Jurnal Fisika 16 (1) (2026) 30-46
Jurnal Fisika
https://journal.unnes.ac.id/nju/index.php/jf/index

Effect of Electrolyte Concentration and Nafion Membrane Separators on Discharge Dynamics and Voltage Stability of Supercapacitors

Jagendra Chaudhari[1*], Samundra Marasini[2], Sangita Rai[2]

[1]Department of Physics, Patan Multiple Campus, Tribhuvan University, Patan Dhoka Lalitpur, Nepal
[2]Department of Physics, Goldengate International College, Tribhuvan University, Kathmandu, Nepal

Article Info

Article History:

Received:
25 November 2025

Accepted:
17 April 2026

Published:
15 May 2026

Keywords:
Supercapacitors, Nafion separator, Self-discharge, Electrolyte concentration, Capacitance, Energy storage

Abstract

This study investigates the effects of Na_2SO_4 electrolyte concentration and Nafion membrane separators on the self-discharge behavior, discharge dynamics, capacitance, and voltage stability of supercapacitors, aiming to identify optimal conditions for enhanced charge retention and long-term energy storage. Supercapacitors were fabricated with Nafion separators and charged at different voltages (1.0, 1.2, and 1.4 V) for varying durations (1, 1.5, and 2 minutes). Self-discharge was monitored, capacitance was calculated using the capacitor discharge equation, and discharge tests were conducted through a 500-ohm resistor to simulate realistic operating conditions. The results demonstrate that supercapacitors with Nafion separators and 0.5 M Na_2SO_4 electrolyte exhibit significantly lower self-discharge rates and more stable voltage profiles compared with those using napkin paper separators. Additionally, higher charging voltages and longer charging times improve charge retention. These findings indicate that the combination of Nafion membranes and optimized electrolyte concentration effectively enhances supercapacitor performance, providing a practical strategy for reliable and efficient energy storage applications.

✉ Correspondence address:
Department of Physics, Patan Multiple Campus, Tribhuvan University, Patan Dhoka Lalitpur, Nepal
E-mail: jc.jagendra@gmail.com

p-ISSN 2088-1509

INTRODUCTION

Supercapacitors (electric double-layer capacitors; EDLCs) have received significant interest as energy storage devices with high power density, fast charge–discharge ability, long life cycle and large environmental stability in addition to their relatively low maintenance when compared to batteries (Schneuwly & Gallay, 2000; Iro et al., 2016; Shrestha et al., 2017). However, although having these merits, the general use of such devices are hampered by a number of crucial issues especially because of self-discharge phenomena, dependence on electrolyte for charge retention and semi-permeability-related restraints over ion transport (Volfkovich et al., 2023; Shang et al., 2023). When open-circuit is considered, self-discharge induces fast loss of energy, thus the effective energy density decreases a lot and the practical application is restricted significantly, which will hinder the application in wearable devices and long-term emerging storage systems.

Among these electrode materials, activated carbon (AC) is still the mostly utilized one for EDLCs owning to its large specific surface area, adjustable pore structure and chemical stability (Yang, 1998; Manocha, 2003). However, the electrochemical capacitance of AC-based supercapacitors is primarily attributed to the effective utilization of pore surfaces where it was controlled by the interaction between electrolyte ions and electrode pores (Supiyeva et al., 2023). A disparity between pore size and solvated ion dimensions can lead to the electrochemical inactivity of large portion of surface area, which leads to low capacitance and poor rate performance. Moreover, the electrode–separator interfacial interactions are pivotal in governing ion-transport resistance, charge redistribution and long-term stability.

Consequently, the separator materials are essential in the design of supercapacitors. Paper-based separators are popular due to their low cost and simple fabrication even though they usually show poor mechanical stability, electrolyte leakage, uncontrolled ion transport and can lead to self-discharge. Proton-conducting polymer, Nafion membranes on the other hand possess good ionic conductivity, superior chemical and mechanical stability along with enhanced electrochemical durability (Pazhamalai et al., 2022). Nafion has been used as a polymer electrolyte and separator for flexible SCs and solid state SC devices [100-102], Li-ion batteries (LIB) (Pandey et al., 2011), RFB shows remarkable improvements in CE, VE capacity retentionKarimi et al., 2023; Mehboob et al., 2023). However, due to Nafion's compact polymer structure, its reduced uptake potential for electrolyte within the porous carbon electrodes might cause greater interfacial inductive loss and lower surface area directly available for OER reaction (Pazhamalai et al., 2022). This trade-off points to the importance of systematic assessments of Nafion membranes vs. typical separators under different electrolyte conditions.

Electrolyte concentration, the other inevitable parameter determining super-capacitor performance is a determinant for energy density, power density and charge retention (Fu et al., 2023; Zallouz et al., 2024). The high concentration of electrolytes leads to an increase in charge carrying ion availability results higher capacitance, while excessive amount causes the increase in internal resistance also restrict the movement of ions (Mendhe & Panda, 2023). It has been shown for potassium acetate and other aqueous electrolytes that an optimal salt concentration is reached where ion adsorption as well as the resistance are balanced leading to a maximal capacitance and rate capability (Azmi et al., 2023). In addition, the electrodeposition behavior, ion desorption and long-term cycling stability are also greatly influenced by the electrolyte composition (Min et al., 2023; Jiang et al., 2024). Although several methods, including polymer electrolytes (Wang et al., 2023), bilayer heterogeneous systems (Liu et al., 2024) and electrolyte engineering have been developed to mitigate against self-discharge, the combined effect of the concentration of electrolyte and type of separator on discharge characteristics and charge retention are not sufficiently known, especially for AC-based supercapacitors.

From the fabrication point of view, a stable and uniform dispersion of activated carbon is important to guarantee reproducibility of electrode performance. Homogeneous distributions are

important in coatings, inks ceramics, and nanocomposites but dispersing carbonaceous materials at the nanoscale is difficult (Nguyen & Vincent, 2013; Minami et al., 2010; Alafogianni et al., 2016). The addition of surfactants such as cetyl trimethylammonium bromide (CTAB) enhances wettability and dispersion stability of particle (Shah et al., 2011a), while physical methods including sonication and electrophoretic deposition (EPD) facilitate well-controlled film formation process (Taurozzi et al., 2011a; Nikolaev, 2017). EPD, in particular, has been successfully applied to prepare AC electrodes with controlled mass loading and uniformity (Shrestha et al., 2017), and it can be improved by auxiliary agents as Nafion (Zhang et al., 2022).

Research Gap

Although authors have reported significant investigations on activated carbon-based supercapacitors, electrolyte optimization and separators materials separately 28] the combined and systematic effect of electrolyte concentration and Nafion membrane as separator on discharging dynamics for the supercapacitor behavior; followed by charge retention have not been well studied. Especially, the majority of the previous studies mainly focus on capacitance improvement and cycling stability, whereas self-discharge characteristics as well as voltage decay at various charging voltages and different charging durations have not been systematically quantified. In addition, there are few cases in which Nafion membranes and commercial paper type separators are compared experimentally under the same electrolyte concentrations and conditions. Hence, the best balance of electrolyte–separator system for achieving self-discharge and voltage stability in supercapacitors has been a controversial issue.

Novelty and Contribution of the Present Study

The novelty of the current study is a systematic experimental investigation on coupled influence of electrolyte concentration and Nafion membrane separators on discharge dynamics and charge retention in supercapacitors. In contrast to previous works, this study directly compares the Nafion membrane with regular napkin paper separators employing a 0.5 M and 1 M Na_2SO_4 electrolyte solution at two concentrations by controlling the charging voltage range (1.0–1.4 V) and charging time period. The study is the first to clearly show that a decreased electrolyte concentration (0·5 M Na_2SO_4) by use of a Nafion separator effectively suppresses self-discharge and improves voltage stability, resulting in increased charge retention. In addition, quantitative analysis of the effect of charging voltage and charging time on self-discharge performance is conducted, offering practical guidance for operating condition optimization. These results provide a new approach to develop supercapacitors with high long-term energy retention and good operation stability by using Nafion membranes at an optimal electrolyte concentration.

MATERIALS AND METHOD

Experimental setup for Ultra-Sonication

In the experiment, the first step involved preparing electrodes to supply DC voltage to the solution during sonication. Aluminum plates measuring 5.5 cm by 1.3 cm were used as parallel electrodes, separated by a 1 cm distance, and fitted into a rubber cork (as shown in Figure 3.1). A solution of AC (Activated Carbon) and CTAB (Cetyl Trimethyl Ammonium Bromide) was then prepared in 10 ml of distilled water at a concentration of 1 g/Liter, with different AC: CTAB ratios (2:0.5, 2:1, 2:1.5, 2:2, 2:2.5). Once the solution was prepared, bottles with fitted corks containing the electrodes were subjected to sonication, where different DC voltages (0V, 3V, 5V, 7V, 9V, 12V) were applied. The sonication times were varied across three sets of experiments: 10 minutes, 30 minutes, and 60 minutes.

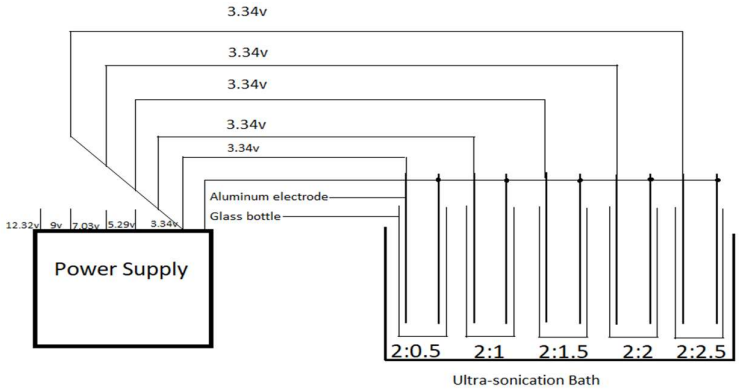

Figure 1. Schematic diagram for the whole setup for dispersion using 3.34 dc voltage.

The experiment started with no DC voltage applied (for the first set), and then a DC voltage of 3.34V was supplied for the second set, and so on for each subsequent voltage level. All different voltages were supplied for each set using the aluminum plate electrodes, as depicted in Figure 1. For the setup, materials such as wires, glass bottles, aluminum plates, power supplies, corks, and spokes were sourced from an electrical shop. The ultrasonic bath and CTAB, which was used for dispersion in the experiment, were imported from Central Drugs House (P) Ltd. in New Delhi, India. The CTAB used was a white powder with a minimum assay of 99.0%, and its impurities were within the specified limits: 0.1% for sulphated ash, 0.001% for heavy metals (Pb), and 0.5% for cetyldimethylamine. This setup was used to investigate the effects of sonication under different voltages and solution ratios.

Dispersion of AC with Sonication in DC Electric Field

In this experiment, a mixture of AC (Activated Carbon) and CTAB (Cetyl Trimethyl Ammonium Bromide) was prepared in 10 ml of distilled water at a concentration of 1 g/L for different AC: CTAB ratios (2:0.5, 2:1, 2:1.5, 2:2, 2:2.5). Five different mixtures with varying AC: CTAB ratios were sonicated for 30 minutes and then left for sedimentation for 24 hours. To analyze the optical properties, a UV-Visible Spectrometer was used, following the Beer-Lambert Law. This law states that absorbance (A) is directly proportional to the concentration (c) of a solution and the path length (l) through which light travels, and is expressed as:

$$\mathrm{A} = \epsilon \mathrm{clA} \tag{1}$$

Where ε is the molar absorptivity. According to this law, absorbance increases with concentration and path length, although at high concentrations, light reflection by the sample can cause deviations. The relationship between absorbance and transmittance (T) is given by:

$$A = 2 - \log_{10} \mathrm{T} \tag{2}$$

After the 24-hour sedimentation period, the absorbance of each mixture was measured using a UV-Vis spectrophotometer (USB 2000, Photonics), and the data was analyzed using Origin software. For the next set of experiments, a 3.34V DC source was applied to each mixture, and absorbance was again recorded. Similar experiments were carried out by applying different DC voltages: 5.32V, 7.03V, 9V, and 12.32V. After the 24-hour sedimentation period for each voltage level, the absorbance curves were plotted and analyzed using Origin software. This process helped to study the impact of different AC: CTAB ratios and varying DC voltages on the optical properties of the mixture.

Electrophoresis of Activated Carbon

Stainless steel plates (5×2 cm) set parallel with 1 cm between them were coated using

electrophoretic deposition (EPD) to create the activated carbon (AC) electrodes (Figure 2). A well-dispersed AC liquid was produced by mixing 3.75 g/L of AC with cetyl trimethylammonium bromide (CTAB)/distilled water (240 mL) using sonication over 6 hours and then setting aside for sedimentation for a further 24 hours, to remove undispersed agglomerates. Undiluted supernatant was loaded for precipitation. The EPD's parameters were optimized using the AC: CTAB (2:3, 2:4, 2:5, and 2:6) and the applied DC voltage (3–12.5 V), with a cycle of 5 min ON/5 min OFF that was repeated five times. It was these variables that enabled the uniform, adherent and high-surface-area AC coatings that were found to be necessary for enhancing the electrode conductivity, electrochemical surface area, stable supercapacitor operation and self-discharge performance of the electrodes. Figure 3(a) and figure 2(b) show the configuration of electrodes and the experimental apparatus for deposition.

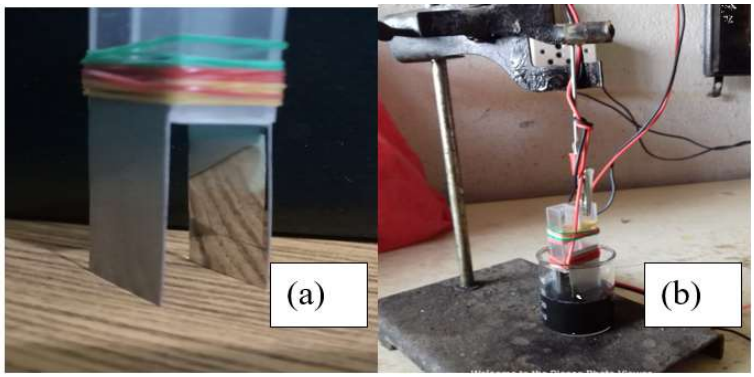

Figure 2. Steel plate arrangement of electrodes for (a) EPD and (b) Electrophoretic deposition of AC.

Fabrication of Supercapacitor

The AC-coated electrodes were dried at 150°C for 6 hours and assembled into supercapacitors in the form of using napkin paper or Nafion membranes as separators with a 0.5 M and suspension (Figure 3). The electrodes were wetted with the electrolyte, set together with the separator, and dried for 45 minutes. Supercapacitors were then charged at 1.0 V, 1.2 V and 1.4 V for different times (1 min, 1.5 min and 2 min) followed by the detection of self-discharge rate and discharge rate. By correlating the optimized AC dispersion and EPD conditions with electrode uniformity and surface properties, this process was able to directly assess how high quality of the electrode affects charge retention, voltage stability, overall supercapacitor performance. The comprehensive investigation of voltage, time, electrolyte concentration and separator type we conducted facilitated the determination of low self-discharge efficiency energy-storage process conditions, which have significance for practical high-performance supercapacitor fabrication.

Figure 3. Supercapacitor arrangement.

RESULTS AND DISCUSSION

Optimization of CTAB Amount for Dispersion of AC under DC field.

In the experiment, a 1g/L solution of AC and CTAB was sonicated under applied DC voltages (Ambika et al., 2020) 3.0V and allowed to sediment for 24 hours. From the photographs (Figure 4), the solution with a AC: CTAB ratio of 2:1.5 appeared the darkest at 3V, indicating the best dispersion of AC. This suggests that at lower voltages, the 2:1.5 ratio optimizes the interaction between CTAB and AC, leading to effective dispersion. The absorbance measurements of dispersed solutions of AC and CTAB at different AC: CTAB ratios (2:0.5, 2:1, 2:1.5, 2:2, 2:2.5) under applied DC voltages 3.0 V.

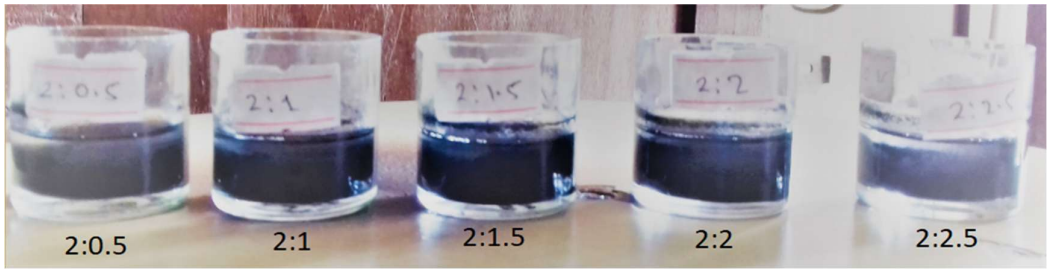

Figure 4. Photograph of dispersed solution of AC and CTAB after 30 minutes' sonication and 24 hours' sedimentation at 3.0 V applying DC voltage.

Figure 5, which shows the absorbance with applied voltage 3.0 V, indicates that the highest absorbance occurs at the AC:CTAB ratio of 2:1.5, suggesting optimal dispersion at this ratio. As the CTAB concentration increases, the absorbance gradually increases until it peaks at the 2:1.5 ratio, beyond which further increases in CTAB lead to a decrease in absorbance. Under 3.0 V it shows the same trend, with the highest absorbance observed at the 2:1.5 ratio, further confirming that this ratio achieves the best dispersion of AC particles. These results indicate that at lower voltages, a CTAB:AC ratio of 2:1.5 is optimal, while higher voltages favor lower CTAB concentrations (2:0.5) for efficient dispersion of AC particles (Daintree & Biggs, 2010).

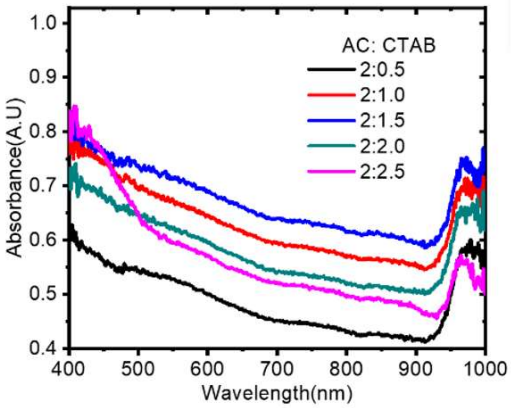

Figure 5. Absorbance of dispersed solution of AC and CTAB mixed in different ratios (2:0.5, 2:1, 2:1.5, 2:2, 2:2.5) having concentration 1g/Liter at 3.0 V applied voltage

The observed trends in absorbance can be attributed to the interplay between the concentration of CTAB and the applied DC voltage, which influences the dispersion and stabilization of AC particles. At 3V, the 2:1.5 AC: CTAB ratio is optimal for dispersion because it strikes a balance between the hydrophilic and hydrophobic properties of CTAB. At this ratio, CTAB molecules effectively adsorb onto the surface of the AC particles, preventing aggregation while maintaining sufficient electrostatic repulsion to keep the particles dispersed in the solution. The gradual increase in absorbance with increasing CTAB concentration up to the 2:1.5 ratio indicates better dispersion as the surfactant concentration rises, but after this point, further increases in CTAB concentration lead to micelle formation or aggregation, which reduces the dispersion efficiency and, consequently, the absorbance (Rauf et al., 2016).

Absorbance at selected wavelength with different ratio of AC and CTAB

The variation in absorbance of the dispersed solution with increasing CTAB concentration is evident in Figure 6. This can be attributed to the effect of CTAB on the dispersion of AC particles and how the CTAB concentration influences the dispersion efficiency. Figure 7 reveals a clear trend: as the CTAB concentration increases from 0.5 to 1, the absorbance rapidly increases, with a peak at the AC: CTAB ratio of 2:1.5. This is likely because this ratio provides an optimal balance between dispersing the AC particles and preventing their aggregation, which increases the surface area exposed to light. However, as the CTAB concentration exceeds this optimal point (i.e., at the 2:2 ratio), the absorbance decreases. This suggests that higher CTAB concentrations beyond a certain point result in the formation of aggregates or micelles, reducing the effective dispersion of AC particles in the solution (Shang et al., 2019), thus lowering absorbance.

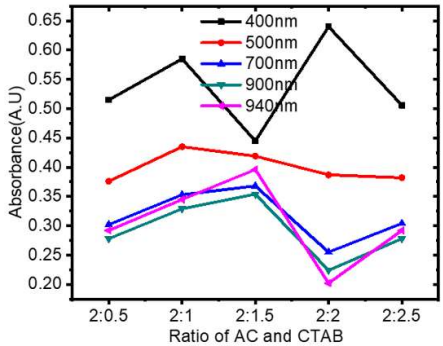

Figure 6. Variation of absorbance of dispersed solution of AC with varying CTAB amount at

different wavelengths with 3.0 V applied voltage

For 700nm, 900nm and a second peak at 940nm the highest absorbance values were obtained using the AC: CTAB ratio of 2:1.5 indicating this as the optimal dispersant ratio. Once more the reduction of absorbance at higher CTAB concentration on excess surfactant results in decreased dispersion. At 5V, 7V and 9V, absorbance still becomes maximal at the 2:1.5 ratio; however, as we increased voltage to 12V, for all combination of CTAB ratio stands with very distinct shape whereby a larger rate of concentration (0.5) presents itself as optimum showing an inversion in such behavior by inducing only minimum amounts of CTAB for obtaining maximum particle formation unusual phenomenon was observed to our surprise. This means that the particles were effectively dispersed by electrostatic forces at larger voltages even in lower CTAB. This can be explained by the stronger electric field, which assists AC particles in dispersing that they agglomerate as well even without high surfactant.

As is demonstrated in Fig. 6, the absorbance of the dispersion solution of AC and CTAB varies sensitively with the molar ratio of AC/CTAB and applied voltage (Pang et al., 2015). For all applied voltages, the highest absorbance was obtained at 2 AC: CTAB ratio of 1.5 indicating an optimal dispersion of AC particles. As the CTAB/AC ratio exceeded this value (2:2 or 2:2.5), absorbance decreased because of aggregation or micellization of AC particles, which stops their dispersion. This behavior was observed at different wavelengths (400-940nm), the absorbance increased in general with addition of CTAB from 0.5 to 1ml and it decreased as the concentration further increased. However, when we applied higher voltage 12 V, more diluted ctab:0/5); as consequence led to stronger electrostatic forces and dispersions of AC particles. Therefore, the data indicate that CTAB addition enhances dispersion up to a point and too much surfactant results in poor dispersion efficiency; 2:1.5 is the best for most cases.

Optimization of Electric field for Electrophoretic deposition of AC

When examining the EPD process, the solution of AC and CTAB with concentration of 7.5 g/L and 2:1.5 (AC: CTAB) ratio was used at 3V, 5V, 7.5V, 9.5V and 12.5V. As the applied voltage increased, the uniformity of the deposition improved, with the best results seen at 9.5V. Below this voltage, the deposition was irregular and rough, with precipitation observed at 3V, 5V, and even 7.5V, indicating poor particle mobility and uneven deposition. At 9.5V, the deposition was the smoothest while higher voltages (12.5V) caused increased precipitation and thicker films, but the deposition quality deteriorated. These observations align with the idea that an intermediate voltage provides the most balanced conditions for EPD, suggesting 9.5V/cm as the optimal field for the best deposition (Figure 7). Thus, the combination of a specific AC: CTAB ratio and applied voltage plays a crucial role in achieving efficient dispersion and deposition in electrophoretic processes (Esfahani et al., 2017).

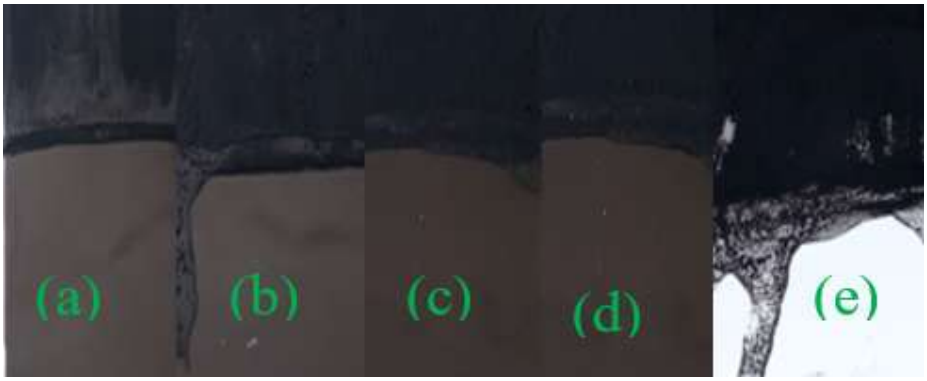

Figure 7.cElectrodes after electrophoretic deposition for 50 minute by applying different DC voltages

(a) 3.0 V, (b) 5.0 V, (c) 7.5 V, (d) 9.5 V, (e) 12.5 V in the dispersed solution of AC in distilled water with AC: CTAB=2:1.5.

Optimization Ratio of CTAB and AC for the best EPD

During the fabrication of super capacitor, the electrodes prepared by taking AC: CTAB ratio (2:1.5) at 9.5V could not hold the charge due to improper thickness and to achieve the optimal thickness of electrodes, EPD process was tested with different AC to CTAB ratio (In this study, four different solutions were prepared by varying the AC to CTAB ratio, with CTAB concentration fixed at 7.5g/L and AC varying (CTAB: AC ratios of 2:3, 2:4, 2:5, and 2:6). Further ratio above 2:6 is the limitation of this research for optimization ratio. After 6 hours of sonication and 24 hours of sedimentation, these solutions were used for EPD by applying an optimized electric field of 9.5V/cm for 50 minutes. Figure 9 shows the photographs of the electrodes after the EPD process for the different CTAB: AC ratios. From the inspection of the deposited electrodes, it was observed that the deposition was most uniform for the 2:5 and 2:6 CTAB: AC ratios (Figure 8c, 8d) (Maciąg et al., 2021). While, the deposition was irregular and not uniform for the 2:3 and 2:4 ratios (Figure 8a, 8b). These findings suggest that higher amounts of AC in the solution result in better deposition quality. Specifically, when the ratio of CTAB: AC is 2:5 or 2:6, the deposition is not only uniform but also of better quality. This indicates that increasing the AC content relative to CTAB improves the efficiency of electrophoretic deposition on stainless steel plates, with 2:5 and 2:6 ratios providing the optimal results for uniform and high-quality films.

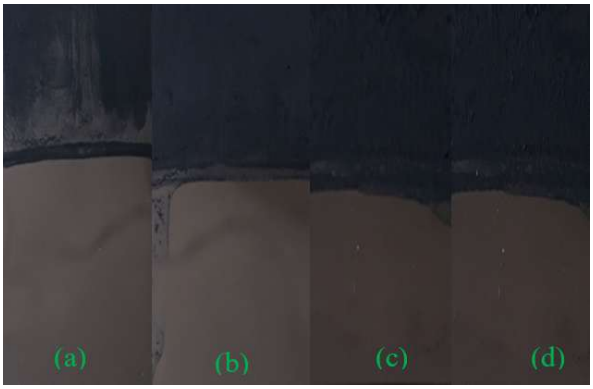

Figure 8. Electrodes after electrophoretic deposition for 50 minute by applying 9.5 volt in the solution of different amount of AC (CTAB: AC= (a) 2:3, (b) 2:4; (c) 2:5, (d) 2:6)

Supercapacitor Fabrication

The SC were fabricated using two AC electrodes prepared by electrophoretic deposition, with Na_2SO_4 (1M and 0.5M) used as the electrolyte and napkin paper or Nafion membrane serving as separators. After fabrication, the supercapacitors were dried and then charged at various voltages (1V, 1.2V, 1.4V) and for different time periods (45 seconds, 1 minute, 1.5 minutes, and 2 minutes). The self-discharge behavior of these supercapacitors was observed, with the self-discharge curves presented in Figure 9. Figure 9 shows the self-discharge behavior of the supercapacitor prepared with a 1M Na_2SO_4 electrolyte and napkin paper as a separator (Ricketts, 2000). It is observed that the output voltage is not constant over time, indicating a self-discharge phenomenon. This is typical of supercapacitors, where the stored charge leaks over time due to several factors. The observed high self-discharge can be attributed to charge leakage at the electrical double layer (which forms at the interface between the electrode and the electrolyte), impurities present in the electrode material causing redox reactions, and excess ion concentration due to the high dissociation voltage limit of the electrolyte (Du et al., 2021).

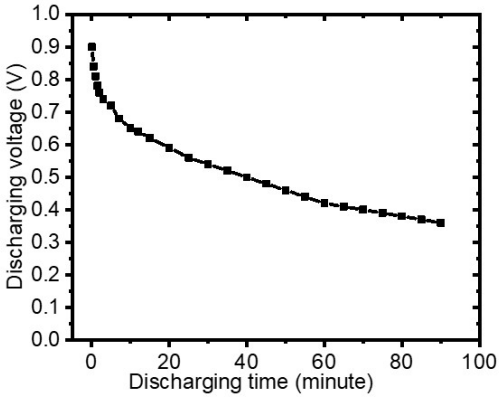

Figure 9. Self-discharge of supercapacitor fabricated by using paper (napkin) separator, charging time 45 sec, electrolyte concentration 1 m Na_2SO_4

In this case, the choice of napkin paper as a separator may contribute to higher leakage, as its ionic conductivity and dielectric properties may not be as efficient as other materials like Nafion. Furthermore, high electrolyte concentration can increase the ion leakage, leading to faster self-discharge. This suggests that improving the material properties of both the separator and the electrolyte, as well as optimizing the electrode fabrication process, could reduce self-discharge rates and improve the overall performance of the supercapacitor (Jangid et al., 2021). The results from Figure 10 highlight the need for better charge retention and less leakage in order to enhance the charge holding capability of supercapacitors.

The second experiment investigated the fabrication of SCs using a Nafion membrane as a separator, and the self-discharge characteristics of these supercapacitors were evaluated. The results are shown in Figure 10, which displays the self-discharge curve for the supercapacitor prepared with a Nafion separator and 1M Na_2SO_4 as the electrolyte, after charging for 1 minute. Figure 10 indicates that the voltage drops rapidly up to approximately 0.70V, after which the voltage decreases more slowly, maintaining charge for up to 1.5 hours or even longer (Ricketts, 2000). This slow voltage drop is indicative of improved charge retention compared to the supercapacitor with the napkin paper separator, as observed in the previous experiment. The initial rapid voltage drop can be attributed to the typical behavior of supercapacitors, where they discharge quickly in the early phase of self-discharge due to the initial release of stored charge at the interface between the electrode and electrolyte. However, the slower discharge rate after this point suggests that the Nafion membrane effectively reduces the charge leakage, helping the supercapacitor maintain its charge over a prolonged period.

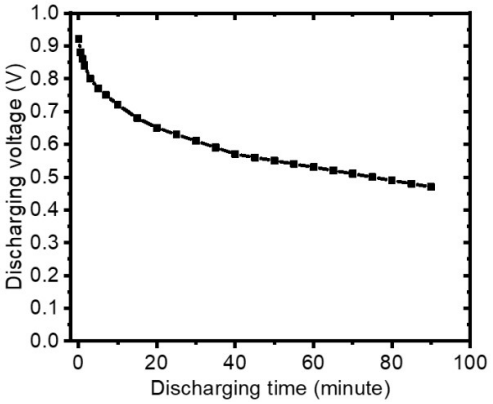

Figure 10. Self-discharge of supercapacitor fabricated by using Nafion separator with

charging time 1 minutes 1M Na_2SO_4 electrolyte

This behavior aligns with the general characteristics of self-discharge observed in carbon-based supercapacitors. In supercapacitors, self-discharge is as a result of the charge that leaks from electrical double layer at the electrode-electrolyte interface. For SCs of Nafion separators, the rate of self-discharge is much lower than that for resistive capacitors and napkin paper separators, indicating a good charge retention. The possible reason may be that this porous Nafion membrane has higher proton conductivity than napkin paper due to its very low resistance and better ion-conducting performance. Less self-discharge and steadier voltage with the Nafion separator mean the better performance in terms of charge retention capacity. This is important in the application of supercapacitors, as a decrease in self-discharge rate directs to an increase on the duration for which it keeps charged, therefore demanding less frequent recharge and improving performance. It in turn, greatly enhances the stability and performance of supercapacitors which now make it a promising material for high-performance energy storage applications (Jiang et la., 2025).

Figures 11 and 12 show the self-discharge curves of the SCs at different charging voltages and time, using Nafion separators, with an electrolyte of 0.5M Na2SO4. These results show how the self-discharge property of SCs varies as a function of the electrolyte concentration and charging voltage. In Fig. 11, the CSs were charged with 1 V and 1.2 V during one minute durations. From the results, it can be seen that the self-discharge curve for the SCM charged at 1V decreased faster than that of charged at 1.2V, which is related to a lower energy stored in the supercapacitor when being charged by a small voltage. SCs charged at higher voltages tend to have higher stored charge, which is then slowly discharged (as for SC) although with a slower self-discharge rate (such as with the SC charged at 1.2 V). Once the rapid voltage drop occurs, after few hours they both may present a slow discharge phase holding charge during several hours even if equilibrium finally occurs. The higher voltage (1.2V) provides a more stable voltage over the usable energy capacity because there is a greater amount of charge stored in the 1.2V double layer and this results in low rates of self-discharge compared to the 1V charge.

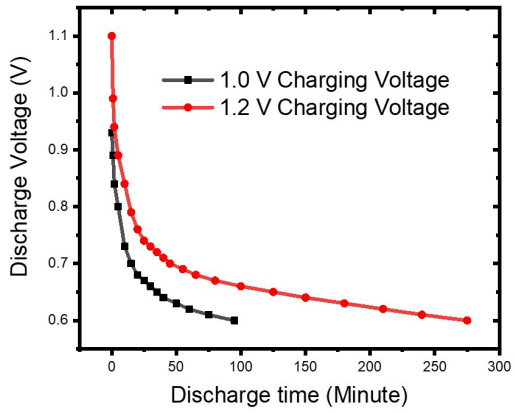

Figure 11. Self-discharge of supercapacitor fabricated by using Nafion separator with charging voltage 1 and 1.2 V with 0.5M Na_2SO_4 as an electrolyte.

Figure 12 The self-discharge curves of SCs with 1.4V charging voltage and 0.5M Na_2SO_4 electrolyte by the charging time were set as 2 m in. With increasing voltage and charging time, the SCs exhibit an even lower degree of self-discharge and more stable electrode potential compared with so-called SCs in Figure 11. Higher voltage combined with a higher charging duration gave rise to increased charge storage, leading to slower self-report discharging rate (Nkembi et al., 2024). It is interesting to note that SC with charging voltage of 1.4 V, which is for a period of 2 minutes,

demonstrates the lowest discharge rate minimizing the in time previous hours five than maintain voltages maintaining. Such a superior performance is due to the higher charging voltage and optimization of electrolyte concentration (0.5M Na_2SO_4), which helps further improve the ionic conductivity and charge tolerance of SC.

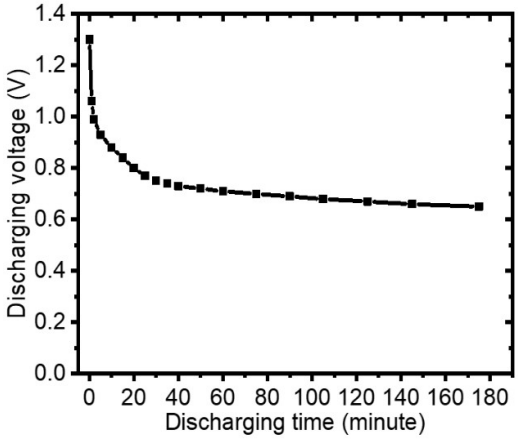

Figure 12. Self-discharge of supercapacitor fabricated by using Nafion separator charging time 2 minutes with 1.4 V and electrolyte 0.5 M Na_2SO_4

The reduction of the electrolyte concentration down to 0.5M Na_2SO_4 (formerly 1M in our previous tests) has a crucial impact on SCs performance. At 0.5M, the self-discharge is still low with stable voltage profiles of the SCs, however the discharge rate gets attenuated indicating that at these rates, SCs hold their charge for longer time periods. The lower electrolyte concentration delivers the lower ion dissociation which however reduces risk of high ions concentration and potential redox reaction at the electrode surface induced, and thus also suppresses unwanted self-discharge (Wu et al., 2015). This influence of the electrolyte concentration in charge leakage is reflected in an increased charge retention and a decreased self-discharge over time, for SCs built with 0.5M Na_2SO_4 than for SCs produced with higher concentrations of the electrolyte.

Discharging a SC at constant resistance (500 ohm)

The experiment described in the provided findings involves the discharge behavior of a SC after it was charged at 1.2V for 1.5 minutes and then discharged by connecting a 500-ohm resistor in series. The voltage of the SC dropped from 0.77V to 0.13V in 120 seconds, and then from 0.30V to 0.16V over the next 80 seconds. The capacitance of the SC was calculated using the capacitor discharge equation:

$$C = \frac{t}{R \ln\left(\frac{V_0}{V_t}\right)} \tag{2}$$

Here C is the SC capacitance, t =1/2πf is the discharging time, R = 500 Ω (resistance value), V0=0.77V (the initial voltage) and Vt is the voltage at time t after discharging respectively. The capacitance calculated from the slow discharge region (between 0.30V and 0.16 V) was 0.21F, which is very useful to evaluate the performance of the SC. Faster first-phase discharge was also suggested by the voltage decline between 0.77V and 0.13V in the first 120 s. This is what would happen if you tried the same thing in a supercapacitor, for instance: placing a resistor in series makes the voltage drop like a rock, because all that energy has to go somewhere and is flying out of your capacitor. Discharge is the rate at which voltage falls and is determined by R time, where charge and discharge are proportional to how fast the voltage drops (R) × intensity (C). In the next 80 s, the voltage decreases from 0.30V to 0.16V with a gentler slope after the obvious voltage falling (Fig.S3), which represents a

slow discharge procedure. This is a supercapacitor behavior, as its discharge rate decreases when its energy content reduces (Isayev & Kurmanov, 2023). The low discharge shows that the energy is being release more slowly, as per figure 13, then during a longer period voltage sustain and power supply. Calculation of Capacitance The obtained capacitance was 0.21 F, which is an indication of the amount of energy stored in SC during its discharge. The capacitance value obtained is similar to the supercapacitor which has a relatively large variation in the range few F up to natural F according to material and structure of capacitor. The value found above is representative of the ability of the supercapacitor to store and release charge over time. The Nafion membrane owned high ionic conductivity and stability, it plays a key role for the charge storage and release property of the device. The concentration of the electrolyte used (0.5M Na_2SO_4) is not high, indicating moderate ionic conductivity and thus balancing between charge storage and self-discharge. This electrolyte concentration enables a more or less constant discharge characteristic but also low problems such as self-discharge, as well as rapid charge leakages.

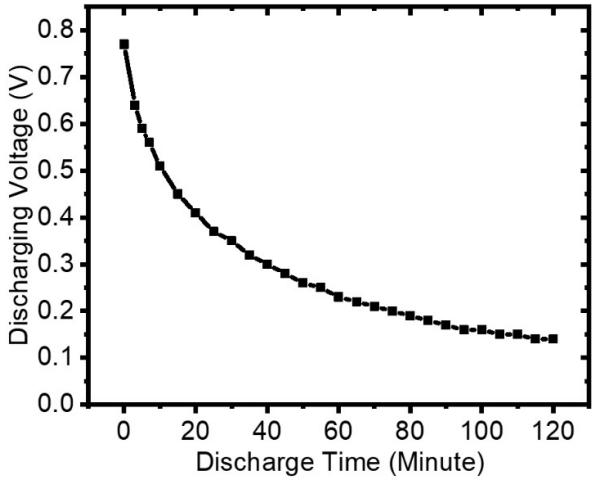

Figure 13. Discharging of SC by connecting 500-ohm resistance in series with 1.5 minutes charging 0.5M Na_2SO_4 electrolyte with Nafion membrane

The results of this experiment provide useful insights into the charging and discharging behavior of supercapacitors with Nafion membrane separators and Na_2SO_4 electrolyte. The rapid initial discharge followed by a slow, more stable voltage drop is characteristic of supercapacitor behavior, where the initial quick release of charge is followed by a slower discharge phase. The calculated capacitance of 0.21 Farad provides an indication of the energy storage capacity of the supercapacitor. The use of the 500-ohm resistance and the provided formula gives a straightforward method to evaluate the capacitance and discharge characteristics, allowing for performance analysis under realistic operating conditions (Ramirez-Nava, et al., 2021). This behavior also supports the idea that the Nafion membrane and 0.5M Na_2SO_4 electrolyte are effective in providing good charge retention and stable voltage discharge in the supercapacitor.

CONCLUSION

In summary, the dispersion of AC in water with cationic surfactant CTAB under applied DC electric fields has been investigated and it is found that both the AC:CTAB ratio and applied voltage are very important to achieve better dispersion. For a 0-7V DC field a 2:1.5 ratio was found to be optimum for dispersion whereas in the 7-12V range a 2:0.5 ratio of AC:CTAB produced the best result. The investigation results reveal that the lower voltage needs a higher concentration of CTAB for good

dispersion, while under high voltage even small amount of CTAB could achieve a good dispersion, indicating that surfactant can be reduced to some extent when an electric field is applied. The best value of voltage for the EPD process is 9.5V and the maximum CTAB:AC ratio was found to be equal to 2:5 and 2:6 for given Nanoscale Res Lett values of EPD respectively. The EPD deposited electrodes were used for supercapacitor fabrication, and its self-discharge investigation showed that the supercapacitor can retain 0.59 V of voltage for 5 h. The next step of the work will be to optimize AC dispersion with the help of an alternating current field, two mixed surfactants and higher voltage, etc., as well as to promote stability and performance of supercapacitor.

REFERENCE

Nguyen, V. S., R., D., & Vincent, B. (2013). Dispersion of nanoparticles: From organic solvents to polymer solutions. Ultrasonics Sonochemistry, 20(4), 1-9. https://doi.org/10.1016/j.ultsonch.2013.07.015

Minami, D., Horikoshi, S., Sakai, K., Sakai, H., & Abe, M. (2011). Dynamic Adsorption Behavior of Surfactants on Single-Wall Carbon Nanotubes in Aqueous Media by Experimentation and Molecular Dynamics Simulation. Journal of the Japan Society of Colour Material, 84(2), 39-42. https://web.archive.org/web/20181103133140id_/https://www.jstage.jst.go.jp/article/shikizai/84/2/84_2_39/_pdf

Alafogianni, P., Dassios, K., Farmaki, S., Antiohos, S. K., Matikas, T. E., & Barkoula, N. M. (2016). On the efficiency of UV–vis spectroscopy in assessing the dispersion quality in sonicated aqueous suspensions of carbon nanotubes. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 495, 118-124. https://doi.org/10.1016/j.colsurfa.2016.01.053

Tan, Y., & Resasco, D. E. (2005). Dispersion of single-walled carbon nanotubes of narrow diameter distribution. The Journal of Physical Chemistry B, 109(30), 14454-14460. https://doi.org/10.1021/jp052217r

Yang, R. T. (1992). Active carbon. By H. Jankowska, A. Swiatkowski, and J. Choma, Ellis Horwood, West Sussex, England, and Prentice-Hall, Englewood Cliffs, NJ, 1991, 280 pp.

Manocha, S. M. (2003). Porous Carbons. Sadhana Part 1&2. 28: 335-348.

Shah, S. K., Bhattarai, A., & Chatterjee, S. K. (2011). Surfactants, its applications and effects on environment. Bibechana, 7, 61-64. https://doi.org/10.3126/bibechana.v7i0.4047

Iro, Z. S., Subramani, C., & Dash, S. S. (2016). A brief review on electrode materials for supercapacitor. International Journal of Electrochemical Science, 11(12), 10628-10643. https://doi.org/10.20964/2016.12.50

Schneuwly, A., Bärtschi, M., Hermann, V., Sartorelli, G., Gallay, R., & Koetz, R. montena components SA, 1728 Rossens, Switzerland

Taurozzi, J. S., Hackley, V. A., & Wiesner, M. R. (2011). Ultrasonic dispersion of nanoparticles for environmental, health and safety assessment–issues and recommendations. Nanotoxicology, 5(4), 711-729. https://doi.org/10.3109/17435390.2010.528846

Nikolaev, A. Y. (2017, February). Simulation of the plain milling process. In IOP conference series: materials science and engineering. 177(1) 012080. DOI 10.1088/1757-899X/177/1/012080

Shrestha, M., Amatya, I., Wang, K., Zheng, B., Gu, Z., & Fan, Q. H. (2017). Electrophoretic deposition of activated carbon YP-50 with ethyl cellulose binders for supercapacitor electrodes. Journal of Energy Storage, 13, 206-210. https://doi.org/10.1016/j.est.2017.07.015

Wang, R., Qian, Y., Li, W., Zhu, S., Liu, F., Guo, Y., ... & Liu, L. (2018). Performance-enhanced activated carbon electrodes for supercapacitors combining both graphene-modified current collectors and graphene conductive additive. Materials, 11(5), 799. https://doi.org/10.3390/ma11050799

Ramirez-Nava, J., Martínez-Castrejón, M., García-Mesino, R. L., López-Díaz, J. A., Talavera-Mendoza, O., Sarmiento-Villagrana, A., ... & Hernández-Flores, G. (2021). The implications of membranes used as separators in microbial fuel cells. Membranes, 11(10), 738. https://doi.org/10.3390/membranes11100738

Isayev, N., & Kurmanov, S. (2023). The function of the time constant in RC series circuit signal filtering. Technobius Physics, 1(3), 0002. https://doi.org/10.54355/tbusphys/1.3.2023.0002

Wu, W., Shabhag, S., Chang, J., Rutt, A., & Whitacre, J. F. (2015). Relating electrolyte concentration to performance and stability for NaTi2 (PO4) 3/Na0. 44MnO2 aqueous sodium-ion batteries. Journal of The Electrochemical Society, 162(6), A803. DOI 10.1149/2.0121506jes

Nkembi, A. A., Simonazzi, M., Santoro, D., Cova, P., & Delmonte, N. (2024). Comprehensive review of energy storage systems characteristics and models for automotive applications. Batteries, 10(3), 88. https://doi.org/10.3390/batteries10030088

Jiang, J. S., Que, L. F., Li, R. C., Yu, F. D., Wang, X., Wu, J. H., ... & Xie, Y. M. (2025). Dual salt electrolyte design enabled by synergistic solvation and interfacial regulation for fast charging of lithium ion batteries. Journal of Energy Chemistry, 112, 484-494. https://doi.org/10.1016/j.jechem.2025.08.071

Jangid, A., Verma, K. D., Sinha, P., & Kar, K. K. (2021). Separator material selection for supercapacitors. In Handbook of Nanocomposite Supercapacitor Materials III: Selection (pp. 201-232). Cham: Springer International Publishing.

Du, Y., Mo, Y., & Chen, Y. (2021). Effects of Fe impurities on self-discharge performance of carbon-based supercapacitors. Materials, 14(8), 1908. https://doi.org/10.3390/ma14081908

Maciąg, F., Moskalewicz, T., Kowalski, K., Łukaszczyk, A., Hadzhieva, Z., & Boccaccini, A. R. (2021). The effect of electrophoretic deposition parameters on the microstructure and adhesion of zein coatings to titanium substrates. Materials, 14(2), 312. https://doi.org/10.3390/ma14020312

Esfahani, S. L., Rouhani, S., & Ranjbar, Z. (2017). Optimization the electrophoretic deposition fabrication of graphene-based electrode to consider electro-optical applications. Surfaces and Interfaces, 9, 218-227. https://doi.org/10.1016/j.surfin.2017.10.001

Pang, S., Ma, C., Zhang, N., & He, L. (2015). Investigation of the solubility enhancement mechanism of rebaudioside D using a solid dispersion technique with potassium sorbate as a carrier. Food Chemistry, 174, 564-570. https://doi.org/10.1016/j.foodchem.2014.11.113

Shang, Z., An, X., Seta, F. T., Ma, M., Shen, M., Dai, L., & Ni, Y. (2019). Improving dispersion stability of hydrochloric acid hydrolyzed cellulose nano-crystals. Carbohydrate polymers, 222, 115037. https://doi.org/10.1016/j.carbpol.2019.115037

Rauf, A., Baloch, M. K., Khan, A., Khan, Z., & Rauf, S. (2016). Effect of concentration and molecular mass of peo on the micellization and thermodynamic behaviour of cetyltrimethylammonium bromide (ctab) in aqueous peo-ctab mixed system. Journal of the Chilean Chemical Society, 61(3), 3013-3017. http://dx.doi.org/10.4067/S0717-97072016000300001

Daintree, L., & Biggs, S. (2010). Particle-particle interactions: The link between aggregate properties and rheology. Particulate Science and Technology, 28(5), 404-425. https://doi.org/10.1080/02726351.2010.504127

Ambika, P., Joshi, L. P., & Shrestha, S. P. (2020). Influence of direct current field on dispersion of activated carbon. Journal of Nanoparticle Research, 22(4). DOI:10.1007/s11051-020-04816-8

Fu, X., Wen, J., Xia, C., Liu, Q., Zhang, R., & Hu, S. (2023). Nafion doped polyaniline/graphene oxide composites as electrode materials for high performance flexible supercapacitors based on Nafion membrane. Materials & Design, 236, 112506. https://doi.org/10.1016/j.matdes.2023.112506

Zallouz, S., Dentzer, L., & Matei Ghimbeu, C. (2024). Carbon Capacitors Operating at 1.8 V Based on Concentrated Aqueous Electrolytes: Impacts of the Electrolyte Concentration and Carbon Properties. ACS Applied Energy Materials, 7(4), 1448–1460. https://doi.org/10.1021/acsaem.3c02593

Mendhe, A., & Panda, H. S. (2023). A review on electrolytes for supercapacitor device. Discover Materials, 3(1). https://doi.org/10.1007/s43939-023-00065-3

Azmi, S., Klimek, A., & Frackowiak, E. (2023). Why electrochemical capacitor electrolytes should not be ignored? Electrochimica Acta, 452, 142347. https://doi.org/10.1016/j.electacta.2023.142347

Mehboob, S., Lee, J.-Y., Hun Ahn, J., Abbas, S., Do, X. H., Kim, J., Shin, H.-J., Henkensmeier, D., & Ha, H. Y. (2023). Perfect capacity retention of all-vanadium redox flow battery using Nafion/polyaniline composite membranes. Journal of Industrial and Engineering Chemistry, 121, 348–357. https://doi.org/10.1016/j.jiec.2023.01.038

Karimi, M. B., Mohammadi, F., Ghahramani, M., & Javanbakht, M. (2023). Fabrication and Evaluation of Electrospun Nafion Membranes as Gel Polymer Electrolytes for High-Performance Lithium-Ion Batteries. The Journal of Physical Chemistry C, 127(47), 22943–22954. https://doi.org/10.1021/acs.jpcc.3c06931

Zhang, D., Qin, T., Wu, S., Guo, X., Wang, C., & Xiang, Q. (2022). Nafion-assisted electrophoretic deposition of ZIF-8 derivative N-doped porous carbon coating as high-performance supercapacitor electrode. Materials Letters, 323, 132579. https://doi.org/10.1016/j.matlet.2022.132579

Pazhamalai, P., Krishnamoorthy, K., Manoharan, S., Mariappan, V. K., & Kim, S.-J. (2022). Monolithic integration of MoS2 quantum sheets on solid electrolyte for self-charging supercapacitor power cell governed by piezo-ionic effect. Sustainable Materials and Technologies, 33, e00459. https://doi.org/10.1016/j.susmat.2022.e00459

Supiyeva, Z., Pan, X., & Abbas, Q. (2023). The critical role of nanostructured carbon pores in supercapacitors. Current Opinion in Electrochemistry, 39, 101249. https://doi.org/10.1016/j.coelec.2023.101249

Li, W., Wu, M., Yang, W., Zhao, M., & Lu, X. (2023). Effects of electrode mass loading on the self-discharge of supercapacitors. Electrochimica Acta, 438, 141550. https://doi.org/10.1016/j.electacta.2022.141550

Bassembek, U., Saif, O., Muhandiram, D., Ummethala, R., Soltani, N., Ohlckers, P., & Lu, P. (2024). Post-Treatment of Carbon Nanotubes Based Electrodes to Realize Low Self-Discharge Supercapacitors. 2024 IEEE 23rd International Conference on Micro and Miniature Power

Systems, Self-Powered Sensors and Energy Autonomous Devices (PowerMEMS), 215–218. https://doi.org/10.1109/powermems63147.2024.10814559

Yan, X., Guo, Q., Huang, W., Xiong, Y., Jing, S., Zhang, X., Huang, F., & Ge, X. (2023). Conjugated supercapacitor with suppressed self-discharge constructed by pairs of prelithiated Nb₂O₅@C with optimized elemental and phase purity in the carbon shell. Carbon Neutralization, 2(3), 300–309. https://doi.org/10.1002/cnl2.55

Min, X., Tan, J., Dong, T., Li, Y., Pei, M., Wang, C., Fu, X., Zhou, H., Yin, J., & Zhang, X. (2023). Reversible transformation between solid and liquid states of Na₂S₂O₃·5H₂O leads to supercapacitor electrolytes with low volatilization and low self-discharge. New Journal of Chemistry, 47(25), 11770–11773. https://doi.org/10.1039/d3nj00134b

Jiang, X., Zhang, H., Qu, Y., Wang, Z., Xie, Y., Zhang, W., Hu, H., & He, Z. (2024). Engineering electrolyte strong-weak coupling effect toward wide-temperature supercapacitor. Energy Storage Materials, 68, 103374. https://doi.org/10.1016/j.ensm.2024.103374

Shang, W., Yu, W., Xiao, X., Ma, Y., He, Y., Zhao, Z., & Tan, P. (2023). Insight into the self-discharge suppression of electrochemical capacitors: Progress and challenges. Advanced Powder Materials, 2(1), 100075. https://doi.org/10.1016/j.apmate.2022.100075

Wang, W., Zeng, Q., Wang, R., Wang, G., & Li, C. (2023). Bipolar ionomer electrolytes with desirable self-discharge suppression for supercapacitors. Journal of Energy Chemistry, 78, 422–429. https://doi.org/10.1016/j.jechem.2022.12.046

Liu, Y., Dong, K., Lv, T., Chen, Z., Cao, S., Zheng, F., & Chen, T. (2024). Constructing bilayer heterogeneous organogel electrolytes of Lewis acidic/basic polymers to suppress self-discharge of supercapacitors. Chemical Engineering Journal, 479, 147716. https://doi.org/10.1016/j.cej.2023.147716

Volfkovich, Yu. M. (2023). Self-Discharge of Supercapacitors: A Review. Russian Journal of Electrochemistry, 59(1), 24–36. https://doi.org/10.1134/s1023193523010123