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IMPROVING THE PERFORMANCE OF ENVIRONMENTALLY FRIENDLY FLEXIBLE BATTERIES WITH SODIUM ALGINATE-NaCl AS ELECTROLYTE

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Abstract

The use of synthetic polymer-based electrolytes is often hindered by obstacles related to cost and environmental impact. Alginate is a marine biopolymer that is potentially abundant in Indonesia. This study aims to optimize the composition of a mixture of sodium alginate and NaCl as an integrated electrolyte-separator system to create a flexible battery that not only has stable electrochemical performance but also has the pure mechanical integrity of a bio-based material. The statistical analysis used in this study was a 1-factor Completely Randomized Design consisting of three levels. The electrolyte was prepared by mixing sodium alginate and NaCl, which was then molded and dried to form a membrane. The sodium alginate-NaCl electrolyte membrane ratios were 5:2, 5:3, and 5:4 (w/w). The best ratio for the water uptake physical property with a value of 51.624±0.06, and the best tensile strength was found in the 5:3 ratio, with a value of 0.755±0.06 MPa. The best electrochemical properties were obtained at a ratio of 5:2, with proton conductivity, voltage, and tensile strength values of 1.54×10-5 S/cm; 0.511±0.01 volts, and 0.196±0.007 mA, respectively.

Keywords: bio-based materials, marine based electrolyte, marine biopolymer, proton conductivity, sustainable energy storage

Peningkatan Kinerja Baterai Fleksibel Ramah Lingkungan Dengan Elektrolit Alginat-NaCl

Abstrak

Penggunaan elektrolit berbahan dasar polimer sintetik sering kali menghadapi kendala terkait biaya dan dampak lingkungan. Alginat merupakan biopolimer laut yang berpotensi melimpah di Indonesia. Penelitian ini bertujuan untuk mengoptimalkan komposisi campuran antara natrium alginat dan NaCl sebagai sistem pemisah elektrolit terintegrasi sehingga tercipta baterai fleksibel yang tidak hanya memiliki kinerja elektrokimia yang stabil, namun juga memiliki integritas mekanis murni dari bahan berbasis bio. Analisis statistik yang digunakan pada penelitian ini adalah rancangan acak lengkap 1 faktor yang terdiri dari 3 level. Elektrolit terbuat dari pencampuran natrium alginat dan NaCl kemudian dicetak dan dikeringkan hingga membentuk membran. Variasi membran elektrolit natrium alginat-NaCl 5:2, 5:3, dan 5:4 (b/b).

Perbandingan 5:4 menunjukkan performa sifat fisik water uptake terbaik dengan nilai 51,624±0,06 dan nilai kuat tarik terbaik pada perbandingan 5:3 dengan nilai 0,755±0,06 MPa. Performa terbaik sifat elektrokimia diperoleh pada perbandingan 5:2 dengan nilai konduktivitas proton, tegangan, dan kuat arus berturut-turut 1,54×10-5 S/cm; 0,511±0,01 V; dan 0,196±,007 mA.

Keywords: biopolimer laut, elektrolit berbasis kelautan, konduktivitas proton, material berbasis bio, penyimpan energi berkelanjutan

INTRODUCTION

A battery is an electrochemical device that converts chemical energy into electrical energy through redox reactions (Hamid *et al.*, 2016; Saputra & Yulianti, 2021). Batteries are the main energy source for portable electronic devices and smartphones, and their use is predicted to continue to increase until they reach a global capacity requirement of 1,300 GW by 2030 (Mejame *et al.*, 2020; Obaita *et al.*, 2023). However, the current dominance of conventional batteries, such as lithium-ion batteries, poses serious environmental problems because they contain dangerous and toxic materials (B3) that are difficult to recycle and have the risk of exploding (Triaswinanti *et al.*, 2023; Nanda *et al.*, 2024).

As wearable device technology continues to develop, the need for flexible batteries is becoming increasingly urgent. Conventional components, such as polyethylene (PE) and polypropylene (PP)-based separators, are no longer adequate because they are rigid, have low heat resistance, and risk leaking if bent (Li *et al.*, 2016). As a solution, research is now turning to the development of solid or gel electrolytes, which also function as separators (Ue *et al.*, 2020; Li *et al.*, 2021).

The use of marine biopolymers, especially sodium alginate, offers great potential because it is abundant in Indonesia, biodegradable, and has good thermal stability (Soeda *et al.*, 2015; Cahyono *et al.*, 2021). Alginate not only functions as a polymer matrix that can trap electrolytes well, but also acts as a natural binder that reduces resistance and increases ion transport (Teng et al., 2021). Although several other polymers such as chitosan, carrageenan, and polyvinyl alcohol (PVA) have been studied as environmentally friendly membranes, alginate has specific advantages in forming stable hydrogel networks for battery systems (Schlemmer *et al.*, 2021; Anindhita *et al.*, 2023; Ibrahim *et al.*, 2024;).

The main challenge in using alginate hydrogels is optimizing their ionic conductivity and mechanical stability. The use of NaCl as an electrolyte salt is a safe, inexpensive option that is compatible with water-based systems. However, an inappropriate NaCl concentration can disrupt the integrity of the gel structure or inhibit ion movement due to high viscosity.

Therefore, this study aimed to determine the optimal electrolyte composition by optimizing the ratio of sodium alginate to NaCl. The main focus of this research is to achieve a balance between high ionic conductivity and stable mechanical strength. Through this concentration modification, an integrated electrolyte-separator system can be created to replace dangerous synthetic materials while providing a safe, flexible, and sustainable energy storage solution. The aim of this study was to optimize the composition of a mixture of sodium alginate and NaCl as an integrated electrolyte-separator system to create a flexible battery that not only has a stable electrochemical performance but also has the pure mechanical integrity of a bio-based material.

MATERIALS AND METHODS

Electrolyte Membrane Manufacturing

The preparation of sodium alginate-NaCl electrolyte membranes was based on the research conducted by Kim *et al.* (2023). The first step in preparing the electrolyte membrane was to prepare sodium alginate and NaCl solutions. The sodium alginate solution was prepared by dissolving 5 g of sodium alginate in 100 mL of distilled water.

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The NaCl solution was prepared by dissolving NaCl in varying ratios of 2, 3, and 4 g (Table 1) in 100 mL of water. The next step was to mix the two solutions using a magnetic stirrer at 80°C and 1,000 rpm for 30 min until they were homogeneous. The homogeneous sodium alginate-NaCl solution was poured into Petri dishes (30 g each) and then dried at room temperature (± 25°C) by leaving them in an open room until a membrane formed. The dried membrane was then removed from the molds. The electrolyte membrane was subjected to several tests, including proton conductivity analysis, water uptake, tensile strength, and FTIR.

Anode Membrane Manufacturing

The process of preparing the chitosan-PVA anode solution was based on the research conducted by Widiarti *et al.* (2017). The chitosan-PVA solution was prepared by preparing a 2% (w/v) chitosan solution by dissolving 2 g of chitosan in 100 mL of 1% acetic acid solution and a 5% PVA solution by dissolving 5 g of PVA in 100 mL of distilled water using a magnetic stirrer at a speed of 1400 rpm, then heated to a temperature of 90°C until homogeneous. The chitosan and PVA solutions were mixed at a chitosan: PVA ratio of 3:1 (v/v). This ratio of chitosan and PVA was based on the best results from a study conducted by Fitroh (2025). The chitosan and PVA solutions were mixed using a magnetic stirrer at a speed of 1400 rpm, and then heated at 50°C for 20 min until homogeneous. The homogeneous solution was then cooled to room temperature.

Paper Battery Manufacturing

The manufacture of paper batteries refers to the modifications of the research conducted by Kadam *et al.* (2016). The first step in manufacturing paper batteries is to evenly coat one side of the sodium alginate-NaCl electrolyte gel membrane with a chitosan-PVA solution as the anode. The next step was to coat the opposite side with carbon ink as the cathode. The anode and cathode must not touch each other at either end of the cell. The assembled paper battery was then analyzed electrically using a digital multimeter.

Proton Conductivity Analysis

The proton conductivity of the electrolyte membrane was analyzed according to Madaswamy *et al*. (2021). The electrolyte membrane was measured and cut into 2.5×2.5 cm pieces. The cut membranes were then inserted into a clamping chip with opposite anode and cathode. The purpose of this analysis was to determine the effect of variations in the sodium alginate-NaCl membrane ratio on the proton conductivity value that occurs through the movement of H+ ions in the membrane. The proton conductivity was determined using electrochemical impedance spectroscopy (EIS). The membrane proton conductivity can be calculated using the following formula:

$$\sigma = G\frac{L}{A}$$

where
σ=proton conductivity (S/cm)
L=distance between the two electrodes (cm)
G=conductivity value (S)
A=surface area (cm^2)

Water Uptake Analysis

The sodium alginate-NaCl electrolyte membrane was cut to a specified size of 2×2 cm, as described by Lusiana et al. (2017). First, the membrane was dried using a dehydrator at 50°C for 24 h and then weighed as a dry weight. Soaking was carried out in water to determine the water absorption of the membrane, which was carried out for 24 h until it was fully

Table 1 Formulation of the composition of the electrolyte membrane and anode membrane of paper battery

Formula	Composition	F1(b/b)	F2(b/b)	F3(b/b)
Electrolyte membrane	Sodium alginate-NaCl	5:2	5:3	5:4
Anode membrane	Chitosan-PVA	6:5	6:5	6:5

hydrated. The soaked membrane was then removed, cleaned with tissue to remove excess water droplets from the membrane surface, and weighed to obtain the wet weight. This weighing was performed to determine the difference in membrane weight between the wet and dry states. The water absorption of the membrane was calculated using the water uptake formula.

$$\text{Uptake (\%)} = \frac{W_{wet} - W_{dry}}{W_{wet}} \; 100\%$$

where
Uptake = water absorption (%)
W_{wet} =mass of wet membrane after immersion in water (g)
W_{dry} =mass of dry membrane before immersion (g)

Tensile Strength Analysis of Membranes

The tensile strength of the electrolyte membrane was tested using an autographic tensile strength tester. A 4×1 cm piece of membrane was attached to the Autograph device, as described by Lusiana *et al.* (2019). The ends of the membrane were attached to the testing device, and the puller was set to a load of one kilogram-force. The membrane was then pulled at a speed of 1 cm/min until it broke. Changes in the length of the membrane and mass of the puller were recorded and calculated using the tensile strength formula.

$$\text{Tensile strength } (\sigma) = \frac{F}{A}$$

where
σ =tensile strength of membrane (N/m^2)
F = tensile force at the point of membrane rupture (N)
A =surface area of the membrane (m^2)

Battery Electrycity Analysis

Battery testing included voltage testing of the voltage produced by the battery, as described by Logan *et al.* (2006). Battery electricity testing was performed using a digital multimeter in units of volts, milliamps, and milliwatts. The digital multimeter was first set for voltage and current measurements, starting from the smallest scale. The electrodes (anode-cathode) on the battery were connected to cables connected to the digital multimeter. The measurement results appeared on the digital multimeter screen and were observed. The resistance was calculated using the following formula:

$$I = \frac{E}{R}$$

where
R=internal obstacles (Ω)

Power calculation by dividing the power obtained by the surface area of the anode. The value can be obtained using the following formula:

$$P = I \times E$$

where
P = electric power (W)
I = electric current (mA)
E = electric voltage (V)

Membrane Function Group Analysis

Functional group analysis was performed as described by Nandiyanto *et al.* (2019). The functional group testing of separator membranes was performed using potassium bromide (KBr) reagent. Membrane testing was performed using KBr powder that was ground using a mortar. The powder was then placed into a cylindrical hole at the center of the sample container. A 2×2 cm membrane sample was attached to the container and placed in a diffuse reflectance spectroscopy (DRS) device. The infrared light on the membrane was then recorded as waves with a spectrum range between 500-3500 cm^{-1}. The functional groups of the sodium alginate-NaCl separator membrane were analyzed using a PerkinElmer Spectrum One Fourier transform infrared (FTIR) spectrometer. The purpose of this test was to determine the changes in the functional groups of the sodium alginate-NaCl membrane.

Data Analysis

The experimental design of this study was intended to identify the optimal composition of electrolyte membranes derived

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from a mixture of sodium alginate and NaCl. The membrane properties were evaluated across different composition ratios using a completely randomized design (CRD), which enabled the assessment of the effects of the factors on the response variables. The primary factor examined was the sodium alginate-to-NaCl ratio (5:2, 5:3, and 5:4). Data were analyzed using analysis of variance (ANOVA) with the support of Microsoft Excel 2021 and SPSS version 26.0. When ANOVA indicated significant differences ($p<0.05$), Duncan's multiple range test (DMRT) was performed at a 95% confidence level. The water uptake, tensile strength, proton conductivity, and electrical performance of the selected flexible batteries were expressed as the mean values of three replicates along with the standard deviations. The results were subsequently presented graphically and descriptively interpreted.

RESULTS AND DISCUSSION

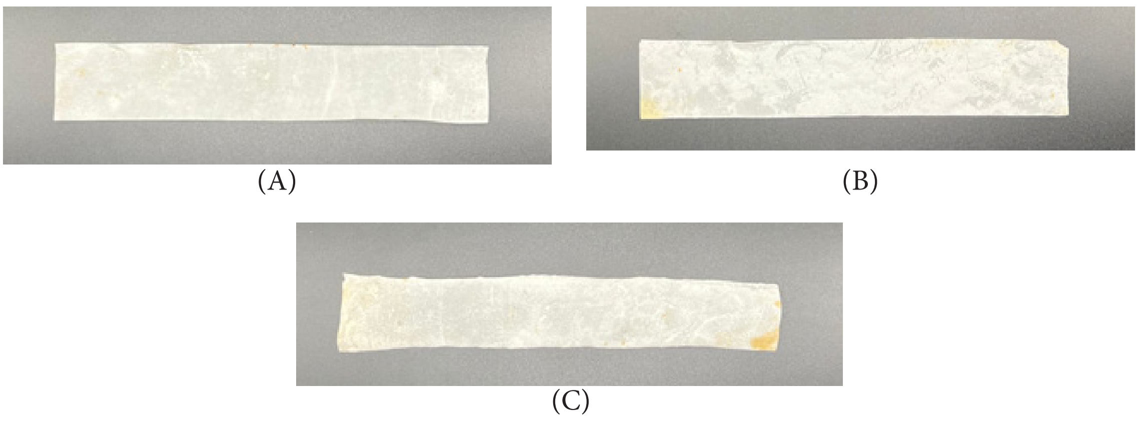
Characteristics of Sodium Alginate-NaCl Electrolyte Membranes

Alginate is a natural polymer derived from seaweeds, such as *Turbinaria sp.* and *Sargassum sp.* It is composed of mannuronic (M) and guluronic (G) acid units, which confer impressive mechanical strength to the material. To convert this polymer into a battery electrolyte, NaCl was added. The resulting Na^+ and Cl^- ions fill the gaps between the polymer chains, creating "highways" that boost ionic conductivity and accelerate charge transport. For a flexible battery to function effectively, its electrolyte must balance conductivity with physical durability and eco-friendliness. (Subaryono, 2010; Wafiroh *et al.*, 2016). The structure of the electrolyte membrane is illustrated in Figure 1.

The resulting membranes were thin, smooth, and mostly white with a slight gray tint, with an average thickness of 0.018 cm. We noticed that adding more salt changed the appearance: the 5:2 ratio was the lightest, while higher salt concentrations (5:3 and 5:4) shifted the color toward a deeper grayish-white. This observation is consistent with that of Kamisyah *et al.* (2020). The membranes were smooth, slightly rigid, and elastic. Although they are denser and stronger when dry, they become significantly more flexible when wet. However, higher salt levels can make the material stiffer or more brittle, depending on how it is dried (Halim *et al.*, 2016).

Conductivity Proton Membrane Electrolyte Sodium Alginate-NaCl

Proton conductivity is an important factor in polymer electrolytes. The proton conductivity of a membrane is the ability of protons to move from the cathode to the anode (Kharisma *et al.*, 2020). The higher the conductivity value, the better the quality of the polymer in terms of proton conduction (Julian & Santoso, 2016). The ability of a membrane to generate protons that act as electrolytes in batteries can be indicated by its proton conductivity level. The proton conductivity values of the sodium alginate-NaCl membranes are shown in Figure 2.



(A) (B) (C)

Figure 1 Sodium alginate-NaCl electrolyte membranes with different ratios (A) 5:2 (w/w); (B) 5:3 (w/w); (C) 5:4 (w/w)

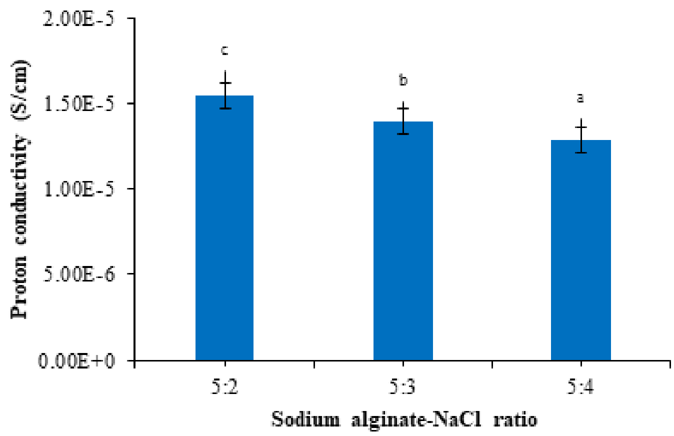


Figure 2 Effect of different ratios on the proton conductivity of sodium alginate-NaCl electrolyte membranes; Superscript letters (a, b, c) indicate significant differences (p<0.05) among treatments.

The results of this study show that the sodium alginate–NaCl membrane achieved its highest proton conductivity at a ratio of 5:2, reaching 1.54×10^{-5} S/cm. Statistical analysis via ANOVA and Duncan's post-hoc tests confirmed that the specific ratio of these components significantly impacted the membrane performance (p<0.05). This optimal 5:2 ratio suggests a balanced interaction, where Na^+ and Cl^- ions effectively fill the polymer matrix to create efficient conduction pathways without compromising the structural integrity of the membrane. In contrast, increasing the NaCl concentration to ratios of 5:3 and 5:4 led to a decline in conductivity to 1.39×10^{-5} S/cm and 1.29×10^{-5} S/cm, respectively. This decrease is likely due to the formation of ion aggregates and saturation of the polymer space, which obstructs the "proton hopping" mechanism and disrupts the hydration network necessary for smooth ion migration (Ghadafi, 2016; Kaklamani *et al.,* 2018).

Compared to the existing literature, the performance of the Na-alginate–NaCl (5:2) membrane outperforms the carrageenan-PVA system reported by Ibrahim *et al.* (2024), which achieved a lower value of 8.09×10^{-6} S/cm. Furthermore, these results are comparable to those of the alginate-glyconic acid system developed by Fauzlin *et al.* (2020), which recorded 5.32×10^{-5} S/cm. However, these values remain significantly lower than those of specialized systems, such as the 4% sodium alginate membrane by Liu *et al.* (2014) or the sodium thiocyanate-doped alginate by Diana *et al.* (2021), which reached the "high range" classification of 10^{-2} to 10^{-3} S/cm (Mendes *et al.*, 2024). This disparity highlights that while the 5:2 ratio successfully utilizes Cl^- groups to attract and accelerate proton transport (Sundarti *et al.*, 2017), the current system falls within the "low range" conductivity category of 10^{-3}-10^{-5} S/cm, suggesting that further optimization of environmental factors, such as humidity, or the addition of specific plasticizers, may be needed to achieve industrial-grade performance.

Analysis of Water Uptake by Electrolyte Membranes

The absorption function of the membrane as a medium for H^+ proton transport is related to its proton conductivity (Mendes *et al.*, 2024). Greater water absorption improves the hydrophilic properties of the membrane, facilitating electron transport. Excessive water absorption causes increased membrane swelling, which can lead to a loss of mechanical stability. The results of the water-uptake analysis are shown in Figure 3.

The water uptake test results showed that the 5:3 ratio achieved the highest average absorption at 80.411±0.04%, followed by the 5:2 treatment at 61.411±0.05% and the 5:4 treatment at 51.624±0.06%. However, Duncan's post-hoc test revealed that these differences were not statistically significant (p>0.05). Water uptake is a vital factor in

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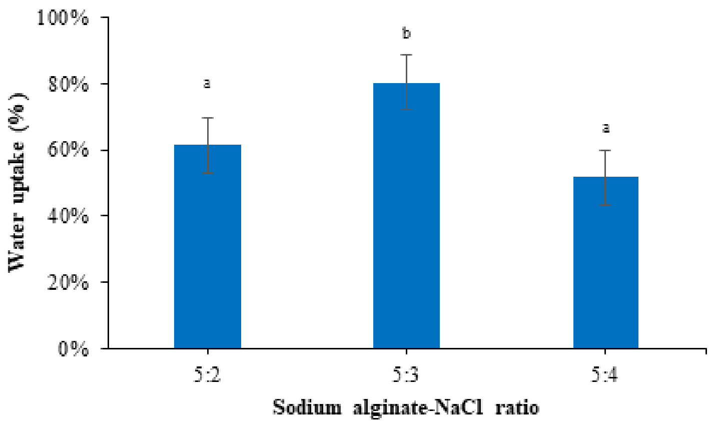

Figure 3 Effect of different ratios on water uptake of sodium alginate-NaCl electrolyte membranes; Superscript letters (a, b, c) indicate significant differences (p<0.05) among treatments.

determining membrane performance, as a higher water content typically increases ion mobility and proton conductivity (Qiao *et al*., 2012; Muliawati & Mirzayanti, 2021). In this system, NaCl facilitates water absorption through ionic hydration, where Na+ and Cl- ions attract water molecules to form hydration layers. This layer acts as a transport medium for protons (H +) while simultaneously stabilizing the alginate gel structure to maintain flexibility and prevent the membrane from becoming brittle (Khairatunnisa, 2007; Sugianto, 2023; Al Fath *et al.*, 2024).

Despite the benefits of hydration, this study observed that water uptake peaked at a 5:3 ratio and then declined at a 5:4 ratio. This decline suggests that a high concentration of NaCl leads to ion aggregation, which reduces porosity and inhibits further absorption of water. Similar to the findings of Kusumastuti *et al*. (2021), these aggregates suppressed the mobility of the polymer chains. Crucially, high water uptake does not always translate to higher conductivity; if the absorbed water is trapped within ion aggregates, as likely occurred in the 5:3 and 5:4 treatments, it will fail to facilitate effective ion transport. Furthermore, excessive absorption can lead to swelling, compromising the mechanical stability of the membrane. Therefore, achieving an optimal hydration point is essential to balance the high conductivity with physical durability.

Tensile Strength Analysis of Electrolyte Membranes

Tensile strength measurements were performed to determine the ability of the membrane to resist external physical damage, which is a critical factor for battery safety (Ibrahim *et al*., 2024). The test results showed that the 5:2 ratio achieved the highest tensile strength at 0.728±0.4 MPa, followed by the 5:3 and 5:4 ratios at 0.646±0.2 MPa and 0.523±0.4 MPa, respectively. Despite the numerical differences, ANOVA statistical tests indicated no significant difference across all the treatments (p>0.05). The strength of these membranes is primarily influenced by the interaction between the hydroxyl (-OH) and carboxylate (-COO) groups of the alginate with the Na^{+} and Cl^{-} ions from salt. These ions form ionic bonds with the polymer chains, increasing the network density and reinforcing the membrane structure (Wafiroh *et al.*, 2016; Yan *et al*., 2021). The tensile strength test results for the sodium alginate-NaCl membrane are shown in Figure 4.

However, the tensile strength values obtained in this study were relatively low compared to those of other polymer systems. For instance, Ibrahim *et al*. (2024) reported a higher value of 2.3 MPa for carrageenan-PVA (3:1), whereas Hermanto *et al*. (2019) achieved 1.91 MPa using an alginate-chitosan blend. Much higher values have been recorded in systems utilizing inorganic fillers or synthetic stabilizers, such as alginate-zeolite-

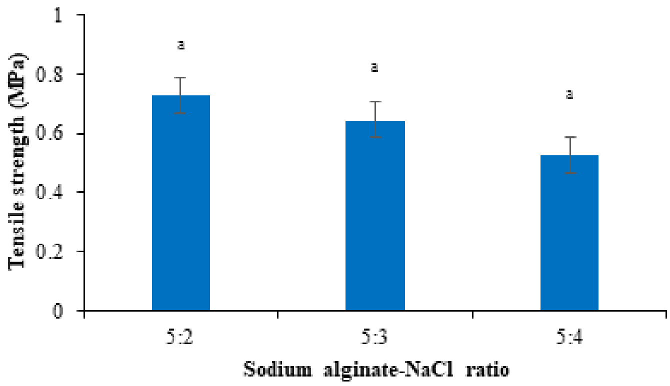

Figure 4 Effect of different ratios on the tensile strength of sodium alginate-NaCl electrolyte membranes; Superscript letters (a, b, c) indicate significant differences ($p<0.05$) among treatments.

kaolin (27.94 MPa) (Athaillah *et al.*, 2018) and PVA-sodium alginate (3.26 MPa) (Ramadhani & Kusumawati, 2023). These comparisons suggest that while the 5:2 ratio provides the best internal bonding for this specific mixture, the addition of a secondary polymer or cross-linking agent may be necessary in future research to achieve the superior mechanical toughness required for high-performance flexible batteries.

Battery Performance Analysis

Voltage represents the electrical potential difference between the battery cathode and anode, dictating the energy available to drive the charge through a circuit. The voltage generated by batteries utilizing a sodium alginate–NaCl electrolyte is shown in Figure 5. The highest mean voltage was observed in the 5:2 ratio treatment, reaching 0.511±0.01 V. In comparison, the 5:3 and 5:4 treatments yielded voltages of 0.337±0.01 V and 0.452±0.06 V, respectively.

Analysis of variance (ANOVA) indicated that the ratio of sodium alginate to NaCl had a significant effect on the output voltage ($p<0.05$). Theoretically, increasing the NaCl concentration enhances the ionic conductivity by expanding the population of Na^+ and Cl^- charge carriers (Lubis *et al.*, 2025). Furthermore, hydroxyl (–OH) groups within the matrix facilitate hydrogen bonding, which supports proton transfer and maintains membrane hydration, thereby stabilizing the battery voltage (Kamisyah *et al.*, 2020).

The discharge current of the paper battery, generated through the interaction within the sodium alginate–NaCl electrolyte at varying ratios, is shown in Figure 6. The maximum current was recorded in the 5:2

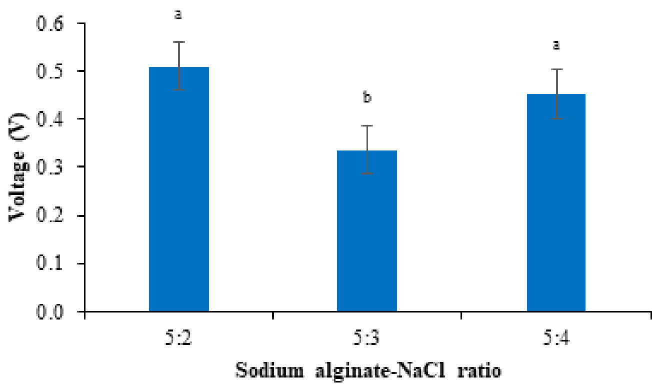

Figure 5 Effect of different ratios on the electrical voltage of sodium alginate-NaCl electrolyte membranes; Superscript letters (a, b, c) indicate significant differences ($p<0.05$) among treatments.

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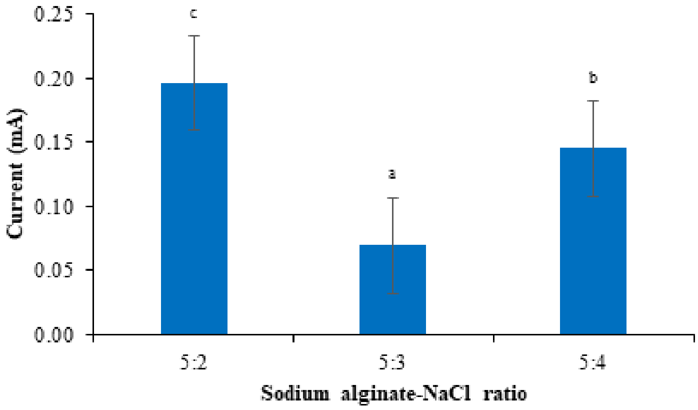

Figure 6 Effect of different ratios on the electrical current strength of sodium alginate-NaCl membranes; Superscript letters (a, b, c) indicate significant differences ($p<0.05$) among treatments.

ratio treatment at 0.196±0.007 mA. A decrease was observed at the 5:3 ratio (0.069±0.003 mA), followed by an increase at the 5:4 ratio (0.145±0.010 mA). These results suggest that increasing the NaCl concentration does not correlate linearly with the current intensity. Statistical analysis via ANOVA confirmed that the sodium alginate–NaCl ratio significantly influenced the current output ($p<0.05$).

In comparison to the existing literature, Ibrahim *et al.* (2024) reported a significantly lower current of 0.008±0.001 mA using a 20:4 (w/w) sodium alginate–NaCl electrolyte. Conversely, Da Silva and Maulana (2025) achieved a higher current of 2.6 mA using a 48 g/L NaCl solution. The presence of carboxylate groups ($–COO^{–}$) within the sodium alginate structure is fundamental to the electrical activity of the membrane (Herlina *et al.*, 2021). The ionic interactions between these carboxylate groups and the Na^{+} and $Cl^{–}$ ions establish a conductive pathway that facilitates efficient charge transport through the matrix. In this system, NaCl serves as a source of mobile charge carriers, thereby enhancing the ionic conductivity of the polymer electrolyte (Da Silva & Maulana, 2025). Furthermore, the synergistic combination of sodium alginate and NaCl yields a membrane that integrates robust mechanical properties with effective ionic transport, ultimately contributing to stable battery performance and charge-discharge cycle durability (Wafiroh *et al.*, 2016).

The highest electrical power was generated at a ratio of 5:4, amounting to 66.003±12.2 mW, followed by 5:2 at 35.475±2.2 mW and 5:3 at 65.998±1.4 mW. Duncan's further analysis showed that the electrical power generated in the 5:2 treatment was significantly different from that in the 5:3 and 5:4 treatments. This indicates that the higher the NaCl composition, the greater is the electrical power generated. The results of research conducted by Ibrahim *et al.* (2024) obtained a power value from sodium alginate-NaCl 20:4 electrolyte of 0.0019±0.0004 mW.

NaCl acts as a source of Na^{+} and $Cl^{–}$ ions, which are the main charge carriers in polymer-electrolyte systems. NaCl increases the concentration of moving ions and reduces the internal resistance of the battery, thereby increasing the electrical power generated (Da Silva & Maulana, 2025). The hydroxyl group (-OH) plays a role in the formation of hydrogen bonds that facilitate the transfer of protons and ions in the electrolyte membrane, thereby increasing the ionic conductivity and charge transfer efficiency in the battery (Herlina *et al.,* 2021). The carboxylate group (-COO) interacts ionically with Na^{+}, enabling more efficient ion transport, thereby increasing the energy storage and release capacity, that is, the battery power (Maharani *et al*., 2017). The electrical power generated can be seen in Figure 7.

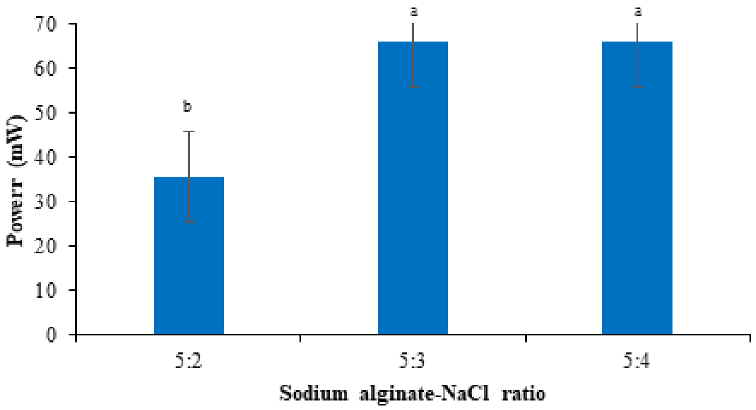

Figure 7 Effect of different ratios on the electrical power of sodium alginate-NaCl electrolyte membranes; Superscript letters (a, b, c) indicate significant differences (p<0.05) among treatments.

Analysis of Electrolyte Membrane Function Groups

Fourier transform infrared (FTIR) spectroscopy was employed within the 400–4,000 cm^{-1} range to characterize the chemical structure of the sodium alginate–NaCl membranes (Figure 8 and Table 2). The spectra revealed characteristic polysaccharide peaks, most notably the hydroxyl (–OH) stretching vibration at 3,301.31 cm^{-1}. This group, along with carboxylates (–COO^{-}) identified at 1,794.64 cm^{-1} and 1,642.46 cm^{-1}, is essential for maintaining membrane hydration and facilitating proton transport via hydrogen bonding (Wafiroh *et al.*, 2016; Kamisyah *et al.*, 2020). Additional peaks at 2,898.17 cm^{-1} and 1,446.67 cm^{-1} correspond to C–H alkane vibrations, representing the alginate carbon skeleton, whereas peaks between 1,155.37 and 1,030.03 cm^{-1} confirm the presence of glycosidic C–O–C bonds (Ibrahim *et al.*, 2024).

The absence of significant peak shifts or new functional groups indicates that no covalent chemical reactions occurred between sodium alginate and NaCl. Instead, the interaction remains purely ionic, with NaCl serving as a source of mobile charge carriers within the polymer matrix. This structural stability suggests that the electrolyte performance is driven by the synergistic relationship between the functional groups of alginate and the added salt, which together establish efficient conduction pathways without altering the fundamental chemical identity of the polymer.

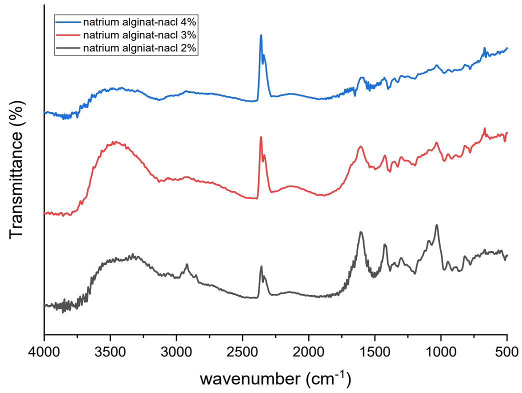

Figure 8 FTIR spectrum of sodium alginate-NaCl electrolyte membrane

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Table 2 Functional groups of sodium alginate-NaCl membrane

No	Wavenumber (cm^{-1})	Functional groups
1	3.301,31	Hydroxyl group (O-H)
2	2.898,17	Alkane group (C-H)
3	1.794,64	Carbonyl group (C=O)
4	1.642,46	Carbonyl group (C=O)
5	1.446,67	Alkane group (C-H)
6	1.155,37 and 1.030,03	Alkoxy group (C-O)
7	877,65	Alkane group (C-H)

CONCLUSION

This study shows that using a mix of sodium alginate (from seaweed) and NaCl makes flexible batteries work better and stay strong. The best results were obtained from a 5:2 ratio, which carried electricity more efficiently than other natural materials, such as carrageenan. Interestingly, adding too much salt actually slowed down the electricity because the salt particles became crowded and blocked the flow. While the battery needs to absorb some water to keep electricity moving, we found that a careful balance is needed to prevent the battery from swelling or becoming too weak. Overall, this 5:2 membrane is a safe, flexible, and eco-friendly alternative to toxic conventional batteries, making it an excellent choice for future green electronics.

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