scale centrifuge was operated at different centrifugal intensity values. After centrifuging, the corresponding cake solids contents of the cake formed above the liquid were measured. Plots of shear values versus corresponding cake solids contents

(%) were created to investigate the effect of centrifugal force on cake solids content for different polymer doses, and to determine the best cake content that could be obtained by centrifuge.

3. Results and discussion

3.1. Characterization of as–received sludge – Prediction of conditioning demand for each sludge type

Characteristics of the three as–received sludge types (feed to centrifuge) studied are presented in Table 4. This study only presents the most representative parameters related to polymer demand for sludge conditioning. It was found that the soluble protein, polysaccharides and COD concentrations were much lower in AEDS and WAS compared to ADS samples. Also the zeta potential was also more negative for the ADS. This could possibly explain the differences in polymer demand for conditioning as well as dewaterability of the three sludge types studied.

Table 4

3.1.1. Total solids (TS) content and volatile solids (VS) content

TS and VS of the feed sludge to centrifuge are two of the most common parameters often used for sludge characterization as well as determining polymer dosage and types for conditioning. As can be seen from Table 4, TS and VS of ADS and AEDS were lower than those of WAS as a result of digestion process, especially when anaerobic digestion was used. If higher TS and VS led to higher polymer dose for conditioning, WAS could require the highest dose, followed by ADS and AEDS. However, in the next section, it was proved that it may not be accurate to use TS and VS to estimate the conditioning polymer demand for dewatering.

3.1.2. Zeta potential

Zeta potential (ZP) is an important surface property of sludge flocs in terms of flocculation and dewatering [9]. Sewage sludge originating from WWTPs usually has negative ZP [24]. The distinctive feature is the magnitude of ZP which indicates the degree of electrostatic repulsion between adjacent, similarly charged dispersed particles in the sludge. When ZP is small, attractive forces may exceed this repulsion and colloids may flocculate. In contrast, larger magnitude of ZP results in more stable colloids, leading to smaller probability of flocculation [24,25]. As a consequense, more cationic flocculant is needed to neutralize negative charges and reduce the magnitude of ZP. As can be seen from Table 4, ADS and AEDS had higher negative ZP values which were -29.6mV and -26.4mV, respectively, as compared to WAS (-21.3mV). This means the digested sludge may require higher polymer demand for conditioning while WAS may consume less polymer dosage for charge neutralization.

3.1.3. Soluble substances (Soluble biopolymers and soluble COD)

Soluble biopolymers (mainly protein and polysaccharides) which are produced during the digestion process have been demonstrated to be responsible for high polymer demand for sludge conditioning [6,7]. Higgins et al. [2] and To et al. [7] also observed a good relationship between soluble COD and OPD_{CST}. In this study, ADS had a much higher amount of both soluble COD and soluble biopolymers in comparison with AEDS and WAS (Table 4). This suggests that polymer dose needed for conditioning of ADS should be higher than that of AEDS and WAS.

Soluble protein concentration of both sludge types was higher than soluble polysaccharide concentration, especially for ADS and AEDS. This supports the finding reported by Novak et al. [6] that protein is released mostly into the solution during anaerobic digestion. In addition, the ratio of soluble protein to soluble polysaccharides (sP/sPS) increased through the digestion process, with a value of 1.7 for WAS, 3.1 for ADS and 2.8 for AEDS

(Table 4). These experimental results highlight a more important role of protein in determining the polymer demand for sludge conditioning.

3.2. Understanding interaction mechanisms between conditioning polymers and sludge particles

3.2.1. Relationships between sludge characteristics and $\mathrm{OPD_{CST}}$

It can be seen from Table 5, among the parameters studied, soluble protein (sP), soluble polysaccharides (sPS), the ratio of soluble protein to soluble polysaccharides (sP/sPS), the total of soluble protein and polysaccharides (sP+sPS) and soluble COD (sCOD) were found to correlate well with $\mathrm{OPD_{CST}}$ for ADS, AEDS and WAS individually and all sludge type samples (when they were plotted together). These strong linear relationships indicated that larger amounts of these soluble biopolymers can result in higher polymer requirements for conditioning.

Table 5

For each sludge type

It can be seen for ADS that sP, sPS, sP+sPS, sP/sPS and sCOD had good linear relationships with $\mathrm{OPD_{CST}}$. Meanwhile only sPS (R^2=0.74) and sCOD (R^2=0.99) correlated well with $\mathrm{OPD_{CST}}$ for AEDS and WAS, respectively. In terms of TS, VS and ZP, the correlation between $\mathrm{OPD_{CST}}$ and ADS, AEDS and WAS remained insignificant.

For all sludge type samples

Taking characteristics of all sludge samples (three types of sludge) into consideration, almost all soluble components (except for sP/sPS) showed strong correlations with $\mathrm{OPD_{CST}}$. These results confirmed that soluble biocolloid concentration can be used as a crucial factor to determine the $\mathrm{OPD_{CST}}$ for sludge conditioning, which is consistent with the study by Higgins et al. [2]. Although there was an insignificant relationship between $\mathrm{OPD_{CST}}$ and ZP observed for each sludge type, a good relationship ($R^2 = 0.64$) was recorded when ZP of all three sludge types were plotted together. The correlation was negatively linear which indicates that sludge with less negativity of ZP requires less polymer demand for conditioning. This agrees with the statement made in section 3.1.2. Since charge neutralization is one of the main coagulation/flocculation mechanisms [26], ZP can give useful indirect information in determining the conditioning polymer demand. Similar to each sludge type, no relationship was observed between OPD_{CST} and TS, VS for all sludge type samples. These results indicate that TS and VS may not be reliable indicators for determining OPD for conditioning and dewatering.

Figure 2 illustrates relationships between OPD_{CST} and the contents of soluble substances for all sludge type samples. As noted in Figure 2, OPD_{CST} values were the lowest for WAS conditioning (2 – 4 kg/DT) then AEDS (4 – 6 kg/DT) and the highest for ADS (6 – 9 kg/DT). Additionally, these values of OPD_{CST} for the three sludge types were much lower (about 50%) than the full–scale dosages used at the WWTPs (6 – 8 kg/DT in Quakers Hill WWTP, 9-10 kg/DT in St. Marys WWTP and 9 – 12 kg/DT in Wollongong WWTP; see Table 1). However, it is common practice that plant operators tend to add extra polymer to ensure that the solids capture is maximized. In addition, high shear occurring in full-scale centrifuges can also lead to higher polymer demands in practice as compared to OPD_{CST}. Hence, there would always be more polymer amounts in full–scale than what “theoretically” is needed.

Figure 2.

3.2.2. Concept of ‘y–intercept’ in explaining the interaction mechanisms of conditioning polymers and sludge particles

A concept of ‘y–intercept’ in the OPD_{CST} versus soluble biopolymer content curve (Figure 3) was proposed in order to identify polymer demand (PD) for: (i) charge neutralization; and (ii) bridging formation in sludge conditioning. This concept has been mentioned in the work by Higgins et al. [2] to explain the contribution of non–biocolloid fraction to optimal polymer dose for conditioning.

Figure 3.

The relationship between OPD_{CST} and total soluble biopolymers can play a major role in deciding PD and interaction mechanisms of conditioning polymers. As can be seen from Figure 3, the y–intercept for the graph is about 2.5 kg/DT. It suggests that this amount of polymer was not used for charge neutralization since there is zero soluble biocolloids at the y–intercept point. Therefore, the y–intercept value of 2.5 kg/DT can be thought of as the polymer used for bridging formation of a large non–biocolloid fraction and the remaining OPD_{CST} was utilized for charge neutralization of small negative–charged biopolymer particles. For ADS, PD for charge neutralization was higher compared to polymer bridging, and consequently the former prevailed in flocculation. In contrast, AEDS and WAS conditioning were governed mainly by bridging phenomena.

3.2.3. Selection of appropriate polymers for effective conditioning and dewatering of sludge

Since cationic polymers with high and very high molecular weight are widely used for conditioning and dewatering of wastewater sludge, especially for facility using centrifuges [27], the selection of appropriate polymers for conditioning generally focuses on the charge density and configuration of polymers. According to the y–intercept concept, ADS conditioning is mainly controlled by charge neutralization. Therefore, it is likely that polymers with high charge density or mole charge are preferred.

On the other hand, AEDS and WAS flocs may require branched or cross–linked polymers to ‘embrace’ tightly or incorporate these sludge flocs into the larger ones through the bridging formation mechanism. Even with high molecular weight, the linear polymers are not favourable for flocculation of AEDS and WAS due to its weak resistance to high shear, which ultimately leads to broken flocs during dewatering. Higgins et al. [2] carried out a set of experiments to examine the response to shear for different sludge types and concluded that AEDS and WAS are the most sensitive to shear compared to ADS. This means that AEDS and WAS flocs are easily broken during high speed dewatering while ADS has higher floc strength to withstand the shear. Wollongong and Quakers Hill WWTPs have been using high–speed centrifuges for sludge dewatering. The high shear sensitivity of WAS could also be the cause for the high suspended solids content in centrate of Quakers Hill WWTP (Figure 4a) compared to a clear centrate of Wollongong WWTP (Figure 4b). The strength of ADS flocs could be due to the interactions between biopolymers or bio–flocculants (released during digestion) and high charged polymers [9,28,29].

Figure 4.

Zetag 8165 was used in both Wollongong and Quakers Hill WWTPs for sludge conditioning. Zetag 8165 is a cationic, linear and medium–high charge density polymer with very high molecular weight polymer. Thus, this polymer could be suitable for ADS conditioning (full–scale TS of dewatered cake could reach 29%). However, this polymer may not be appropriate for the conditioning of sensitive WAS. Full–scale results show that dewatering of WAS using zetag 8165 only achieved 19–21% of cake solids content with inferior centrate quality (high SS content) (Table 1). Thus, full–scale trial of WAS conditioning using branched polymers is needed to confirm whether branched polymers are preferable to linear polymers. Although branched (or cross–linked) polymers were suggested for conditioning of AEDS, no full–scale evidence is available to support this suggestion as St. Marys WWTP has used belt filter presses and not centrifuges for dewatering.

3.3. Application of Higgins modified centrifugal technique (Higgins MCT) on different sludge types

3.3.1. Estimation of maximum cake solids content achievable by centrifuge

Figure 5 presents the effect of centrifugal intensity on cake solids content of conditioned ADS and WAS at same polymer doses used at the WWTPs studied. It was observed that the increase in centrifugal force resulted in the improvement in cake solids content for both digested (from 2.5% before dewatering to a maximum of 30% after dewatering – Figure 5) and undigested sludge (from 3% before dewatering to maximum 20% after dewatering – Figure 5), which is in agreement with our earlier findings [7]. The maximum values of cake concentration could indicate the limitation of dewatering by centrifuge for ADS and WAS with the polymers and doses in the plants.

Figure 5.

In order to assess the reliability of this method for estimating the full–scale cake solids content, this study compared the maximum cake solids content determined by Higgins MCT and by full–scale dewatering for the two sludge types. As observed from Table 6, after being conditioned at the same dosages utilized at the plants, maximum cake solids contents of ADS and WAS obtained from Higgins MCT were quite similar to those achieved at the two WWTPs, with ADS about 29% and WAS about 21%. These numbers indicate that Higgins MCT is a representative lab–scale method for measuring maximum cake solids content achievable by full–scale centrifugal dewatering. This laboratory method, which can substitute expensive full–scale trials, could confirm whether $\mathrm{OPD_{CST}}$ and polymer types selected by the 'y-intercept' concept could be used in the field.

Table 6

3.3.2. Determination of Optimal Polymer Dose

CST test has been used in many studies to estimate OPD due to its simple and rapid measurement. However, the test determines the most favourable flocculation rather than the final cake solids content. As a result, CST test together with Higgins MCT could be used as a comprehensive solution to identify the polymer dose for both effective conditioning and dewatering. The present study firstly determined the OPD_{CST} for each sludge type studied. Table 7 shows the comparison of OPD_{CST} and the WWTPs' currently used PD for ADS and WAS. Results depict a similarity for both sludge types in that OPD_{CST} values were much lower (50%) than the full–scale PDs. However, the major difference between the full–scale centrifuge and CST test is the shear that sludge cake experiences. It was demonstrated that higher shear creates an additional polymer demand for conditioning [2,10]. Therefore, these results do not guarantee that these lower doses could work in the field. In this case, Higgins MCT, which can reproduce the centrifuge shear exerting on the sludge flocs or cake. Thus, it overcomes the shortcomings encountered by CST test.

Table 7

Higgins MCT was performed both with optimum polymer doses found from CST test (OPD_{CST}) and doses used in full–scale plants for both types of sludge (Figure 6 and 7). Figure 6 and 7 demonstrated whether lower polymer doses for conditioning (which were determined by CST test) can achieve similar cake solids content as compared to higher doses (which were used in the WWTPs). As can be noticed from these graphs, cake solids content of the two doses were quite similar for both ADS (maximum about 29% - Figure 6) and WAS (maximum about 21% - Figure 7). This means the same dewatering efficiency could be achieved by using only half of the polymer amount presently used for conditioning at these WWTPs. In fact, the amounts of polymer used for conditioning at the WWTPs are often based on total solids content of feed sludge to the centrifuge. This may result in overdosed conditioning, which probably incurs higher expense for the same level of performance.

Figure 6.

Figure 7.

It was certainly difficult to convince the plants' operators to try the PD because it seemed to be too low for practical dewatering. Thus, the best option that the study recommended for the WWTPs was to reduce 30 – 40% of their current high polymer dose for conditioning. In full–scale trials, Wollongong WWTP (with ADS at the plant having similar characteristics with the one used for the lab tests) decreased its PD for conditioning from 12 kg/DT to 7.5 kg/DT in their full–scale operation and achieved similar cake solids content (27 – 29%) and centrate quality. The dose of 7.5 kg/DT has been used for dewatering at Wollongong plant for a long period as it has ascertained a stable dewatering performance.

3.3.3. Effects of anaerobic digestion on sludge dewaterability

In order to investigate how digestion, particularly anaerobic digestion, influences dewatering performance, Higgins MCT was used to determine cake solids content of both unconditioned and conditioned ADS (digested sludge) and WAS (undigested sludge). It can be noted in Table 8 that without conditioning, cake solids content of ADS dewatering (16.8%) was slightly lower than that of WAS dewatering (18.7%). However, after being conditioned with the same polymer (Zetag 8165) at their OPD_{CST}, cake solids content of ADS dramatically increased to 28.9% compared to that of WAS (which improved only up to 21.6%). These results show the effect of anaerobic digestion on the down–stream treatment processes or the inter–relationships between anaerobic digestion, sludge conditioning and dewatering. It was previously confirmed that digestion, especially anaerobic digestion, may lead to higher polymer demand for conditioning due to the excessive amount of soluble biopolymers released during the anaerobic digestion process [2,7]. Nevertheless, both experimental and full–scale results illustrate a better dewaterability, in terms of cake solids content, of ADS compared to WAS. The study attributes this phenomenon to the interaction of soluble biopolymers or extracellular polymeric substances (also known as bio–flocculants) with conditioning polymers, which can help to strengthen the floc strength under high shear dewatering of centrifuge.

Table 8

4. Conclusions

This study investigated the representative scientific methodologies to determine the optimum polymer demand and type for effective sludge conditioning and dewatering.

The ‘y–intercept’ concept provided a better understanding of the interactions between polymers and sludge particles during conditioning. Based on this concept, the following conclusions can be made:

- OPD is primarily linked to soluble biopolymers. This helps to explain the high polymer demand needed to condition and dewater ADS. Meanwhile, the composition of AEDS and WAS correlated with lower OPD. This suggests that anaerobically digested sludge does not undergo favourable sludge conditioning.
- The y–intercept concept is a promising approach to explain the interaction mechanisms between sludge and polymer particles in order to select the most suitable polymer type for an effective dewatering of a specific sludge type.
- The y–intercept concept indicates the polymer proportions consumed for charge neutralization and bridging of a given sludge. Based on the experimental results, the study found that conditioning of ADS was predominantly governed by charge neutralization while that of AEDS and WAS were mostly controlled by polymer bridging. As a result, high charge density polymers may be recommended for ADS conditioning while branched (or cross–linked) polymers could be suitable for AEDS and WAS conditioning. However, full–scale trials are necessary to validate this suggestion.

- Further studies are needed to understand the physical and chemical mechanisms affecting conditioning and dewatering of different sludge types.

Higgins modified centrifugal technique (Higgins MCT) is a representative laboratory scale methodology to estimate maximum cake solids content achievable by centrifugal dewatering:

- The technique can be successfully used to evaluate the dewaterability in terms of cake solids content of different sludge types. The similarity of cake solids content obtained by Higgins MCT and full–scale dewatering results has strengthened the reliability of this method.
- This technique can be used to confirm whether OPD_{CST} and polymer types selected by ‘y–intercept’ concept could work in the full–scale dewatering process.

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Table captions

Table 1. General information on waste treatment systems in the three WWTPs studied (provided by plant operators).

Table 2. Concentrations of polymer solutions used for conditioning at the three WWTPs studied.

Table 3. Conversion between RCF and RPM for 7 cm of rotor radius of the lab–scale centrifuge used in this study and centrifugal intensity values used in Higgins MCT

Table 4. Typical characteristics of as–received ADS, AEDS and WAS.

Table 5. Correlation coefficients (R^2) of sludge characteristics with OPD_{CST} for ADS, AEDS and WAS (datasets are provided in the Appendix).

Table 6. Maximum cake solids content determined by Higgins MCT tests and full–scale processes for the two sludge types.

Table 7. Comparison of OPD_{CST} and currently used PD (full–scale) at the WWTPs studied.

Table 8. Cake solids contents of ADS (digested sludge) and WAS (undigested sludge) before and after conditioning (determined by Higgins MCT).

Table 1 General information on waste treatment systems in the WWTPs studied.

WWTPs	Nutrient removal methods[a]	Upstream sludge treatment processes[d]	Sludge types[h]	Dewatering devices	Typical polymer dose (kg/DT[i])	Typical cake solids content (%)	Suspended solids in centrate (mg/L)
Wollongong	BNR[b]	Centrifuge thickening[e] +Anaerobic digestion (mesophilic single-stage)	ADS	Solid bowl centrifuges	9–12	27–29	<100
St. Marys	BNR	DAF[f] +Aerobic digestion	AEDS	Belt filter presses	9–10	15–19	<100
Quakers Hill	IDAL[c]	Gravity thickening[g]	WAS	Solid bowl centrifuges	6–8	19–21	1000–4000

[a] *Waste sludge was collected from these wastewater treatment processes for biosolids treatment.*

[b] *Biological Nutrient Removal.*

[c] *Intermittently Decanted Aeration Laggons.*

[d] *Sludge treatment processes before conditioning and dewatering.*

[e] *Thickening using same polymer for dewatering.*

[f] *Dissolved Air Floatation.*

[g] *No polymer added.*

[h] *Feed sludge to dewatering equipment.*

[i] *kg of powder polymer per ton of dry solids.*

Table 2 Concentrations of polymer solutions used for conditioning at the three WWTPs studied.

WWTPs	Polymer for dewatering	Polymer properties	Solution concentration (% w/v)
Wollongong	Zetag 8165	linear, medium–high charge density, very high molecular weight [16]	0.1
St. Marys	Zetag 8180	linear, high charge density, high molecular weight [17]	0.3 – 0.4
Quakers Hill	Zetag 8165	linear, medium–high charge density, very high molecular weight [16]	0.2 – 0.3

Source: Sydney Water Corporation (2014).

Table 3 Conversion between RCF and RPM for 7 cm of rotor radius of the lab–scale centrifuge used in this study and centrifugal intensity values used in Higgins MCT

Centrifuge speed (rpm)	RCF (xg)	RCT (min)	Centrifugal intensity (xg min)
2000	313	5	1565
		10	3130
		15	4695
		20	6260
2500	489	5	2445
		10	4890
		15	7335
		20	9780
3000	704	5	3520
		10	7040
		15	10560
		20	14080

Table 4 Typical characteristics of as–received ADS, AEDS and WAS.

Sludge type	TS[a] (%)	VS (%)	ZP (mV)	sCOD (mg/L)	sP (mg/L)	sPS (mg/L)	sP+sPS (mg/L)	sP/sPS
ADS	2.5	1.5	-29.6	1111	234	72	306	3.1
	±0.3[b]	*±0.1*	*±0.9*	*±305*	*±89*	*±13*	*±102*	*±0.7*
AEDS	1.9	1.2	-26.4	593	85	31	116	2.8
	±0.6[c]	*±0.4*	*±0.8*	*±167*	*±12*	*±7*	*±18*	*±0.4*
WAS	3.0	2.1	-21.3	486	65	33	99	2.1
	±0.4[d]	*±0.3*	*±1.7*	*±252*	*±20*	*±12*	*±28*	*±0.8*

[a] *Total solids content of feed sludge to dewatering devices.*

[b] *Standard deviation value of seven ADS sampling times from Wollongong WWTP: from May 2013 to March 2014.*

[c] *Standard deviation value of seven AEDS sampling times from St. Marys WWTP: from October 2013 to June 2014.*

[d] *Standard deviation value of seven WAS sampling times from Quakers Hill WWTP: from October 2013 to June 2014.*

Table 5 Correlation coefficients (R^2) of sludge characteristics with OPD_{CST} for ADS, AEDS and WAS (datasets are provided in the Appendix).

Sludge types	TS	VS	ZP	sCOD	sP	sPS	sP+sPS	sP/sPS
ADS[a]	0.00	+0.20	-0.19	+0.90	+0.95	+0.97	+0.92	+0.81
AEDS[b]	+0.06	+0.06	-0.28	+0.27	+0.46	+0.74	+0.59	-0.45
WAS[c]	-0.20	-0.22	+0.39	+0.99	+0.46	+0.35	+0.51	-0.08
All 3 sludge types[d]	-0.06	-0.23	-0.64	+0.88	+0.83	+0.81	+0.86	+0.27

'-': negative linear; '+': positive linear.

[a] *Correlation coefficients (R^2) were obtained by correlating OPD with characteristics of ADS only (from five sampling times).*

[b] *Correlation coefficients (R^2) were obtained by correlating OPD with characteristics of AEDS only (from five sampling times).*

[c] *Correlation coefficients (R^2) were obtained by correlating OPD with characteristics of WAS only (from five sampling times).*

[d] *Correlation coefficients (R^2) were obtained by correlating OPD with characteristics of all sludge samples of ADS, AEDS and WAS together (total 15 samples) on a single graph.*

Table 6 Maximum cake solids content determined by Higgins MCT tests and full–scale processes for the two sludge types.

Sludge types	Maximum cake solids determined by Higgins MCT [a] (%)	Full–scale cake solids at the WWTPs (%)
ADS	28.9 ±0.9	28.3 ±1.2
WAS	21.6 ±0.6	21 ±0.3

[a] *After conditioning with a similar polymer dose used at the two WWTPs (12 kg/DT for ADS and 8 kg/DT for WAS).*

Table 7 Comparison of OPD_{CST} and currently used PD (full–scale) at the WWTPs studied.

Sludge types	OPD_{CST} [a] (kg/DT)	Full–scale PD [a] (kg/DT)
ADS	6	12
WAS	4	8

[a] *Values of OPD_{CST} and full–scale PD presented in this table were obtained from the same samples collected at Wollongong (3rd September 2013) and Quakers Hill (17th December 2013) WWTPs.*

Table 8 Cake solids contents of ADS (digested sludge) and WAS (undigested sludge) before and after conditioning (determined by Higgins MCT).

Sludge types	Maximum cake solids content (%)	
	Without conditioning	With conditioning [a]
Digested sludge (ADS)	16.8	28.9
Undigested sludge (WAS)	18.7	21.6

[a] *Both sludge types were conditioned at their* OPD_{CST} *determined in the last section.*

Figure captions

Figure 1. Modified centrifuge tube before and after Higgins MCT test. The photo on the right shows the dewatered cake separated with the centrate in the Higgins MCT.

Figure 2. Relationships between OPD_{CST} and characteristics of all three sludge type samples (total 15 samples) including: (a) Soluble Protein; (b) Soluble Polysaccharides; (c) Total soluble biopolymers; and (d) Soluble COD.

Figure 3. The use of "y–intercept" concept to determine predominant flocculation mechanisms for ADS, AEDS and WAS conditioning.

Figure 4. Full–scale centrate of (a) WAS dewatering (with suspended solids over 3500mg/L) and (b) ADS dewatering (with suspended solids under 100mg/L) (Sydney Water).

Figure 5. Effect of centrifugal intensity on cake solids content of ADS and WAS conditioned at full–scale polymer dosages.

Figure 6. Higgins MCT test of WAS conditioned at full–scale PD (12 kg/DT) and OPD_{CST} (6 kg/DT).

Figure 7. Higgins MCT test of ADS conditioned at full–scale PD (8 kg/DT) and OPD_{CST} (4 kg/DT).

Figure 1. Modified centrifuge tube before and after Higgins MCT test. The photo on the right shows the dewatered cake separated with the centrate in the Higgins MCT.

Figure 2. Relationships between OPD_{CST} and characteristics of all three sludge types together (total 15 samples) including: (a) Soluble Protein; (b) Soluble Polysaccharides; (c) Total soluble biopolymers; and (d) Soluble COD.

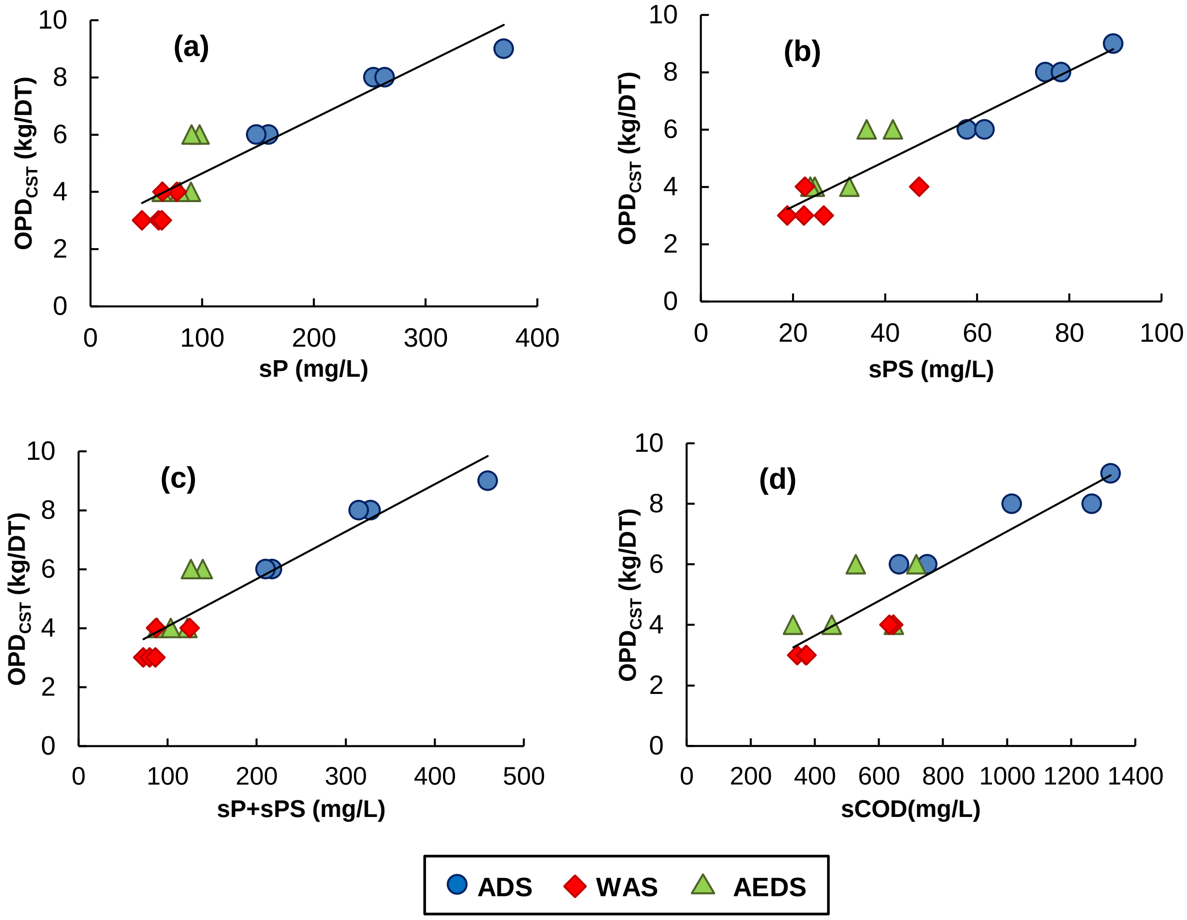


Figure 3. The use of "y–intercept" concept to determine predominant flocculation mechanisms for ADS, AEDS and WAS conditioning.

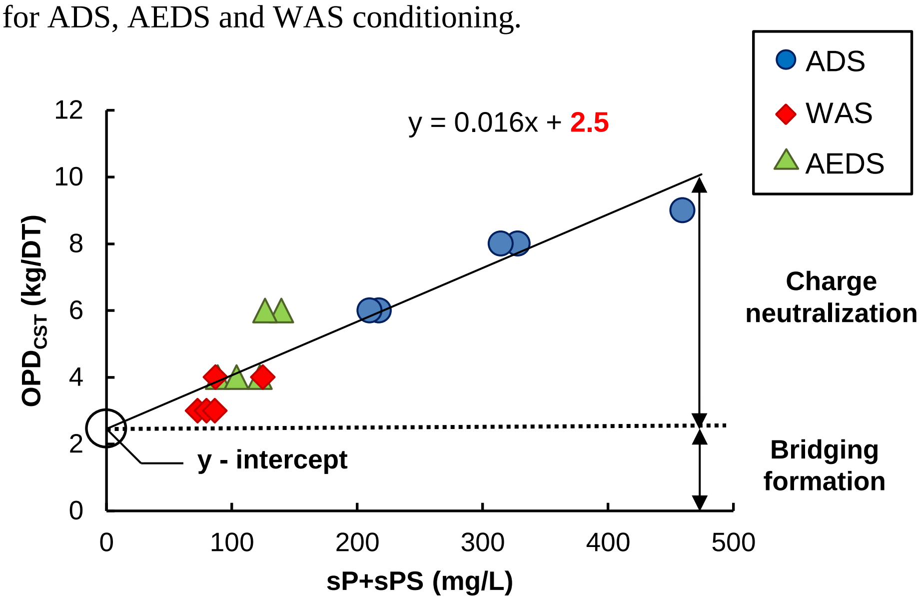
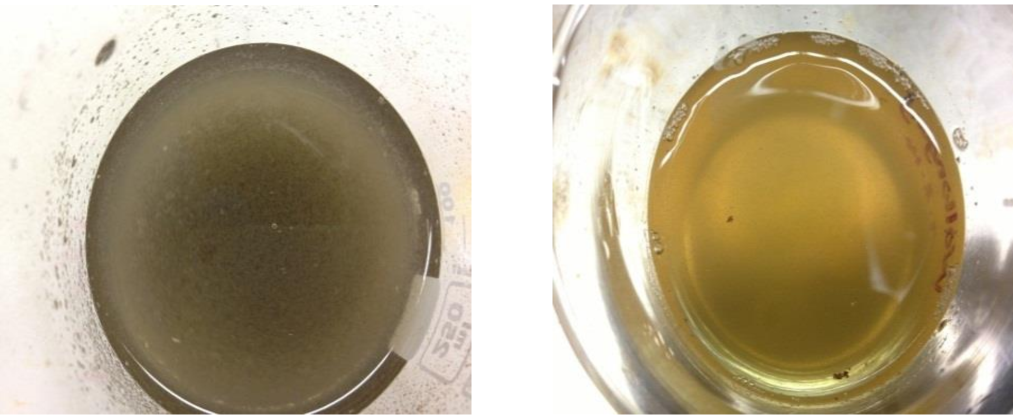


Figure 4. Full–scale centrate of (a) WAS dewatering in Quakers Hill WWTP (with suspended solids over 3500mg/L) and (b) ADS dewatering in Wollongong WWTP (with suspended solids under 100mg/L).



(a) **(b)**

Figure 5. Effect of centrifugal intensity on cake solids content of ADS and WAS conditioned at full–scale polymer dosages.

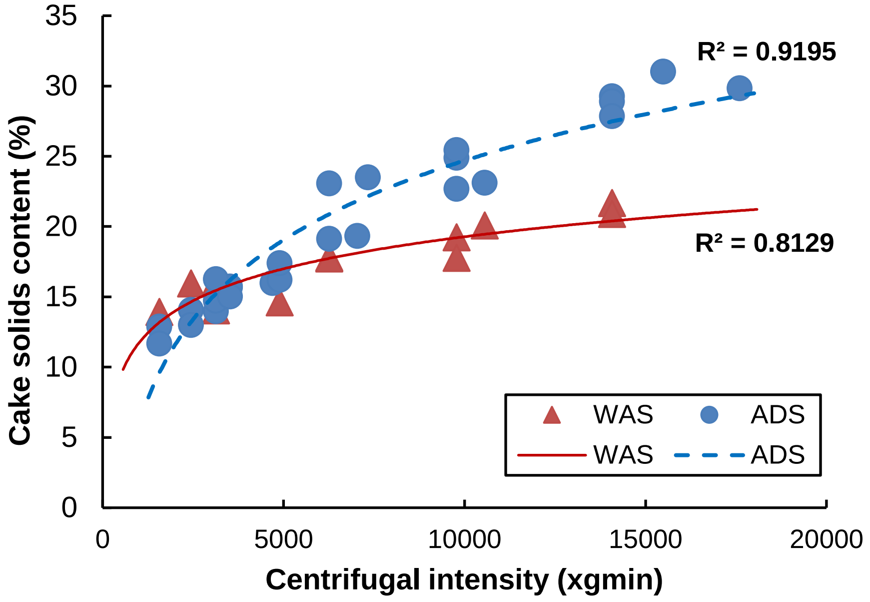


Figure 6. Higgins MCT test of ADS conditioned at full–scale PD (12 kg/DT) and OPD$_{CST}$ (6 kg/DT). [6

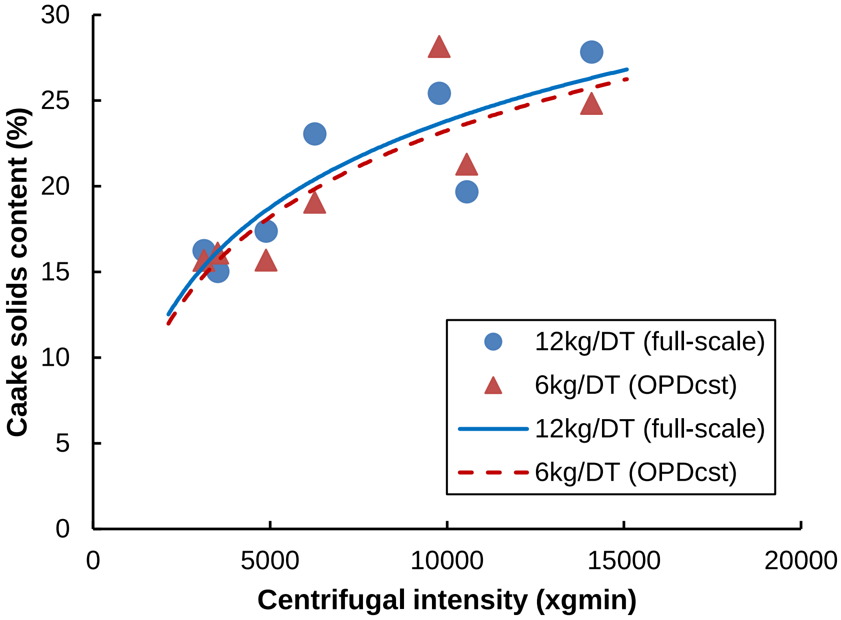
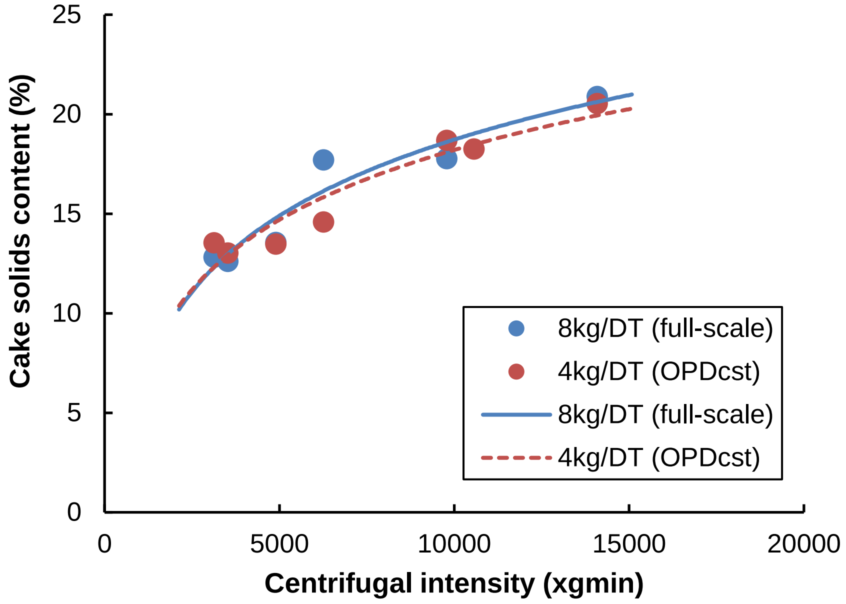


Figure 7. Higgins MCT test of WAS conditioned at full–scale PD (8 kg/DT) and OPD_{CST} (4 kg/DT).



Appendix

Figure A1. Relationships between OPD_{CST} and characteristics of all three sludge types together (total 15 samples) including: (a) Soluble protein–soluble polysaccharides ratio; (b) Zeta potential; (c) Total solids content; and (d) Volatile solids content.

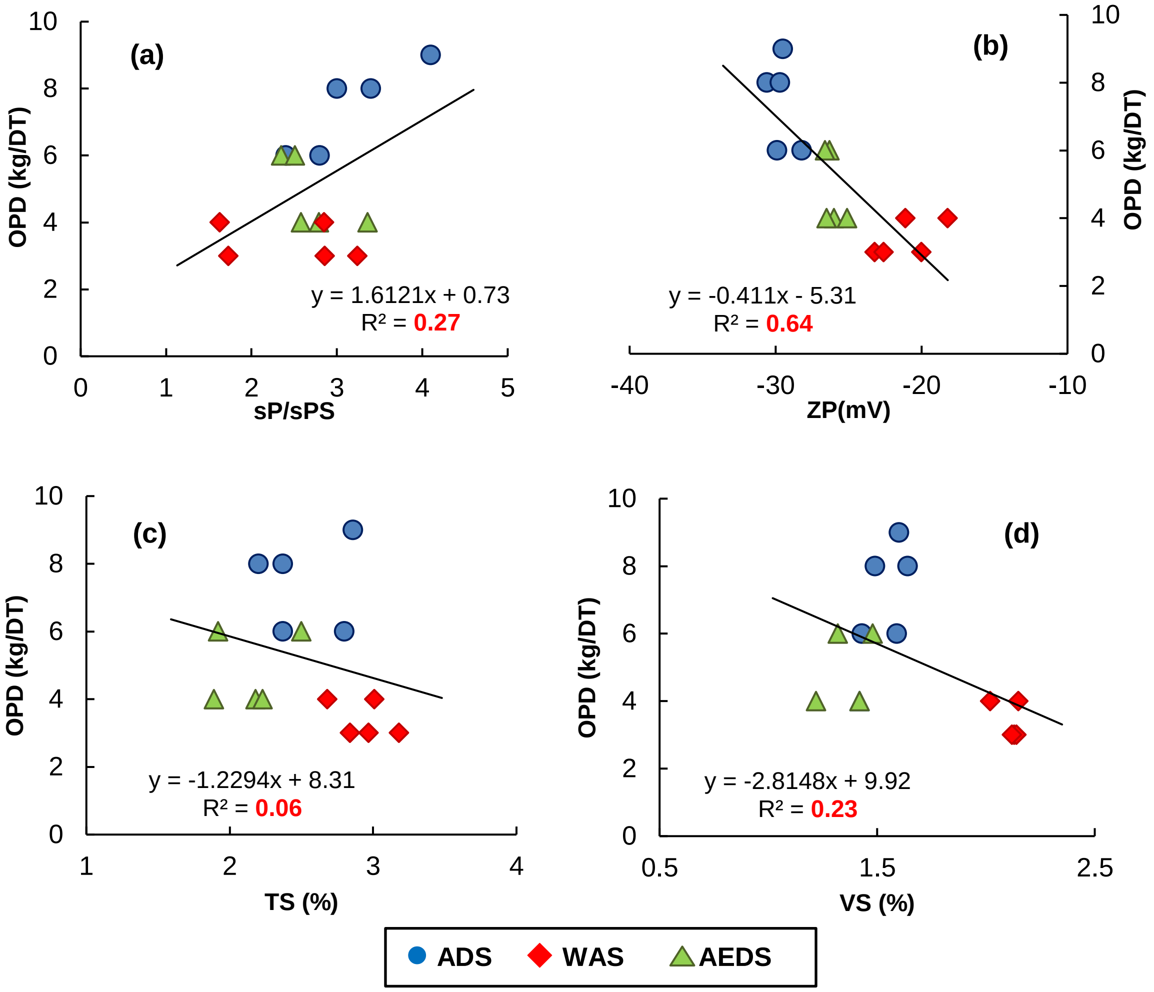
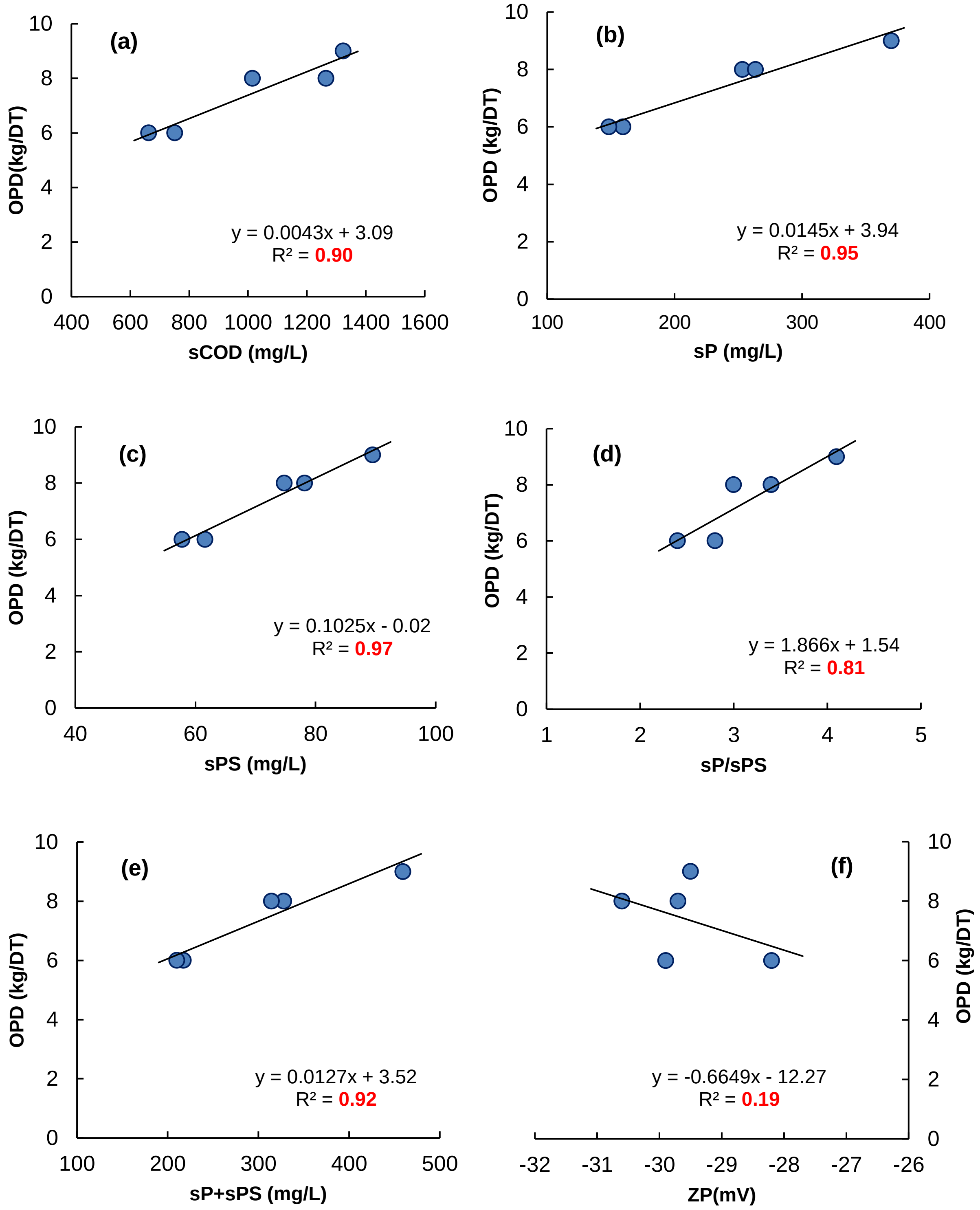


Figure A2. Relationships between $\mathrm{OPD}_{\mathrm{CST}}$ and characteristics of ADS including: (a) Soluble COD; (b) Soluble protein; (c) Soluble polysaccharides; (d) Soluble protein–soluble polysaccharides ratio; (e) Total soluble protein and soluble polysaccharides; (f) Zeta potential; (g) Total solids content; and (h) Volatile solids content.



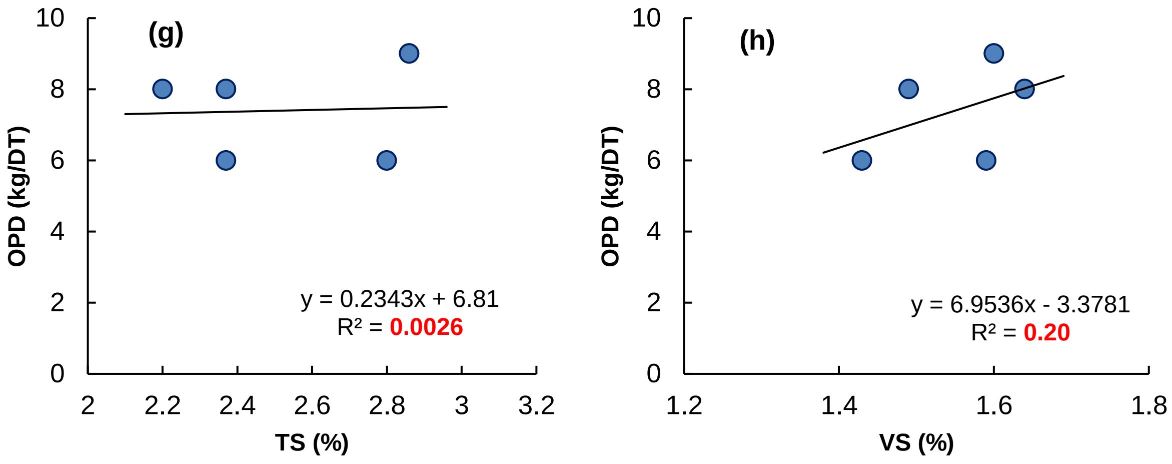
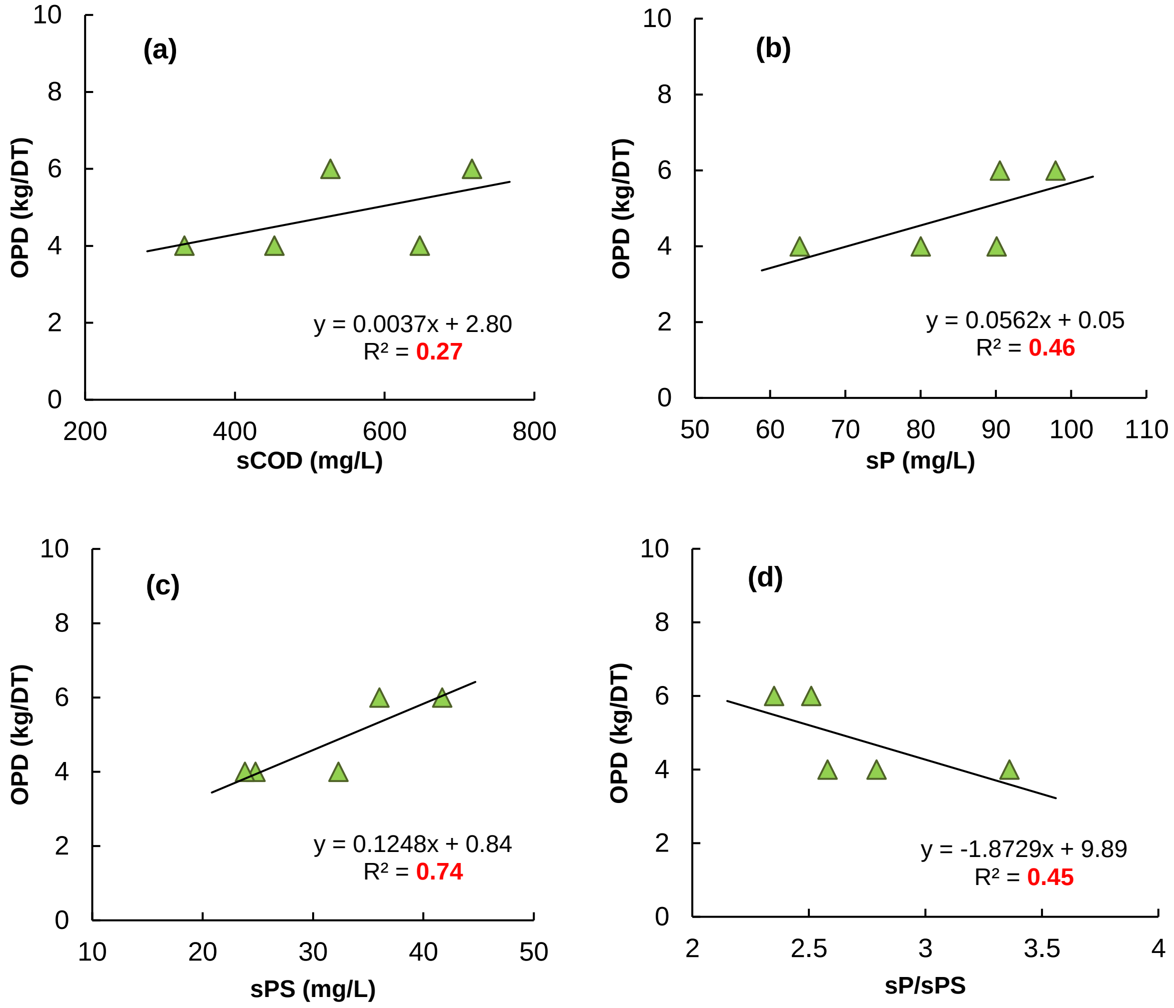

(g)
OPD (kg/DT)
10
8
6
4
2
0
2
2.2
2.4
2.6
2.8
3
3.2
TS (%)
y = 0.2343x + 6.81
R² = 0.0026
(h)
OPD (kg/DT)
10
8
6
4
2
0
1.2
1.4
1.6
1.8
VS (%)
y = 6.9536x - 3.3781
R² = 0.20

Figure A3. Relationships between OPD_{CST} and characteristics of AEDS including: (a) Soluble COD; (b) Soluble protein; (c) Soluble polysaccharides; (d) Soluble protein–soluble polysaccharides ratio; (e) Total soluble protein and soluble polysaccharides; (f) Zeta potential; (g) Total solids content; and (h) Volatile solids content.



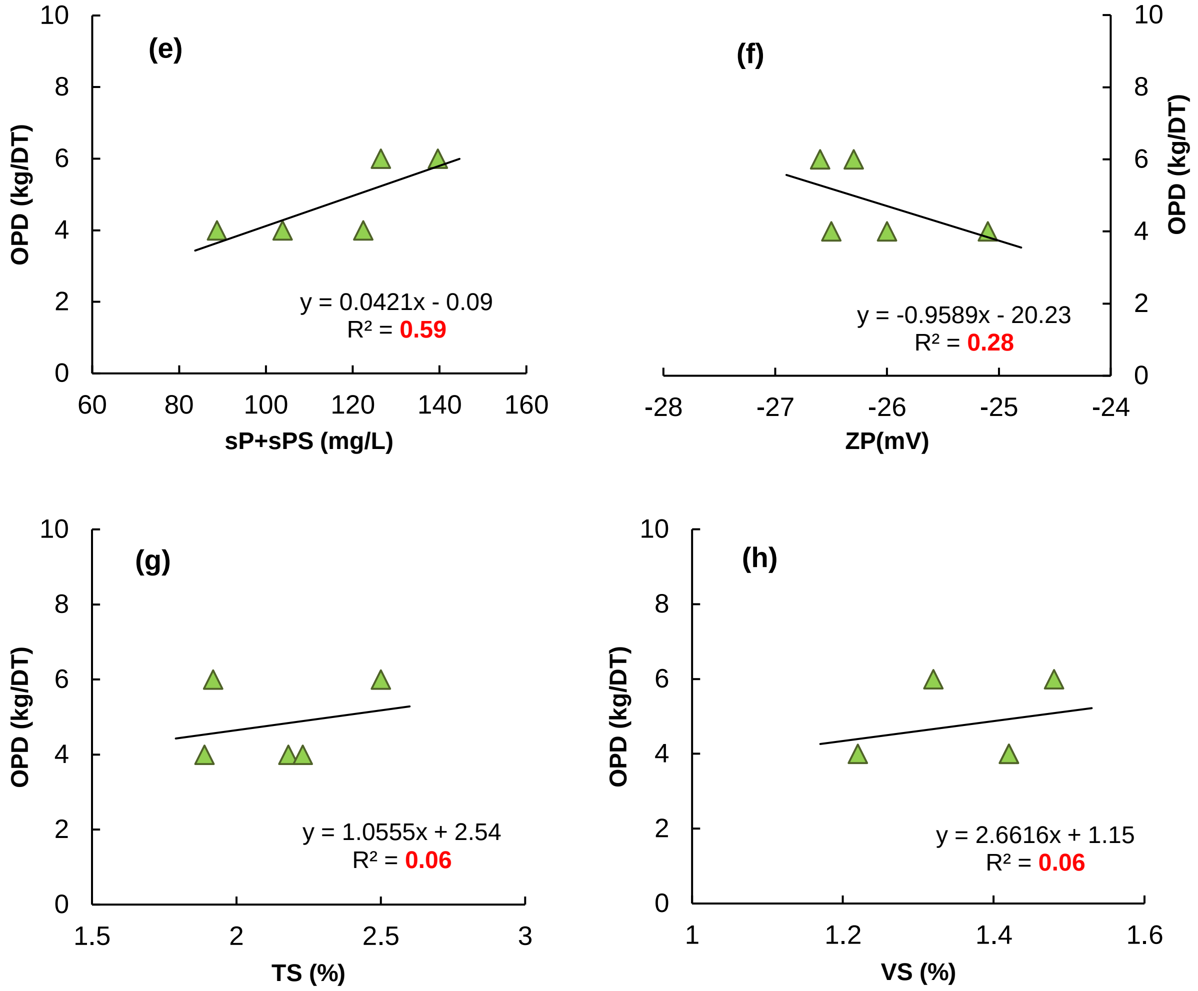
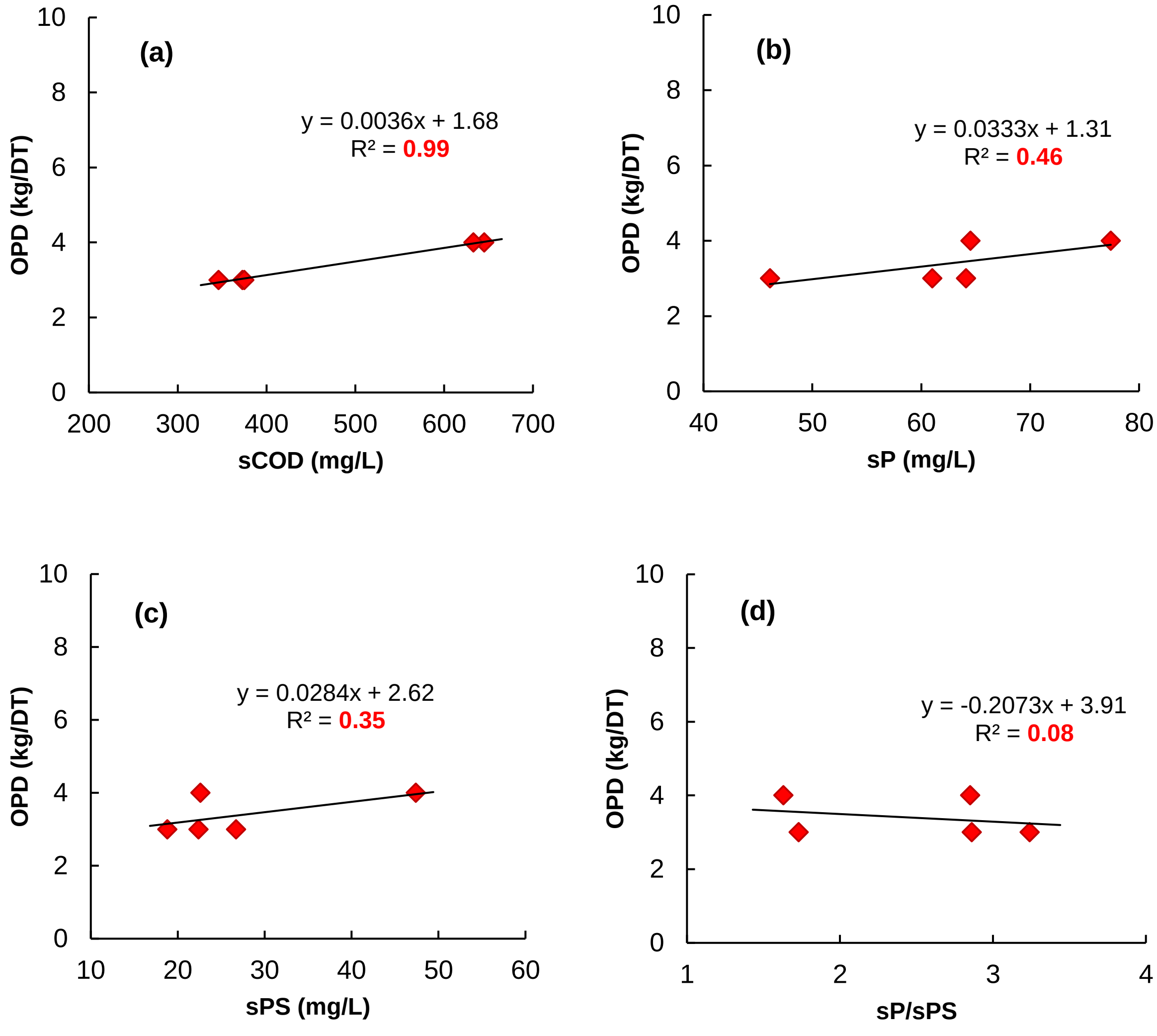
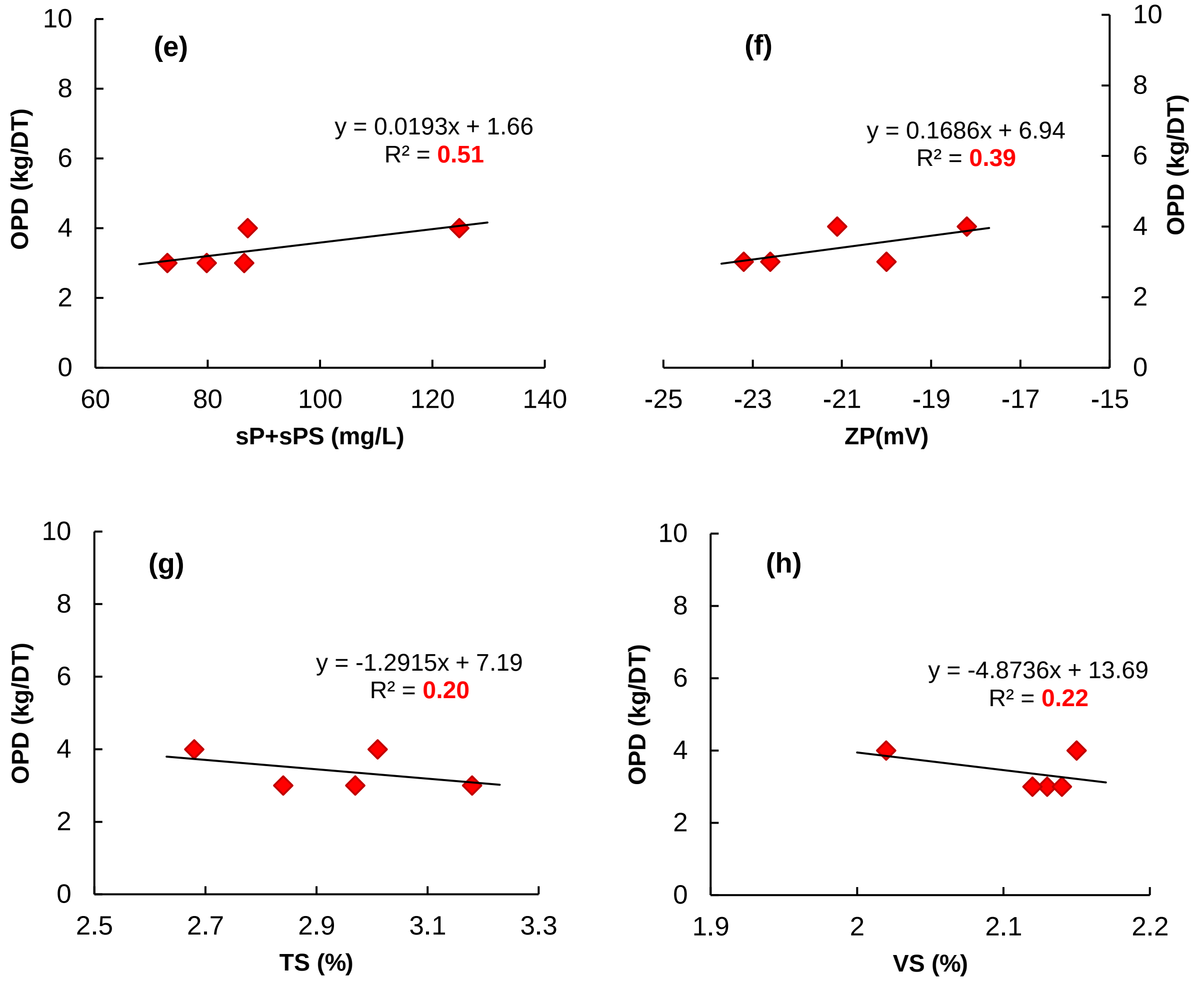

(e)
y = 0.0421x - 0.09
R² = 0.59
OPD (kg/DT)
sP+sPS (mg/L)
0
2
4
6
8
10
60
80
100
120
140
160
(f)
y = -0.9589x - 20.23
R² = 0.28
OPD (kg/DT)
ZP(mV)
-28
-27
-26
-25
-24
0
2
4
6
8
10
(g)
y = 1.0555x + 2.54
R² = 0.06
OPD (kg/DT)
TS (%)
1.5
2
2.5
3
0
2
4
6
8
10
(h)
y = 2.6616x + 1.15
R² = 0.06
OPD (kg/DT)
VS (%)
1
1.2
1.4
1.6
0
2
4
6
8
10

Figure A4. Relationships between OPD_{CST} and characteristics of WAS including: (a) Soluble COD; (b) Soluble protein; (c) Soluble polysaccharides; (d) Soluble protein–soluble polysaccharides ratio; (e) Total soluble protein and soluble polysaccharides; (f) Zeta potential; (g) Total solids content; and (h) Volatile solids content.




(e)
y = 0.0193x + 1.66
R² = 0.51
OPD (kg/DT)
0
2
4
6
8
10
60
80
100
120
140
sP+sPS (mg/L)
(f)
y = 0.1686x + 6.94
R² = 0.39
OPD (kg/DT)
0
2
4
6
8
10
-25
-23
-21
-19
-17
-15
ZP(mV)
(g)
y = -1.2915x + 7.19
R² = 0.20
OPD (kg/DT)
0
2
4
6
8
10
2.5
2.7
2.9
3.1
3.3
TS (%)
(h)
y = -4.8736x + 13.69
R² = 0.22
OPD (kg/DT)
0
2
4
6
8
10
1.9
2
2.1
2.2
VS (%)