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Research Paper

Synthesis and Characterization of Hydrogel Cassava Pulp – Poly (Acrylate – Acrylamide) at Various Concentrations of Acrylic Acid and Crosslinker

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Abstract

Cassava pulp or bagasse is a by-product of cassava processing with high starch and cellulose, showing strong potential for development into various high-value products, including hydrogel. Hydrogel is a polymer capable of absorbing a large amount of water without dissolving and is suitable for several applications. Therefore, this study aimed to synthesize and characterize hydrogel made from cassava waste pulp with different concentrations of acrylamide and acrylic acid (AA). The treatments used were the percentage of acrylic acid, namely 0, 5, 15, 25, and 35%, alongside N, N-methylene bisacrylamide (MBA) percentages (0, 0.5, 1, and 1.5%). Parameters observed were swelling, swelling kinetics, gel fraction, mechanical properties, and surface morphology. The results showed that the addition of acrylic acid and crosslinking with MBA had a significant effect on swelling, gel fraction, and mechanical properties at a significant level of 5%. FTIR confirmed the chemical interaction comprising acrylic-acrylamide acid and MBA in cassava pulp. In line with the analysis, the best treatment was obtained from 25% acrylic acid percentage and 0.5% MBA concentration with 1058% swelling value and 70.05% gel fraction. This hydrogel had a hardness of 6.46 mJ, 5.39 kPa modulus of elasticity, and 4.34×10^{23} m^{-3} active bonds per unit volume, showing the potential for use in agricultural fields as a planting medium, water carrier, and fertilizer protector.

Keywords
Acrylic Acid, Cassava Pulp, Hydrogel, Methylene Bis-Acrilamide, Swelling

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1. INTRODUCTION

Indonesia is one of the largest cassava-producing countries after Nigeria, Thailand, and Brazil. According to MoA (2023), cassava production in 2020, 2021, and 2022 was 16.27, 15.73, and 14.98 metric tons, respectively. A previous study by Chamorro et al. (2025) stated that since the average cassava pulp accounted for 10% fresh harvest, the production level in Indonesia would generate 1.5 million tons of pulp. In Thailand, an average of 5.15 million metric tons of pulp is derived annually from starch industries (Khejornsart et al., 2022).

Cassava pulp is a by-product of cassava processing with high starch and cellulose content, showing potential for development into various high-value products. According to Chamorro et al. (2025), cassava pulp of approximately 10% contains 74-85% starch (dry weight), which is trapped in residual fiber consisting of cellulose and other non-starch polysaccharides. This by-product has numerous advantages, such as being easy to obtain, cheap, and not competing with other industrial uses. The major applications include animal feed, bioethanol, fertilizer, biodegradable polymer, and biocomposites (Prasad et al., 2021). Distantina et al. (2025) stated that cassava pulp or bagasse had low absorption capacity and less stable mechanical properties. This shows the need for molecule modification by combining grafting and cross-linking methods using acrylamide and APS as initiators, to produce hydrogel with high swelling capacity and stable mechanical properties.

Hydrogel is a three-dimensional network hydrophilic polymer capable of absorbing large amounts of water (more than 100 times the dry weight) without dissolving (Ho et al., 2022). There is a growing interest in this polymer due to unique characteristics with several applications, such as planting media and fertilizer carriers, fever plasters, urea immobilization, biomedical applications, biosensors, and disposable diapers (Ali et al., 2024; Shishkhanova et al., 2025). Specifically, hydrogel is made from natural polymer, including carbohydrates, and produces superior characteristics such as being more environmentally friendly (biodegradable), non-toxic, biocompatible, and cheaper raw materials (renewable biosource). Compared to the synthetic type, carbohydrate-based superabsorbent hydrogel is highly absorbent, stronger, resistant to salt, and easily biodegradable, showing potential application in various fields (Qureshi et al., 2020). Sunarti et al. (2019) reported that water binding or absorption capacity and permeability were the most essential characteristics of hydrogel. However, carbohydrate polymer has several weaknesses, including low water absorption and strength. A previous study using natural polymer such as tapioca and corncob has shown sub-optimal results. This is because hydrogel composed of only natural polymer has lower swelling capacity below 1000%, weaker mechanical properties, and reduced durability, showing the need for chemical modifications such as grafting and crosslinking (Puspita et al., 2019; Kurniati et al., 2021; Winarti et al., 2018).

Swelling properties can be improved by adjusting the polymerization parameters, including the monomer concentration, initiator concentration, feed ratio of the raw materials, and cross-linking density. Several methods, such as the incorporation of nanoclay fillers and plasma modification, have been found useful to improve swelling properties of Super Absorbent Hydrogel (SAH).

Previous studies on the manufacture of cassava pulp-based hydrogel were carried out by Puspita et al. (2023) using the MBA crosslinker. The Equilibrium Degree of Swelling (EDS) results obtained were 9178% g/g with a gel fraction of 81.04% at an optimum MBA concentration of 0.5%. The primary focus was on swelling behavior, grafting efficiency, and soil water-holding capacity. However, the combined effects of acrylic acid and MBA concentration, as well as the mechanical stability, structural integrity, and long-term stability of hydrogel characteristics, were not investigated. There was no information on the surface morphology and spectroscopic confirmation of polymer interactions, leaving an important knowledge gap in the comprehension of the structure–property relationship of hydrogel based on cassava pulp.

To overcome the limitations, this study used varying concentrations of acrylic acid (0–35%) and MBA (0–1.5%) to more evaluate how the monomer-to-crosslinker ratio affects swelling behavior, gel fraction, mechanical strength, and network density. The results were expected to provide comprehensive physicochemical and mechanical characterization, including active bond density and FTIR-confirmed chemical interactions, alongside an accurate and useful assessment of hydrogel performance. SEM morphological analysis is used to further enhance structural insights uncovered in previous reports.

2. EXPERIMENTAL SECTION

2.1 Materials

Instruments used in this study were Scanning Electron Microscopy (SEM) (JSM – 6510LA JEOL) and a texture analyzer (Brookfield CT 3). Materials used were cassava pulp from the local starch industry in Bogor, Indonesia. Acrylic acid (Sigma Aldric, Germany), ammonium persulfate (APS) (Merck, Germany), methylene bisacrylamide (MBA) (Merck, Germany), distilled water, ethanol (Emsure, Merck, Germany), potassium hydroxide (KOH) (Merck, Germany), acetone (Merck, Germany), and methanol (Merck, Germany).

2.2 Methods

2.2.1 Preparation of Cassava pulp

Cassava preparation followed the method by Mas'ud et al. (2013) with modifications. Pulp obtained from tapioca craftsmen was washed 2-3 times until clean, dried under the sun for two days, and filtered using a 100-mesh sieve. The characteristics of cassava raw materials were observed to be water content 12.45%, ash 0.56%, fat 3.98%, protein 1.69%, and carbohydrate 82.41%.

2.2.2 Preparation of Acrylic Acid and Acrylamide Solutions

Acrylamide solution was made by dissolving acrylamide into distilled water in a ratio of 1:10 (w/v). Subsequently, acrylic acid was neutralized by mixing KOH in the solution with a ratio of 1:1 (v/v) until reaching a pH of 4.98 (Erizal et al., 2015).

2.2.3 Hydrogel Synthesis by Grafting and Crosslinking

Hydrogel synthesis followed the method by Mas'ud et al. (2013) with slight modifications. Initially, cassava pulp solution was made by dissolving 5 g of cassava pulp and 50 mL of distilled water, stirred using a magnetic stirrer at a temperature of ± 90°C at a speed of 300 rpm until gelatinization. Then the temperature was reduced to 60°C, where a 40% concentration of APS solution was added to the pile solution with 1% of the total solution and stirred for 15 minutes. At homogeneous, 2.5 g of acrylamide dissolved in 25 mL of distilled water was added, followed by neutralized acrylic acid with various percentages of 0, 5, 15, 25, and 35% of the total mixed solution while stirring using a magnetic stirrer at a speed of 400 rpm at 70°C.

The solution obtained from the grafting process was stirred at a constant temperature of 70°C and added with N, N- methyl enebisacrylamide (MBA) at various concentrations of 0, 0.5, 1, and 1.5%. The mixture was stirred to form a gel, washed using ethanol, and filtered. The filtered solids were dried using an oven at a temperature of 60°C. The dry hydrogel characterization included degree of grafting, gel fraction, swelling, swelling kinetics, and mechanical properties.

2.2.4 Degree of Grafting

Grafting degree analysis was performed to determine the percentage of monomers that were successfully grafted onto the main chain of the parent biopolymer. The testing process started with soaking hydrogel in ethanol for 24 hours to remove the formed homopolymer. Furthermore, washing using acetone and drying using an oven at a temperature of 60°C were performed to remove water content and non-reacting chemical substances. The degree of grafting was calculated using Equation (1) (Ling et al., 2022):

$$\text{Grafting Degree (\%)} = \frac{m_g - m_0}{m_0} \times 100\% \tag{1}$$

Remarks:

- m_g = mass of hydrogel after grafting (g)
- m_0 = mass of hydrogel before grafting (g)

2.2.5 Gel Fraction

The method for determining gel fraction, which showed the degree of cross-linking formed, was adapted from Halligan et al. (2023) The measurement of gel fraction started with weighing hydrogel under dry conditions, followed by soaking in water for 24 hours, and drying in an oven at 60°C for 6 hours. Furthermore, the dry mass after immersion was weighed using a digital balance. Gel fraction was determined by Equation (2):

$$\text{Gel Fraction (\%)} = \frac{m_g}{m_0} \times 100\% \tag{2}$$

Remarks:

- m_g = mass of gel remained after soaking (g)
- m_0 = mass of dried hydrogel (g)

2.2.6 Swelling at EDS

Swelling measurement was determined by the percentage ratio of the mass of water absorbed to the initial mass of hydrogel (Kowalski et al., 2024), using Equation (3):

$$\text{EDS (\%)} = \frac{m_s}{m_0} \times 100\% \tag{3}$$

Remarks:

- m_s = mass of hydrogel after soaking for 7 days (g)
- m_0 = mass of dried hydrogel (g)

2.2.7 Kinetics and Diffusion Coefficient

Kinetics of urea absorption was carried out by immersing hydrogel in water and a 0.04 M urea solution for 144 hours. Data collection was carried out in the first 5 hours and every 24 hours. Fick's law was used to determine the rate of diffusion of water and categorize hydrogel based on water inflow and outflow rates. This category was determined from the swelling exponent value obtained using Equation (4):

$$F = \left(\frac{M_t}{M_\infty}\right) = Kt^n \tag{4}$$

The rate of diffusion of water in hydrogel was determined using Equation (5):

$$F = \frac{M_t}{M_\infty} = 4\left(\frac{Dt}{\pi L^2}\right)^{0.5} \tag{5}$$

F is the swelling fraction (g g^{-1}), M_t is the hydrogel mass at immersion time t (h), M_∞ is the equilibrium mass of the hydrogel (g), D is the diffusion coefficient (m^2 h^{-1}), n is the swelling exponent, and K is the swelling constant (h^{-1}). The constant K is determined from the intercept of the regression equation of the relationship between $\ln F$ and $\ln t$, while n is obtained from the slope of the $\ln F$ versus $\ln t$ plot. The diffusion coefficient (D) is determined from the slope of the F curve with respect to $t^{1/2}$ (Jastram et al., 2021; Zhang et al., 2016).

2.2.8 Mechanical Properties

Mechanical properties of hydrogel in this study were tested using a Brookfield CT 3 texture analyzer instrument. The dried hydrogel was immersed in water for 24 hours, drained, and placed in a container. The sample was pressed using a probe to obtain the maximum load data (m, gram), hardness (mJ), and strain (strain ϵ, mm^{-1}).

2.2.9 Surface Morphology (Scanning Electron Microscopy (SEM))

Morphological analysis was performed using a Scanning Electron Microscopy type JSM – 6510LA JEOL. The sample was attached to the sample holder, which had a double adhesive, and was given a gold metal layer. Samples coated with gold were placed on SEM and observed at magnifications of 500 and 2000 times.

2.2.10 Fourier Transform Infrared (FTIR)

FTIR spectra of cassava pulp, MBA, and hydrogel were analyzed using Thermo Scientific Nicolet iS-10 (Detector: iD5 ATR). A 1 gram sample of cassava pulp and MBA, then hydrogel was cut into 5 × 3 cm sizes and analyzed with FTIR at a wavelength of 400 – 4000 cm^{-1}.

2.2.11 Experiment Design and Data Analysis

This study was designed using a two-factor factorial completely randomized design (CRD). The first factor was the percentage of acrylic acid addition, which was varied to 0, 5, 15, 25, and 35%. Meanwhile, the second factor was the concentration of MBA with variations of 0, 0.5, 1, and 1.5%. Each treatment consisted of 3 replications, followed by test data analysis using SAS software, and continued with the Honest Significant Difference test at the 5% level. When there was a significant effect, further testing was carried out with Duncan's Multiple Hose Test.

3. RESULTS AND DISCUSSION

3.1 Gel Fraction

The results of the significant difference test at the 95% confidence interval showed that the acrylic acid percentage and the concentration of the MBA crosslinking agent had a significant effect on the gel fraction value, with a $p < 0.0001$. The gel fraction of the chemically synthesized hydrogel increased with higher acrylic acid content and MBA concentration (Figure 1). According to Halligan et al. (2023), acrylic acid monomers are highly reactive and mobile due to their hydrophilic carboxylate groups, which facilitate the formation of stable cross-linked structures essential for hydrogel networks. The high reactivity toward crosslinking reactions indicates that increasing the acrylic acid proportion promotes a more densely bonded polymer network, resulting in an increased gel fraction.

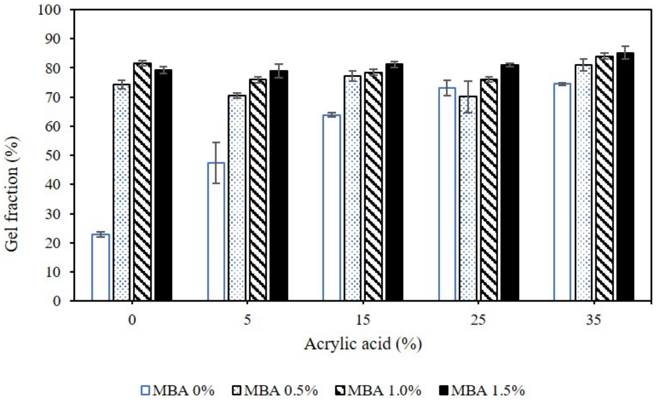

Figure 1. Effect of Concentration of Acrylic Acid and MBA on the Gel Fraction of Hydrogel

MBA is a bifunctional crosslinking agent containing two reactive double bonds that enable binding between different polymer chains. Consequently, higher MBA concentrations increase the number of crosslinking points, leading to a more interconnected polymer network and a higher gel fraction. In this study, the gel fraction ranged from 70% to 85%, which is comparable to the range reported by Batara et al. (2025) (55%–89%). The gel fraction behavior is governed by the synergistic effects of monomer reactivity and crosslinking density. An appropriate ratio of acrylic acid to MBA is crucial for achieving optimal hydrogel properties. Excessive crosslinking can significantly reduce hydrogel flexibility and swelling capacity due to increased structural rigidity (Ribeiro et al., 2025). Conversely, insufficient crosslinking may result in polymer dissolution and poor structural integrity. These findings highlight the importance of precise control over formulation parameters to optimize hydrogel performance for biomedical, agricultural, and environmental applications.

3.2 Degree of Grafting

The results of the significant difference test showed that variation in acrylic acid percentage had a significant effect on the degree of grafting at the 5% significance level, with a p-value < 0.0001. Meanwhile, the concentration of MBA did not show a significant effect (Figure 2). This result indicates that monomer availability is the primary factor controlling grafting efficiency, which is consistent with previous studies on acrylate-based hydrogel systems (Ibrahim, 2019). The relationship between acrylic acid concentration and the degree of grafting (DG) is positively correlated with free-radical formation and polymerization reactions, which facilitate monomer diffusion and enhance polymer–monomer interactions. These effects promote the incorporation of monomers into the polymer backbone (Seidi et al., 2020).

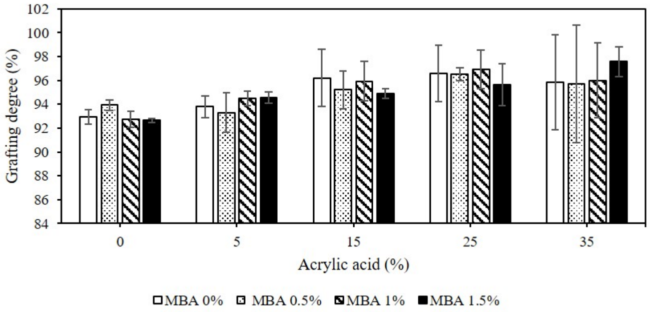

Figure 2. Effect of Concentration of Acrylic Acid and MBA on the Degree of Hydrogel Grafting

The chemical grafting process was carried out using a non-simultaneous method, in which the polymer was first initiated by ammonium persulfate to generate biopolymer radicals. Subsequently, these free radicals interacted with acrylamide and acrylic acid monomers to form covalent bonds during the propagation stage. Increasing monomer concentration enhances diffusion into the polymer chain structure, thereby increasing collision frequency between monomers and polymer chains and ultimately promoting grafting during propagation (Purohit et al., 2023). However, the number of monomers that can participate in grafting has an optimum limit, as most active sites on the polymer matrix (cassava pulp) become occupied at higher monomer concentrations (Chamorro et al., 2025). Figure 3 illustrates the proposed mechanism of hydrogel grafting and swelling.

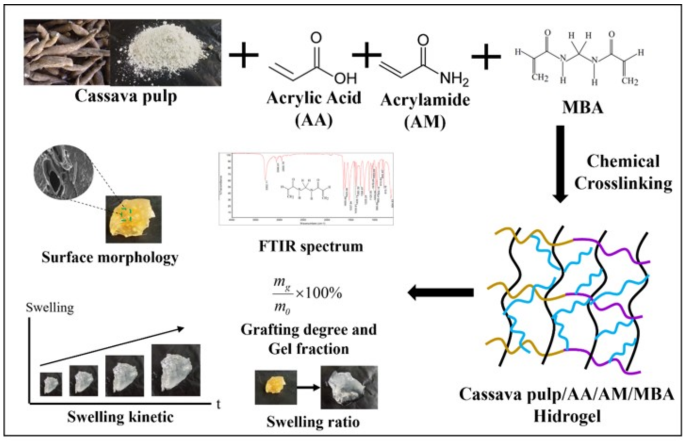

Figure 3. Grafting and Swelling Mechanism of Cassava-Pulp Hydrogel

3.3 Swelling

The results of the significant difference test at the 5% level showed a substantial effect between the interaction of acrylic acid percentage and MBA concentration on the swelling value.

Table 1. The Parameters of Hydrogel Kinetics

Acrylic Acid (%)	Concentration of MBA (%)	n_{water}	n_{urea}	K_{water} (h^{-1})	K_{urea} (h^{-1})	D_{water} ($m^2\ h^{-1}$)	D_{urea} ($m^2\ h^{-1}$)
0	0	0.1289	0.0811	-0.291	-0.235	0.0341	0.0839
5	1	0.3597	0.2333	-1.258	-1.488	0.0739	0.0913
15	0.5	0.6052	0.5400	-2.424	-2.544	0.0966	0.0945
25	0.5	0.8198	0.7259	-3.209	-2.142	0.1108	0.2176
35	0.5	0.8468	0.5780	-2.236	-1.491	0.1579	0.2900

As presented in Figure 4, swelling increased with rising MBA concentration, which was added to the control treatment and 5% acrylic acid. In hydrogel with 15% acrylic acid percentage, swelling decreased when there was an increase in MBA concentration. Wang et al. (2024) stated that higher level of cross-linking in polymer would lead to lower swelling capacity due to the shorter distance. Furthermore, the swelling capacity of hydrogel was affected by the structure and polymer properties, such as the degree of cross-linking, texture, temperature, and interactions between polymer chains and water molecules. The decrease in water absorption was attributed to the hydrophobic characteristics of polymer in hydrogel, which reduced the inherent hydrophilic properties of starch molecules (Kusumawati et al., 2025).

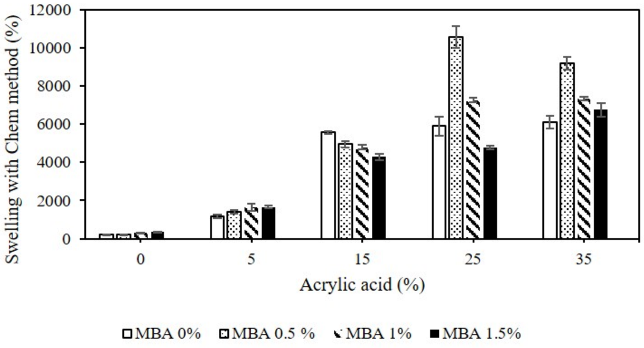

Figure 4. Effect of MBA Percentage on the Swelling of Hydrogel

In hydrogel with a percentage of 25 and 35% ACRYLIC ACID, the addition of MBA with a concentration of 0.5% increased swelling compared to the control. When MBA concentration was increased to 1 and 1.5%, the swelling decreased. These properties are primarily due to the presence of carboxyl functional groups in acrylic acid that promote hydrogen bonding and electrical interactions, leading to more water uptake at moderate levels of crosslinking (Czarnecka and Nowaczyk, 2020). High crosslinker concentration form denser polymeric networks with a small pore size, limiting water absorption (Cheng et al., 2017). In the treatment with less acrylic acid, more crosslinking agents are required to produce a bonded polymer structure and allow water absorption. Hydrogel with 15, 25, and 35% acrylic acid showed the opposite results because further addition of monomer led to the production of more active sites that could form cross-linking. Hydrogel synthesized by hydrophilic polymer using acrylic acid, higher swelling affected hydrophilic group concentration in hydrogel, thereby enhancing electrostatic repulsion between the polymer chains (Alka et al., 2024). Cassava pulp contains starch and cellulose, comprising hydroxylic functional groups, which are hydrophilic in nature. According to Ninciuleanu et al. (2021), the addition of acrylic acid as a monomer and cross-linking causes a degree of swelling in hydrogel polymer chain. This swelling affects pore formation that functions as an outlet and entry channel for water into hydrogel polymer chain.

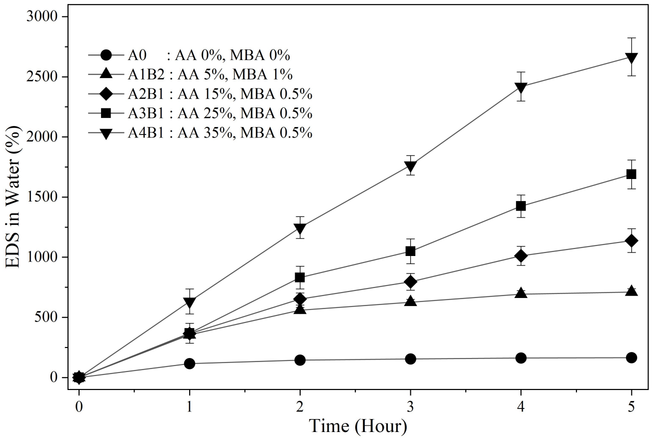

Figure 5. Effect of Immersion Duration on Swelling (EDS) of Hydrogel in Water

The addition of the MBA at extremely high concentration led to tighter crosslinking. Furthermore, there was difficulty for water to penetrate polymer chain, causing a significant decrease in hydrogel swelling (Sairi et al., 2025). The addition of an excessively large amount of MBA increases the number of cross-links in the superabsorbent polymer network. As a result, smaller pore sizes are formed, making water absorption more difficult for the superabsorbent polymer. According to Cheng et al. (2017), when the amount of crosslinking agent is high, the network density increases, causing a reduction in water absorption ability of hydrogel. In this study, swelling value of hydrogel ranged from 224 to 10,576%. The value varied

Table 2. Effect of Acrylic Acid Percentage on the Mechanical Properties of Hydrogel

Acrylic Acid (%)	Concentration of MBA (%)	Hardness (mJ)	Strain (mm^{-1})	Stress (kPa)	Modulus of Elasticity (kPa)	N ($\times 10^{23}$ m^{-3})
5	1.0	17.73	0.34	10.2	20.81	16.75
25	0.5	6.46	0.44	2.37	5.39	4.34
35	0.5	4.03	0.49	1.17	3.45	2.78

significant from other reports by Parvathy et al. (2014), who obtained 4,000 to 15,000%. Cheng et al. (2017) stated that as the amount of MBA increased, the Q value of hydrogel initially rose and decreased gradually. When the amount of crosslinking agent is low, the networking degree of the hydrogel becomes extremely low to form a three-dimensional network. This will cause the formation of polymer that has relatively high water solubility. However, the strength and the water absorption ability of hydrogel are low.

Increasing the amount of acrylamide leads to a greater swelling of hydrogel. Rather et al. (2022) reported that the maximum Q (water absorbance) value of hydrogel was attained at an acrylamide (AM) content of 95% of the total weight. This is because the ratio of hydrophilic polymer/inorganic compounds increases due to the addition of acrylamide. The study by Distantina et al. (2025) showed that swelling capacity increased alongside a high ratio of acrylamide and APS, with the highest value obtained of 1139% obtained at a ratio of 0.1 g APS and 10 g acrylamide. Meanwhile, the highest swelling value was obtained at an AM concentration of 25%. The variation in results was due to the difference in material used during each experiment.

3.4 Swelling Kinetics and Diffusion Coefficient of Hydrogel

Swelling value (EDS) of hydrogel immersed in water and urea solution is shown in Figures 5 and 6. Based on the results, longer immersion time increased swelling value due to the difference in ion concentration between polymer chain system and the surrounding environment, which drives diffusion of water or urea solution into the polymer matrix. Swelling in urea solution was higher than in water, due to the relatively low urea concentration (0.04 M) and the non-ionizable nature. Generally, swelling behavior of hydrogel depends on the ionizable groups attached to the backbone of polymer. This suggests that higher ionizability enhances swelling capacity compared to non-ionizable group. The density of crosslinking also has a significant effect on the properties of hydrogel in an inverse manner (Hussein et al., 2025). In this study, ionizable groups were responsible for the absorption of distilled water, although previous reports stated that interaction between acrylamide containing non-ionizable groups and natural polymer caused swelling.

Hydrogel diffusion type can be classified based on swelling exponent value. As shown in Table 1, the chemical method of hydrogel synthesis with acrylic acid at 15, 25, and 35% belonged to the non-Fickian category, or anomalous diffusion, with a diffusion exponent between 0.5 and 1. This type of diffusion has a rate of water diffusion equivalent to polymer chain relaxation (Ghaffar et al., 2016). Meanwhile, the control treatment and 5% acrylic acid were included in the Fick diffusion category. This behavior explains the results of chemical method of swelling hydrogel testing, which increases with the higher percentage of acrylic acid.

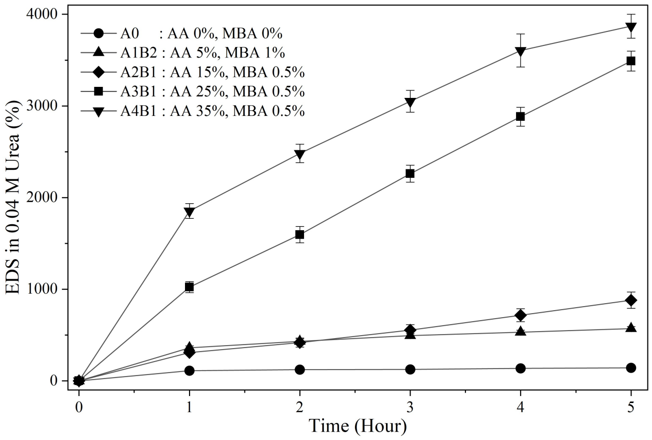

Figure 6. Effect of Immersion Duration on Swelling (EDS) of Hydrogel in 0.04 M Urea

The intercept of the curve from ln F to lnt produces the value of the swelling constant (K). This value also shows the characteristics of hydrogel obtained from polymer chain. Based on the results, a higher percentage of acrylic acid caused an increase in swelling constant when negative sign was ignored. The negative sign shows that the direction of diffusion corresponds to the concentration gradient, namely from high to low. The value of swelling constant is directly proportional to swelling value of hydrogel. Moreover, swelling constant value obtained in this study was approximately the same with Ghaffar et al. (2016), who reported -2.1 to -0.6 h^{-1}.

The diffusion coefficient of hydrogel chemical method is obtained from the slope of the swelling fraction curve with respect to the root of immersion time. This coefficient shows the level of water flow rate in hydrogel (Kanmaz et al., 2018; Phang et al., 2020). As presented in Table 1, diffusion coefficient increased with higher percentage of acrylic acid, showing faster solution transport into the polymer network. Therefore, the absorption of water and urea increased with the higher value of

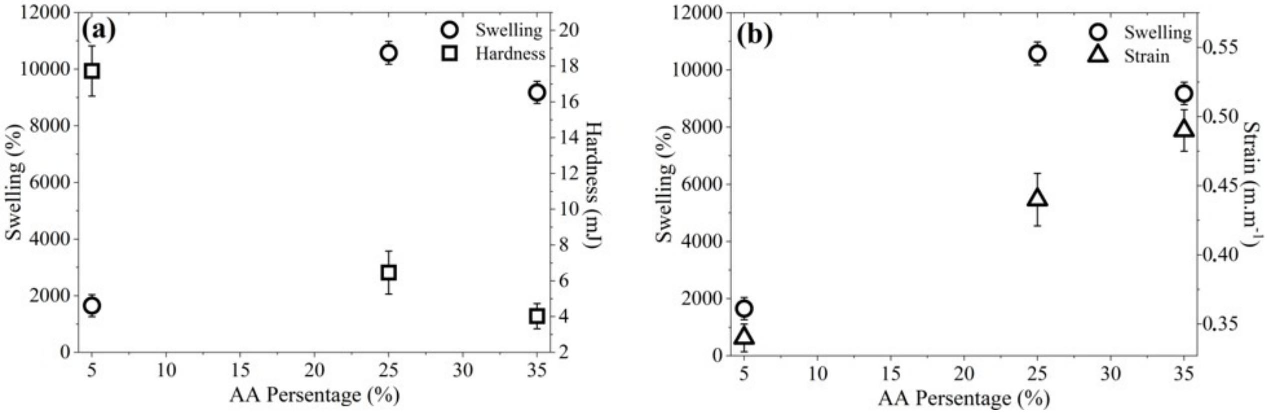

Figure 7. Correlation Between Acrylic Acid Percentage as Well as Swelling and Hardness (a) and Between Swelling and Strain of Hydrogel (b)

the diffusion coefficient (Saruchi et al., 2019), consistent with swelling results in Figure 4. The diffusion coefficient obtained are comparable to previous studies, which have 0.1 to 0.27 m^2h^{-1} (Ghaffar et al., 2016).

3.5 Mechanical Properties of Hydrogel

The test results in Table 2 showed that hydrogel had a lower hardness value with a higher percentage of acrylic acid. Based on the swelling test, the higher percentage of acrylic acid produced a hydrogel with better water absorption ability. Therefore, polymer chains in high-swelling hydrogel experienced greater stretch than the lower-swelling sample. This stretching of polymer structure produces lower crosslinking density, showing that the sample with higher swelling requires less energy to deform, and the addition of greater crosslinker decreases hardness. According to Wang et al. (2024), a higher level of cross-linking in polymer produces lower swelling capacity, making gel harder and stronger. Chemical crosslinking forms covalent bonds between polymer chains, creating a 3D network that significantly alters the structure, often making it more rigid and less flexible (Yammine et al., 2025). The reduced homogeneity of the material will decrease crystallinity, causing a corresponding reduction in mechanical properties. Table 2 shows the stress value, which is directly proportional to the hardness value. In line with the analysis, hydrogel of 5% acrylic acid showed the highest hardness value, compared to 25% and 35% that were reduced. The strain value was higher when a greater percentage of acrylic acid was added. This result is in accordance with the swelling kinetics analysis using Fick's Law, where a high percentage of acrylic acid improves the ability of polymer chain to relax based on water diffusion (Ghaffar et al., 2016). A comparison with the results obtained from other systems showed that synthesized hydrogel had similar mechanical properties to the established polysaccharide-based hydrogel, which generally had a significant difference between swelling capacity and mechanical strength (Najihah et al., 2024). For example, cellulose-based hydrogel showed high elasticity with low mechanical reliability due to weaker intermolecular forces in highly hydrated conditions (Zhu et al., 2020). Synthetic polyacrylate-based hydrogel often possess excellent mechanical properties but have limited swelling capacity. Therefore, the cassava pulp-poly(acrylate-acrylamide) hydrogel provides a balanced combination of swelling performance and mechanical stability, making it suitable for applications requiring moderate strength, such as wound dressings and agricultural soil conditioners. These results also show the tunability of hydrogel mechanics through acrylic acid and MBA concentrations, suggesting that further optimization of crosslinking density and polymer architecture can obtain more durable and functional materials.

The correlation between swelling and hardness with the different concentrations of acrylic acid is shown in Figure 7a. Based on the results, hydrogel showed a significant increase in swelling but a decreased hardness value with a rise in acrylic acid from 5 to 25%. Different patterns in Figure 7b showed that the strain had a corresponding rise alongside acid. Hydrogel, with a 25%, is the optimal treatment for swelling. This is because higher swelling correlates with an increase in polymer chain stretching due to the ingress of water. The maximum stretch causes the bonds between polymer chains to be less strong, thereby reducing the energy required for deformation.

3.6 Morphological Structure of Hydrogel

Figure 8 shows the morphology of the control sample, while Figure 9 presents hydrogel with 25% acrylic acid and 0.5% MBA. The images showed that the control sample had a dense and smooth surface, while the addition of 25% acrylic acid and 0.5% MBA had more pores, holes, and a wrinkled surface. Similarly, Tao et al. (2018) stated that the SAPs had a loose and porous wrinkled surface, alongside several creases and holes. These pores are areas where water permeates, and external stimuli interact with grafted copolymer hydrophilic group (Pourjavadi, 2007). According to Ozan et al. (2023), pores are useful for the penetration of water into the polymeric network and allow the absorption of corresponding SAPs. In this study, the addition of acrylic acid and MBA percentages affected the size of holes formed. The surface differentiation among hydrogel could provide an advantage over other formulations by improving product robustness and ensuring consistent performance under various storage conditions (Perwatasari et al., 2025).

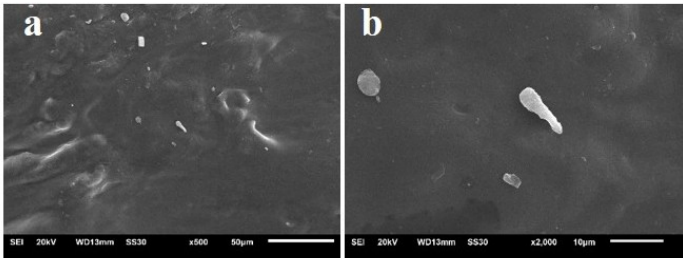

Figure 8. Morphology of the Control Sample in the Magnitude of (a) 500 and (b) 2000 ×

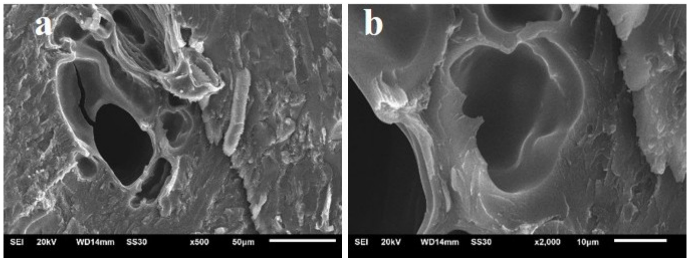

Figure 9. Morphology of 25% Acrylic Acid and 0.5% MBA Sample in the Magnitude of (a) 500 and (b) 2000 ×

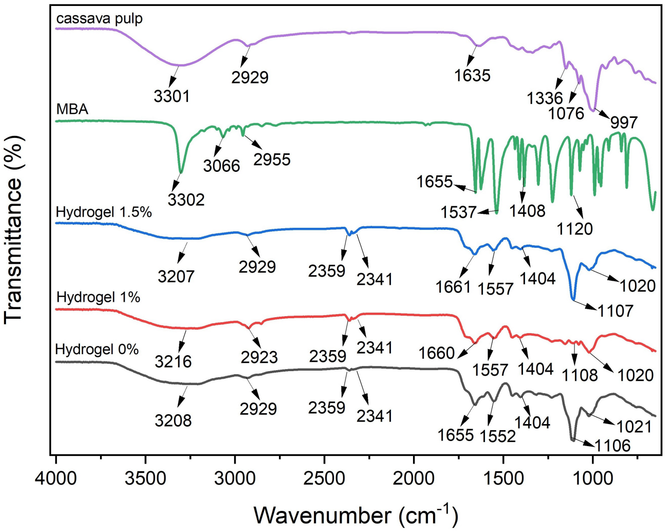

Figure 10. FTIR Spectra of Cassava Pulp Waste, MBA, and Cassava Pulp Hydrogel Crosslinked MBA

3.7 FTIR

Figure 10 shows that in cassava pulp, the absorption at 3301 cm^{-1} is a hydroxy group (−OH). The small peak at 2929 cm^{-1} shows a C−OH group, while 1336 cm^{-1} and 1076 cm^{-1} are C−O groups bound to cellulose. The band at 1076 cm^{-1} also shows C−O−C glycosidic bonds in starch, and 991 cm^{-1} shows C−O group or ether bond. The results were consistent with Distantina et al. (2025), who identified cassava pulp absorption values of 3425.5 cm^{-1}, 2931.80 cm^{-1}, 1373.32 cm^{-1}, and 1026.13 cm^{-1}, respectively, showing the presence of −OH (hydroxyl), C−H (methyl), and C−O (ether) groups as constitutive components.

In cassava pulp hydrogel, optimum concentrations were 1.0% and 1.5%, which showed shifts in various functional groups due to the chemical reaction in acrylic-acrylamide acid and MBA. These peaks imply a polymerization reaction within hydrogel. The shift at wavelengths 3208–3216 cm^{-1} shows OH stretching vibration, characterized by a sloping peak. As reported by Razali et al. (2015), O−H groups can be substituted with polyacrylamide chains. Additional shifts at 1106–1108 cm^{-1} correspond to C−O stretching vibrations. The occurrence of new peaks further confirms successful polymerization and crosslinking, including bands at 1661 cm^{-1} (C=O stretching of carbonyl groups in cellulose/hemicellulose), 1557 cm^{-1} (N−H bending from acrylamide groups), and 1404 cm^{-1} (C−N stretching). A peak at 1020 cm^{-1} is attributed to carbonyl-related vibrations associated with glycosidic bonds in grafted cellulose or starch structures.

4. CONCLUSIONS

In conclusion, the addition of acrylic acid and MBA has a substantial effect at the 5% level of significance on swelling, gel fraction, and hydrogel mechanical properties. Higher acrylic acid correlates with a greater percentage of gel fraction and the swelling value, but the mechanical properties decrease. Furthermore, FTIR confirms the chemical interaction, including acrylic-acrylamide acid and MBA in cassava pulp. Based on the results, the best treatment is obtained from a 25% acrylic acid and a 0.5% MBA concentration with a 10.58% swelling value and a 70.05% gel fraction. This hydrogel has a hardness of 6.46 mJ, 5.39 kPa modulus of elasticity, and 4.34×10^{23} m^{-3} active bonds per unit volume.

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