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Extracellular polymeric substances as a bioflocculant for clay and mud flocculation

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ABSTRACT

Extracellular polymeric substances (EPS) from wastewater sludge are a promising biodegradable alternative to synthetic polyacrylamide-based flocculants. EPS can be extracted from both conventional activated sludge and aerobic granular sludge (AGS). In this study, we focus on EPS from AGS (named Kaumera). We found that Kaumera when used as extracted does not flocculate with clay particles. However, aging (solubilizing) Kaumera in water of low conductivity at a particular pH (≈ 3 h at pH 12 and 2–3 days at pH 7) leads to significant flocculation. The optimal flocculation (largest median floc sizes, D_{50}) is found around 200 mg/g, even so flocculation occurred for dosages as low as 33 mg/g, which is the lowest dosage used in this article. Furthermore, the maximum floc sizes are attained within 20 min of stirring between clay and EPS, when the flocculant dosage is close to the optimal dosage. This study presents a working protocol for flocculating clay and mud suspensions using EPS extracted from wastewater residual sludge (AGS) and similar biopolymers as bioflocculants.

1. Introduction

Sediment management has become an important approach for controlling excess nutrients in freshwater lakes and ponds, while also maintaining the depth of ports and harbors and protecting water quality and ecosystems [1–3]. Dredging is an effective method for managing sediments in freshwater lakes, enabling the removal of nutrient-rich sediments to mitigate eutrophication [3,4]. Dredged sediments typically contain only ≈ 10% solid matter, necessitating dewatering for efficient transport and reclamation [1,5]. Flocculation and coagulation are commonly employed methods to enhance dewatering processes. They are the process by which colloidal particles come together to form aggregates (or flocs). When flocculating agents are inorganic salts, they are typically referred to as coagulants; when they are organic or carbon-based polymers, they are known as flocculants [6,7]. Flocculants are used extensively in many industries for sediment management. Most of these flocculants are petroleum-based polyacrylamide (PAM) polymers which are cost effective and highly efficient to capture fines [8,9]. However, these polymers are synthesized from non-renewable sources and are often not biodegradable [10,11]. Additionally, the PAM-based polymers can undergo degradation, potentially releasing acrylamide monomers, a known toxin and potential carcinogen [12,13]. Therefore, there is a need for sustainable alternatives to these synthetic flocculants. In recent years, biopolymers have emerged as a promising eco-friendly solution for effective sediment management [14]. These natural polymers derived from microbial, plant, and animal resources [14–16] show great potential as a biodegradable and non-toxic flocculant. Research on their mechanisms, optimization, and applications is ongoing [17].

Flocculation is also a phenomenon that occurs in natural water systems such as estuaries [18,19] where flocculation is induced by salt minerals and suspended natural organic matter. This natural organic matter often comes in the form of extracellular polymeric substances (EPS) [20]. EPS is a complex polymeric gel consisting of several macromolecules such as proteins, polysaccharides, DNA, lipids, glycoproteins, and humic substances [21,22]. These polymers are produced by microorganisms like bacteria during cell metabolism. Flocculation is particularly studied in the field of wastewater treatment [23–25], where the purpose is to dewater sludges to provide clean water [26,27]. In wastewater treatment, the bacteria produce EPS to form the matrix in which they are immobilized and aggregate as flocs, biofilms, sludge and granules [28,29].

Approximately 180 km^3 of sewage is treated globally in WWTPs each year, making it one of the largest biotechnologies in terms of volume [30,31]. Consequently, significant amounts of excess biomass are

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produced globally, much of which is currently disposed of without being utilized, despite the growing interest in resource recovery from wastewater worldwide [32–35]. Making use of this excess biomass into deriving some valuable products will decrease the overall residuals to be disposed of, reducing the costs and carbon footprint, thereby increasing the sustainability of the WWTPs by contributing towards a circular economy [36,37]. The organics present in residual sludge contain valuable nutrients like carbon, phosphorus and nitrogen that can be recovered. These can be converted into valuable products such as polyhydroxyalkanoates (PHA), and hydrocolloids [37,38]. This not only improves resource recovery but also helps replace petroleum-based chemicals in society. EPS is one of such valuable resources extracted from wastewater treatment residual sludge [39–44].

In the Netherlands, a full scale aerobic granular sludge (AGS) technology, called 'Nereda® technology' was developed for wastewater treatment [45,46]. The AGS technology enabled more efficient resource recovery compared to conventional activated sludge [47,48]. The EPS extracted from Nereda® granules has been given the brand name Kaumera [48–50]. EPS from granular sludge like Kaumera has seen applications in agriculture, construction, textile, and paper industries as bio-stimulant, composite material and flame retardant, due to its unique properties [40,41,51,52].

One of the disadvantages of EPS based flocculation is that the supernatant water remains turbid after flocculation. This would be a problem for water treatment purposes but not for other industrial applications linked to sediment management. For instance, flocculation is used in the mining industries to thicken clayey slurries upon deposition in a tailing pond [53–55]. The use of a bioflocculant can also increase light penetration in water bodies to stimulate biological activity [56–58] or reduce the spread of dredging plumes [59–61]. For such applications, the aggregation ability between mineral sediment particles and bioflocculant is most relevant. In this article, we present a new application for Kaumera, namely, as a bioflocculant. We derive a protocol to prepare the Kaumera stock suspension for flocculating clay suspensions. We used mineral sediment particles consisting of fine clay and silt of colloidal size (in the μm range) [62,63].

2. Materials and methods

2.1. Solvent

The primary solvent used in all experiments is the tap water provided and monitored by the company, Evides. The pH and conductivity of the water is ≈ 8 and ≈ 440 μS/cm, respectively.

2.2. Clay stock suspension

The clay used in all experiments is natural Dutch clay called Vingerling K−122, purchased from Sibelco Europe. It is a non-swelling chamotte clay (high silica and alumina content) with a baking colour of orange-red. A slurry of this clay was prepared in tap water with a clay concentration of 194.4 g/L. The particle size distribution (PSD) of clay was analyzed using static light scattering (Malvern MasterSizer 2000 and 3000). The median size of the clay particles (D_{50}) was found around 6 μm.

2.3. Flocculant - Kaumera

There are various extraction protocols for retrieving Kaumera, which are typically optimized for extraction yield. A hot-alkaline extraction protocol is followed for the extraction of Kaumera from raw sludge [48]. Details about extraction can be found in Felz et al. [64] and Bahgat et al. [48]. Two sketches illustrating the laboratory and treatment plant extractions are given in Fig. 1 and Fig. 2. The extracted Kaumera is a hydrogel and can be stored at low temperatures ($< 7^{\circ}$ C). After spray drying or freeze drying, Kaumera can also be stored at room temperature and has longer shelf-life. We use spray-dried Kaumera from the Zutphen extraction plant in all experiments, unless otherwise specified. In Zutphen, the dairy wastewater from Royal FrieslandCampina, gets converted to granular sludge. The excess granular sludge (raw sludge) is then collected and thickened by adding a cationic PAM-based polyelectrolyte (SNF EM 722) over a conveyor belt prior to the hot-alkali extraction, as shown in Fig. 2 below. The EPS extracted from this sludge is called Kaumera. Kaumera is composed primarily of glycoproteins in their acidic forms, with a molecular weight range of about 50–150 kDa [49]. Since Kaumera is marketed as a chemical substance, it also undergoes certification in European Union (EU) by Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). Details on composition of Kaumera from Zutphen are provided in the supplementary section (see subsection A.7).

2.3.1. Kaumera stock suspension

Kaumera stock suspensions were made by dispersing 1 g/L Kaumera in tap water. The Kaumera suspension is also prepared in acidic and basic pH. Sodium hydroxide (NaOH pellets) and hydrochloric acid (1 M HCl) were utilized to prepare the Kaumera suspensions at pH 12 and pH 1.5, respectively. The final Kaumera concentration for all stock suspensions is 1 g/L. Several stock suspensions were made for pH 1.5 (acidic), pH 7 (neutral) and pH 12 (basic). The pH and conductivity of the stock suspensions are provided in Table 1.

2.4. Setup and analysis

The flocculation experiments are conducted by following a unique setup as shown in Fig. 3. The experimental setup consists of a peristaltic pump (Watson-Marlow 323Du), an inline camera, a particle size analyzer, a magnetic stirrer and sample jar (see Fig. 3). The clay and Kaumera suspensions are circulated within the setup through pipes with internal diameter of 6 mm. This setup allows us to combine images captured by the inline camera (Malvern HydroInsight) and the particle sizes estimated by laser diffraction (Malvern Mastersizer 2000 and 3000).

The particle sizes are obtained from static light scattering (SLS) [65]. The resulting scattering patterns are converted into particle sizes and volume-based size distribution by applying Mie scattering theory. A Fourier-transform infrared (FTIR) spectroscopy (PerkinElmer Spectrum 100) of the clay, the supernatants after flocculation and Kaumera are provided in the supplementary section. Additionally, zeta potential measurements (Malvern Zetasizer Nano) of Kaumera and Kaumera-clay flocs are also provided in the supplementary section (see subsection A.8).

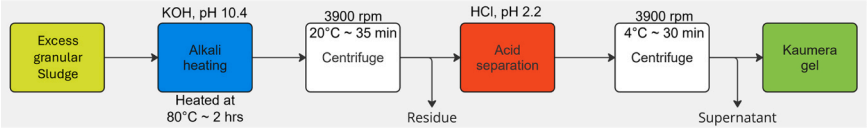


Fig. 1. Schematic of Kaumera laboratory extraction.

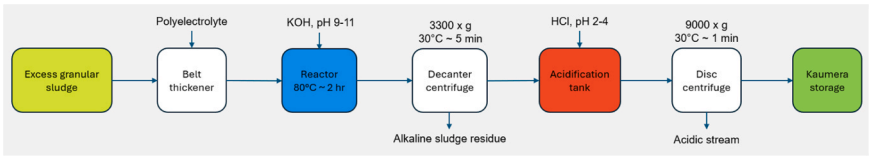


Fig. 2. Schematic of Kaumera Zutphen plant extraction.

Table 1
Table on pH and conductivity.

Kaumera suspension pH	Flocculant aging	Flocculant dosage (mg/g)	Kaumera + clay suspension pH	Kaumera + clay suspension conductivity (μS/cm)
12	3–5 hr	200	10	550
7	3–5 hr	200	7.5	485
7	1 day	200	7.5	485
7	2 days	200	7.5	507
1.5	3–5 hr	200	2	-

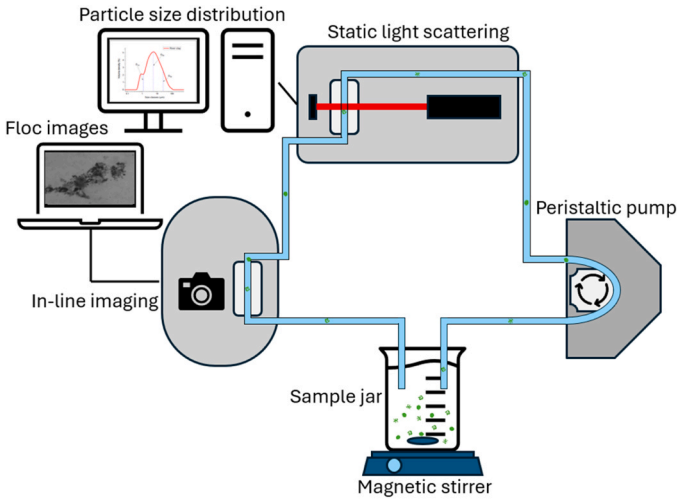


Fig. 3. Schematic of the experimental set-up.

2.5. Experimental protocol

The peristaltic pump is adjusted to ensure proper circulation of the suspensions with minimal shear stress (see Fig. 3). The pump head tends to disrupt flocs, however, the flocs are circulated through small pipes (inner diameter of 6 mm), and the pipe size and shear within the pipes are more significant factors affecting floc sizes. The shear rate experienced by the flocs within the pipes is controlled by adjusting the flow rate through the pipe. Hence, the peristaltic pump is set to 30 rpm which corresponds to a shear rate of $\approx 60\ s^{-1}$.

Similarly, the magnetic stirrer speeds are set to ensure a good mixing of the flocculant and clay without imparting excessive shear stress that could disintegrate the formed flocs. The magnetic stirrer speed was not recorded and therefore the reproducibility is controlled by the shear in the tube. Consequently, the dominant source of shear arises from flow-induced stress within the pipes.

The flocculation performance is evaluated by carefully studying the particle size distribution (PSD) of clay and the evolution of the PSDs over time after the addition of the flocculant in measured amounts. Initially, a background scan is performed on ≈ 500 mL of the solvent circulating the system using the particle size analyzer. A specific volume from the clay stock suspension containing 0.5 g of clay, is then added to the solvent. The sample jar is stirred using a magnetic stirrer gently.

The particle size analysis is then initiated, and after the first PSD measurement (t = 0, in the figures) of the clay suspension is completed, a specific amount of Kaumera is added to the sample jar to achieve a final circulating volume of ≈ 600 mL, with a final clay concentration of ≈ 0.83 g/L. A glass rod is used for ≈ 5 s to ensure proper dispersal of the flocculant, immediately after its addition to the system. The Kaumera to clay dosage is adjusted by the amount of Kaumera added to the system from the stock suspension (1 g/L). The pH and conductivity of the clay and Kaumera suspensions, and their mixture are measured (see Table 1). Subsequently, a PSD is measured every 1 min to observe the changes in the particle sizes. The measurements are done for a period of about 20–60 min until a steady state (when the floc sizes are constant or undergoes a gradual change) is reached. Meanwhile, images from HydroInsight are captured periodically. A standard jar-test style validation is not performed in this study, as flocculation ability (with floc size as the associated parameter) is our main focus and not turbidity.

3. Results

In this section, we show how factors such as pH, aging of Kaumera, Kaumera dosage and presence of additives affect flocculation performance.

3.1. Role of pH

Kaumera stock suspensions were prepared at three different pH conditions, as elaborated in subsubsection 2.3.1. The Particle Size Distributions (PSDs) of these Kaumera suspensions were measured by using a modified version of the protocol described in subsection 2.5. Specifically, after the initial background scan of the tap water was completed, a specific amount of Kaumera from the prepared stock suspensions was added to the system. The particle size measurements of the Kaumera suspension were then initiated. After the PSDs reached a steady state (stable or only gradual change in PSD), specific amounts of clay were added to the system to have a final Kaumera to clay ratio of ≈ 200 mg/g.

At neutral and higher pH, the Kaumera formed an open and loose aggregate (Fig. 4). It was anticipated that this would lead to good flocculation between Kaumera and clay particles. Moreover, at low pH, the Kaumera formed dense coils which resulted in poor flocculation of clay particles, as initial experiments demonstrated (see subsection A.1). Therefore, we discarded experiments with Kaumera at pH 1.5 and performed further experiments with Kaumera suspensions prepared at pH 7 and pH 12.

3.2. Role of flocculant aging

Kaumera stock suspensions were made at pH 12 and pH 7. These stock suspensions were aged (stirred for a specific amount of time) for different times: 3–5 h (freshly dissolved), 1 day, 2 days, 3 days, 5 days and 6 days. Flocculation experiments were performed, after a specific Kaumera aging time, by mixing clay and Kaumera using the protocol given in subsection 2.5. Both Kaumera and clay concentrations were kept the same for all aging experiments, with a Kaumera to clay ratio of 200 mg/g. The results are displayed in Fig. 5.

Kaumera showed good flocculation properties when freshly dissolved at pH 12, and its performance dropped over aging time. The Kaumera showed good flocculation after 2–3 days of stirring at pH 7. It

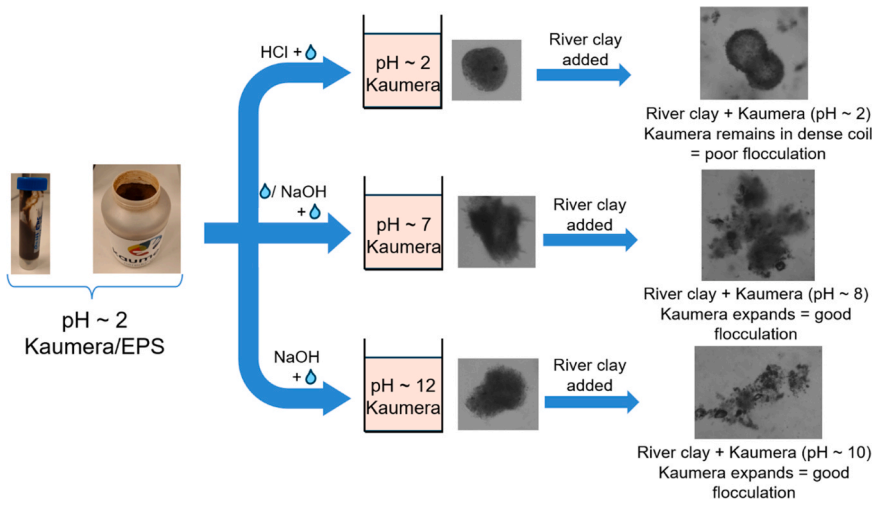


Fig. 4. Kaumera particles and Kaumera-clay flocs at different pHs. The size of the Kaumera particles ≈ 80 μm. The Kaumera-clay floc size in acidic pH is ≈ 40 μm while in neutral and basic pH is ≈ 150 − 200 μm at a flocculant dosage of about 200 mg/g (The Kaumera in neutral pH was measured after 2 days of aging).

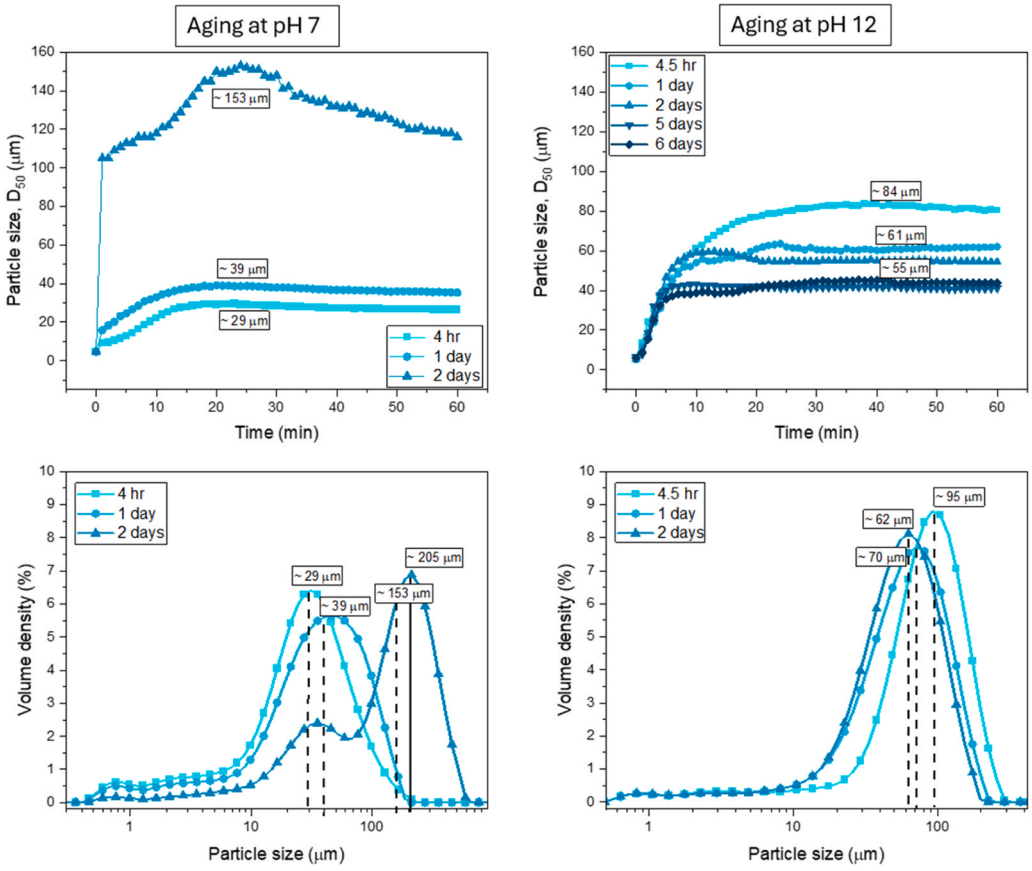


Fig. 5. Flocculation efficiency (Median size of Kaumera-clay flocs) of Kaumera at pH 7 and pH 12, aged to different durations for a flocculant to clay ratio of 200 mg/g. The median floc size, D_{50} is recorded overtime (top figures). The peak floc sizes are indicated in the bottom figures.

showed poor flocculation before and after that aging duration. Additional flocculation experiments were performed using a Kaumera stock suspension at pH 12 aged for a longer period (see subsection A.2), which showed that flocculation efficiency decreased for longer Kaumera aging period. Therefore, we performed further experiments with Kaumera stock suspensions freshly dissolved and aged 2–3 days at pH 12 and pH 7, respectively.

3.3. Role of flocculant dosage

Kaumera stock suspensions aged accordingly to pH 7 and pH 12 were used to determine the dosage that gave the maximum median floc sizes (D_{50}). The results are displayed in Fig. 6.

The dosage corresponding to a maximum D_{50} for the Kaumera – clay flocs within a period of about 20–30 min was considered the optimal dosage. The optimal dosage was found to be around 200 mg/g for both

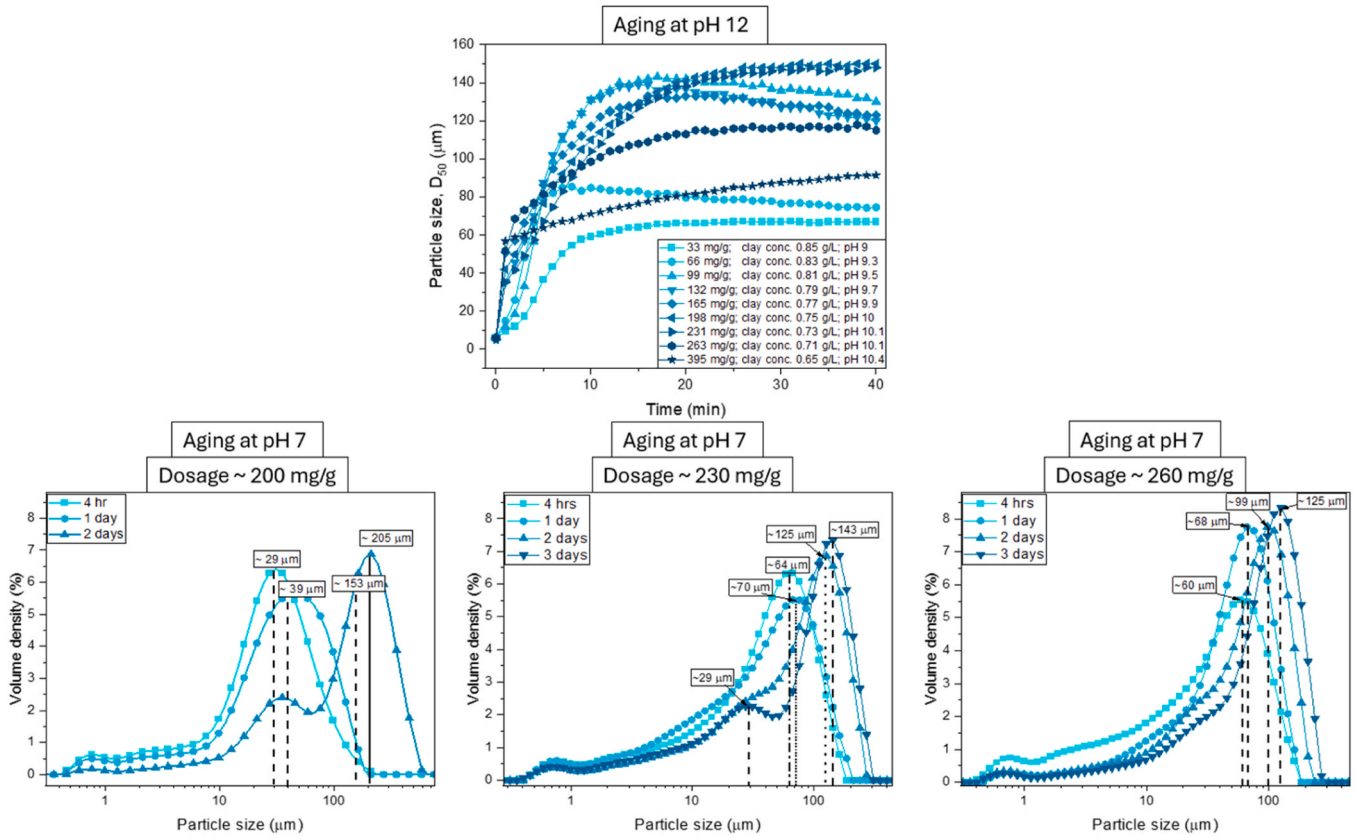


Fig. 6. Flocculation efficiency of different dosages of Kaumera aged at pH 7 (clay concentration ≈ 0.83 g/L) and pH 12 (clay content ≈ 0.5 g in each jar leading to the clay concentrations indicated in the legend).

pH 7 and pH 12, though flocculation is observed for dosages as low as 33 mg/g, which is the lowest dosage used in this article.

3.4. Role of additives

The extraction yield of Kaumera largely depends on the quality of the excess sludge during the wastewater treatment process [47]. When the

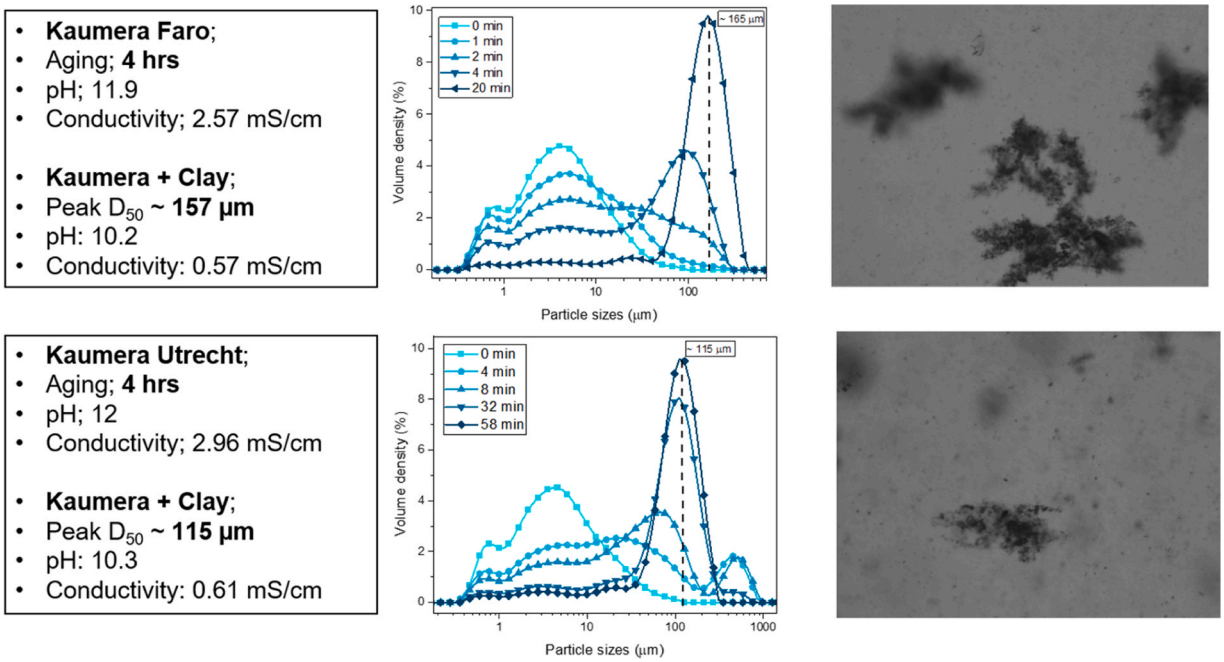


Fig. 7. Flocculation efficiency of Kaumera (Faro and Utrecht) extracted from excess sludge without using polyelectrolyte thickener. Kaumera Faro shows faster kinetics and bigger floc sizes compared to Kaumera Utrecht.

excess sludge is insufficiently thick – due to factors such as waste type, seasonal variations, or treatment process parameters - a sludge thickener is used to enhance the extraction yield. The Zutphen Kaumera plant uses a PAM-based polyelectrolyte (SNF EM 722) as a sludge thickener (see subsection A.3). Since the Kaumera extraction process is performed at high temperatures and extreme pH conditions (see Fig. 2), degradation of these PAMs is expected. Therefore, the flocculation properties exhibited by Kaumera are likely not influenced by the presence of residual PAMs. This was verified by extracting Kaumera from Faro and Utrecht Nereda® sludge granules that did not have any added sludge thickeners (See subsection A.4 for details on processing conditions at the Faro and Utrecht resource recovery plants). The Kaumera was extracted from both sources (granular sludge without additives) using the protocol given in subsection 2.3 (see Fig. 1). Faro and Utrecht Kaumera stock suspensions were prepared at pH 12 using the protocol described in subsubsection 2.3.1. The flocculation experiments were performed using freshly dissolved Kaumera following the protocol given in subsection 2.5. The Kaumera to clay dosage of 200 mg/g was used and all other experimental parameters were kept same.

Both Faro and Utrecht Kaumera showed good flocculation when freshly dissolved at pH 12 (see Fig. 7). The Faro Kaumera reached maximum floc size ($D_{50} \sim 157$ μm) faster than the Utrecht Kaumera ($D_{50} \sim 115$ μm) despite having similar pH and conductivity after flocculation with clay.

4. Discussion

4.1. Role of pH

Previous studies on microbial EPS have shown that the structure and surface properties of EPS have a pH dependence [66,67]. EPS is a complex mixture of several macromolecules, including amphoteric substances, and species with neutral, positively, and negatively charged groups [21]. Therefore, changing the pH can result in destroying or restructuring of the EPS matrix. At low pH, Kaumera aggregates to form a dense coil exposing just the hydrophilic parts of the biopolymer chain (Fig. 4). At low pH the functional groups of the EPS get protonated, charges are neutralized, hydrophilic-hydrophobic interactions and intermolecular hydrogen-bonding dominate, which results in the formation of these dense aggregates.

Consequently, the denser coils have less surface area to interact with the colloidal clay particles in the suspension. This leads to poor flocculation performance. Contrastingly, at neutral and higher pH, Kaumera forms a more open structure. The functional groups in EPS are deprotonated and become charged, electrostatic repulsions dominate which results in the formation of these looser aggregates. The open coils benefit from increased surface area that leads to more effective interactions between the clay particles in the suspension and Kaumera. Hence, higher number of clay particles get trapped by Kaumera aggregates, resulting in large flocs.

4.2. Role of flocculant aging

When Kaumera gel at ≈ pH 2 is exposed to a higher pH, it is more likely to undergo hydrolysis and biological degradation at a faster rate. The Kaumera polymer chains get released into the solvent more readily at pH 12 resulting in short aging times (3–5 h) for good flocculation (see Fig. 5). At pH 7, the Kaumera polymers take much longer (2–3 days) to be solubilized. According to Wang et al. [67], EPS releases chains more readily at higher pH. Consequently, this results in shorter aging times at pH 12 compared to pH 7. Previous studies on PAMs have similarly shown longer aging times at pH 7 [68,69]. According to Owen et al. [68], dissolution of powdered PAMs is a slow process. It takes about 72 h (3 days) to maximize the release of discrete chains from highly agglomerated species in solution. Further aging beyond this duration results in conformational changes in polymer chains leading to their shrinkage and reduced flocculation efficiency [70]. As this phenomenon is driven by physical processes, it is not limited to polyacrylamides but is also applicable to biopolymers such as Kaumera. Finally, we define optimal aging as the duration of solubilizing Kaumera until discrete polymer chains are at a maximum equilibrium concentration in the suspension. Around this aging time, polymer chains reach maximum extension in the solvent and this improves flocculation efficiency. See subsection A.9 for results showing direct effects of aging in Kaumera at different pH's.

4.3. Role of flocculant dosage

The flocculant dosage (ratio of the amount of flocculant to the amount of clay) determines the flocculation performance. The optimal flocculant dosage (optimal flocculant to clay ratio) leads to the formation of the largest flocs within a short duration of time. Previous studies have shown that the optimal ratio, which depends on the type of flocculant, is linked to optimal floc settling velocities [53,71]. The optimum dosage is a function of the coverage of the polymers on the clay particles and the extension of polymer tails into the solution [72]. This extension is a function of the molecular mass of the polymer but also shear stresses and ionic strength. It is therefore anticipated that the optimal flocculant dosage in a saline environment will lead to a different optimal flocculant to clay ratio.

When using Kaumera for the flocculation of clay, the optimal dosage is around 200 mg/g (see Fig. 6) for Kaumera aged at both pH 7 and pH 12. The variation of PSDs over dosage shown by Kaumera (Fig. 6) are quite similar to the trends reported for cationic PAM flocculants [71]. The main differences are that the value of the optimal flocculant dosage is 10 times lower and the flocs obtained are 10 times larger for polyacrylamides. The reason lies in the complex structure of Kaumera, which, unlike the PAM flocculant, is not a linear polymer with similar surface charge groups. Nonetheless, since the optimal particle size using Kaumera is about 150–200 μm, particles at optimal flocculant dosage or below will settle, as was indeed observed for 33 mg/g dosage, which is the lowest dosage used in this article. (D_{50} is found to be approximately 65 μm). Therefore, despite not being as efficient as conventional PAMs, Kaumera can be used as a (bio)flocculant. Furthermore, the PSD of clay particles flocculated with the cationic polyelectrolyte SNF EM 722 is provided in the supplementary section (see subsection A.10) as a control and comparison with a PAM flocculant. The clay-polymer flocs formed using this PAM flocculant at a dosage of 5 mg/g resulted in peak floc sizes of around 390 μm (see subsection A.10). Additionally, the flocculation performance in saline environments and at lower dosages needs to be further investigated. This is however, out of scope of the present study.

4.4. Role of additives

The source of the wastewater sludge (municipal, dairy, industrial etc.) and the operational conditions together determine the granule formation in the reactor tanks. The Zutphen resource recovery plants receive dairy waste, and the processing conditions were not optimized, resulting in poor granules. Hence, sludge thickeners were added to the sludge. Both Faro and Utrecht Kaumera extraction plants receive municipal wastewater, and their processing conditions are optimized, resulting in good quality granules. Since the granules are good, sludge thickeners are not needed for the sludge processing.

Both Faro and Utrecht Kaumera show good flocculation of the clay particles (Fig. 7). The flocculation tests were conducted according to the protocol mentioned in subsection 2.5. Therefore, the flocculation properties of the Kaumera are not dependent on added polyelectrolytes for excess sludge thickening. Though large flocs were produced by both Kaumera polymers, the Faro Kaumera showed better flocculation performance than the Utrecht Kaumera. The Faro Kaumera-clay flocs were larger and showed faster settling kinetics. This is likely due to the

differences in the structure and composition of the two EPS. For these two samples, we took additional FTIR data for the supernatants, provided in the supplementary material (see subsection A.5). The FTIR signal from clay particles (primarily Si-O absorptions and structural OH bending [73]) are absent in the FTIR spectrum of the supernatant. This gives additional confirmation that there are no clay particles remaining in the supernatant.

4.5. Comparison with other biopolymers

EPS and other biopolymers have been investigated for flocculating fine sediments, as reviewed in [14,16,17]. Flocculation efficiency is typically assessed by measuring residual turbidity after the flocculation test. Many studies combine biopolymers with salts to enhance flocculation. However, test protocols vary across studies leading to a wide range of optimal flocculant dosages, from 0.1 to 200 mg/g [20,34,74–76].

More importantly, most investigations did not focus on flocculant dosage in terms of flocculant aging [14]. We see from the here presented results that flocculant aging shows a more prominent effect (sometimes more crucial) on flocculation performance than flocculant dosages (see Fig. 5 and Fig. 6). Furthermore, the aging behavior exhibited by Kaumera is not restricted to biopolymers alone; it is a general physico-chemical process. Similar aging behaviors have been studied in, for instance, polyacrylamides [68,69]. Despite its significance, aging behavior is often neglected/overlooked in sediment flocculation studies using biopolymers. Hence, the aging behavior of biopolymers in various solvents should be studied as an important factor in improving flocculation efficiency of bioflocculants (See subsection A.9 for results on aging of Kaumera). A next step would be to provide a full molecular characterization of Kaumera as a function of time, direct quantification of residual PAM, and changes in turbidity after flocculation.

5. Conclusions

Extracellular polymeric substances extracted from aerobic granular sludge (Kaumera), when used as extracted does not flocculate with clay particles. The present study demonstrates that aging (solubilizing) Kaumera in water of low conductivity for a given amount of time at a particular pH enables to use Kaumera as a bioflocculant. Several pH (1.5, 7 and 12) was tested for aging. It was verified that Kaumera did not solubilize readily at pH 1.5. At pH 12, the optimal aging time was found to be 3–5 h. Around this aging time, polymer chains reach maximum extension in the solvent, and this implies that when this Kaumera is mixed with a clay suspension, the obtained flocs have the highest median particle size, D_{50} compared to other aging times. When the pH is 7, the optimal aging time is found to be 2–3 days. Alternatively, Kaumera can be stirred for 3 h at pH 12 and be neutralized to pH 7 using NaOH. Though this introduces residual salts, it does not significantly affect flocculation performance (see subsection A.6). The dosage corresponding to a maximum D_{50} for the Kaumera – clay flocs within a period of about 20–30 min was considered the optimal dosage. The optimal dosage was found to be 200 mg/g for both pH 7 and pH 12, though flocculation is observed for dosages as low as 33 mg/g, which is the lowest dosage used in this article.

In Europe, annually around 300 Mt (dry matter) sediments are dredged to maintain various ports and waterways. The port of Antwerp, for instance, generates about 0.45 Mt of dredged sediments annually [77]. Typical flocculant dosage for dewatering dredged sediments is about 0.5–12 mg per g total suspended solids [1,20,75]. This implies that about 225–5400 tonnes of dry flocculant are required annually. This is within the expected range of large-scale Nereda installation (personal communication, Kaumera Sales and Services B. V.). Despite the fact that commercial PAM based flocculants are cheaper, Kaumera has the advantage to be an environmentally friendly and EU certified replacement to PAMs.

This study provides a practical guideline for using Kaumera and similar EPS biopolymers extracted from excess sludge as sustainable bioflocculants for sediment flocculation. These findings support the broader adoption of environmentally friendly flocculants in water treatment and sediment management.

CRediT authorship contribution statement

Adarsh Shajimon: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Mark C.M. van Loosdrecht:** Writing – review & editing, Supervision, Conceptualization. **Claire Chassagne:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2026.124495.

Data availability

Data will be made available on request.

References

[1] Sina Haasler, Morten Lykkegaard Christensen, Kasper Reitzel, Synthetic and biopolymers for lake restoration–an evaluation of flocculation mechanism and dewatering performance, J. Environ. Manag. 331 (2023) 117199, https://doi.org/10.1016/j.jenvman.2022.117199.
[2] Gustav Simoni, Peam Cheali, Peter Roslev, Sina Haasler, Kasper Reitzel, Aiden Mark Smith, Mette Helene Sahl Haferbier, Morten Lykkegaard Christensen, Flocculating and dewatering of lake sediment: an in-situ pilot study comparing synthetic polymers and biopolymers for restoring lake water quality and reusing phosphorus, Sci. Total. Environ. 913 (2024) 169597, https://doi.org/10.1016/j.scitotenv.2023.169597.
[3] Hongyong Xiang, Xiang Li, Rui Xiao, Jie Chen, Wentao Dai, Is dredging an effective ecological restoration method to improve water quality in freshwater ecosystems? Ecol. Eng. 209 (2024) 107425 https://doi.org/10.1016/j.ecoleng.2024.107425.
[4] Mumtahina Riza, Mohammad Nazmul Ehsan, Md. Nahid Pervez, Mirza Mohammad Omar Khyum, Yingjie Cai, Vincenzo Naddeo, Control of eutrophication in aquatic ecosystems by sustainable dredging: effectiveness, environmental impacts, and implications, Case Stud. Chem. Environ. Eng. 7 (2023) 100297, https://doi.org/10.1016/j.cscee.2023.100297.
[5] Zhenzhen Song, Weijun Zhang, Hongyu Gao, Dongsheng Wang, Comprehensive assessment of flocculation conditioning of dredged sediment using organic polymers: Dredged sediment dewaterability and release of pollutants, Sci. Total. Environ. 739 (2020) 139884, https://doi.org/10.1016/j.scitotenv.2020.139884.
[6] John Bratby, Coagulation and flocculation, Uplands Press Limited, 1980. https://es.ircwash.org/sites/default/files/253-80CO-1277.pdf.
[7] Claire Chassagne, Introduction to colloid science: Applications to sediment characterization (2021), https://doi.org/10.34641/mg.16.
[8] R. Hecker, P.D. Fawell, A. Jefferson, The agglomeration of high molecular mass polyacrylamide in aqueous solutions, J. Appl. Polym. Sci. 70 (11) (1998) 2241–2250, https://doi.org/10.1002/(SICI)1097-4628(19981212)70:11%3C2241::AID-APP18%3E3.0.CO;2-7.

[9] R. Hecker, P.D. Fawell, A. Jefferson, J.B. Farrow, Flow field-flow fractionation of polyacrylamides: commercial flocculants, Sep. Sci. Technol. 35 (4) (2000) 593–612, https://doi.org/10.1081/SS-100100178.

[10] Biswajit Ray, Broja M. Mandal, Dispersion polymerization of acrylamide, Langmuir 13 (8) (1997) 2191–2196, https://doi.org/10.1021/la9605044.

[11] Gang Wu, Liangmin Yu, Xiaohui Jiang, Synthesis and properties of an acrylamide-based polymer for enhanced oil recovery: a preliminary study, Adv. Polym. Technol. 37 (8) (2018) 2763–2773, https://doi.org/10.1002/adv.21949.

[12] Boya Xiong, Rebeca Dettam Loss, Derrick Shields, Taylor Pawlik, Richard Hochreiter, Andrew L. Zydney, Manish Kumar, Polyacrylamide degradation and its implications in environmental systems, NPJ Clean. Water 1 (1) (2018) 17, https://doi.org/10.1038/s41545-018-0016-8.

[13] Sanket J. Joshi, Raeid M.M. Abed, Biodegradation of polyacrylamide and its derivatives, Environ. Process. 4 (2017) 463–476, https://doi.org/10.1007/s40710-017-0224-0.

[14] Xincheng Jiang, Yisen Li, Xiaohui Tang, Junyi Jiang, Qiang He, Zikang Xiong, Huaili Zheng, Biopolymer-based flocculants: a review of recent technologies, Environ. Sci. Pollut. Res. 28 (2021) 46934–46963, https://doi.org/10.1007/s11356-021-15299-y.

[15] Hitesh Jethani, Umesh H. Hebbar, Plant-based biopolymers: emerging bio-flocculants for microalgal biomass recovery, Rev. Environ. Sci. Bio/Technol. 20 (1) (2021) 143–165, https://doi.org/10.1007/s11157-020-09561-x.

[16] Hossein Salehizadeh, Ning Yan, Recent advances in extracellular biopolymer flocculants, Biotechnol. Adv. 32 (8) (2014) 1506–1522, https://doi.org/10.1016/j.biotechadv.2014.10.004.

[17] Nahid Molaei, Omar Bashir Wani, Erin R. Bobicki, A comparative study of biopolymer adsorption on model anisotropic clay surfaces using quartz crystal microbalance with dissipation (QCM-D), J. Colloid Interface Sci. 615 (2022) 543–553, https://doi.org/10.1016/j.jcis.2022.01.180.

[18] A.J. Manning, P.L. Friend, N. Prowse, C.L. Amos, Estuarine mud flocculation properties determined using an annular mini-flume and the LabSFLOC system, Cont. Shelf Res. 27 (8) (2007) 1080–1095, https://doi.org/10.1016/j.csr.2006.04.011.

[19] Claire Chassagne, Zeinab Safar, ZhiruiDeng, Qing He, Andrew J. Manning, Flocculation in Estuaries: Modeling, Laboratory and In-situ Studies, in: Andrew J. Manning. (Ed.), Sediment Transport, IntechOpen, Rijeka, 2021, https://doi.org/10.5772/intechopen.100404.

[20] Zhirui Deng, Dong Huang, Qing He, Claire Chassagne, Review of the action of organic matter on mineral sediment flocculation, Front. Earth Sci. 10 (2022) 965919, https://doi.org/10.3389/feart.2022.965919.

[21] Hans-Curt Flemming, Jost Wingender, The biofilm matrix, Nat. Rev. Microbiol. 8 (9) (2010) 623–633, https://doi.org/10.1038/nrmicro2415.

[22] Jost Wingender, Thomas R. Neu, Hans-Curt Flemming, What are bacterial extracellular polymeric substances? Springer, 1999 https://doi.org/10.1007/978-3-642-60147-7_1.

[23] Chai Siah Lee, John Robinson, Mei Fong Chong, A review on application of flocculants in wastewater treatment, Process. Saf. Environ. Prot. 92 (6) (2014) 489–508, https://doi.org/10.1016/j.psep.2014.04.010.

[24] John Bratby, Coagulation and flocculation in water and wastewater treatment, IWA Publ. (2016), https://doi.org/10.2166/9781780407500.

[25] Mark C.M. van Loosdrecht, Per Halkjær Nielsen, Carlos M. Lopez-Vazquez, Damir Brdjanovic, Experimental methods in wastewater treatment, IWA publishing, 2016, https://doi.org/10.2166/9781780404752.

[26] Xiang Xia, Shuhuan Lan, Xudong Li, Yifei Xie, Yajie Liang, Peihan Yan, Zhengyang Chen, Yunxiao Xing, Characterization and coagulation-flocculation performance of a composite flocculant in high-turbidity drinking water treatment, Chemosphere 206 (2018) 701–708, https://doi.org/10.1016/j.chemosphere.2018.04.159.

[27] TorOve Leiknes, The effect of coupling coagulation and flocculation with membrane filtration in water treatment: a review, J. Environ. Sci. 21 (1) (2009) 8–12, https://doi.org/10.1016/S1001-0742(09)60003-6.

[28] Guo-Ping Sheng, Han-Qing Yu, Xiao-Yan Li, Extracellular polymeric substances (EPS) of microbial aggregates in biological wastewater treatment systems: a review, Biotechnol. Adv. 28 (6) (2010) 882–894, https://doi.org/10.1016/j.biotechadv.2010.08.001.

[29] Thomas Seviour, Nicolas Derlon, Morten Simonsen Dueholm, Hans-Curt Flemming, Elisabeth Girbal-Neuhauser, Harald Horn, Staffan Kjelleberg, Mark C.M. Van Loosdrecht, Tommaso Lotti, M.Francesca Malpei, et al., Extracellular polymeric substances of biofilms: suffering from an identity crisis, Water Res. 151 (2019) 1–7, https://doi.org/10.1016/j.watres.2018.11.020.

[30] Linwei Wu, Daliang Ning, Bing Zhang, Yong Li, Ping Zhang, Xiaoyu Shan, Qiuting Zhang, Mathew Robert Brown, Zhenxin Li, Joy D. Van Nostrand, et al., Global diversity and biogeography of bacterial communities in wastewater treatment plants, Nat. Microbiol. 4 (7) (2019) 1183–1195, https://doi.org/10.1038/s41564-019-0426-5.

[31] Statista, Wastewater generation key facts globally, 2020. https://www.statista.com/statistics/1124488/key-facts-wastewater-generation-globally.

[32] Jeremy S. Guest, Steven J. Skerlos, James L. Barnard, M.Bruce Beck, Glen T. Daigger, Helene Hilger, Steven J. Jackson, Karen Karvazy, Linda Kelly, Linda Macpherson, et al. *A new planning and design paradigm to achieve sustainable resource recovery from wastewater*. 2009. https://doi.org/10.1021/es9010515.

[33] Stanley B. Grant, Jean-Daniel Saphores, David L. Feldman, Andrew J. Hamilton, Tim D. Fletcher, Perran L.M. Cook, Michael Stewardson, Brett F. Sanders, Lisa A. Levin, Richard F. Ambrose, et al., Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability, science 337 (6095) (2012) 681–686, https://doi.org/10.1126/science.1216852.

[34] Xiuhong Zhang, Jie Sun, Xiuxiu Liu, Jiti Zhou, Production and flocculating performance of sludge bioflocculant from biological sludge, Bioresour. Technol. 146 (2013) 51–56, https://doi.org/10.1016/j.biortech.2013.07.036.

[35] Mark C.M. Van Loosdrecht, Damir Brdjanovic, Anticipating the next century of wastewater treatment, Science 344 (6191) (2014) 1452–1453, https://doi.org/10.1126/science.1255183.

[36] Ewa Neczaj, Anna Grosser, Circular economy in wastewater treatment plant–challenges and barriers, in: Proceedings, 2, MDPI, 2018, p. 614, https://doi.org/10.3390/proceedings2110614, 11.

[37] Xiaodi Hao, Xiangyang Wang, Ranbin Liu, Shuang Li, Mark C.M. van Loosdrecht, Han Jiang, Environmental impacts of resource recovery from wastewater treatment plants, Water Res. 160 (2019) 268–277, https://doi.org/10.1016/j.watres.2019.05.068.

[38] Xiaodi Hao, Ji Li, Ranbin Liu, Mark C.M. van Loosdrecht, Resource recovery from wastewater: what, why, and where? Environ. Sci. Technol. 58 (32) (2024) 14065–14067, https://doi.org/10.1021/acs.est.4c05903.

[39] T.T. More, Jay Shankar Singh Yadav, Song Yan, Rajeshwar Dayal Tyagi, Rao Y. Surampalli, Extracellular polymeric substances of bacteria and their potential environmental applications, J. Environ. Manag. 144 (2014) 1–25, https://doi.org/10.1016/j.jenvman.2014.05.010.

[40] Y.M. Lin, K.G.J. Nierop, E. Girbal-Neuhauser, M. Adriaanse, M.C.M. Van Loosdrecht, Sustainable polysaccharide-based biomaterial recovered from waste aerobic granular sludge as a surface coating material, Sustain. Mater. Technol. 4 (2015) 24–29, https://doi.org/10.1016/j.susmat.2015.06.002.

[41] Weiqi Xue, Qian Zeng, Sen Lin, Feixiang Zan, Tianwei Hao, Yuemei Lin, Mark C. M. van Loosdrecht, Guanghao Chen, Recovery of high-value and scarce resources from biological wastewater treatment: sulfated polysaccharides, Water Res. 163 (2019) 114889, https://doi.org/10.1016/j.watres.2019.114889.

[42] Inci Karakas, Stanley B. Sam, Ender Cetin, Ebru Dulekgurgen, Gulsum Yilmaz, Resource recovery from an aerobic granular sludge process treating domestic wastewater, J. Water Process. Eng. 34 (2020) 101148, https://doi.org/10.1016/j.jwpe.2020.101148.

[43] Xingyu Chen, Yu-Jen Lee, Tian Yuan, Zhongfang Lei, Yasuhisa Adachi, Zhenya Zhang, Yuemei Lin, Mark C.M. van Loosdrecht, A review on recovery of extracellular biopolymers from flocculent and granular activated sludges: cognition, key influencing factors, applications, and challenges, Bioresour. Technol. 363 (2022) 127854, https://doi.org/10.1016/j.biortech.2022.127854.

[44] Stanley Bortse Sam, Ebru Dulekgurgen, Characterization of exopolysaccharides from floccular and aerobic granular activated sludge as alginate-like-exoPS, Desalin. Water Treat. 57 (6) (2016) 2534–2545, https://doi.org/10.1080/19443994.2015.1052567.

[45] Mario Pronk, M.K. De Kreuk, B. De Bruin, P. Kamminga, R. van Kleerebezem, M.C. M. Van Loosdrecht, Full scale performance of the aerobic granular sludge process for sewage treatment, Water Res. 84 (2015) 207–217, https://doi.org/10.1016/j.watres.2015.07.011.

[46] M.K. De Kreuk, L.M.M. De Bruin, M.C.M. Van Loosdrecht, Aerobic granular sludge: From idea to pilot plant, Aerob. Granul. Sludge (2005) 111–123, https://doi.org/10.2166/9781780402055.

[47] Yarlagadda V. Nancharaiah, Manjunath Sarvajith, Aerobic granular sludge process: a fast growing biological treatment for sustainable wastewater treatment, Curr. Opin. Environ. Sci. Health 12 (2019) 57–65, https://doi.org/10.1016/j.coesh.2019.09.011.

[48] Nouran T. Bahgat, Philipp Wilfert, Leon Korving, Mark van Loosdrecht, Integrated resource recovery from aerobic granular sludge plants, Water Res. 234 (2023) 119819, https://doi.org/10.1016/j.watres.2023.119819.

[49] P.K. Wilfert, M.C. van Loosdrecht, S. Velasquez Posada, S.J. Picken, C. Chassagne, Y. Lin, A. Raja, G.Y. Kleine, A. Shajimon, L.M. Chen, M.C. van Loosdrecht, Kaumera Methods Manual: A comprehensive guide to lab extraction and characterization methods for extracellular polymeric substances (EPS), Delft University of Technology, 2024.

[50] Ji Li, Xiaodi Hao, Wei Gan, Mark C.M. van Loosdrecht, Yuanyuan Wu, Recovery of extracellular biopolymers from conventional activated sludge: potential, characteristics and limitation, Water Res. 205 (2021) 117706, https://doi.org/10.1016/j.watres.2021.117706.

[51] Nam Kyeun Kim, Ningtao Mao, Richard Lin, Debes Bhattacharyya, Mark C.M. van Loosdrecht, Yuemei Lin, Flame retardant property of flax fabrics coated by extracellular polymeric substances recovered from both activated sludge and aerobic granular sludge, Water Res. 170 (2020) 115344, https://doi.org/10.1016/j.watres.2019.115344.

[52] Simon Felz, Thomas R. Neu, Mark C.M. van Loosdrecht, Yuemei Lin, Aerobic granular sludge contains Hyaluronic acid-like and sulfated glycosaminoglycans-like polymers, Water Res. 169 (2020) 115291, https://doi.org/10.1016/j.watres.2019.115291.

[53] A. Sworska, J.S. Laskowski, G. Cymerman, Flocculation of the Syncrude fine tailings: Part I. Effect of pH, polymer dosage and Mg2+ and Ca2+ cations, In, Int. J. Mineral. Process. 60 (2) (2000) 143–152, https://doi.org/10.1016/S0301-7516(00)00012-0.

[54] Yaguan Ji, Qingye Lu, Qingxia Liu, Hongbo Zeng, Effect of solution salinity on settling of mineral tailings by polymer flocculants, Colloids Surf. A Physicochem. Eng. Asp. 430 (2013) 29–38, https://doi.org/10.1016/j.colsurfa.2013.04.006.

[55] Qiuyi Lu, Bin Yan, Lei Xie, Jun Huang, Yang Liu, Hongbo Zeng, A two-step flocculation process on oil sands tailings treatment using oppositely charged polymer flocculants, Sci. Total. Environ. 565 (2016) 369–375, https://doi.org/10.1016/j.scitotenv.2016.04.192.

[56] Piotr Maćczak, Halina Kaczmarek, Marta Ziegler-Borowska, Recent achievements in polymer bio-based flocculants for water treatment, Materials 13 (18) (2020) 3951, https://doi.org/10.3390/ma13183951.
[57] Paul L.A. Erftemeijer, Roy R. Robin Lewis III, Environmental impacts of dredging on seagrasses: a review, Mar. Pollut. Bull. 52 (12) (2006) 1553–1572, https://doi.org/10.1016/j.marpolbul.2006.09.006.
[58] Victoria L.G. Todd, Ian B. Todd, Jane C. Gardiner, Erica C.N. Morrin, Nicola A. MacPherson, Nancy A. DiMarzio, Frank Thomsen, A review of impacts of marine dredging activities on marine mammals, ICES J. Mar. Sci. 72 (2) (2015) 328–340, https://doi.org/10.1093/icesjms/fsu187.
[59] W. Ali, D. Enthoven, C. Chassagne, R. Helmons, Effect of flocculation on turbidity currents, Front. Earth Sci. 10 (2022) 1014170, https://doi.org/10.3389/feart.2022.1014170.
[60] Fengpeng Zhang, Xuguang Chen, Jinzhong Liu, Yangyang Zhang, A new countermeasure to deep-sea mining sediment plumes: Using flocculant to enhance particles settling, Appl. Ocean. Res. 142 (2024) 103811, https://doi.org/10.1016/j.apor.2023.103811.
[61] Shaheen Akhtar Wahab, Claire Chassagne, Rudy Helmons, 2025, Effect of Flocculation on the Propagation of a Turbidity Current in the Presence of a Bed, In: Available at SSRN 5338378. https://dx.doi.org/10.2139/ssrn.5338378.
[62] G.W. Brindley, 1978, An Introduction to Clay Colloid Chemistry, by H. Van Olphen, John Wiley & Sons, New York, London, Sydney, Toronto, 1977. 318 pp. 39 figures, graphs and tables." In: Clays and Clay Minerals 26.1, pp. 79–79. https://doi.org/10.1346/CCMN.1978.0260111.
[63] Faiza Bergaya and Gerhard Lagaly. *Handbook of clay science*. Newnes, 2013.
[64] Simon Felz, Salah Al-Zuhairy, Olav Andreas Aarstad, Mark C.M. van Loosdrecht, Yue Mei Lin, Extraction of structural extracellular polymeric substances from aerobic granular sludge, JoVE (J. Vis. Exp.) 115 (2016) 54534, https://doi.org/10.3791/54534.
[65] Hendrik Christoffel van de Hulst, Light scattering by small particles, Dover Publications, 1981.
[66] Iztok Dogsa, Manfred Kriechbaum, David Stopar, Peter Laggner, Structure of bacterial extracellular polymeric substances at different pH values as determined by SAXS, Biophys. J. 89 (4) (2005) 2711–2720, https://doi.org/10.1529/biophysj.105.061648.
[67] Ling-Ling Wang, Long-Fei Wang, Xue-Mei Ren, Xiao-Dong Ye, Wen-Wei Li, Shi-Jie Yuan, Min Sun, Guo-Ping Sheng, Han-Qing Yu, Xiang-Ke Wang, pH dependence of structure and surface properties of microbial EPS, Environ. Sci. Technol. 46 (2) (2012) 737–744, https://doi.org/10.1021/es203540w.
[68] A.T. Owen, P.D. Fawell, J.D. Swift, J.B. Farrow, The impact of polyacrylamide flocculant solution age on flocculation performance, Int. J. Min. Process. 67 (1-4) (2002) 123–144, https://doi.org/10.1016/S0301-7516(02)00035-2.
[69] A.T. Owen, P.D. Fawell, J.D. Swift, The preparation and ageing of acrylamide/acrylate copolymer flocculant solutions, Int. J. Min. Process. 84 (14) (2007) 3–14, https://doi.org/10.1016/j.minpro.2007.05.003.
[70] Werner-Michael Kulicke, Reinhard Kniewske, Long-term change in conformation of macromolecules in solution, 2. Poly (acrylamide-co-sodium acrylate) s, In, Die Makromol. Chem. Macromol. Chem. Phys. 182 (8) (1981) 2277–2287, https://doi.org/10.1002/macp.1981.021820817.
[71] Ahmad Shakeel, Zeinab Safar, Maria Ibanez, Leon van Paassen, Claire Chassagne, Flocculation of clay suspensions by anionic and cationic polyelectrolytes: a systematic analysis, Minerals 10 (11) (2020) 999, https://doi.org/10.3390/min10110999.
[72] R. Hogg, The role of polymer adsorption kinetics in flocculation, Colloids Surf. A Physicochem. Eng. Asp. 146 (1-3) (1999) 253–263, https://doi.org/10.1016/S0927-7757(98)00723-7.
[73] J.J.V.S. Madejová, FTIR techniques in clay mineral studies, Vib. Spectrosc. 31 (1) (2003) 1–10, https://doi.org/10.1016/S0924-2031(02)00065-6.
[74] Victor Ajao, Harry Bruning, Huub Rijnaarts, Hardy Temmink, Natural flocculants from fresh and saline wastewater: comparative properties and flocculation performances, Chem. Eng. J. 349 (2018) 622–632, https://doi.org/10.1016/j.cej.2018.05.123.
[75] Chao Guo, Leicheng Guo, Sarah Bass, Andrew J. Manning, Zhongwu Jin, Yinjun Zhou, On the role of organic matter composition in fresh-water kaolinite flocculation, J. Environ. Manag. 345 (2023) 118576, https://doi.org/10.1016/j.jenvman.2023.118576.
[76] Zhirui Deng, Qing He, Andrew J. Manning, Claire Chassagne, A laboratory study on the behavior of estuarine sediment flocculation as function of salinity, EPS and living algae, Mar. Geol. 459 (2023) 107029, https://doi.org/10.1016/j.margeo.2023.107029.
[77] Ruben Snellings, Özlem Cizer, Liesbeth Horckmans, Paweł.T. Durdziński, Philippe Dierckx, Peter Nielsen, Koenraad Van Balen, Lucie Vandewalle, Properties and pozzolanic reactivity of flash calcined dredging sediments, Appl. Clay Sci. 129 (2016) 35–39, https://doi.org/10.1016/j.clay.2016.04.019.