Journal of Physics: Theories and Applications E-ISSN: 2549-7324 / P-ISSN: 2549-7316
J. Phys.: Theor. Appl. Vol. 10 No. 1 (2026) 61-80 doi: 10.20961/jphystheor-appl.v10i1.111141

Electrolyte concentration and nafion membrane effects on supercapacitor discharge dynamics and charge retention

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

[*]Corresponding author: jc.jagendra@gmail.com

Received 17 November 2025, Revised 23 February 2026, Published 31 March 2026

Abstract: Supercapacitors (SCs) are promising energy storage devices due to their high charge retention and rapid discharge capabilities. However, the efficiency of supercapacitors can be influenced by factors such as the choice of separator material and electrolyte concentration. This study investigates the performance of SCs fabricated using Nafion separators with Na_2SO_4 electrolytes of varying concentrations (1M and 0.5M) and charging conditions. The objective of this research is to evaluate the self-discharge behavior, capacitance, and voltage stability of supercapacitors to determine the optimal configuration for high-performance energy storage. The methodology involves fabricating SCs with Nafion separators and charging them under different voltages (1V, 1.2V, 1.4V) for varying time intervals (1 minute, 1.5 minutes, and 2 minutes). Self-discharge characteristics were monitored, and capacitance was calculated using the capacitor discharge equation. The experiments also included discharge tests using a 500-ohm resistor to simulate realistic usage. Major findings include that SCs with Nafion separators and 0.5M Na_2SO_4 electrolyte exhibit significantly lower self-discharge rates and more stable voltage profiles than those with napkin paper separators. Higher charging voltages and longer charging times lead to better charge retention. These results suggest that Nafion membranes and optimized electrolyte concentrations enhance supercapacitor performance, making them suitable for long-term, efficient energy storage applications.

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

1. Introduction

Homogeneous solutions play a critical role in various industrial applications such as coatings, paints, inks, drug delivery systems, ceramics, and nanocomposites (Nguyen & Vincent, 2013). Achieving a homogeneous dispersion, particularly for nanoparticles, is challenging in both scientific and technological fields. Researchers are continuously exploring methods for better dispersion with minimal effort and cost (Minami et al., 2010 and Alafogianni et al., 2016). Activated carbon (AC), known for its large surface area and

excellent adsorptive properties, has wide applications ranging from water purification to gas adsorption (Yang, 1998). AC's porous structure, with pore volumes ranging from 0.20 to 0.60 cm^3/g, makes it an ideal adsorbent for industrial applications (Manocha, 2003). However, dispersing AC, particularly in the nanometer scale, remains a challenge. Surfactants like Cetyl Trimethylammonium Bromide (CTAB) are commonly used to enhance dispersion by improving the wetting properties of particles (Shah et al., 20111). Physical methods such as sonication have also proven effective in dispersing particles by applying shear forces that break particle agglomerates. Sonication, using ultrasound waves, induces cavitation, which helps break molecular bonds and separates clumps of particles.

In addition to dispersion, AC's potential for use in supercapacitors has drawn attention. Supercapacitors, also known as electric double layer capacitors (EDLCs), store energy electrostatically and offer high power density, long life cycles, and low maintenance compared to traditional batteries (Iro et al., 2016 and Shrestha et al., 2017). The performance of supercapacitors is closely linked to the properties of the electrode materials, with activated carbon being a preferred choice due to its high surface area and conductive properties (Schneuwly & Gallay, 2000). The primary goal of this research is to optimize the dispersion of AC using CTAB under direct current (DC) fields for the fabrication of supercapacitors. Specifically, we aim to determine the optimal weight ratio of AC to CTAB, identify the optimal voltage for electrophoretic deposition (EPD), and fabricate supercapacitor electrodes with enhanced performance.

Various methods are employed for the dispersion of nanomaterials such as activated carbon (AC), carbon nanotubes (CNTs), and silver nanowires. These methods include ultra-sonication, magnetic stirring, milling, and ultrasound probe techniques. Each method serves to disperse particles in suspensions effectively, often using surfactants like SDBS, CTAB, and SDS to stabilize the dispersion (Taurozzi et al., 2011 and Nikolaev, 2017). For thin film deposition, techniques are divided into physical and chemical methods. Physical methods include Physical Vapor Deposition (PVD) and sputtering, while chemical methods involve processes like Chemical Vapor Deposition (CVD), spray pyrolysis, spin-coating, and electrophoretic deposition (EPD). These methods are used to create thin films for various applications, offering advantages such as ease of use, cost-effectiveness, and precise control over the film properties (Hwang et al., 2007; Anwar et al., 2015 and Amarollahi et al., 2015).

The dispersion of carbon-based nanomaterials and supercapacitor technologies reveals significant advancements in both dispersion techniques and the development of high-performance electrodes. Tan et al. explored the dispersion of single-walled carbon nanotubes (SWNTs), demonstrating that surfactants effectively suspend nanotubes without affecting their narrow diameter distribution (Tan et al., 2005). Schneuwly et al. reviewed supercapacitors, highlighting the hybridization of rechargeable batteries and supercapacitors for enhanced energy density and long-lasting performance (Schneuwly et al., 2000).

Research by Rastogi et al. compared the dispersion effectiveness of various surfactants, finding that Triton X-100 achieved the best dispersion of carbon nanotubes,

while SDS provided the least (Rastogi et al., 2008). In 2017, Shrestha et al. focused on electrophoretic deposition (EPD) of AC for supercapacitor (SC) electrodes, demonstrating the technique's high efficiency in fabricating electrodes with controlled mass (Shrestha et al., 2017). Wang et al. further improved supercapacitor electrodes by incorporating graphene-modified current collectors, significantly enhancing cycling stability (Wang et al., 2018). Poudel and Pandey investigated the effects of direct current (DC) fields on the dispersion of AC, finding that a lower DC voltage during sonication resulted in better dispersion stability (Poudel et al., 2018 & Pandey et al., 2018).

Overall, these studies contribute to a deeper understanding of nanomaterial dispersion methods and their applications in energy storage devices, particularly in enhancing the performance of supercapacitors. Techniques like sonication, electrophoretic deposition, and surfactant-assisted dispersion continue to evolve, offering promising solutions for efficient nanomaterial handling and supercapacitor fabrication. This study is motivated by the need to improve the efficiency of AC dispersion in various applications and minimize the environmental impact of surfactant use, which may contribute to pollution and toxicity in aquatic systems.

2. Materials and Methods

2.1. 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.

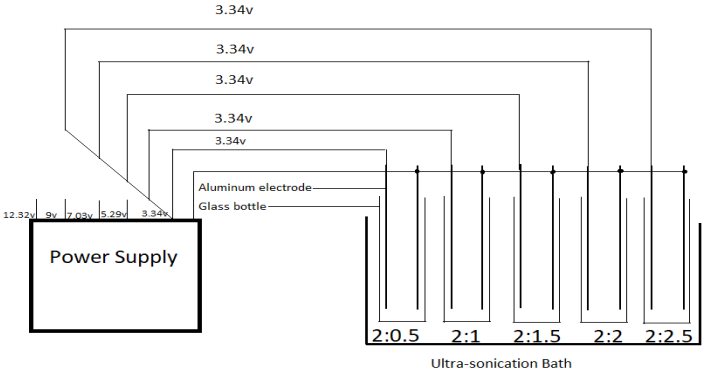

Figure 1. Schematic diagram for the whole setup for dispersion using 3.34 dc voltage.

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.

2.2. 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.

2.3. Electrophoresis of Activated Carbon

In the experiment, electrophoretic deposition (EPD) of activated carbon (AC) was performed on stainless steel plates with dimensions of 6 cm × 3 cm. Two plates were arranged parallel to each other, with a separation of 1 cm, as shown in Figure 2. The solution of AC and CTAB was prepared at a concentration of 3.75 g/L in 240 ml of distilled water. The solution was sonicated for 6 hours to ensure thorough mixing, and then left for sedimentation for 24 hours. After the sedimentation period, the clear upper solution was used for the electrophoretic deposition process. The EPD process was carried out under varying conditions, including different AC: CTAB ratios (2:3, 2:4, 2:5, 2:6) and

applied DC voltages (3V, 5V, 7.5V, 8.5V, 9.5V, 10V, 12.5V). The goal was to determine the optimum ratio of CTAB to AC and the optimum DC voltage that resulted in the best deposition quality. The procedure involved starting with the prepared solution containing CTAB and AC, and applying different voltages to perform the electrophoretic deposition.

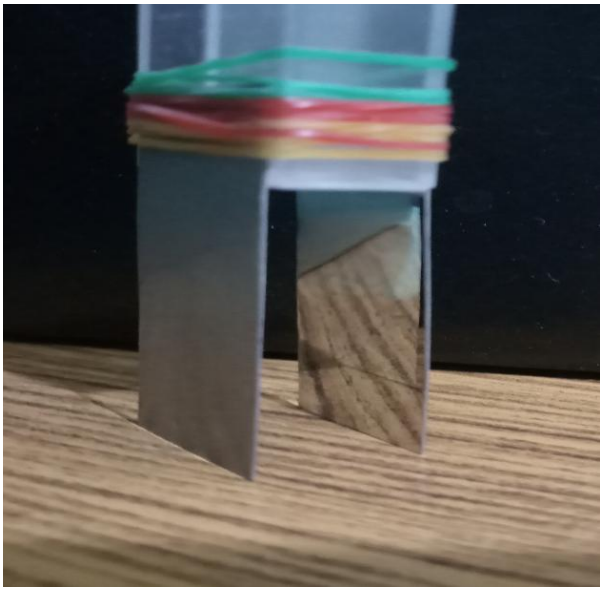

Figure 2. Steel plate arrangement of electrodes for EPD

The electrophoretic deposition process was carried out by applying direct voltage to the plates for 5 minutes, followed by turning off the voltage for 5 minutes. This cycle was repeated five times to achieve the best possible deposition. During the experiment, the optimal voltage and ratio of CTAB to AC were identified for the most effective deposition of activated carbon on the steel plates. The setup and procedure were designed to optimize the EPD process, which depends on both the voltage applied and the concentration of the materials in solution. By experimenting with different voltage values and ratios of CTAB to AC, the study aimed to identify the conditions that would result in the most efficient deposition, contributing to a better understanding of the electrophoretic deposition technique in the context of activated carbon materials. Figures 2 and 3 illustrate the experimental setup, showing the steel plate arrangement and the apparatus used for electrophoretic deposition. The voltage application and cycling were critical to the success of the deposition process, ensuring that the material was evenly deposited on the steel plates.

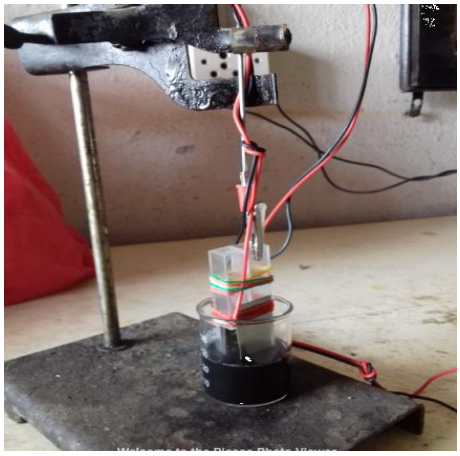

Figure 3. Electrophoretic deposition of AC.

2.4. Fabrication of Supercapacitor

The electrodes prepared through the electrophoretic deposition (EPD) process were used to construct supercapacitors after being dried in an oven at 140°C for 6.5 hours. The supercapacitors were assembled using 1M and 0.5M Na_2SO_4 as the electrolyte and napkin paper and Nafion membrane as separators. The electrodes were soaked in the electrolyte, briefly dried, and then assembled with the separator placed between them, followed by drying the entire system for 45 minutes. The supercapacitors were then charged at voltages of 1V, 1.2V, and 1.4V for varying time intervals (1 minute, 1.5 minutes, and 2 minutes) to observe the charging behavior. After charging, the self-discharge of the supercapacitors was monitored, and the discharge rate was analyzed. The results were used to determine the optimal voltage and time conditions for efficient charge retention and to assess the self-discharge characteristics of the supercapacitors, providing insight into their performance under different charging conditions.

Figure 4. Supercapacitor arrangement.

3. Result and Discussion

3.1. Absorbance of CTAB Solution in Water

In this part of the experiment, a 1 g/L CTAB solution was prepared by dissolving 0.01 g of CTAB in 10 ml of distilled water, and the solution was sonicated for 20 minutes to disperse the CTAB. The absorbance of the dispersed CTAB solution was then measured using a UV-Visible spectrophotometer with two different reference setups: one with an empty cuvette and the other with a cuvette containing just water. The results, as shown in Figure 5, revealed two distinct absorbance peaks at 380 nm and 970 nm. The peak at 380 nm is likely due to the absorbance of light by CTAB molecules, although CTAB typically absorbs light at a much lower wavelength of around 205 nm, which is outside the visible range of the spectrometer (Movchan et al., 2013). Therefore, the absorption observed at 380 nm may not be directly attributed to CTAB itself but could instead be the result of impurities or contaminants in the CTAB sample, which could have contributed to the absorption in the visible spectrum. The peak at 970 nm, on the other hand, is likely due to the absorption of light by water molecules, as water typically absorbs light in this wavelength range.

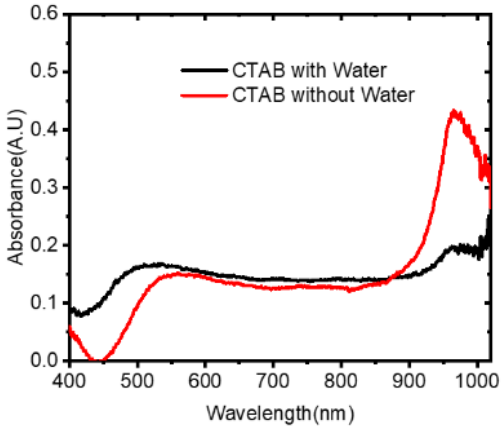

Figure 5. Absorbance of CTAB in water with 1g/Liter concentration by taking empty cuvette and cuvette with water reference.

The discrepancy between the expected absorbance of CTAB at 205 nm and the observed peak at 380 nm could be explained by the limitations of the spectrophotometer in measuring outside the visible spectrum, as well as the potential interference from other substances in the solution. This suggests that while the primary absorbance of CTAB occurs at 205 nm, the visible absorbance observed at 380 nm could be a combined effect of CTAB and its impurities or the interaction between CTAB and water molecules in the solution.

3.2. Optimization of CTAB Amount for Dispersion of AC under Different DC fields.

In the experiment, a 1g/L solution of AC and CTAB was sonicated under different applied DC voltages (0V, 3.34V, 5.0V, 7.0V, 9.0V, 12.0V) and allowed to sediment for 24 hours. From the photographs (Figure 6), the solution with a CTAB:AC ratio of 2:1.5 appeared the darkest at both 0V and 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. However, as the voltage increased to 7V, 9V, and 12V, all solutions appeared equally dark, suggesting that higher voltages resulted in more uniform dispersion, regardless of the AC:CTAB ratio. This indicates that at higher voltages, the electric field enhanced the dispersion of AC particles across all ratios, making it harder to visually distinguish the best dispersion.

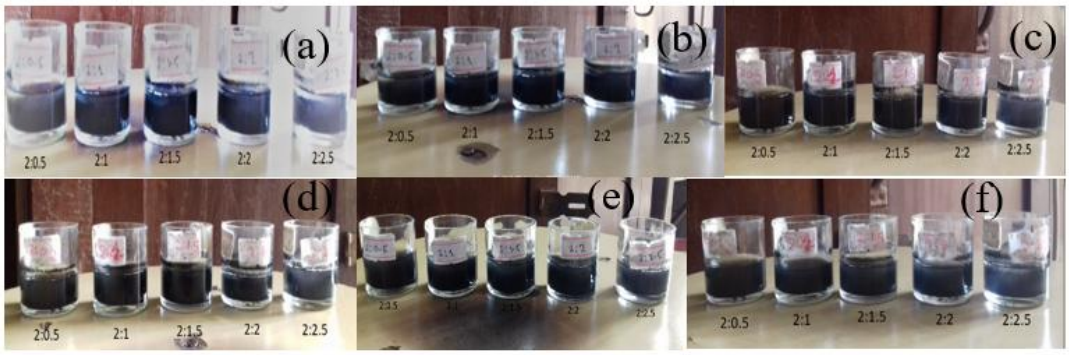

Figure 6. Photograph of dispersed solution of AC and CTAB after 30 minutes' sonication and 24 hours' sedimentation (a) 0.0V, (b) 3.0 V, (c) 5.0 V, (d) 7.0 V, (e) 9.0 V, (f) 12.0 V applying DC voltage.

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 various applied DC voltages (0V, 3V, 5V, 7V, 9V, 12V) reveal important trends in dispersion efficiency. Figure 7a, which shows the absorbance without applied voltage (0V), 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. Similarly, Figures 7b and 7c (under 3V and 5V DC) show 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. However, as the applied voltage increases to Figures 7d, 7e, and 7f (7V, 9V, and 12V), a shift is observed. At higher voltages (especially 9V and 12V), the maximum absorbance is now seen at the lower CTAB ratio (2:0.5), suggesting that at stronger electric fields, a lower CTAB concentration is more effective for dispersing AC. 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.

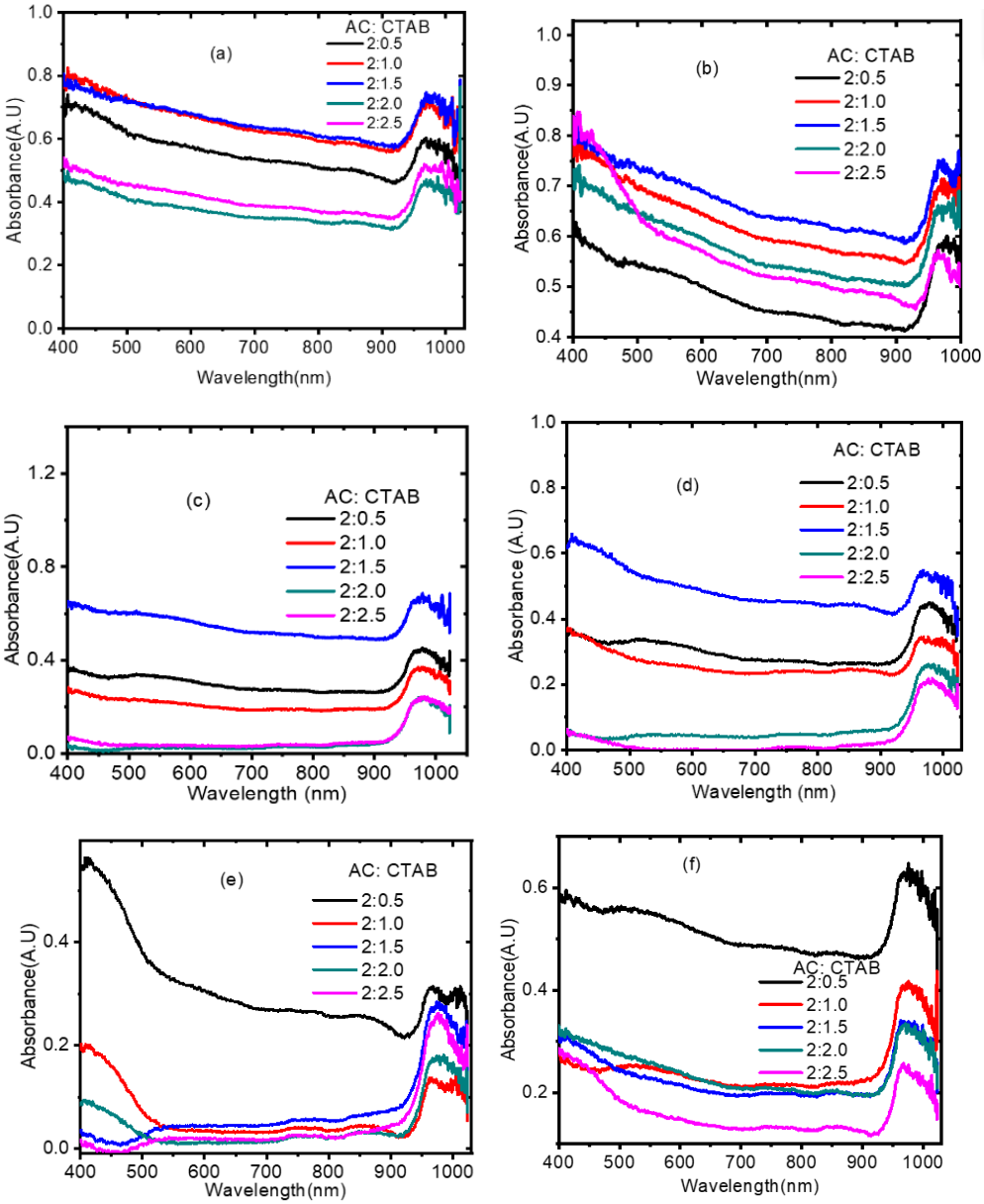

Figure 7: Absorbance of dispersed solution of AC and CTAB mixed in different ratios (2:0.5, 2:1, 2:1.5, 2:2, 2:2.5) having concentration 1g/Liter (a) 0.0 V, (b) 3.0 V, (c) 5.0 V, (d) 7.0 V, (e) 9.0 V and (f) 12.0 V applied voltage

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 lower voltage applications (0V, 3V, and 5V), 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. However, as the applied voltage increases (7V, 9V, 12V), the maximum absorbance shifts to the lower CTAB concentrations (2:0.5). This suggests that at higher voltages, the stronger electric field causes more efficient dispersion of AC particles, even at lower concentrations of CTAB. The increase in voltage likely enhances the movement of AC particles, helping them to remain well-dispersed even with a smaller amount of surfactant. Furthermore, at higher voltages, the formation of micelles or excessive aggregation is less pronounced, allowing for better dispersion with reduced CTAB concentration. The decrease in absorbance at higher CTAB ratios under higher voltage conditions further supports this, as excess surfactant can cause unwanted aggregation, reducing the overall dispersion of AC in the solution.

3.3. Absorbance at selected wavelength with different ratio of AC and CTAB

The variation in absorbance of the dispersed solution with increasing CTAB concentration across different applied voltages is evident in Figure 8. This can be attributed to the effect of CTAB on the dispersion of AC particles and how the applied voltage influences the dispersion efficiency. Figure 8a (0V) 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, thus lowering absorbance.

In Figure 8b (3V), similar trends are observed, but with a slight variation in the wavelength-dependent absorbance. For most wavelengths (700nm, 900nm, and 940nm), the highest absorbance occurs at the 2:1.5 AC: CTAB ratio, reaffirming that this ratio provides the best dispersion. The lower absorbance at higher CTAB concentrations (e.g., 2:2) again suggests that excess surfactant leads to diminished dispersion, likely due to aggregation. Moving to Figure 8c (5V), Figure 8d (7V), and Figure 8e (9V), the absorbance continues to show a maximum at the 2:1.5 ratio, but the shift in maximum absorbance at various wavelengths indicates the influence of the applied voltage on the dispersion behavior. Higher voltages promote better dispersion of AC particles even with higher CTAB concentrations, reducing the negative effect seen at lower voltages. In Figure 8f (12V), a noticeable shift in the absorbance pattern is seen, with the highest absorbance occurring at the lowest CTAB concentration (2:0.5), especially at wavelengths like 940nm. This suggests that at higher voltages, the electrostatic forces are strong enough to effectively disperse the AC particles, even with lower amounts of CTAB. This is likely due to the stronger electric field that helps overcome the tendency for AC particles to aggregate, even in the absence of a high surfactant concentration.

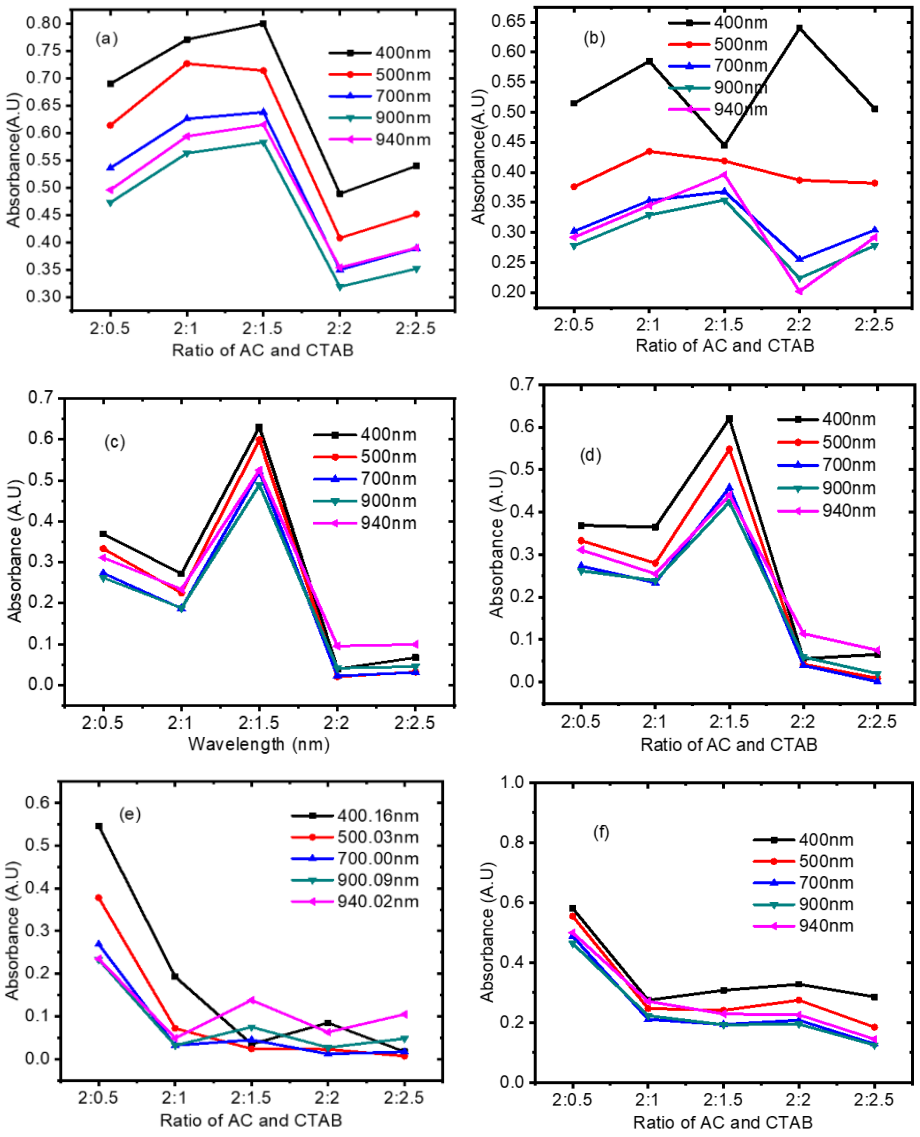

Figure 8. Variation of absorbance of dispersed solution of AC with varying CTAB amount at different wavelengths with (a) 0.0 V, (b) 3.0 V, (c) 5.0 V, (d) 7.0 V, (e) 9.0 V, (f) 12.0 V, applied voltage

The findings presented in Figure 8 indicate that the absorbance of dispersed solutions of AC and CTAB is highly dependent on the ratio of AC to CTAB and the applied voltage. Under all applied voltages, the 2:1.5 AC: CTAB ratio consistently resulted in the highest absorbance, suggesting it provides the optimal dispersion of AC particles. As the CTAB concentration increased beyond this ratio (e.g., 2:2 or 2:2.5), absorbance decreased, likely due to the aggregation or micelle formation of AC particles, which hinders their dispersion. This trend was observed across various wavelengths (400nm to 940nm), with absorbance generally increasing as CTAB concentration increased from 0.5 to 1.5 but decreasing at higher concentrations. Interestingly, at higher applied voltages (9V and 12V), lower CTAB concentrations (such as 2:0.5) resulted in higher absorbance, indicating that stronger electrostatic forces helped disperse AC particles more effectively. Thus, the data suggest that while increasing CTAB improves dispersion to a point,

excessive surfactant leads to diminishing returns in dispersion efficiency, with the 2:1.5 ratio being optimal for most conditions.

3.4. Optimization of Electric field for Electrophoretic deposition of AC

The findings suggest a clear relationship between the applied voltage and the dispersion of AC and CTAB solutions. Figure 9 illustrates how varying the voltage affects the electrophoretic deposition process. At 0V, the best dispersion was observed for the solution with a 2:1.5 AC: CTAB ratio, which remained optimal as voltage increased up to 7V. However, when the voltage was raised to 9V, the solution with a 2:0.5 AC: CTAB ratio exhibited the best dispersion, and this trend continued with 12V. This suggests that at lower voltages, higher CTAB concentrations are more effective in dispersing AC, while at higher voltages, lower CTAB concentrations yield better dispersion, possibly due to the influence of electrostatic forces promoting more uniform particle distribution.

When examining the EPD process, the solution with a CTAB concentration of 7.5 g/L and a 2:6 AC: CTAB ratio was used. 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, producing uniform films with optimal thickness, 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 9). 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.

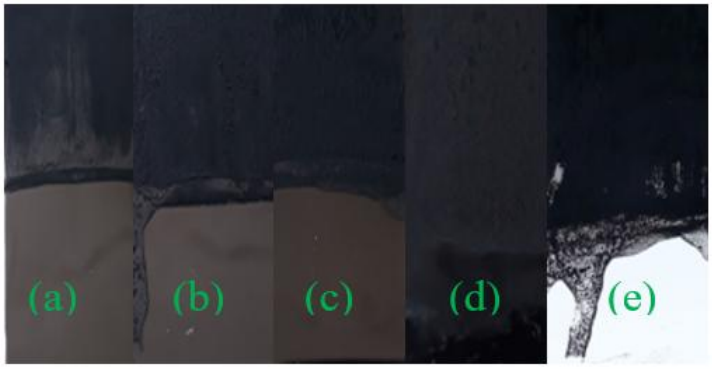

Figure 9. Electrodes after electrophoretic deposition for 50 minute by applying different DC voltages (a) 3.0 V, (b) 5.0 V, (c) 7.5 V, (d) 9.5 V, (e) 12.5 V in the dispersed solution of AC in distilled water with AC: CTAB=2:6.

3.5. Optimization Ratio of CTAB and AC for the best EPD

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). 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 10 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 10c, 10d). The deposition was irregular and not uniform for the 2:3 and 2:4 ratios (Figure 10a, 10b). 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.

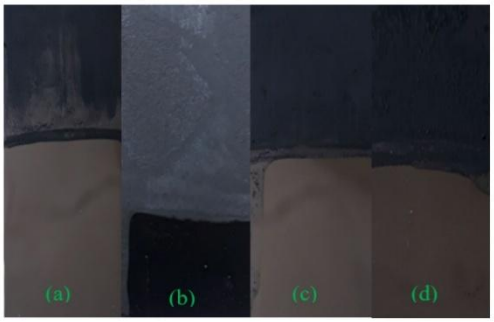

Figure 10. Electrodes after electrophoretic deposition for 50 minute by applying 9.5 volt in the solution of different amount of AC (CTAB: AC= (a) 2:3, (b) 2:4; (c) 2:5, (d) 2:6)

3.6. 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 (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 11. Figure 11 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.

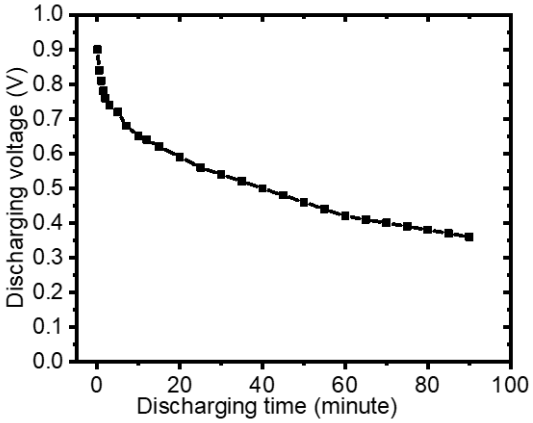

Figure 11. Self-discharge of supercapacitor fabricated by using paper (napkin) separator, charging time 45 sec, electrolyte concentration 1 m Na_2SO_4

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. The results from Figure 11 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 12, 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 12 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.

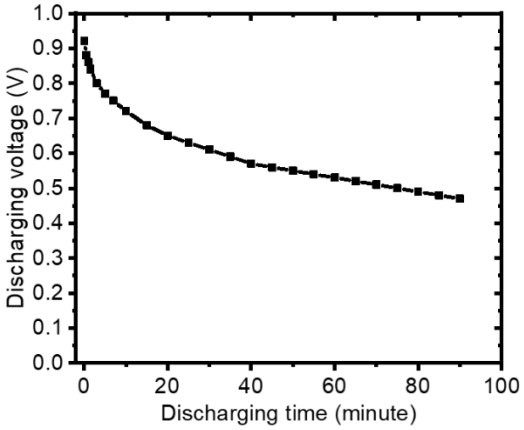

Figure 12. Self-discharge of supercapacitor fabricated by using Nafion separator with charging time 1 minutes 1M Na_2SO_4 electrolyte

This behavior aligns with the general characteristics of self-discharge observed in carbon-based supercapacitors. In supercapacitors, self-discharge occurs due to charge leakage from the electrical double layer formed at the electrode-electrolyte interface. In the case of SCs with Nafion separators, the rate of self-discharge is relatively low compared to conventional capacitors and the SCs with napkin paper separators, which demonstrates better charge retention. The Nafion membrane, being a proton-conductive polymer, likely contributes to better ion conduction and reduced leakage compared to napkin paper, which may have higher resistance and poorer ion-conducting properties. The lower self-discharge and more stable voltage observed with the Nafion separator are indicative of improved performance in terms of charge holding capacity. This is crucial for practical applications of supercapacitors, as a lower self-discharge rate means the device will retain its charge for longer periods, reducing the need for frequent recharging and enhancing overall efficiency. Therefore, the use of Nafion membrane as a separator significantly improves the stability and performance of supercapacitors, making it a promising material for high-performance energy storage applications.

Figures 13 and 14 display the self-discharge curves of SCs fabricated using Nafion separators with 0.5M Na_2SO_4 as the electrolyte, under varying charging voltages and times. These figures illustrate how the self-discharge behavior of the SCs changes as the electrolyte concentration and charging voltage are modified.

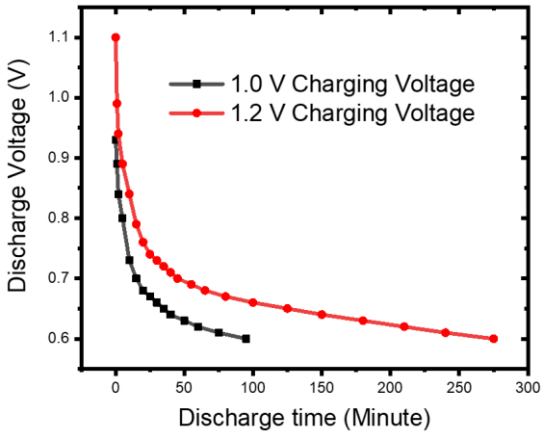

Figure 13. Self-discharge of supercapacitor fabricated by using Nafion separator with charging voltage 1 and 1.2 V

In Figure 13, SCs were charged at 1V and 1.2V for 1-minute intervals. The results show that the self-discharge curve for the SC charged at 1V drops more rapidly than the one charged at 1.2V. This faster voltage drop can be attributed to the lower initial charge stored in the supercapacitor when charged at a lower voltage. Supercapacitors charged at higher voltages generally store more charge, leading to a slower self-discharge rate, as seen in the SC charged at 1.2V. However, despite the initial difference, both capacitors eventually show a slow discharge phase after the rapid voltage drop, holding charge for several hours. The higher voltage (1.2V) gives a more stable voltage over time due to a higher energy storage capacity in the double-layer, which reduces the rate of self-discharge compared to the 1V charge. Figure 14 presents the self-discharge curves of SCs with 1.4V charging voltage and 0.5M Na_2SO_4electrolyte, using charging times of 1.5 minutes and 2 minutes. With the increase in voltage and charging time, the SCs show even lower self-discharge and more stable voltage than the SCs in Figure 13. The longer charging time and higher voltage result in higher charge storage, which in turn leads to a slower self-discharge rate. This extended charge holding capability is a characteristic of supercapacitors with higher initial charge and increased electrolyte concentration, which together contribute to a more stable voltage over time. It is noteworthy that the SC charged with 1.4V and a 2-minute charging time shows the slowest discharge rate, maintaining voltage for over 5 hours. This enhanced performance can be attributed to the higher charging voltage and the optimized electrolyte concentration (0.5M Na_2SO_4), which increases the ionic conductivity and charge storage capacity within the SC.

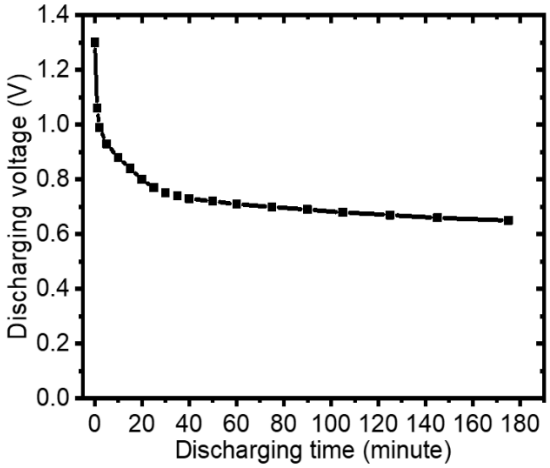

Figure 14. Self-discharge of supercapacitor fabricated by using Nafion separator charing tie 2 minutes with 1.4 V and electrolyte 0.5 M Na_2SO_4

The decrease in electrolyte concentration from 1M (in previous experiments) to 0.5M Na_2SO_4 plays a significant role in the performance of the SCs. At 0.5M, the SCs still show low self-discharge and stable voltage profiles, but the discharge rate is less steep, meaning the SCs retain their charge for longer periods. The lower concentration of the electrolyte may result in lower ion dissociation, but this also reduces the likelihood of excess ion concentration and potential redox reactions at the electrode surface, which could lead to unwanted self-discharge. The effect of the electrolyte concentration on charge leakage is evident in the fact that SCs with 0.5M Na_2SO_4 exhibit better charge retention and slower self-discharge over time compared to SCs made with higher concentrations of the electrolyte.

3.7. 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:

$$C = \frac{t}{R \ln\left(\frac{V_0}{V_t}\right)} \tag{3}$$

Where, C is the capacitance of the SC, t is the discharging time, R is the resistance (500 ohms), V_0 is the initial voltage (0.77V) and V_t is the voltage after discharging. The calculated capacitance in the slow discharge region (from 0.30V to 0.16V) was 0.21 Farad, which provides important insights into the performance of the SC. The voltage drop from 0.77V to 0.13V in the first 120 seconds indicates a relatively rapid discharge in the initial phase. This is typical in supercapacitors, where the voltage drops quickly when a resistor is placed in series because the stored charge is being released rapidly. The rate of discharge is governed by the R time constant, where R and C control how quickly the voltage decreases. After the initial steep voltage drop, the voltage drops more

gradually from 0.30V to 0.16V in the next 80 seconds, reflecting a slow discharge process. This behavior is characteristic of supercapacitors, where the discharge rate slows down as the capacitor's stored energy decreases. The slow discharge suggests that the energy is being released more gradually, which allows for a longer duration of power supply at lower voltage. Capacitance Calculation: The calculated capacitance of 0.21 Farad is a measure of the energy storage capacity of the supercapacitor in the discharge phase. The capacitance value is consistent with what would be expected for a supercapacitor, which typically has capacitance values ranging from a few Farads to several thousand Farads, depending on the material and design of the capacitor. The value obtained here reflects the effectiveness of the supercapacitor in storing charge and releasing it over time. Effect of Nafion Membrane and Electrolyte: The supercapacitor used 0.5M Na_2SO_4 electrolyte with a Nafion membrane separator. Nafion membranes are known for their high ionic conductivity and stability, which ensures efficient charge storage and discharge characteristics. The electrolyte concentration (0.5M Na_2SO_4) is low, which suggests that the ionic conductivity is moderate, allowing for a balance between charge storage and self-discharge. This electrolyte concentration supports a relatively stable discharge profile while minimizing issues like high self-discharge or rapid leakage of charge.

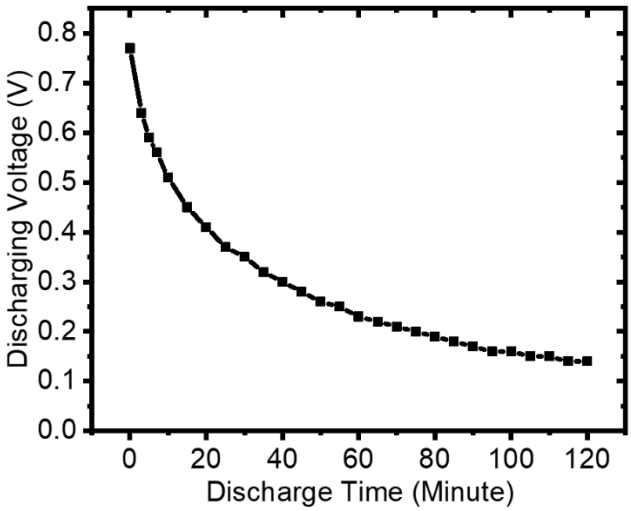

Figure 15. Discharging of SC by connecting 500-ohm resistance in series with 1.5 minutes charging 0.5M Na_2SO_4 electrolyte with Nafion membrane

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. 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.

4. Conclusion

In conclusion, the dispersion AC in water using the cationic surfactant CTAB under varying DC electric fields has been successfully studied, revealing that the AC:CTAB ratio and the applied voltage play crucial roles in achieving optimal dispersion. Under a 0-7V DC field, the best dispersion was achieved with a 2:1.5 ratio of AC to CTAB, while in the 7-12V range, the 2:0.5 ratio was most effective. The results indicate that lower voltage requires a higher amount of CTAB for effective dispersion, whereas higher voltage can achieve better dispersion even with a lower amount of CTAB, suggesting the potential for minimizing surfactant usage under increased electric fields. The optimal voltage for the EPD process was found to be 9.5V, with the best CTAB:AC ratio for EPD being 2:5. A supercapacitor was fabricated using electrodes prepared via the EPD process, and its self-discharge study demonstrated the ability to hold a voltage of 0.59V for up to 5 hours. Future work will focus on further optimization of AC dispersion using alternating current fields, mixed surfactants, and higher voltages, as well as improving the stability and performance of the supercapacitor.

References

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.

Amrollahi, P., Krasinski, J. S., Vaidyanathan, R., Tayebi, L., & Vashaee, D. (2015). Electrophoretic deposition (EPD): Fundamentals and applications from nano-to micro-scale structures. *Handbook of Nanoelectrochemistry, Springer International Publishing Switzerland*.

Anwar, S., Gowthamaraju, S., Mishra, B. K., Singh, S. K., & Anwar, S. (2015). *Material Chemistry and Physics*, 1-7.

Hwang, B. H., Chang, C. L., Hsu, C. S., & Fu, C. Y. (2007). Electrostatic spray deposition of NiO/CGO films. *Journal of Physics D: Applied Physics*, *40*(11), 3448.

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.

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

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.

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

Nikolaev, A. Y. (2017, February). Simulation of the plain milling process. In *IOP conference series: materials science and engineering* (Vol. 177, No. 1, p. 012080). IOP Publishing.

Pandey, A. (2018). Influence of direct current field on dispersion of activated carbon. M.Sc. Dissertation, Dean Office, Institute of Science and Technology, Tribhuvan University, Nepal.

Poudel, K. (2018). Study on effect of direct current field on dispersion of activated carbon in cationic surfactant. M.Sc. Dissertation, Dean Office, Institute of Science and Technology, Tribhuvan University, Nepal.

Rastogi, R., Kaushal, R., Tripathi, S. K., Sharma, A. L., Kaur, I., & Bharadwaj, L. M. (2008). Comparative study of carbon nanotube dispersion using surfactants. *Journal of colloid and interface science*, *328*(2), 421-428.

Schneuwly, A., Bärtschi, M., Hermann, V., Sartorelli, G., Gallay, R., & Koetz, R. montena components SA, 1728 Rossens, Switzerland Tel.:+ 41 26 411 85 50; Fax:+ 41 26 411 85 05; Email: adrian. schneuwly@ montena. com* Paul Scherrer Institut, 5232 Villigen, Switzerland.

Shah, S. K., Bhattarai, A., & Chatterjee, S. K. (2011). Surfactants, its applications and effects on environment. *Bibechana*, *7*, 61-64.

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.

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.

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.

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.

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.

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.