ARC Training Centre for the Transformation of Australia's Biosolids Resource

Project 1A Novel biosolids processing routes for next generation, high quality products

Impact of Non-Degradable Organics Composition on Sludge Rheology and Dewaterability Performance

This report summarises was authored by Dr. Stephan Tait, The University of Queensland (UQ), summarising the thesis and journal papers from the PhD work of Dr. Seyedali Tabatabaei, PhD, RMIT.

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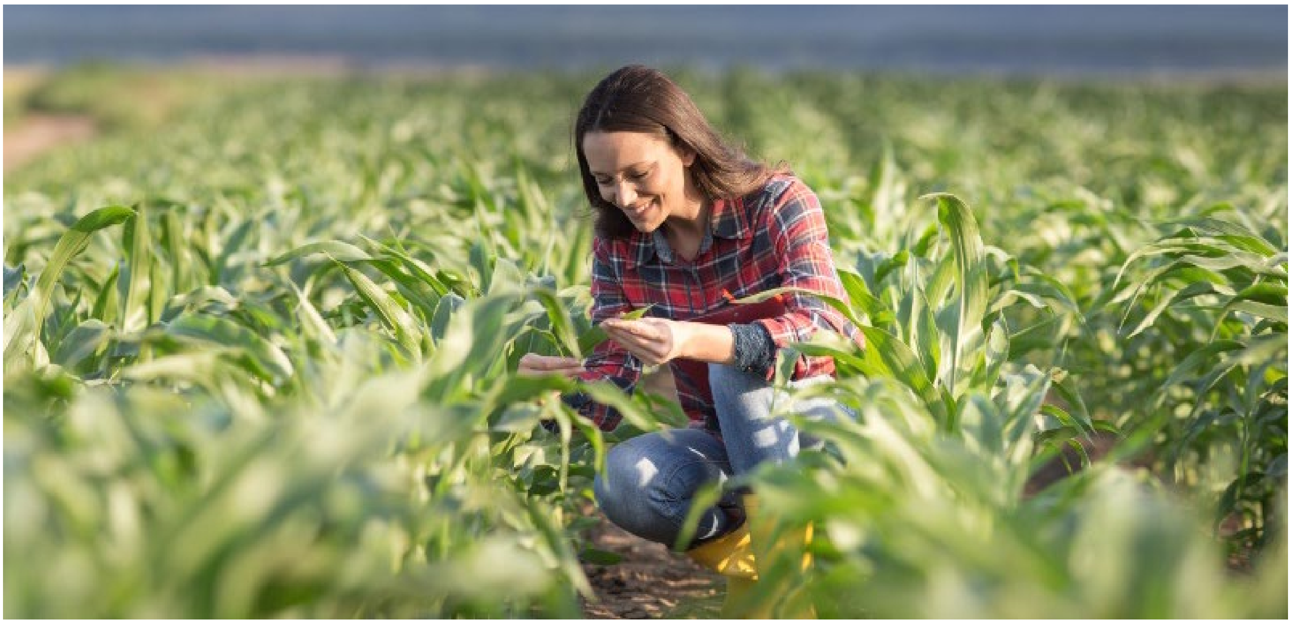

Novel biosolids processing routes for next generation, high quality products

Project 1A (Theme 1)

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Industry Partners:

Melbourne Water – Victoria (MW)

South East Water – Victoria (SEW)

Greater Western Water

South Australian Water – South Australia (SA Water)

Water Corporation – Western Australia (Water Corp)

Urban Utilities – Queensland (UU)

Water Research Australia (Water RA)

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United Nations Sustainability Goals Addressed

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Abbreviations

ACWEB	Australian Centre for Water and Environmental Biotechnology
AD	Anaerobic digestion
ATR-FTIR	Attenuated Total Reflectance – Fourier Transform Infrared Spectroscopy
ARDC	Australian Research Data Commons
BTT	Bucher Twist Test
COD	Chemical Oxygen Demand
EAIT	Engineering Architecture and Information Technology
EPS	Extracellular Polymeric Substances
MW	Melbourne Water
NDO	Non-Degradable Organics
PCA	Principal Component Analysis
RAC	Research Advisory Committee
RMIT	Royal Melbourne Institute of Technology
SAWater	South Australian Water
SEW	South East Water
SRT	Solids Retention Time
SW	Sydney Water
TS	Total Solids (dry matter)
UQ	The University of Queensland
UU	Urban Utilities
VS	Volatile Solids (organic dry matter)
WaterCorp	Water Corporation
Water RA	Water Research Australia

Summary

Dewatering is a critical step in wastewater sludge and biosolids management, directly influencing final sludge amounts, their handling, and transportation costs. Despite extensive operational experience, dewatering performance remains difficult to optimise, partly due to the complex and variable composition of sludge. Specifically, previous studies have shown an importance of sludge rheological properties (e.g., yield stress and viscosity) and effects of Extracellular Polymeric Substances (EPS) on dewatering but have not resolved important links between sludge organic matter composition, rheological characteristics, and dewaterability performance.

To address the above knowledge gap, the current work carried out three integrated investigations, combining full-scale sludge characterisation with laboratory scale experiments, measuring sludge composition, sludge digestion performance, rheological characteristics, and sludge dewaterability.

In the first investigation, 19 sludges were sampled from 11 full-scale plants of the partners with a wide range of sludge types and digestion configurations, rheological properties were quantified, and dewaterability was tested using two bench-scale approaches namely a centrifuge cup method and a Bucher Twist Test (BTT) system. Sludge composition was analysed through conventional metrics and advanced FTIR spectroscopy coupled with principal component analysis (PCA) for spectral fingerprinting. Results showed that a higher organic fraction (VS/TS) increased yield stress and viscosity, leading to poorer dewaterability, and with a greater effect for digested sludge than for raw waste activated sludge, indicating an importance of the higher non-degradable organics fraction in digested sludge. The concentration of EPS alone was found to be insufficient to explain compositional effects on rheological and dewatering behaviour of sludges. Instead, an FTIR–PCA analysis showed that specific chemical functional groups in the sludge matrix (e.g., amide, carboxyl, and hydroxyl groups) were mechanistically linked to yield stress, viscosity, and dewaterability. This suggested an importance of using spectral fingerprinting in addition to whole sludge analysis in future studies seeking to optimise dewaterability.

The second study assessed the role of pre-thickening flocculant polymers dosed prior to anaerobic digestion on digestion performance, in-digester rheology, and post-digestion dewaterability. Three polymer types (synthetic powder, synthetic liquid, and biopolymer) were tested. The results showed that polymer choice and applied dose were important for sludge flow properties (i.e., in-digester mixing), digestion performance, and post-digestion dewaterability.

Specifically, optimal flocculant dosing reduced yield stress by 20–40% (i.e. would improve in-digester mixing), increased methane yield by 15–25%, and improved post-digestion dewaterability. In contrast, overdosing, particularly of biopolymers, inhibited VS destruction due to excessive biomass aggregation, and did not improve in-digester rheology nor final dewatering. Pre-thickening polymers degraded during digestion to variable extents but did retain some residual functionality (8–25%), reducing further flocculant requirements for final dewatering. The results highlighted the importance of improved pre-thickening polymer dosing strategies not only to minimise chemical use/cost, but also to prevent adverse impacts on digestion and post-digestion dewatering.

The third investigation used viscosity modifiers with unique chemical characteristics to study the distinct effects of carrier fluid viscosity and particle-induced viscosity on sludge dewatering performance. Xanthan gum (XG), a soluble carrier-fluid viscosity modifier, markedly increased yield stress and consistency index, which resulted in up to 94% reduction in water removal efficiency (WRE). In contrast, PMMA did not alter rheology, but improved dewaterability, likely due its hydrophobic nature. Fumed silica, a hydrophilic additive, showed a moderate effect with sludges tested at 2% total solids (TS), but an almost comparable effect to XG when sludges were tested at 4% TS. This indicated that carrier-fluid viscosity was most important for dilute sludges, but particle-induced viscosity may become equally important at higher sludge solids concentrations. The chemical characteristics of the additives resemble native sludge components, which also have variable chemical characteristics; in this way matrix composition is expected to uniquely influence rheology and dewaterability performance for sludges.

Overall, the results showed that incremental reductions in organic fraction can yield substantial gains in reducing biosolids export volumes, while strategic polymer dosing for pre-digestion sludge thickening can also deliver combined benefits for digestion, and downstream dewatering. The work also demonstrated that integrating compositional analysis via spectral fingerprinting, rheology, and bench-scale dewatering tests can provide a robust, mechanistic basis for optimising sludge treatment and biosolids management into the future.

1 Background and Motivation

Dewatering is one of the most important processing steps for wastewater sludge management, reducing the amount of sludge water to handle and transport, and thereby minimising costs (Boguniewicz-Zablocka et al., 2021). However, dewatering is often difficult to optimise, partly owing to a complex composition of sludge, specifically its organic fraction making the sludge generally more difficult to dewater (An et al., 2017; Girault et al., 2015; Wei et al., 2018a; Yu et al., 2017). One important class of organic components known to strongly influence dewaterability is Extracellular Polymeric Substances (EPS) (Cao et al., 2021). EPS is generated by microbial growth in the treatment plant which form stable, gel-like structures held together by electrostatic and hydrogen bonds (Li et al., 2021).

The flow characteristics (i.e. rheological properties) of sludge also have a strong impact on dewaterability performance (Hong et al., 2018). Important characteristics include yield stress, the force required to initiate flow, and viscosity, and the internal resistance to flow (Tabatabaei et al., 2025a). In general, elevated yield stress and viscosity are associated with decreased sludge dewaterability performance, with a high yield stress suggesting a more rigid sludge structure that tends to retain water and a viscous sludge hindering movement of water during dewatering (Tabatabaei et al., 2025a).

Sludge flow behaviour and hence dewatering is expected to be influenced by its organic particulate fraction suspended in a water-based carrier fluid (Tabatabaei et al., 2025a). For example, an elevated viscosity in the carrier fluid can increase flow resistance and inhibit drainage, while inter-particle networks can contribute to structural rigidity and affect yield stress (Singh et al., 2020; Weheliye et al., 2020). However, the relative contributions of carrier-fluid vs. inter-particle networks may be independent, synergistic, or antagonistic, and have not been separately resolved by past studies (Tabatabaei, 2025).

Despite previous advances in understanding rheology, dewaterability, and sludge composition (organic matter/EPS, particulate vs. liquid carrier fluid), available knowledge is lacking on how these important aspects link together to influence dewaterability performance and affect the ability to identify and select optimal sludge dewatering strategies.

This research aims to address the above identified knowledge gap, performing the following three integrated research investigations:

1. a study of the influence of organic matter and EPS composition on rheological properties and dewaterability of diverse sludge types sampled from full-scale plants of our project partners across Australia and using advanced data processing and statistical modelling methods to link composition, rheology and dewaterability.

This work was described by Tabatabaei et al. (2025a)

2. a study of the effects of coagulants+polymer flocculants dosed prior to anaerobic digestion for pre-thickening of sludge (dose point 2, Figure 1), both on (a) digestion performance, (b) in-digester rheological properties, and (c) final post-digestion dewatering performance.

   This work was described by (Tabatabaei et al., 2025b).

3. a fundamental investigation on the role of the carrier-fluid viscosity and particle-induced viscosity on rheological characteristics and dewaterability performance of sludges. This study used model viscosity modifier compounds.

   This work was described by (Tabatabaei et al., 2026)

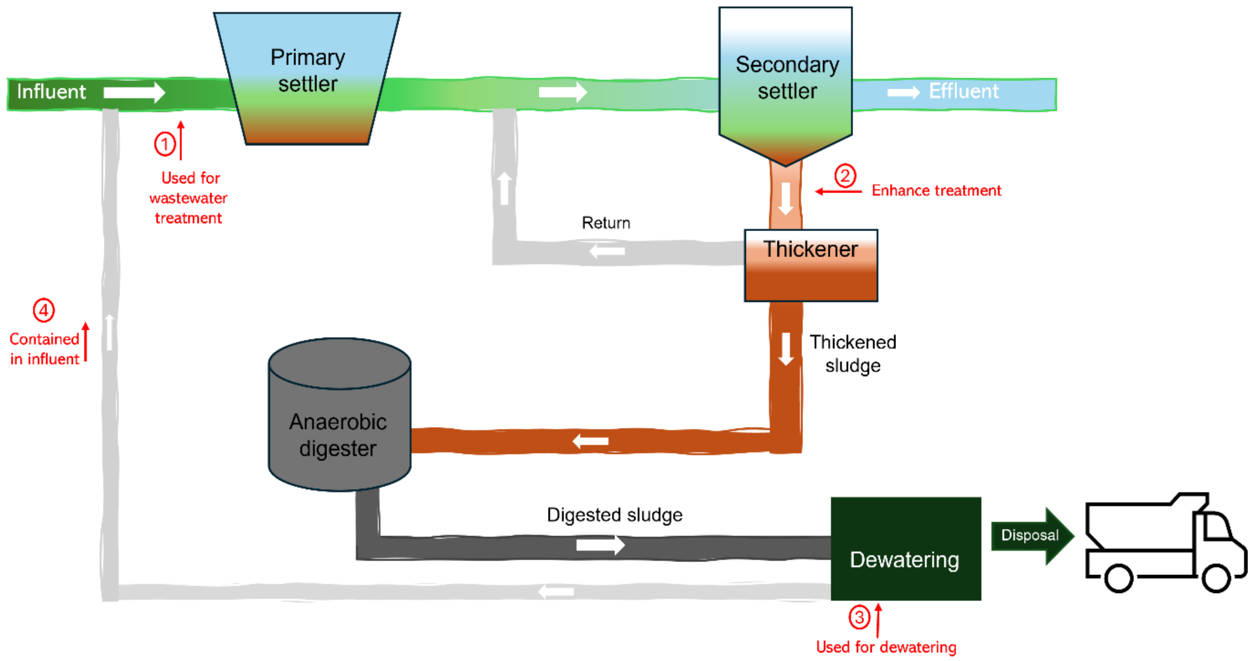


Figure 1: Application of flocculant polymers at various stages of a wastewater treatment process. Excess polymers used during pre-thickening prior to digestion (dose point 2) may persist during digestion depending on its biodegradability and so may influence final dewatering. Source: Tabatabaei (2025)

2 Methods

The detailed approaches and methods used in each of the three investigations are described in the published journal papers (Tabatabaei et al., 2026; Tabatabaei et al., 2025a; Tabatabaei et al., 2025b). This section provides a summary overview.

2.1 Full-scale sludge characterisation study (Tabatabaei et al., 2025a)

Different sludges were collected from full-scale treatment plants of the project partners as summarised in Table 1. The plants were selected for sampling based on their range of different anaerobic digestion conditions, with Melbourne Water- ETP, Urban Utilities (UU) Luggage Point, Great Western Water-Melton, Water Corporation Woodman Point, and Sydney Water (SW) plants all using mesophilic digestion at 35-40°C, Southeast Water Mt. Martha using thermophilic digestion at 55-65°C, and UU Oxley Creek and SW St Marys pre-treating sludge by thermal hydrolysis prior to digestion. The feed sludges at these plants were Waste Activated Sludge (WAS), primary sludge (PS), or mixed sludge. All samples were stored in a refrigerator at 4 °C until testing typically within 2 weeks.

Table 1: Characteristics of anaerobically digested sludge (DS) and waste activated sludge (WAS) samples sampled at full-scale from the project partner sites (Tabatabaei et al., 2025a).

Sample	State, Utility, Site	Feed, digestion method	TS %	Thickened sample VS/TS% (TS = 4.5±0.1%)
DS from ETP	Victoria- Melbourne Water- ETP	PS+WAS, mesophilic	2.50±0.10 %	72.0±0.5 %
DS from Mt Martha	Victoria- Southeast Water- Mt. Martha	PS+WAS, thermophilic	1.40±0.02 %	73.1±0.2 %
DS from Melton	Victoria- Great Western Water- Melton	PS+WAS, mesophilic	2.21±0.05 %	76.0±1.0 %
DS from Malabar	NSW- Sydney Water- Malabar	PS, mesophilic	2.30±0.02 %	59.0±1.0 %
DS from Wollongong	NSW- Sydney Water- Wollongong	PS+WAS, mesophilic	2.63±0.02 %	63.0±0.5 %
DS from North-head	NSW- Sydney Water- North-head	PS, mesophilic	3.50±0.05 %	69.5±0.2 %
DS from Bondi	NSW- Sydney Water- Bondi	PS, mesophilic	2.06±0.02 %	75.7±0.1 %
DS from St. Marys	NSW- Sydney Water- St. Marys	PS+WAS, THP	2.94±0.01 %	53.3±0.2 %
DS from Luggage-point	Queensland- Urban Utilities- Luggage-point	PS+WAS, mesophilic	2.81±0.01 %	73.4±0.1 %
DS from Oxley Creek	Queensland- Urban Utilities- Oxley Creek	PS+WAS, THP	4.75±0.1 %	66±0.1 %
DS from Woodman Point	Western Australia- Water Corporation- WP	PS+WAS, mesophilic	3.07±0.02 %	79.6±0.2 %
WAS from ETP	Victoria- Melbourne Water- ETP	-	3.30±0.05 %	76.5±0.1 %
WAS from Mt Martha	Victoria- Southeast Water- Mt. Martha	-	3.75±0.05 %	85.5±0.1 %
WAS from Melton	Victoria- Great Western Water- Melton	-	0.48±0.01 %	84.5±0.5 %
WAS from Wollongong	NSW- Sydney Water- Wollongong	-	4.5±0.1%)	71.9±0.1 %
WAS from St. Marys	NSW- Sydney Water- St. Marys	-	1.56±0.01 %	64.7±0.2 %
WAS from Luggage-point	Queensland- Urban Utilities- Luggage-point	-	4.5±0.1%)	81.3±0.3 %
WAS from Oxley Creek	Queensland- Urban Utilities- Oxley Creek	-	0.52±0.005 %	77.95±0.05 %
WAS from Woodman Point	Western Australia- Water Corporation- WP	-	3.07±0.05 %	85.8±0.2 %

To reliably compare rheological and dewaterability characteristics of the different sludges, the samples were pre-thickened using centrifugation up to a standardized Total Solids (TS) concentration of 4.5% for testing. For tests on digested sludge, samples were pre-flocculated with a cationic emulsion polymer flocculant for the pre-thickening. For WAS samples, iron chloride was used for coagulation followed by polymer flocculant for flocculation pre-thickening. The sludges were also separately tested at their native TS. The sludge samples were analysed for their rheological characteristics (Section 2.4) and dewaterability performance (Section 2.5).

EPS was extracted from the sludge samples for compositional analysis using a chemical method (formaldehyde + sodium hydroxide). This used a formaldehyde and NaOH extraction from the pellet collected from centrifuging of the sludge sample. The supernatant from this centrifugation was separately analysed as a soluble/colloidal fraction. EPS extraction was conducted at native TS of each sample, with the test results normalized back to the volatile solids (VS) amount originally present in each tested sample. Extracted EPS and soluble/colloidal fraction were analysed for chemical oxygen demand (COD), protein, and polysaccharides (Section 2.6).

All sludge samples, as well as the extracted EPS and soluble/colloidal fractions were also analysed by Fourier Transform Infrared Spectroscopy (FTIR) (Section 2.6), and to build statistical models of composition using Principal Component Analysis (PCA) (Section 2.7).

2.2 Study of the Effect of Pre-thickening Flocculant on Anaerobic Digestion and Post-Digestion Dewaterability (Tabatabaei et al., 2025b)

WAS samples used as substrate and anaerobically digested sludge used as a microbial inoculum were collected in May and June (Winter) from Melbourne Water Eastern Treatment Plant. The WAS was stored at 4°C prior to the tests, and inoculum was stored under anaerobic conditions at 37°C for several days to degas prior to the tests. These samples were analysed for TS, VS, total and soluble chemical oxygen demand (TCOD and SCOD, respectively), and pH (Section 2.6).

Three polymer flocculant types were tested as pre-thickening additives, namely; (1) a synthetic powder flocculant - SNF FLOPAM^{TM} FO4490 (POW), (2) a synthetic emulsion flocculant - SNF EM440HIB (EMU), and a mix of (3) Tanfloc MT (BIO) and POW used in a 1:0.2 mass ratio (designated BIOPOW throughout). The co-dosing of BIO and POW in the BIOPOW mix balanced chemical costs with flocculation performance, avoiding the excessive use of BIO. All flocculants were prepared in water stock solution for use in the tests.

The tests were set up by:

a) adding inoculum and WAS substrate (at a ratio of 2 on a VS basis), and polymer flocculant (as relevant) to 500 mL test bottles with a 250 mL working volume;

b) flushing each bottle with high-purity nitrogen gas to establish anaerobic conditions;

c) promptly sealing the bottle with a rubber septa to capture and measure biogas produced; and

d) placing the bottles in a temperature-controlled incubator (Figure 2).

Figure 2: Apparatus of the anaerobic digestion experiments, including (top) the test bottles in the incubator, the closed incubator, and (bottom) the water displacement manometer and GC used to measure biogas volume and composition. Source: Tabatabaei (2025).

Each of the three polymer flocculants were tested as additives at four dosages (nil or no-polymer as a control; low dose; optimal dose; and high dose). The dosages were determined using scoping experiments.

The tests were performed in replicate with six bottles for each dosage condition. Two bottles each were sacrificed at specified time intervals (days 2, 7, and 15 (end of experiment)) to measure sludge rheological properties (Section 2.4), and composition (SCOD, TS, and VS, Section 2.6) in duplicate. Separate test bottles were run as parallel blanks and controls containing only inoculum and polymer at each dose (i.e. no WAS), to assess polymer degradability.

Biogas volume was measured periodically using a water displacement manometer, and biogas composition was measured using an Agilent 8860 Gas Chromatography system equipped with a thermal conductivity detector (GC-TCD) (Figure 2).

To determine methane contributions from all components added to each test bottle (i.e. inoculum, WAS substrate, and polymer, as relevant), a linear model (Equation 1):

$$CH_{4,cumulative} = VS_{DS} \cdot B_{15,\ DS} + VS_{WAS} \cdot B_{15,\ WAS} + VS_{poly} \cdot B_{15,\ poly} \quad (1)$$

to fit the cumulative methane produced up to the end of the experiment (day 15) ($CH_{4,cumulative}$) was used; VS_{DS}, VS_{WAS}, and VS_{poly} are the respective VS masses of inoculum, WAS, and polymer initially added to each test, and $B_{15,\ DS}$, $B_{15,WAS}$, and $B_{15,poly}$ are the respective methane contributions of inoculum, WAS, and polymer, determined as fitted variables by linear regression analysis of the test data.

Dewaterability of sludge samples prior to and after digestion was measured using the centrifuge cup method (Section 2.5). For dewaterability testing, samples were pre-flocculated with EMU at the optimal dosage for each sample, and the amount of flocculant required being recorded for analysis.

2.3 Fundamental study of the role of carrier-fluid viscosity and particle-induced viscosity in determining sludge dewaterability performance (Tabatabaei et al., 2026)

As before (Section 2.2), WAS and DS were collected from MW ETP, in this case during December to January (Summer). Both WAS and DS were stored at $4^{O}C$ prior to use in these experiments. The sludge samples were characterised for TS, VS, soluble and total COD (SCOD and TCOD) and pH (Table 2). The collected sludges were then diluted with supernatant to achieve 2.0% TS or centrifuge pre-thickened up to 4.0% TS for testing, giving two different TS concentrations for testing.

Table 2: Characteristics of native waste activated sludge (WAS) and anaerobically digested sludge (DS) used in the polymer degradation experiments (triplicate analysis with means and standard errors reported)

Variable	WAS	DS
TS (wt.%)	2.87±0.05%	2.36±0.01%
VS/TS (%)	79.0±0.8%	73.6±0.2%
SCOD (mg/L)	470±20	590±20
TCOD (mg/L)	12,200±500	7,000±400
PH	6.2±0.1	7.2±0.1

Viscosity modifiers were added to the tests, which were xanthan gum (XG), a soluble ingredient, added to modify (increase) carrier fluid viscosity, and polymethyl methacrylate (PMMA) and fumed silica used as insoluble particulate viscosity modifiers. The fumed silica was expected to be hydrophilic, whilst PMMA was hydrophobic and had a relatively lower specific surface area than silica. PMMA also served as a model additive resembling native microplastics which may be found in sludge. After adding the additives, the sludge samples were agitated at 300 rpm for 1 hour to ensure thorough mixing before analysis and were then allowed to rest for at least 1 hour prior to testing.

The samples (with additives at a range of dosages) were analysed for rheological characteristics (Section 2.4) and dewaterability using the centrifuge cup method (Section 2.5). For this, samples were pre-flocculated with a cationic polymer, SNF FLOPAM™FO4490, with the optimal dosage being used for each sample, and with this dosage being recorded as an experimental measure for analysis.

To investigate relationships between additive type, rheological characteristics and sludge dewaterability, a multivariate analysis of variance (MANOVA) was performed to assess outcomes across all treatment groups. Interaction effects were also explored to evaluate whether different additives exerted distinct influences on sludge rheology and water release efficiency (WRE) calculated by Equation 2:

$$\text{WRE\%} = \frac{\text{Initial water content} - \text{Final water content}}{\text{Initial water content}} \times 100 \quad (2)$$

The strength and significance of relationships were evaluated based on the coefficient of determination (R^2) and p-values derived from ANOVA tables, with a 5% significance threshold. Linear modelling was also used to clarify significant relationships identified.

2.4 Rheological measurements

Rheological measurements were undertaken using a rheometer (DHR3, TA Instruments) at constant temperature and using either bob and cup geometry or a vane geometry, depending on the TS content of the samples being tested (Tabatabaei et al., 2025b). To determine the rheological parameters, a Herschel-Bulkley model (Equation 3) was fitted to the test data:

$$\tau = \tau_y + k \cdot \gamma^n \quad (3)$$

where τ is measured stress, τ_y is yield stress, k is a parameter called the consistency factor, γ is applied shear rate, and n is a parameter called the flow behaviour index. The fitted parameters were τ_y, k, and n, estimated by non-linear regression.

2.5 Dewaterability testing

Dewaterability measurements were performed by two different bench-scale test approaches (Figure 3), namely:

1. a centrifuge cup method (Wei et al., 2018b) which involves centrifuging of a sludge sample on a piece of belt filter fabric on a perforated plate, and measuring TS content of the cake that collects on the filter fabric; and
2. a Bucher Twist Test (BTT) using an apparatus provided by Suez, which involves twisting of a sludge sample in a filter sock on a mounting frame and collecting the solid cake produced in the sock and measuring its TS.

The centrifuge cup method was expected to provide a measure aligned with conventional dewatering such as a belt filter press or centrifuge, whereas the BTT allowed controlled mechanical shear and pressure to be applied reflective of full-scale dewatering operations. A comparison of measurements by the two methods provided cross-validation.

2.6 Analytical methods

TS and VS was determined using APHA method 2540B and APHA method 2540E, respectively (APHA, 2005). Protein was determined using the Bradford method and polysaccharides using the Anthrone method. COD was measured according to the HACH procedure 8000. pH was recorded with a calibrated pH meter (ThermoOrion, Model 550A).

Figure 3: Apparatus used for sludge dewaterability testing, showing (top) metal plate, filter, ring, and centrifuge cup assembly, and (bottom) the BTT apparatus, including in operation, and the solid cake collected from the device. Source: Tabatabaei (2025).

FTIR measurements were performed in the attenuated total reflectance (ATR) mode with a PerkinElmer 100 FTIR Spectrometer with a scanning range of 4000 cm^{-1} to 550 cm^{-1} with accumulations set to 32 scans with a resolution of 1 cm^{-1}. FTIR spectra were separately measured for whole sludge samples, and soluble/colloidal and extracted EPS fractions (Section 2.1). For this, samples were first pre-dried in an oven at 105 °C overnight and finely ground by hand prior to analysis.

2.7 Advanced Statistical Modelling by Principal Component Analysis (PCA)

FTIR data were analysed by Principal Component Analysis (PCA), which is a statistical approach that reduces the dimensionality of a dataset, meaning it reduces a larger dataset with several independent variables, to a smaller dataset for analysis with a smaller number of linearly independent predictor variables, commonly referred to as Scores.

PCA also gives a measure of how the Scores are influenced by the original predictor variables (so-called loadings), which in this case were the FTIR wavelengths at which measurements had been performed. The loadings can be used to identify chemical functional groups in the samples that were analysed.

3 Key Findings and Interpretation

3.1 Full-scale sludge characterisation study (Tabatabaei et al., 2025a)

This study assessed the effects of EPS and sludge composition on rheology and dewaterability, by analysing various sludges collected from diverse full-scale WWTPs of the project partners.

3.1.1 Sludge composition

EPS and colloidal/soluble fractions were found to vary between the various sludges (Figure 4). WAS samples generally had a higher EPS content than digested sludge samples, especially those collected from plants with a thermal hydrolysis process (THP). This may indicate that supernatant from the centrifuge return (with soluble/colloidal components) may incorporate into the WAS in these plants. The EPS and soluble/colloidal fractions for digestate samples for the primary-sludge only plants and the other non-THP plants were not significantly different.

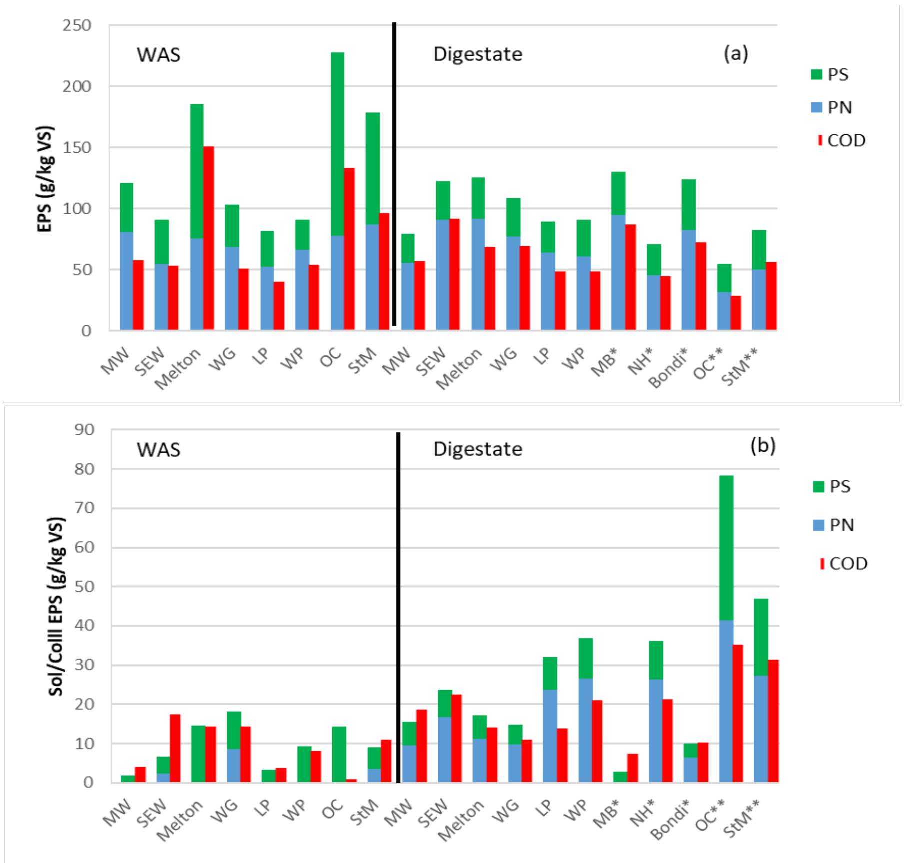


*Figure 4: Measured composition of (a) extracted EPS and (b) Soluble/Colloidal fraction, for waste activated sludge (WAS) and anaerobically digested sludge (Digestate) sampled from full-scale project partner sites. These sites included sites with * primary sludge only fed digestion and ** thermal hydrolysis processes fed with WAS. Sample codes were Melbourne Water – ETP (MW), Mt. Martha (SEW), Melton, Wollongong (WG), Luggage Point (LP), Woodman Point (WP), Malabar (MB), North-head (NH), Bondi, Oxley Creek (OC), St. Marys (StM). Sourced from (Tabatabaei et al., 2025a)*

The FTIR-ATR results showed that the sludge samples were mainly differentiated on a Scores plot in principal component 1 (PC1), with extracted EPS being substantially differentiated from other samples (Figure 5). The inset ATR spectra in Figure 5 showed major absorption peaks at 1600 cm^{-1} which could be related with the stretching vibrations of C=O and C-N of amide I of proteins (Bhatti and Hamid, 2014), and also at 1400 cm^{-1}, 800 cm^{-1}, and 600 cm^{-1} (Lin et al., 2019). Overall, the results indicated that the chemical extraction of EPS resulted in a much more complex (and variable) FTIR signature.

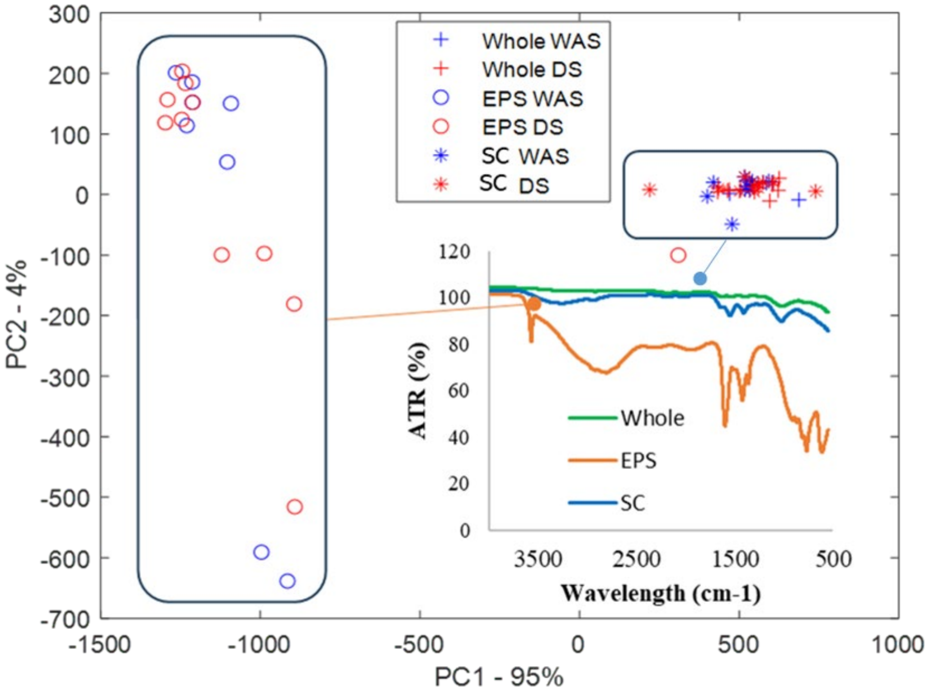


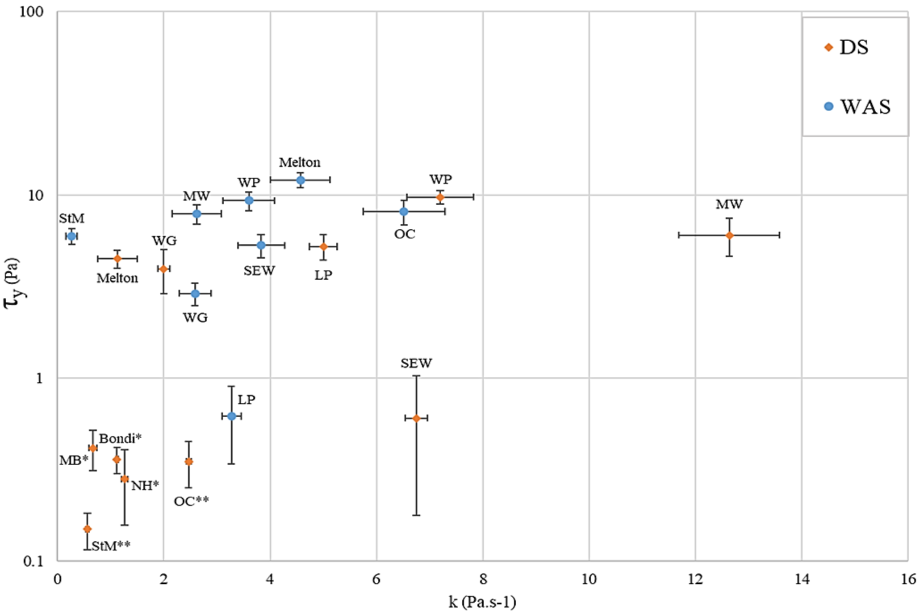
Figure 5: Principal Component Analysis (PCA) results of the FTIR spectra collected for waste activated sludge (WAS) and anaerobically digested sludge (DS) samples collected from full-scale partner sites, and analyses performed on whole sludge samples, extracted EPS, and a colloidal/soluble fraction (CS). An inset also demonstrates the observed differentiation between FTIR-ATR spectra for these distinct samples. Sourced from (Tabatabaei et al., 2025a)

3.1.2 Sludge rheological characteristics

Figure 6 presents rheological characteristics for the various full-scale sludges, which shows these mainly varied between plants rather than between WAS and anaerobic digested sludge (DS). The results highlighted two groups;

1. DS from plants fed with primary sludge and thermal hydrolysate, with low τ_y and k, resulting in a low predicted in-digester viscosity; and
2. all other materials.

This was likely related to the organic fraction, with DS from the primary sludge and hydrolysate fed plants having very low VS/TS ratios.



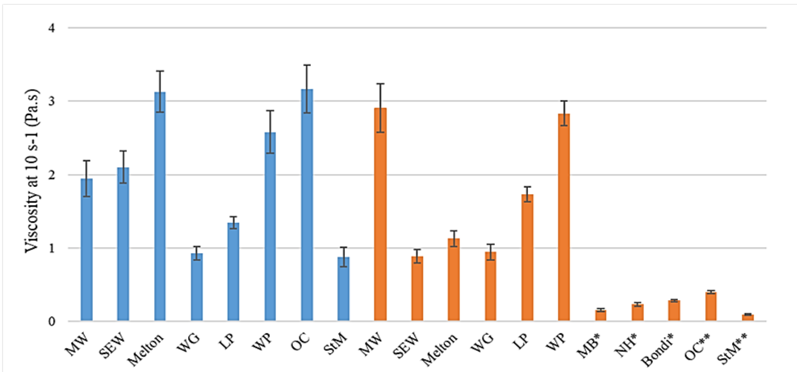


Figure 6: Herschel Bulkley parameters (Equation 2) determined for waste activated sludge (WAS) and anaerobically digested sludge (DS) from full-scale project partner sites, including (top) yield stress (τy) and consistency index (k), and (bottom) predicted viscosity at a typical in-digester shear rate of 10 s^{-1}. Error bars represent 95% confidence intervals on fitted parameter values. Sample codes were Melbourne Water – ETP (MW), Mt. Martha (SEW), Melton, Wollongong (WG), Luggage Point (LP), Woodman Point (WP), Malabar (MB), North-head (NH), Bondi, Oxley Creek (OC), St. Marys (StM). Sourced from (Tabatabaei et al., 2025a)

Generally, a lower organic fraction resulted in lower values for τ_y and *k*. However, while THP is expected to generally decrease sludge τ_y and viscosity, these effects could not be separated in the current work from the simple effect of low organic fraction (VS/TS ratio). North-Head and Bondi had higher organic fractions (VS/TS ratios) compared to other plants in their group, indicating that sludge feed type is separately important.

3.1.3 Dewaterability

Dewaterability (i.e., dewatered cake TS) was measured by two methods (Section 2.5), and the results from the two methods were found to be largely comparable (Table 3). BTT generally achieved a higher dewaterability (by approximately 40% relative, or between 2% and 7% absolute), but the comparable results in indicated that both methods were valid and complementary.

Dewaterability was very strongly correlated with organic fraction (VS/TS ratio), with a lower VS/TS ratio generally achieving better dewaterability (a higher cake TS). This is known for WAS (Wang et al., 2020) and digested sludges (Kopp and Dichtl, 2001). The magnitude of this effect of VS/TS for DS was about double that for WAS, indicating that organic fraction has a stronger impact in DS, here attributed a higher proportion of non-degradable organics (NDO) in the DS (Tabatabaei et al., 2025a). This highlighted the importance of NDO on dewaterability performance.

Table 3: Dewaterability results, showing solid concentrations of the dewatered cake from the two test methods. Note, the VS/TS ratio data are the same as that in Table 2.

Sample		VS/TS%	Dewatered cake TS% Centrifuge-cup	Dewatered cake TS% BTT
Digested sludge samples (4.5%)	DS_ETP	72.0±0.5	13.0±0.1 %	14.0±0.1 %
	DS_Mt Martha	73.1±0.2	15.3±0.1 %	22.0±1.0 %
	DS_Melton	76.0±0.1	16.5±0.5 %	23.8±0.1 %
	DS_Malabar	59.0±1.0	23.0±0.5 %	30.5±0.5 %
	DS_Wollongong	63.0±0.5	16.6±0.4 %	22.4±1.0 %
	DS_North-Head	69.5±0.2	21.7±0.2 %	28.1± 0.3 %
	DS_Bondi	75.7±0.1	20.4±0.4 %	27.7±0.5 %
	DS_St. Marys	53.3±0.2	25.6±0.3 %	32.6±0.5 %
	DS_Luggage-point	73.4±0.1	15.5±0.2 %	19.7±0.3 %
	DS_Oxley Creek	66.0±0.1	15.6±0.3 %	26.5±0.5 %
	DS_Woodman Point	79.6±0.2	12.8±0.1 %	14.5±0.3 %
Waste activated sludge samples (4.5%)	WAS_ETP	76.5±0.1	14.1±0.2 %	17.8±1 %
	WAS_Mt Martha	85.5±0.1	12.5±0.5 %	16.5±0.7 %
	WAS_Melton	84.5±0.5	12±0.5 %	14.5±0.4 %
	WAS_Wollongong	71.9±0.1	15.3±0.1 %	19.0±1 %
	WAS_St. Marys	64.7±0.2	16.0±0.2 %	20.7±0.3 %
	WAS_Luggage-point	81.3±0.3	16.2±0.5 %	20.1±0.2 %
	WAS_Oxley Creek	77.9±0.1	14.8±0.1 %	19.8±0.5 %
	WAS_Woodman Point	85.8±0.2	12.1±0.2 %	14.9±0.3 %

3.2 Study of the Effect of Pre-thickening Flocculant on Anaerobic Digestion and Post-Digestion Dewaterability (Tabatabaei et al., 2025b)

This study explored the effects of polymer flocculants dosed for pre-thickening prior to anaerobic digestion on the digestion performance, and post-digestion dewaterability. A low, optimal and high dose were tested to explore the impacts of under and overdosing of pre-thickening polymer flocculants.

3.2.1 Methane production effects

Figure 7 presents methane production data and shows that an increase in polymer dose from low to optimum dose specifically resulted in an increase in methane production, in this case mostly attributable to the degradation of the polymer itself. In contrast, further increases in polymer to an overdose resulted in a decreased or nil effect on methane production, indicating that overdosing of polymer has a detrimental effect on digestion performance.

The synthetic polymers (POW and EMU, Section 2.2) did not greatly influence VS degradation within the 15-day test timeframe, regardless of dosing level, but at the overdose conditions the biopolymer mix BIOPOW (Section 2.2) did notably decrease VS removal efficiency. Polymer overdosing is therefore both a waste of chemicals and can negatively influence digestion process performance.

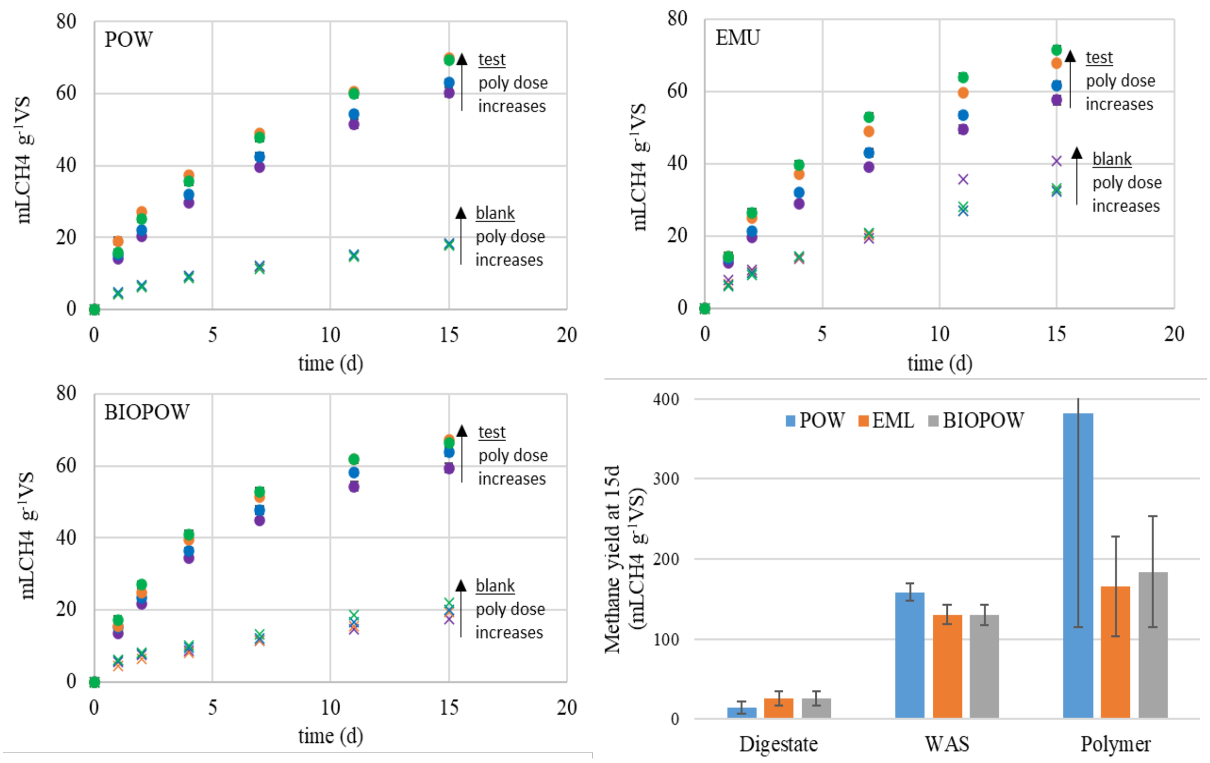


Figure 7: Impact of pre-thickening polymer dosing on methane production during digestion. The "blank" tests contained no WAS substrate. Arrows in the plots indicate trend for increasing polymer dosing. The bar graph in the bottom right shows calculated (fitted) contributions of inoculum (digestate), WAS, and polymer to overall methane yield. Error bars are 95% confidence intervals. The results are normalised with respect to total VS added to each batch test (i.e. inoculum + WAS + polymer). Sourced from (Tabatabaei et al., 2025b)

3.2.2 Rheological effects

The impact of polymer dose on rheological characteristics was measured. The results indicated that polymer had moderate mixed effect on digestate rheology (Figure 8), ranging from a negative effect from an underdose of POW resulting in a higher viscosity likely from poor floc structure formation, through to a positive effect for the optimum dose for EMU reducing viscosity.

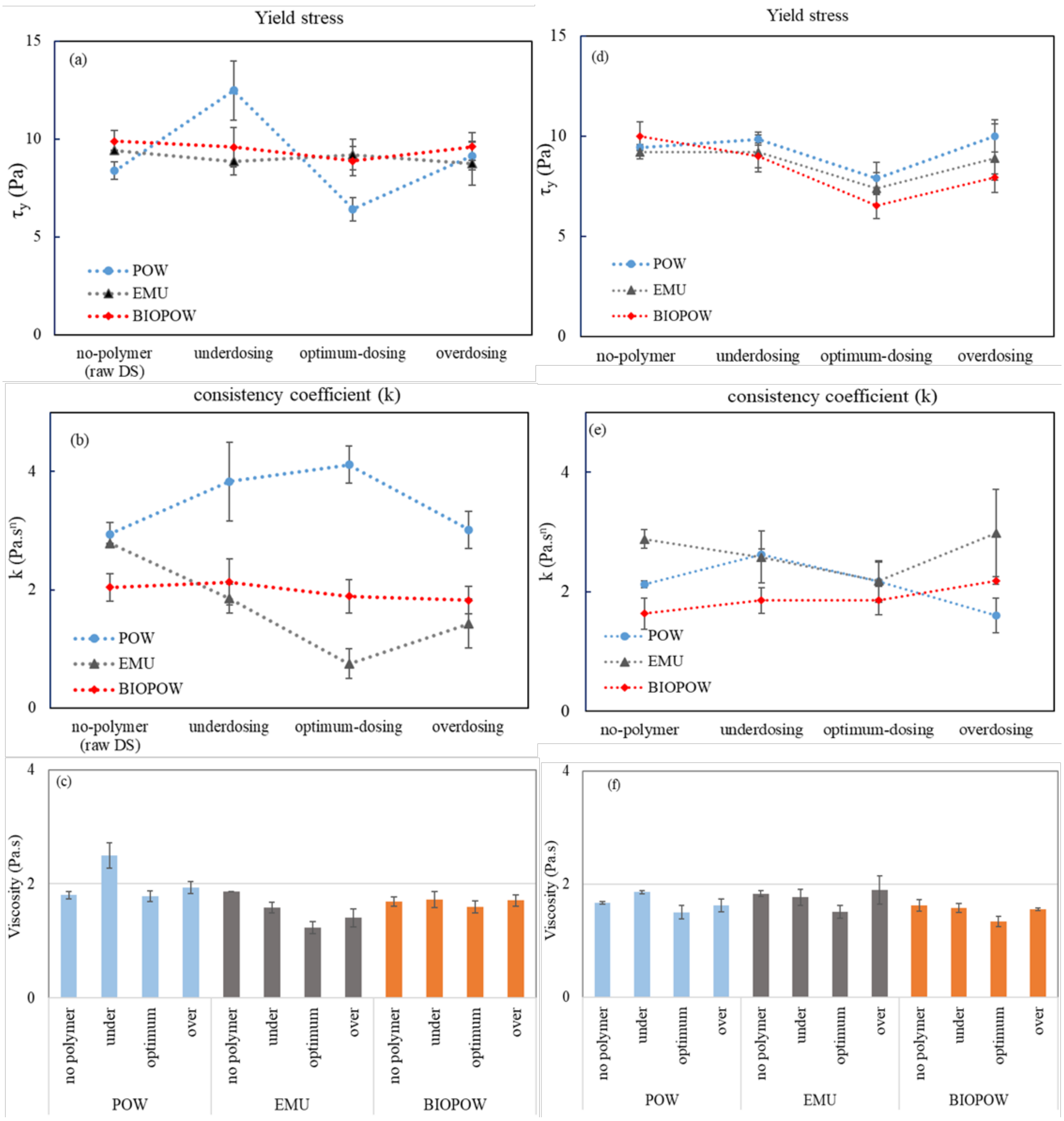


Figure 8: Impact of polymer dosing on rheological properties and predicted in-digester viscosity at a typical shear rate of 10s^{-1} for (a-c) fresh digested sludge (DS) tested at 4.5% total solids, and (d-f) sludge after 15 days of digestion tested at 4.5% total solids. Error bars show 95% confidence intervals. Sourced from (Tabatabaei et al., 2025b)

Polymer addition at the optimal dose consistently improved rheological properties during digestion, decreasing both yield stress and k. This reduction in rheological parameters indicates a more fluid-like behaviour of the sludge, favourable for in-digester mixing. In contrast, underdosing or overdosing showed limited or no effect, but yield stress was relatively higher for overdosed samples, suggesting that excess polymer and its self-entanglement can cause flow restriction.

Optimising polymer dosage likely promoted formation of larger, more stable flocs, reducing internal friction and resistance to flow (Tabatabaei et al., 2025b). The resulting improved flowability could reduce mechanical energy required for in-digester mixing, and downstream pumping and dewatering of the sludge.

3.2.3 Dewaterability and residual effects

Dewaterability measured for sludge samples after 15 days of digestion showed cake TS% was generally highest for the optimal pre-thickening dose of polymer. Polymer dose prior to digestion also significantly influenced polymer dose required for the final dewatering step after digestion. Samples with BIOPOW and EMU dosed prior to digestion required the highest additional doses of polymer for the dewaterability testing. Interesting, all the polymers retained some residual effects after 15 days of digestion, noted as a reduction in the additional polymer dose required for the dewaterability testing. However, this residual effect was mixed, with POW showing the highest but most variable retention averaging at 25%, while EMU and BIOPOW each exhibited a much lower retained effect of around 8%.

3.3 Fundamental role of carrier-fluid viscosity and particle-induced viscosity in determining sludge dewaterability performance (Tabatabaei et al., 2026)

The individual effects of carrier-fluid viscosity and particle-induced viscosity were explored to clarify their impacts on sludge rheological properties and dewaterability performance. This used xanthan gum (XG), PMMA and fumed silica as distinct viscosity modifiers.

3.3.1 Rheological effects

The addition of the soluble viscosity modifier xanthan gum (XG) substantially and linearly increased yield stress for sludges tested at both 2% and 4% TS (Figure 9). This trend was consistent with expectations for XG, known for its ability to increase liquid-phase viscosity (Song et al., 2006).

Addition of PMMA had minimal impact on rheological characteristics, and no significant effect on predicted in-digester viscosity (Figure 9). PMMA particles would increase suspended solids in the sludge matrix, but this did not show a substantial impact on sludge flow behaviour.

The response for PMMA may be related to its hydrophobicity, potentially discouraging interactions with and impact on the sludge carrier fluid. Moreover, considering that PMMA could resemble microplastics possibly found in sludge, the results indicate such microplastics would have minimal influence on sludge viscosity.

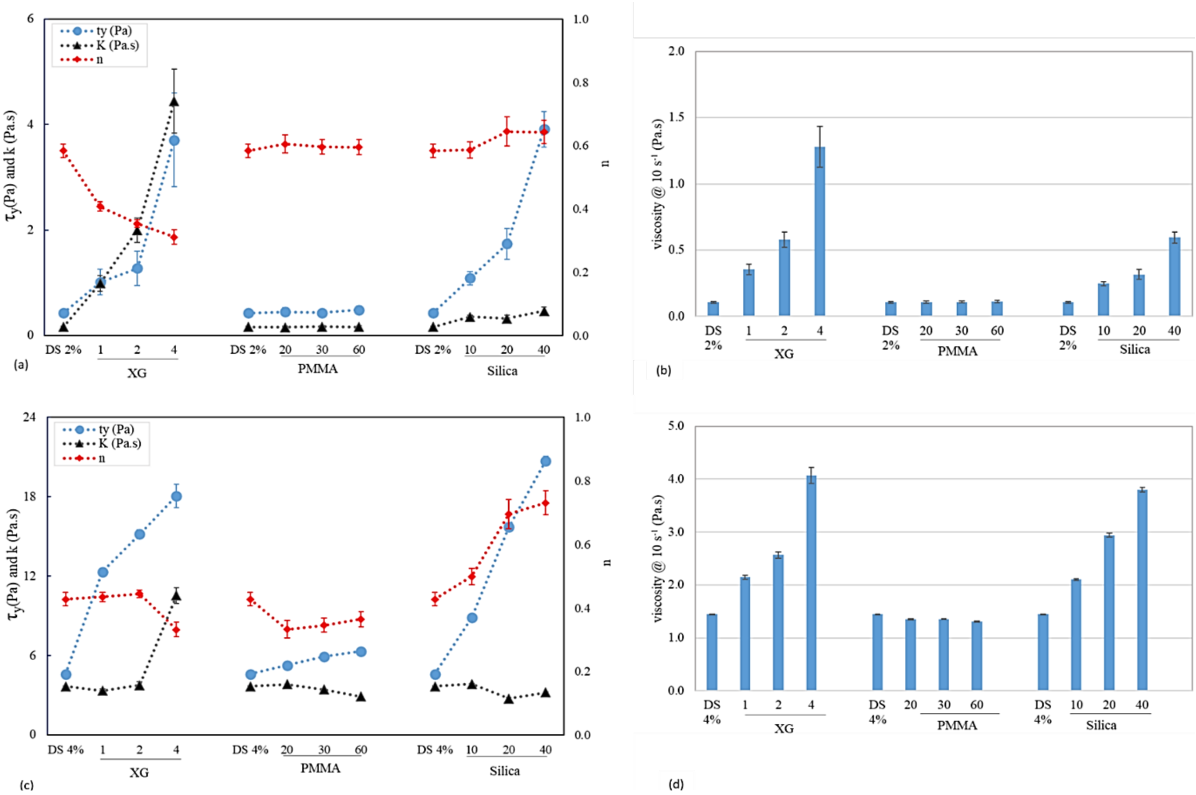


Figure 9: Measured rheological properties for digested sludge and predicted in-digester viscosity, for tests with viscosity modifiers. Results are presented for (a, b) sludge samples tested at 2% TS, and (c, d) sludge samples tested after pre-thickening to 4% TS. Viscosity modifier dosages are given in g/kg sludge. Error bars represent 95 % confidence intervals on fitted parameter values. Sourced from (Tabatabaei et al., 2026)

In the case of fumed silica, an increase in dose sharply increased yield stress (Figure 9). The viscosity of sludge tested at 2% TS was noticeably by silica, but to a lesser extent than XG. When sludge was tested at 4% TS, the impact of silica was comparable to XG. This indicated with increasing sludge TS, particle-induced viscosity effects increase. Fumed silica also increased predicted in-digester viscosity, likely forming particulate network structures contributing to greater resistance to flow (Kawaguchi, 2020).

3.3.2 Dewatering effects

Adding XG decreased cake solids from dewatering (Table 4). When silica was added, there was no notable change in cake solids. However, dosing with silica increased initial sample TS by the additional particulate dose, so that water release efficiency (WRE) (Equation 2) had deteriorated, consistent with expectations from the observed increase yield stress and viscosity with silica addition noted in Section 3.3.1.

An increase in silica dose also increased polymer requirements for final dewatering, possibly due to disruption of polymer bridging, particularly at higher dosages (Tabatabaei et al., 2026).

XG also increased polymer demand for dewatering, thickening the carrier fluid which likely required more polymer to bridge and aggregate floccules having movement and interaction of sludge particles limited within the thickened carrier fluid.

Table 4: Cake solids concentrations after dewatering, and the influence of viscosity modifiers.

Viscosity modifier dosages (g/kg sludge)		Cake TS% after dewatering	Viscosity modifier dosages (g/kg sludge)		Cake TS% after dewatering
Digested sludge tested at 2% TS	DS-2%	11.5±0.3	WAS tested at 2% TS	WAS-2%	9.3±0.2
	XG 1	8.8±0.4		XG 1	7.8±0.2
	XG 2	7.3±0.3		XG 2	7.0±0.6
	XG 4	6.1±0.4		XG 4	5.8±0.2
	PMMA 20	17.9±0.4		PMMA 20	15.4±0.3
	PMMA 30	21.3±0.1		PMMA 30	21.3±0.5
	PMMA 60	29.9±0.4		PMMA 60	28.7±0.2
	Silica 10	11.2±0.3		Silica 10	9.2±0.2
	Silica 20	11.6±0.4		Silica 20	9.5±0.3
	Silica 40	12.2±0.3		Silica 40	10.2±0.3
Digested sludge tested at 4% TS	DS-4%	11.7±0.2	WAS tested at 4% TS	WAS-4%	9.6±0.2
	XG 1	5.0±0.2		XG 1	5.3±0.4
	XG 2	4.8±0.5		XG 2	5.1±0.3
	XG 4	4.5±0.1		XG 4	4.7±0.3
	PMMA 20	15.5±0.4		PMMA 20	15.3±0.3
	PMMA 30	15.9±0.1		PMMA 30	16.1±0.5
	PMMA 60	17.1±0.3		PMMA 60	17.4±0.5
	Silica 10	11.5±0.4		Silica 10	11.0±0.3
	Silica 20	11.4±0.3		Silica 20	11.0±0.1
	Silica 40	11.8±0.4		Silica 40	11.9±0.5

Interestingly, PMMA addition significantly improved dewaterability with a much higher cake solids concentration at increased PMMA dose, especially for sludge tested at 2% TS. However, when sludge was tested at 4% TS, cake solids concentration was largely consistent across the PMMA doses. This suggested that at low sludge solids concentration, PMMA can enhance sludge dewaterability independent of its lack of effects on rheological properties noted in Section 3.3.1 above, but not so at higher sludge TS.

For both digested sludge and WAS, dewatering outcomes and the effects of viscosity-modifier additives were consistent, suggesting that effects of the additives were not greatly influenced by compositional differences between digested sludge and WAS.

4 Implications for Industry

4.1 Full-scale sludge characterisation study (Tabatabaei et al., 2025a)

The results from the analysis of composition, rheology and dewaterability of the various full-scale sludges from partner sites clearly showed:

1. organic fraction (VS/TS) strongly influences dewaterability performance. A 1% reduction in VS/TS ratio resulted in an estimated 0.32% increase in final dewatered cake solids, and as such, by reducing organic fraction from 73% to 68% (5%, a realistic goal for VS destruction improvement by sludge pre-treatment) this would reduce wet solids export from a plant by 25% per year, with 15% attributed to improved VS destruction, and 10% to improved dewaterability;
2. bench-scale dewaterability test methods (centrifuge cup, BTT) giving comparable results, potentially offering complementary tools for future investigations seeking to optimize dewatering performance; and
3. FTIR spectral fingerprinting can provide meaningful compositional analysis relevant to dewaterability performance. In the future, it may be possible to develop predictive models from FTIR analysis for sludges to optimize dewaterability.

4.2 Pre-thickening Flocculant Effects on Anaerobic Digestion and Post-Digestion Dewaterability (Tabatabaei et al., 2025b)

The results from the study on the effect of pre-thickening polymer flocculant on digestion performance and post-digestion dewaterability showed that:

1. polymer flocculant choice and applied dose were important for sludge flow properties (i.e., in-digester mixing) and post-digestion dewaterability; and

2. polymer flocculants degrade to variable extents during digestion, with the result being:

   a) increased methane production; and

   b) retention of some of the polymer's functionality after 15 days of digestion, reducing the polymer requirements for final dewatering.

Overall, the results highlighted the importance of improved and optimised polymer dosing strategies not only to minimise chemical use/cost for pre-thickening, but also to prevent adverse impacts on digestion and post-digestion dewatering.

4.3 Fundamental role of carrier-fluid viscosity and particle-induced viscosity during sludge dewaterability (Tabatabaei et al., 2026)

The fundamental study on the role of carrier-fluid viscosity and particle-induced viscosity showed:

1. the impact of viscosity modifiers was highly explainable from their unique chemical properties such as solubility, hydrophobicity, and bonding capabilities;

2. carrier-fluid viscosity is highly influential for dewaterability at lower sludge solids concentrations (e.g., 2% TS); particle-induced viscosity from hydrophilic components can become equally important at higher sludge solids concentrations; and

3. microplastics at concentrations which may be present in sludges would unlikely influence sludge flow properties but may improve dewaterability performance due to their hydrophobicity.

Similar to the tested viscosity modifiers, native sludge components, such as extracellular polymeric substances (EPS), can significantly affect viscosity and dewaterability, and these components can be present in both hydrophobic and hydrophilic fractions, and in soluble or particulate-bound forms (Tabatabaei et al., 2025a; Yang et al., 2025). This would also affect polymer demand for dewaterability.

5 Conclusions

The following conclusions can be drawn from the thesis investigations of Tabatabaei (2025):

1. **Organic fraction was a key determinant of sludge dewaterability.**
   Specifically, a higher VS/TS ratio increased yield stress and viscosity of sludges, leading to poorer dewaterability, while reductions in VS/TS (improvements in sludge destruction) systematically increased cake solids.

2. **EPS concentration alone is insufficient to explain rheological and dewatering behaviour of sludges, in terms of compositional effects.**
   Although bulk EPS quantities correlated weakly with dewaterability performance, an FTIR–PCA analysis showed that specific functional groups (e.g., amide, carboxyl, and hydroxyl groups) within EPS and whole sludge were instead mechanistically linked to yield stress, viscosity, and dewaterability. This suggested an importance of using spectral fingerprinting in addition to whole sludge measures to clarify compositional effects on dewatering performance.

3. **Strategic polymer dosing for pre-thickening before digestion can enhance both digestion performance and dewaterability, but overdosing is detrimental.**

   Optimal doses of synthetic and biopolymer flocculants reduced yield stress (≈20–40%), improved methane yield (≈15–25%), and enhanced digestate dewaterability, and a fraction of the polymers effect was retained post-digestion and decreased polymer demand for final dewatering. However, excessive dosing, particularly with biopolymers, inhibited VS destruction and degraded overall performance.

4. **Mechanistic understanding enables practical optimisation of sludge treatment and biosolids management.**

   Integrating rheology, improving VS destruction, analysing EPS chemistry, and using dewaterability testing methods (e.g. centrifuge cup and Bucher Twist Test) can provide a robust basis for optimising polymer use, digestion strategies, and sludge dewaterability, leading to more sustainable and cost-effective sludge management. This may in the future increasingly use **rheological and compositional analysis techniques** outlined and in the current work.

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