Flocculation Performance of Industrial Sugarcane Juice by Acrylamide-Based Anionic Flocculant

Eva Oktavia Ningrum[1*], Agung Subyakto[1], Wirawan Ciptonugroho[2], Shania Lorensa[1], Devianti Anggraini Ramadhani[1], and Agus Surono[1]

[1]*Department of Industrial Chemical Engineering, Faculty of Vocational Studies, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya, 60111, Indonesia*

[2]*Department of Chemical Education, Faculty of Teacher Training and Education, Universitas Sebelas Maret, Jl. Ir. Sutami 36A, Kentingan, Surakarta 57126, Indonesia*

* ***Corresponding author:***

email: eva-oktavia@chem-eng.its.ac.id

Received: February 19, 2022
Accepted: December 24, 2022

DOI: 10.22146/ijc.73150

Abstract: *Despite the widespread use of ionic polymer flocculants in sugar refineries, there is still insufficient knowledge on the relationship between the polymer properties and the efficiency of flocculation. This paper describes the performance of poly(sodium acrylate-co-acrylamide) (poly(SA-co-AAm)) as an anionic flocculant in the flocculation–coagulation of sugarcane juice from the sugar factory Gempolkrep PTPN X Mojokerto. Poly(SA-co-AAm) was successfully prepared via free radical polymerization of sodium acrylate and acrylamide with respective molar ratios of 40:60, 50:50, and 60:40, and compared with the commercial flocculant Accofloc. It was found that the mud height of the sugarcane decreased with increasing SA:AAm ratio. However, mud height increase was observed with further increasing SA:AAm ratio. Furthermore, increasing the flocculant dosage did not induce any significant change in the mud height and pH. The total dissolved solids (TDS) significantly decreased when the ratio of sodium acrylate:acrylamide was changed from 40:60 to 50:50, whereas a further change to 60:40 increased the TDS value again. It is also noticed that the tendency of turbidity is consistent with the TDS value. These results demonstrate that poly(SA-co-AAm) is a feasible alternative to the commercial flocculant owing to its good flocculation–coagulation performance with an optimum SA:AAm ratio of 50:50.*

Keywords: *flocculation; flocculant; polymers; sugarcane*

■ INTRODUCTION

Sugarcane is a primary raw material for the production of high-purity sucrose, which is vastly used in daily consumption and the food industry. In addition, sugar and sugarcane production plays an important role in the rural economy through agricultural income, job creation, and support for the rural economy [1]. In Indonesia, the demand for raw sugar for food and beverages is continuously increasing; in 2017, 6.32 million tons of sugar were consumed, and the demand increased by 6% in 2018 [2]. With an annual population growth of 1.3%, the growth in sugar consumption has averaged 4.3% per year since 2008, which has resulted in a large gap between production and sugar demand. The current sugar production in the form of white crystal sugar shows a deficit of 100,000 to 300,000 tons per year or 3 to 10% of consumption. As a result, Indonesia became the world's largest sugar importer in 2017–2018 with 4.45 million tons imported [3].

Sugarcane is first milled after being harvested to collect the primary juice, which is further processed to obtain sucrose as the final product. Sugarcane juice is a complex liquid medium that contains many insoluble and suspended organic and inorganic constituents in a colloidal solution. This colloid is composed of sucrose (810–870 g/kg Brix), reducing sugar (30–60 g/kg Brix), oligosaccharides (0.6–6 g/kg Brix), polysaccharides including gums and dextrans (2–8 g/kg Brix), inorganic salts (15–37 g/kg Brix), organic non-sugar substances (16.8–52 g/kg Brix), and insolubles (1.5–10 g/kg Brix) [4]. Apart from sucrose, the other constituents must be removed to obtain a refined juice with low turbidity [5]. The removal of suspended solids and non-sucrose impurities can be achieved by clarification [6-7]. Clarification can be conducted by adding lime milk ($Ca(OH)_2$) followed by passing SO_2 (sulfidation) or CO_2 gas (carbonation) through the juice to generate insoluble calcium phosphate flocs ($Ca_3(PO_4)_2$), which can be readily separated by decantation. Decantation can also facilitate the formation of phosphate flocs by adding lime (CaO) to adjust the pH of the juice heated at 75 °C to 7.8 and boiling the limed juice [8]. It has been reported that the settling rate and the strength of the flocs formed can be accelerated by introducing an anionic copolymer [9-10]. Copolymers are also known to accelerate the flocs enlargement, leading to faster precipitation [11].

Anionic acrylamide copolymer flocculants are charged copolymers due to the presence of carboxylate, sulfonate, or phosphonate functional groups [12-13] These copolymers can be prepared by copolymerizing acrylamide with another vinyl-type monomer bearing the corresponding functional groups or with another chemically modified polyacrylamide [14]. Six different polymerization approaches can be applied to synthesize anionic polyacrylamide (APAM), i.e., homopolymerization posthydrolysis, homopolymerization cohydrolysis, copolymerization, inverse emulsion polymerization, precipitation polymerization, and radiation polymerization [15-17]. The flocculant properties of the obtained APAM, including reactivity, hydrophobicity or hydrophilicity, and formation of hydrogen bonds, depending on the constituent monomers. The solution pH also affects the formation and reactivity of flocculant molecules. The intrinsic viscosity and solubility properties, which determine the molecular weight of APAM, are the most critical parameters during polymerization [18]. The APAM chains stretched under high charge densities induce an increase in the adsorption capacity and bridging effects that contribute to the efficient removal of organic particles. A combination of P_2O_5 and APAM flocculant has been shown to efficiently improve the clarification of sugarcane juice [19]. Doherty et al. showed that the combination of acrylamide copolymers and quaternary ammonium compounds of trimethylammonium ethyl methacrylate (TMAEMAC) or cationic trimethylammonium ethyl acrylate chloride copolymers are more effective in flocculating sugarcane juice than TMAEMAC homopolymers [11]. The patch charge mechanism responsible for the residual turbidity in clarified juice using an anionic flocculant is minor and has a high negative charge. Six different starch-based anionic copolymers were synthesized and tested by Khalil and Aly [20] as flocculants in ferric laurate suspensions, finding that the flocculation performance of the copolymers was determined by the type of acid groups, the length of the alkyl chain bearing the carboxyl group, the chemical structure of the flocculant, the flocculant molar mass, and the pH of the suspension. In cane sugar juice, binding of copolymer microflocs most likely proceeds primarily by the attraction of the negatively charged acrylate groups to dipositive ionic bridges (e.g., Ca^{2+}), which are adsorbed to negative charges on the microfloc particles. However, it is still possible that they may proceed by two other mechanisms i.e., attraction of the negatively charged acrylate groups to positive charges on the surface of the microfloc particles and hydrogen or dipolar bonding between the acrylamide groups and the microfloc particles [21-25].

Although ionic polymer flocculants are essential in the sugar refinery, systematic studies to correlate the polymer properties and the efficiency in the flocculation have rarely been reported. With this aim, this paper describes the synthesis and characterization of different poly(sodium acrylate-*co*-acrylamide)s (poly(SA-*co*-AAm)s) as flocculating agents. Since ionic content is one of the most important parameters that affect flocculation performance, knowledge of the acrylamide/acrylate ratio in these copolymers is a subject of interest. Therefore, the performance of the copolymers to settle sugarcane juice collected from a sugar refinery in various acrylamide/acrylate ratios is evaluated by means of the floc settling rate and size, turbidity analysis, total dissolved solids (TDS), and final pH.

■ EXPERIMENTAL SECTION

Materials

Acrylamide 99%, acrylic acid 99%, and ammonium persulfate > 98% were purchased from Sigma Aldrich Co. USA, and were used without any further modifications. Sodium acrylate (NaAc) was prepared by neutralization of acrylic acid (AAm) with 12 mL of 2 N NaOH solution by the addition of active carbon (PT. Mapalus Makawanua Charcoal Industry) and 5 g of sodium carbonate (Na_2CO_3, Merck, Germany). A clear solution of sodium acrylate was obtained for further synthesis of poly(SA-*co*-AAm). All materials were used as received. Distilled water was used throughout all experiments.

Instrumentation

Scanning electron microscopy (SEM)

The surface morphology of acrylamide, acrylic acid, and the poly(SA-*co*-AAm) flocculant samples was observed using a scanning electron microscope (HITACHI, FLEXSEM 1000, Japan).

Fourier transform infrared (FTIR) spectroscopy

The functional groups of acrylamide, sodium acrylate, and the poly(SA-*co*-AAm) flocculant samples with various concentrations were identified using FTIR spectroscopy. The FTIR spectra were obtained using a 550 Series II IR spectrometer (METTLER TOLEDO Instrument Co., Ltd., Switzerland) in a range of 500–4000 cm^{-1} by using ATR method.

Proton nuclear magnetic resonance (1H-NMR) spectroscopy

^{1}H-NMR spectroscopy (MR400 DD2, Agilent, USA) was employed to determine the chemical structure of the poly(SA-*co*-AAm) gel. To measure the spectra, the gels (20 mg) were dissolved in 1 mL of D_2O as a solvent.

Procedure

The preparation of the anionic flocculant poly(SA-*co*-AAm) consisted of two consecutive steps, i.e., the synthesis of sodium acrylate followed by the synthesis of poly(SA-*co*-AAm). For the first step, 8.8 mg of sodium carbonate (Na_2CO_3), 5 g of activated carbon, and 3.170 g of acrylic acid were charged into a glass beaker. Subsequently, 12 mL of 2 N NaOH was added to neutralize the acrylic acid and to generate sodium acrylate. The resulting product mixture was filtered to obtain a clear solution of sodium acrylate. Next, the as-obtained sodium acrylate was mixed with 4.69 g of acrylamide and 30 mL of distilled water in a three-necked round bottom flask. After a homogeneous solution was obtained, the solution was purged with N_2 gas and then heated to 50 °C. Subsequently, 0.03 g of ammonium persulfate was introduced as an initiator to conduct the free radical polymerization reaction for 3 h under an N_2 atmosphere. Once the reaction was completed, a transparent polymer was obtained with a 95% yield. The polymer product was then collected and washed three times with 100 mL of ethanol. The polymer was then dried in an oven at 50 °C for three days. Following this procedure, three different samples of poly(SA-*co*-AAm) were prepared using initial concentration ratios of sodium acrylate and acrylamide of 40:60, 50:50, and 60:40.

Analysis of coagulation–flocculation

The coagulation-flocculation experiments were performed using a conventional jar apparatus or flocculator (VELP Scientifica Srl, Flocculator JLT6, Italy). This apparatus allowed four beakers to be agitated simultaneously. Meanwhile, sugarcane juice was provided by the Gempolkrep Mojokerto (PTPN X) sugar factory located in East Java, Indonesia which was taken before entering the clarifiers. This sugarcane juice's maximum $Ca(OH)_2$ content is 1200 ppm. For each test, 1000 mL of sugar juice was charged into a glass beaker. The juice was subsequently heated to 70 °C followed by the addition of the anionic flocculant at various concentrations and dosages (0, 2, 4, and 6 ppm). Stirring at 120 rpm for 1 min (rapid stirring) was applied to promote the coagulation process. After 15 min, the stirring rate was lowered to 10 rpm. Subsequently, the beakers were carefully removed from the flocculator, and the flocs were allowed to settle for a certain time (0–60 min) before the analysis. To provide a comparison, commercial flocculant Accofloc was used as a reference. The most commonly used anionic flocculant with high molecular weight in sugar factories in Indonesia is

Accofloc A-110. The chemical constituent of this flocculant is anionic polyacrylamide.

Analysis of TDS

The TDS of sugarcane juice was determined by performing three repetitions for each sodium acrylate to acrylamide ratio. The flocculant-treated sugar juice (50 mL) was placed into an Erlenmeyer, and the TDS was measured using a conductivity meter (Eutech Instrument, CON 700, Singapore).

Analysis of turbidity

The juice turbidity is a valuable parameter to determine the effectiveness of the clarification process. Therefore, the turbidity of the sugarcane juice was measured before and after adding the poly(SA-*co*-AAm) flocculant using a turbidimeter (Eutech Instruments, TN-100, Singapore) and repeated three times.

Analysis of pH

The pH was measured using a pH meter (Trans Instruments, BP3001, Singapore) before and after adding the poly(SA-*co*-AAm) flocculant.

■ RESULTS AND DISCUSSION

Investigation of the Surface Morphology by SEM

Fig. 1 presents an SEM micrograph with 500× magnification showing the surface morphology of the three poly(SA-*co*-AAm) samples, in which clear differences with the commercial flocculant Accofloc can be observed. Thus, at a low concentration of sodium acrylate compared with that of acrylamide, the morphology surface appears flat, and neither aggregation nor pores are observed (Fig. 1(a)). With increasing the sodium acrylate concentration to a sodium acrylate:acrylamide ratio of 50:50, the surface morphology remains flat (Fig. 1(b)). However, upon further increasing the ratio to 60:40, a layer and fold region on the surface with some holes is observed (Fig. 1(c)). By further increasing the concentration of the sodium acrylate:acrylamide ratio up to 80:20 (data is not shown) the pores are clearly observed throughout the surface of the synthesized flocculant. In contrast, the SEM image of Accofloc shows aggregation (Fig. 1(d)).

Identification of the Functional Groups by FTIR Spectroscopy

FTIR spectroscopy was performed to identify the functional groups present in poly(SA-*co*-AAm), and the corresponding spectra are displayed in Fig. 2. In the spectrum of sodium acrylate, the bands at 1694.01, 1634.45, and 1429.86 cm^{-1} correspond to the C=O groups of acrylic acid, the OH of water, and the COO^{-} groups of

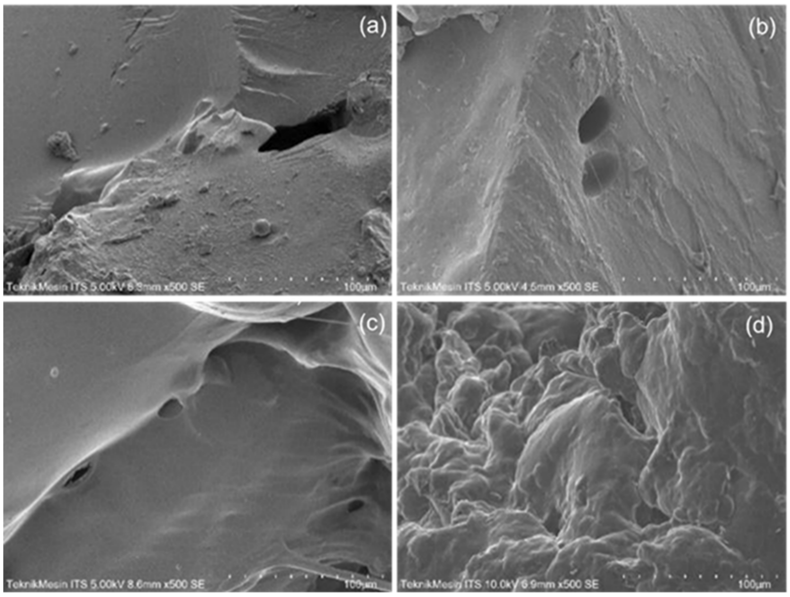


Fig 1. Scanning electron microscopy micrographs of poly(sodium acrylate-*co*-acrylamide) prepared with acrylic acid and acrylamide monomer ratios of (a) 40:60, (b) 50:50, and (c) 60:40 and (d) commercial flocculant Accofloc

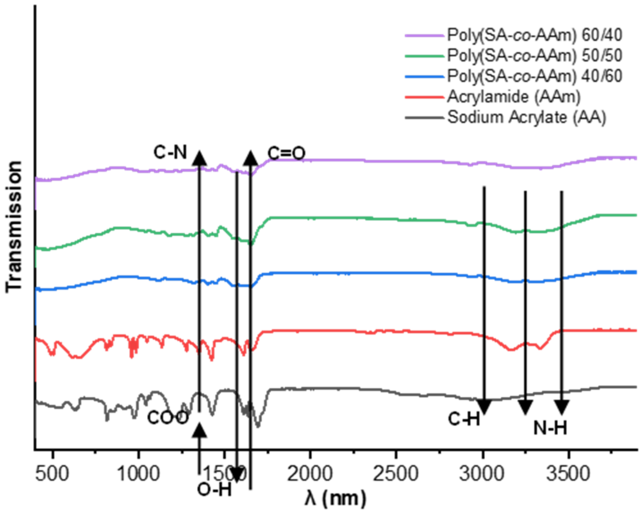


Fig 2. Fourier transform infrared spectra of sodium acrylate, acrylamide, and poly(sodium acrylate-*co*-acrylamide) (poly(SA-*co*-AAm)) samples prepared with sodium acrylate:acrylamide ratios of 40:60, 50:50, and 60:40

acrylate, respectively. In the spectrum of acrylamide, the bands at 3333.46 and 3164.33 cm^{-1} correspond to the NH_2 group, and the band at 2812.07 cm^{-1} indicates the presence of CH and CH_2 groups. The C=O groups and OH of water give rise to bands at 1651.91 and 1610.73 cm^{-1}, respectively. The slight difference of OH in various concentrations indicate the presence of adsorbed water as a solvent detected in the measurement. N–H bond corresponds to the characteristic of the acrylamide unit, with increasing SA to AAm ratio compared to the band of pure Acrylamide (red line) the peak appears weakened. On the contrary, the C-H bond attributes to the sodium acrylate unit which appears sharper and clearly observed with increasing SA to AAm ratio.

In addition, the CN groups of acrylamide produce a band at 1424.54 cm^{-1} [26]. Meanwhile, the spectra of the poly(SA-*co*-AAm) samples with a monomer ratio of 40:60, 50:50, and 60:40 show the bands corresponding to the N–H bond of the acrylamide unit at 3178.85, 3338.26, and 3337.80 cm^{-1}, respectively, and those attributable to the CH and CH_2 groups appear at 2894.269, 2929.05, and 2923.92 cm^{-1}, respectively. Moreover, the bands of the C=O groups of acrylamide and the OH of water are superposed, appearing at 1651.85, 1648.18, and 1654.59 cm^{-1}, respectively. The presence of the COO^- groups of sodium acrylate or CN groups of acrylamide is evidenced by the peaks at 1444.85, 1448.81, and 1448.46 cm^{-1}, respectively. The blue line shows that poly(SA-*co*-AAm) samples with a monomer ratio of 40:60 have a lower and weak band at 1600 cm^{-1} compared to other concentrations. This indicates that the small fraction of the COOH group of acrylic acid during its reaction with NaOH is not completely neutralized while forming the sodium acrylate.

Confirmation of the Chemical Structure by ^{1}H-NMR Spectroscopy

^{1}H-NMR spectra were recorded to confirm the chemical structure of the resulting copolymers. Fig. 3 shows the spectrum of the copolymer prepared with a sodium acrylate:acrylamide ratio of 40:60. Two distinct broad peaks are observable in the regions of 1.23–1.86 and 1.97–2.36 ppm. These two ^{1}H-NMR signals can be ascribed to the presence of protons associated with $-CH(CONH_2)-$and $-CH_2-$groups, respectively, and are indicative of the formation of single bonds connecting the monomers to create a copolymer backbone. Mansri et al. reported a similar feature in the ^{1}H NMR spectra of polyacrylamide prepared via radical copolymerization in an aqueous solution, in which two multiplets appeared at 1.4–1.8 and 2–2.4 ppm [27]. For sodium acrylate, the proton bonded to the secondary carbon resonates at around 1.5–2.0 ppm, whereas the proton attached to the tertiary carbon gives rise to a peak at 2.38 ppm. In the present work, the $-CH_2-$signal attributed to acrylate in the copolymer is hard to identify due to its overlap with the predominant peak of polyacrylamide. Nevertheless, the presence of the CH group from sodium polyacrylate is evidenced by the appearance of a weak peak at around 2.55 ppm. According to this result, the polyacrylamide segment is more predominant in the copolymer, which is expected considering the initial sodium acrylate:acrylamide monomer ratio. In addition, the spectrum around 3.6 ppm (multiplet) and around 1.1 ppm (triplet) appear because the copolymers are not pure compounds but show a broad molar weight distribution and possibly due to impurities in the comonomer.

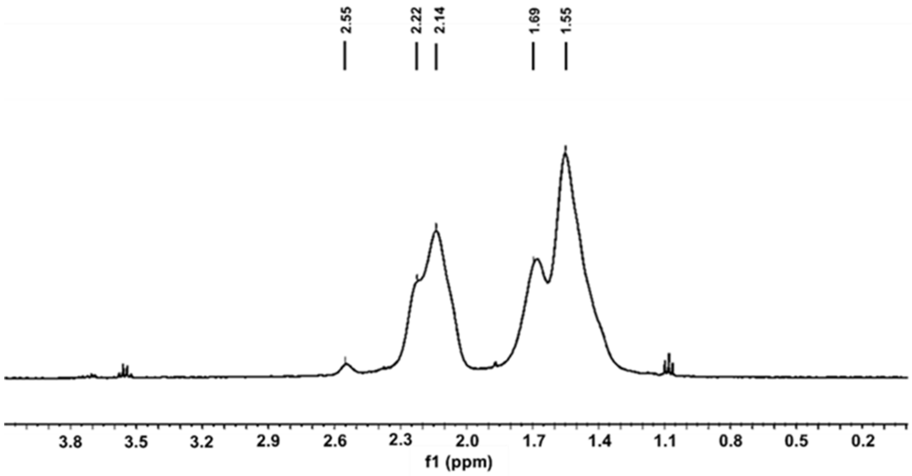
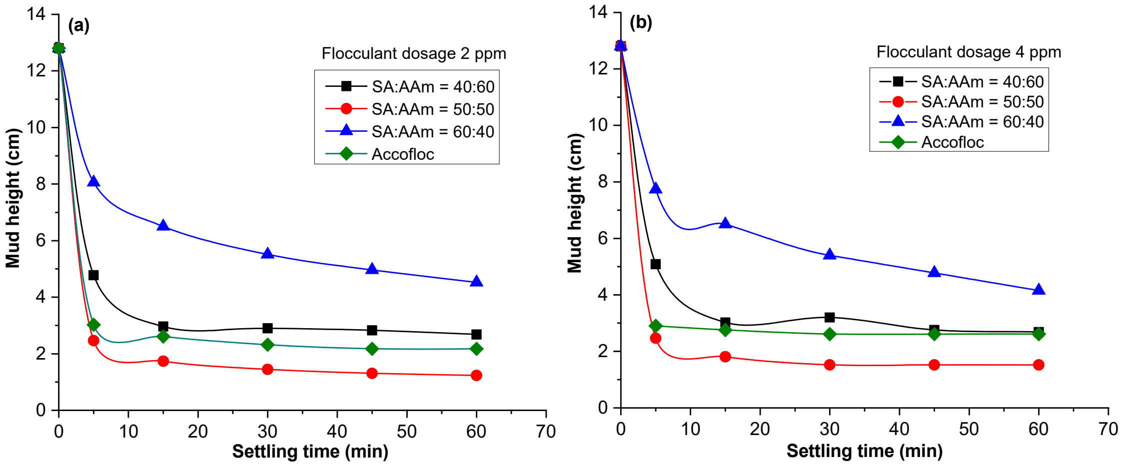


Fig 3. ^{1}H-Nuclear magnetic resonance spectra of poly(sodium acrylate-*co*-acrylamide) prepared with a sodium acrylate:acrylamide ratio of 40:60

Influence of Monomer Concentration of Flocculants on Mud Height

It is noteworthy that the shrinking volume of the settling with time could be attributed to the filling of the cavities between flocs leading to the sediment with a more compact arrangement. Fig. 4 shows the change in the mud height with time at various flocculant dosages and monomer ratios. Compared to the commercial flocculant of Accofloc, the mud heights were larger with the introduction of the copolymer flocculant. In general, at any dosage and at a lower settling time from 0–20 min, the concentration of SA in poly(SA-*co*-AAm) significantly influenced the initial mud height. For instance, at a flocculant concentration of 2 ppm, the mud volume decreased along with the intensified SA:AAm ratio from 40:60 to 50:50 ppm, which is caused by the decrease in the size of the cavities between flocs, shortening the distance between flocs as a result rendering them more compact. However, an appreciable increase in mud height was observable when increasing the SA:AAm ratio to 60:40; the mud height tends to increase significantly. This volume enlargement is caused by the formation of bigger flocs at a higher SA ratio and the presence of nonuniform cavities between the flocs. Higher floc formed with the presence of sufficiently high anion concentration required to facilitate the bridging [28]. Bridging is one of the flocculation mechanisms occurring when using a polymer flocculant, and the preferred one for polymers with long chains.

Fig. 4 also indicates that after 30 min, in all flocculant



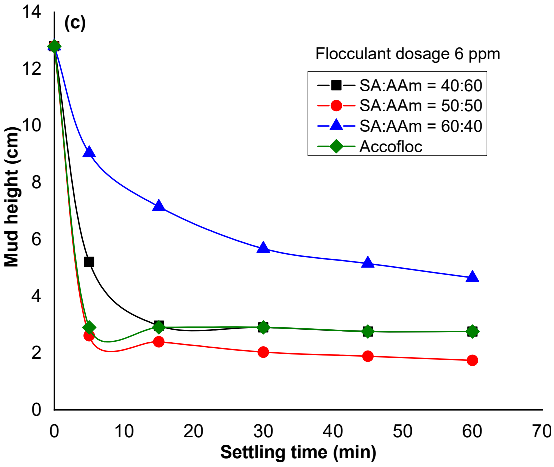


Fig 4. Effect of monomer concentration on the mud height upon addition of poly(sodium acrylate-*co*-acrylamide) dosage (a) 2 ppm, (b) 4 ppm, and (c) 6 ppm in comparison with commercial flocculant

dosage, the highest mud height was obtained when using poly(SA-*co*-AAm) with a monomer ratio of 60:40. Moreover, the commercial flocculant of Accofloc and flocculant with SA:AAm of 40:60 displayed a similar mud volume throughout the settling time and flocculant dosage. Furthermore, the effect of flocculant dosage was also investigated, suggesting a relatively insignificant improvement in the resulting mud heights. These results imply that the loading of SA in the copolymer is more essential to initiate the formation of larger flocs leading to a greater volume of the sediment.

The Influence of SA Content and Flocculant Dosage on the Acidity of Sugarcane Juice

Fig. 5 presents the change in the pH of the sugarcane juice with the flocculant dosage at various monomer ratios. Generally, the increase in the flocculant dosage decreased the pH value of the sugarcane juice. Moreover, the pH decreased gradually with increasing monomer ratio from 40:60 to 50:50, whereas it increased slightly with a further increase in the monomer ratio to 60:40. The addition of the commercial flocculant Accofloc also decreased the pH.

The increase in the poly(SA-*co*-AAm) dosage decreased the pH value. In the absence of a flocculant, the pH was 7.34. Meanwhile, when the flocculant was added, no drastic decrease was found on pH since the alkaline concentration provided was sufficient. In this case, FTIR has previously stated that only a small fraction of the COOH group of acrylic acid neutralized NaOH while forming the sodium acrylate. Therefore, the decrease in the pH value did not significantly affect the sugarcane juice. After the addition of the flocculant, the sugarcane juice had a pH of 7.14–7.34. This value is within the optimal pH range for the sugarcane juice purification process in the sugar factory, which is 7–7.3.

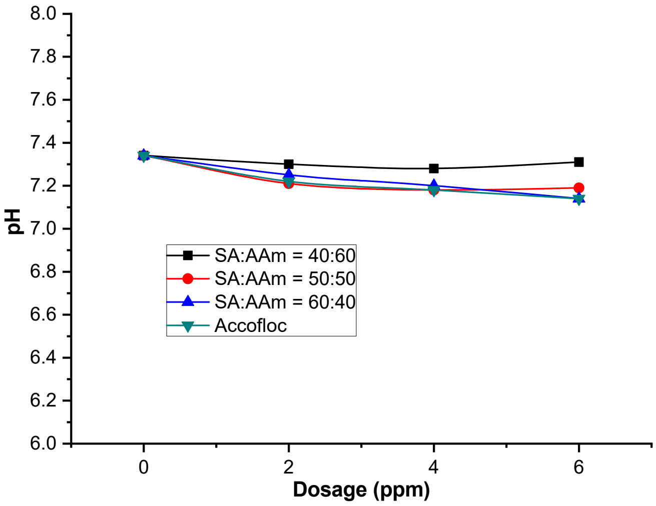


Fig 5. Effect of the flocculant dosage on the pH of a sugarcane juice suspension

Analysis of TDS

The TDS of flocculant with altered monomer ratios and different dosages is given in Fig. 6. The introduction of flocculant with 40:60 SA:AAm ratio insignificantly reduced the TDS at any given dosage.

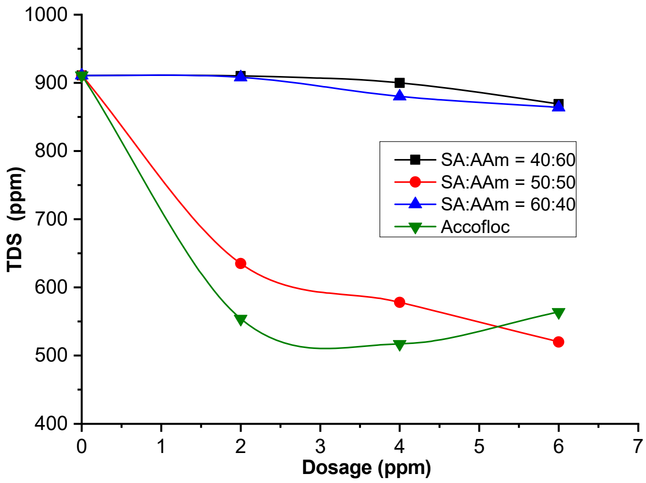


Fig 6. Effect of the flocculant dosage on total dissolved solids (TDS)

A remarkable TDS reduction was achieved once a higher SA:AAm ratio of 50:50 was applied to the sugarcane suspension. At this ratio, the TDS consistently declined from 900 to 520 ppm along with the enriched dosage from 0 to 6 ppm, respectively. Further enrichment of SA:AAm ratio to 60:40 increased the TDS again resembling the resulting TDS from SA:AAm ratio of 40:60. In fact, the SA:AAm ratio can be associated with the concentration of Na^+ cation in the suspension. This can be explained by the fact that an increase in the sodium acrylate concentration increases the number of flocs formed; however, an excessive amount of flocs may cause a collision between aggregated particles, which would then redisperse in the suspension, as previously reported by Mishra et al. [29] and Chan and Chiang [30]. It has been reported by Chan and Chiang [30] that on one hand, the Na^+ cation in the suspension could suppress the electric double layer of a particle favorable to the formation of larger flocs, but on the other hand, the excessive amounts of cations would resist the expansion of polymer chain unfavorable for bridging the interparticle. The minor influence of flocculant dosing at SA:AAm ratio of 40:60 could be reasoned by the insufficient cations available to initiate the flocculation. Meanwhile, the presence of Na^+ became too much at the highest monomer ratio of 60:40 preventing the generation of larger flocs. Furthermore, the addition of 2 ppm Accofloc depressed the TDS as low as 454 ppm before it gradually increased from 517 to 564 ppm following the introduction of the Accofloc from 4 to 6 ppm, respectively. According to Mishra et al., an increase in the flocculant dosage in a sugarcane juice suspension promotes the attraction among impurities and eventually reduces the concentration of dissolved solids in the suspension [29].

Suspension Turbidity

Fig. 7 illustrates the effect of the poly(SA-*co*-AAm) dosage and monomer ratio on the turbidity. In general, the turbidity fell significantly following the addition of the flocculant at 2 ppm because the impurities in the sugarcane juice were adsorbed by the flocculants leading to the precipitation. Furthermore, the turbidity remained constant as the dosage was intensified from 2 to 6 ppm. The addition of flocculants can adsorb the impurities enabling the formation of greater particles. Nevertheless, excessive addition of flocculants may cover the previously formed particles initiating particle redispersion and hindering the formation of larger flocs.

Furthermore, the influence of different flocculants on turbidity was also studied. At any given dosage, the turbidity declined with the increase of the SA:AAm ratio from 40:60 to 50:50. The result was in good agreement with previous studies on phosphate and anionic polyacrylamide flocculant (APF) for sugar cane juice clarification. Further enrichment of the SA ratio to 60:40

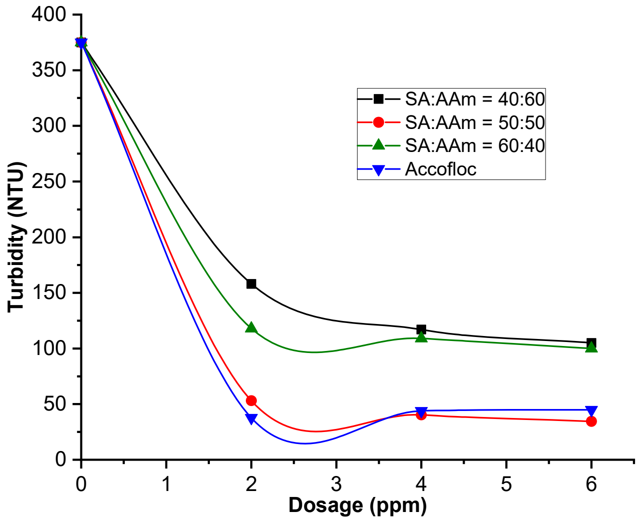


Fig 7. Effect of the flocculant dosage on the turbidity of a sugarcane juice suspension

gave rise to the turbidity as high as copolymer with SA:AAm ratio of 40:60. This also implies that the optimum ratio of 50:50 is responsible for the lowest turbidity of the suspension. The presence of an optimum ratio is due to the copolymer with 50:50 ratio that could provide a sufficient anion concentration for the flocculation without excessively covering the formed particles and bringing about their redispersion in the suspension. Moreover, the turbidity of Accofloc resembled that of the poly(SA-*co*-AAm) with 50:50 ratio. This infers that the SA-*co*-AAm with optimized SA:AAM ratio could assist flocculation as efficiently as the commercial flocculant.

It is noticed that the tendency of turbidity in this figure is also consistent with the TDS result as shown in Fig. 6. Total dissolved solids (TDS) contribute to the measurement of turbidity. The lower the TDS, the less turbidity of the supernatant since most of the particle settled as a consequence of the mud height increase.

■ CONCLUSION

Poly(SA-*co*-AAm) was successfully synthesized as an anionic flocculant for sugarcane juice from sugar factories owned by PT. Perkebunan Nusantara (PTPN) Indonesia. FTIR and NMR analysis showed that the anionic flocculant poly(SA-*co*-AAm) contained all the expected constituent monomer groups. Compared to the commercial flocculant of Accofloc, the mud heights were found to be larger with the introduction of the copolymer flocculant. In general, at any dosage and at a lower settling time from 0–20 min, the concentration of SA in poly(SA-*co*-AAm) significantly influenced the initial mud height. The mud volume decreased along with the intensified SA:AAm ratio from 40:60 to 50:50 ppm. However, an appreciable increase in mud height was observable when increasing SA:AAm ratio to 60:40; the mud height tends to increase significantly. The poly(SA-*co*-AAm) increase caused an insignificant decrease in the pH value and mud height. Concerning the TDS value, a significant decrease was observed upon increasing the sodium acrylate:acrylamide ratio from 40:60 to 50:50, whereas further increase in the monomer ratio to 60:40 increased the TDS value again. Overall, the poly(SA-*co*-AAm) flocculant obtained with a sodium acrylate: acrylamide ratio of 50:50 and a dosage of 6 ppm afforded better results than the commercial flocculant with a dosage of 4 ppm. Although 6 ppm is a relatively higher dosage than that commonly used in sugar plants, this result demonstrates that poly(SA-*co*-AAm) can effectively replace the commercial flocculant due to its good flocculation–coagulation performance. Future work will focus on investigating the flocculation–coagulation performance of poly(SA-*co*-AAm) with a wider range of monomer ratios for the clarification of sugarcane juice.

■ ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the Institut Teknologi Sepuluh Nopember for this work, under the project scheme of the Publication Writing and IPR Incentive Program (PPHKI) 2022.

■ AUTHOR CONTRIBUTIONS

Shania Lorensa and Devianti Anggraini Ramadhani conducted the experiment, Agung Subyakto and Agus Surono conducted the data calculations. Eva Oktavia Ningrum and Wirawan Ciptonugroho wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

■ REFERENCES

[1] Nandhini, T.S.K.D., and Padmavathy, V., 2017, A study on sugarcane production in India, *Int. J. Adv. Res. Bot.*, 3 (2), 13–17.

[2] Reuters, 2017, *Indonesia Raw Sugar Consumption for Food, Beverages Seen Edging up in 2018*, https://www.reuters.com/article/indonesia-sugar-idUSJ9N1I400Q, accessed on February 10, 2022.

[3] Sulaiman, A.A., Sulaeman, Y., Mustikasari, N., Nursyamsi, D., and Syakir, A.M., 2019, Increasing sugar production in Indonesia through land suitability analysis and sugar mill restructuring, *Land*, 8 (4), 61.

[4] Xiao, Z., Liao, X., and Guo, S., 2017, Analysis of sugarcane juice quality indexes, *J. Food Qual.*, 2017, 1746982.

[5] de Mello, M.L., Barros, N.Z., Sperança, M.A., and Pereira, F.M.V., 2022, Impurities in raw sugarcane before and after biorefinery processing, *Food Anal. Methods*, 15 (1), 96–103.

[6] Meng, Y., Yu, S., Qiu, Z., Zhang, J., Wu, J., Yao, T., and Qin, J., 2021, Modeling and optimization of sugarcane juice clarification process, *J. Food Eng.*, 291, 110223.

[7] Umesh Kumar, P.K., and Chand, K., 2015, Application of response surface method as an experimental design to optimize clarification process parameters for sugarcane juice, *J. Food Process. Technol.*, 6 (2), 1000422.

[8] Shi, C., Rackemann, D.W., Moghaddam, L., Wei, B., Li, K., Lu, H., Xie, C., Hang, F., and Doherty, W.O.S., 2019, Ceramic membrane filtration of factory sugarcane juice: Effect of pretreatment on permeate flux, juice quality and fouling, *J. Food Eng.*, 243, 101–113.

[9] Dao, V.H., Mohanarangam, K., Fawell, P.D., Simic, K., Iyer, R., Cameron, N.R., and Saito, K., 2020, Enhanced flocculation efficiency in a high-ionic-strength environment by the aid of anionic ABA triblock copolymers, *Langmuir*, 36 (6), 1538–1551.

[10] Deniz, V., 2015, Dewatering of barite clay wastewater by inorganic coagulants and co-polymer flocculants, *Physicochem. Probl. Miner. Process.*, 51 (1), 351–364.

[11] Doherty, W.O.S., Fellows, C.M., Gorjian, S., Senogles, E., and Cheung, W.H., 2003, Flocculation and sedimentation of cane sugar juice particles with cationic homo- and copolymers, *J. Appl. Polym. Sci.*, 90 (1), 316–325.

[12] Bakir, H., Denman, J.A., and Doherty, W.O.S., 2020, Slow settling behaviour of soil nano-particles in water and synthetic sugarcane juice solutions, *J. Food Eng.*, 279, 109978.

[13] Guan, G., Gao, T., Wang, X., and Lou, T., 2021, A cost-effective anionic flocculant prepared by grafting carboxymethyl cellulose and lignosulfonate with acrylamide, *Cellulose*, 28 (17), 11013–11023.

[14] Rabiee, A., 2010, Acrylamide-based anionic polyelectrolytes and their applications: A survey, *J. Vinyl Addit. Technol.*, 16 (2), 111–119.

[15] Zheng, H., Ma, J., Ji, F., Tang, X., Chen, W., Zhu, J., Liao, Y., and Tan, M., 2013, Synthesis and application of anionic polyacrylamide in water treatment: A review, *Asian J. Chem.*, 25 (13), 7071–7074.

[16] Ma, J., Zheng, H., Tan, M., Liu, L., Chen, W., Guan, Q., and Zheng, X., 2013, Synthesis, characterization, and flocculation performance of anionic polyacrylamide P (AM-AA-AMPS), *J. Appl. Polym. Sci.*, 129 (4), 1984–1991.

[17] Feng, L., Zheng, H., Gao, B., Zhang, S., Zhao, C., Zhou, Y., and Xu, B., 2017, Fabricating an anionic polyacrylamide (APAM) with an anionic block structure for high turbidity water separation and purification, *RSC Adv.*, 7 (46), 28918–28930.

[18] Zheng, H., Ma, J., Zhu, C., Zhang, Z., Liu, L., Sun, Y., and Tang, X., 2014, Synthesis of anion polyacrylamide under UV initiation and its application in removing dioctyl phthalate from water through flocculation process, *Sep. Purif. Technol.*, 123, 35–44.

[19] Mohammed, H., Solomon, W.K., and Bultosa, G., 2016, Optimization of phosphate and anionic polyacrylamide flocculant (APF) level for sugar cane juice clarification using central composite design, *J. Food Process. Preserv.*, 40 (1), 67–75.

[20] Khalil, M.I., and Aly, A.A., 2002, Preparation and evaluation of some anionic starch derivatives as flocculants, *Starch-Stärke*, 54 (3-4), 132–139.

[21] Shen, C.C., Petit, S., Li, C.J., Li, C.S., Khatoon, N., and Zhou, C.H., 2020, Interactions between smectites and polyelectrolytes, *Appl. Clay Sci.*, 198, 105778.

[22] Rabiee, A., Ershad-Langroudi, A., and Zeynali, M.E., 2015, A survey on cationic polyelectrolytes and their applications: Acrylamide derivatives, *Rev. Chem. Eng.*, 31 (3), 239–261.

[23] Thai, C.C.D., Bakir, H., and Doherty, W.O.S., 2012, Insights to the clarification of sugar cane juice expressed from sugar cane stalk and trash, *J. Agric. Food Chem.*, 60 (11), 2916–2923.

[24] Pal, P., Pandey, J.P., and Sen, G., 2018, Grafted sesbania gum: A novel derivative for sugarcane juice clarification, *Int. J. Biol. Macromol.*, 114, 349–356.

[25] Thai, C.C.D., and Doherty, W.O.S., 2013, Effect of Trash on the Coagulation and Flocculation of Sugarcane Juice, Australia, *Proceedings of the 35th Conference of the Australian Society of Sugar Cane Technologists*, Townsville, Queensland, Australia, April 16-18, 2013.

[26] Magalhães, A.S.G., Almeida Neto, M.P., Bezerra, M.N., Ricardo, N.M.P.S., and Feitosa, J.P.A., 2012, Application of FTIR in the determination of acrylate content in poly(sodium acrylate-*co*-acrylamide) superabsorbent hydrogels, *Quim. Nova*, 35 (7), 1464–1467.

[27] Mansri, A., Bendraoua, A., Benmoussa, A., and Benhabib, K., 2015, New polyacrylamide [PAM] material formulations for the coagulation/flocculation/decantation process, *J. Polym. Environ.*, 23 (4), 580–587.

[28] Craciun, G., Ighigeanu, D., Manaila, E., and Stelescu, M.D., 2015, Synthesis and characterization of poly(acrylamide-*co*-acrylic acid) flocculant obtained by electron beam irradiation, *Mater. Res.*, 18 (5), 984–993.

[29] Mishra, A., Agarwal, M., and Yadav, A., 2003, Fenugreek mucilage as a flocculating agent for sewage treatment, *Colloid Polym. Sci.*, 281 (2), 164–167.

[30] Chan, W.C., and Chiang, C.Y., 1995, Flocculation of clay suspensions with water-insoluble starch grafting acrylamide/sodium allylsulfonated copolymer powder, *J. Appl. Polym. Sci.*, 58 (10), 1721–1726.