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Comparative Electrochemical Polymerization of Polyaniline (PANI): Influence of Cyclic vs. Pulse Voltammetry on Electrochemical performance

Sameh A. A. El-Mekawy[1,*], Samir A. Abd El-Makssoud[2], Rana Hamouda[1]

[1] Physics and Math. Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt.

[2] Chemistry Department, Faculty of Science, Port Said University, Port Said, Egypt,

***Corresponding author:** Samehchemist23@gmail.com

ABSTRACT

Conducting polymers (CPs), such as polyaniline (PANI), poly ortho aminophenol (POAP), poly ethylene dioxythiophene (PEDOT) and polypyrrole (PPY) are considered the main materials for supercapacitors, which are one of the most important energy storage devices. This paper focuses on the electrochemical polymerization of PANI by two different methods: cyclic voltammetry (CV) PANI/CV and pulse chronopotentiometry (PC) PANI/PC, then studying the effect of the polymerization method on the resulting polymers. The morphology of the polymer films and the surface roughness (topography) were characterized using scanning electron microscopy (SEM) and atomic force microscopy (AFM), respectively. The electrochemical properties of the fabricated PANI/CV, PANI/PC were investigated via CV and galvanostatic charge-discharge (GCD) using a three-electrode system. The value of the specific capacitance of the prepared polymers reached 276.1 F/g and 536.3 F/g for CV and PC, respectively. Capacitance retention was 66.42% and 56.73% for CV and PC, respectively, after 1000 cycles at 200mV/s. A higher specific capacitance with satisfactory cycling stability was attained in the case of PC polymerization.

Keywords: Supercapacitor, Conducting polymer, Polyaniline, Cyclic voltammetry, Pulse current voltammetry, Specific capacitance

1. INTRODUCTION

The growing global demand for efficient energy storage systems has prompted extensive research into enhanced electrochemical energy storage technologies [1-2]. Supercapacitors (SCs) are among the most promising energy devices because they have a higher energy density than regular capacitors and a higher

power density than secondary batteries [3-4]. A typical supercapacitor contains two electrodes, an electrolyte, and a separator. The composition of the electrodes and the surface properties have a significant impact on the device's capacitance and energy density. The electrolyte, which can be aqueous, organic, or ionic liquid-based, promotes ionic transport between the electrodes and must be compatible with the electrode material in order to provide steady performance and a wide potential window [5-6].

The separator, usually a porous insulating membrane, prevents electrical short-circuiting by keeping the electrodes physically apart while allowing the free movement of ions. The relationship between these components determines the key performance metrics, such as specific capacitance, power and energy density, and cycle life. Careful material selection and design of each component are crucial to optimizing the overall performance of supercapacitors for practical applications [7]. Supercapacitors are generally classified into three main types based on their charge storage mechanisms: electric double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors. EDLCs store charge electrostatically at the electrode–electrolyte interface without any faradaic reactions, typically using carbon-based materials with high surface areas89. In contrast, pseudocapacitors rely on fast and reversible faradaic redox reactions at the surface or near-surface of active materials such as metal oxides or conductive polymers, providing higher capacitance values. Hybrid supercapacitors combine both mechanisms to optimize performance, often pairing different electrode materials to balance energy and power densities [10-11].

The overall performance of a supercapacitor is largely influenced by the properties of its electrode materials, which play a vital role in determining specific capacitance, charge/discharge rates, and long-term stability[12]. Effective electrode design considers factors such as electrical conductivity, surface area, porosity, and electrochemical activity. Among the various materials explored, transition metal oxides (e.g., RuO_2, MnO_2), carbon-based structures (e.g., activated carbon, carbon nanotubes, graphene), and conductive polymers (e.g., polyaniline , polypyrrole, polythiophene) have gained particular attention due to their unique physical and electrochemical properties [13-14]. Transition metal oxides offer high capacitance through redox activity, while carbon materials provide high surface areas and conductivity. Conductive polymers, meanwhile, offer a balanced combination of redox activity, flexibility, and relatively low cost, making them highly attractive for flexible and wearable energy storage applications [15].

Various synthesis methods have been developed to produce CPs, leading to high-performance energy storage devices. Chemical or electrochemical oxidation of monomers are methods used to synthesize CPs, followed by coupling of the charged monomers to produce the polymer chains, which is the simplest system [16-17]. Electrically conducting polymers can show good specific capacitance because of the presence of a π electron conjugation system, which facilitates rapid and reversible redox reactions [18-19]. The good conductivity of CPs arises from the delocalization of electrons along the conjugated polymer backbone, allowing electron transport in the doped state [20-21]. Despite their advantages, CPs face several challenges, including poor long-term stability, limited conductivity, and structural degradation during repeated charge–discharge cycles. An important issue in conducting polymer electrochemical supercapacitor research is achieving high capacitance with larger operating potentials, preferably in aqueous electrolytes.

Among various CPs, polyaniline (PANI) stands out due to its ease of synthesis, environmental stability, and tunable electrical conductivity. Compared to chemical methods, electrochemical routes for preparing PANI are more facile and more easily controlled. While several synthetic techniques for PANI have been explored, the use of pulse voltammetry for its electrodeposition remains relatively under-investigated. Prior studies have primarily focused on conventional constant potential or current methods, leaving a gap in understanding the effects of pulsed electrochemical techniques on PANI’s morphology and performance.

In this study, we aim to synthesize polyaniline electrodes using two different electrochemical methods including cyclic and pulse voltammetry with the objective of enhancing the electrochemical properties and structural stability of the PANI. The capacitive behaviour of the prepared PANI/CV and PANI/PC were systematically investigated by means of cyclic voltammetry and galvanostatic charge discharge measurements. Additionally, the surface morphologies of the synthesized polymers were analyzed and compared through scanning electron microscopy (SEM) and atomic force microscopy (AFM). By comparing the two approaches, this work seeks to contribute new insights into the fabrication of high-performance PANI -based electrodes for supercapacitor applications.

2. MATERIALS AND METHODS

2.1. Materials:

Aniline monomer was purchased from Loba Company (Germany) and was distilled twice to obtain a purity of 99.5%. Sulphuric acid 98% was provided by El- Nasr Pharmaceutical Chemicals (ADWIC, Egypt). Deionized water is used in the preparation of all solutions. The working electrode was made from a glassy carbon disk 3.0 mm diameter (SIGRADUR, Germany) by sealing a 1.0 cm long x 3.0 mm diameter GC rod in a glass tube. The GC working electrode was polished to a mirror finish, then sonicated in water and dried in air before use.

2.2. Electro polymerization:

All electrochemical tests were done with a BioLogic VSP-150 potentiostat/galvanostat that was connected to a computer running EC-Lab software. Platinum was the counter electrode, and a saturated calomel electrode (SCE) was the reference electrode. The aqueous solution of 0.5 M H_2SO_4 used for the polymerization as a supporting electrolyte A 20 minute cleaning with nitrogen gas was done on each solution before each experiment to get rid of any dissolved oxygen. Polymerization was carried out at a potential range from -0.2 to 0.8 V vs. SCE at a scan rate of 50 mVs^{-1}.

2.3. Characterization of the prepared polymers:

The resulting polymer films were characterized by cyclic voltammetry and galvanostatic charge discharge in a free monomer solution of 0.5M H_2SO_4. The scanning electron microscopy, (SEM) was used to study the film morphology and finally Atomic force microscopy (AFM) was employed to relate the topography to the electrochemical performance of the synthesized polymers. The SEM and AFM characterizations were carried out at Faculty of Engineering, Port Said University.

3. RESULTS AND DISCUSSION

3.1. Electrochemical synthesis of PANI:

3.1.1. Synthesis of PANI using cyclic voltammetry (PANI/CV):

The cyclic voltammogram (CV) of polyaniline (PANI) presented in Figure 1 demonstrates the characteristic redox behavior of PANI/CV in the potential range of −0.2 V to +0.8 V versus the SCE as a reference electrode. The CV curve exhibits a pair of well-defined redox peaks corresponding to the electrochemical transitions between the different oxidation states of PANI, primarily from the leucoemeraldine (fully reduced) to emeraldine (partially oxidized) and from emeraldine to pernigraniline (fully oxidized) forms [22].

As the potential increases (evident from the overlapping multiple cycles), the anodic and cathodic peak currents increase proportionally, indicating a surface-confined redox process. The broadness and shape of the peaks suggest a quasi-reversible redox process, which is typical for polymeric films due to structural reorganizations during electron transfer and ion diffusion. The shift in peak potentials further supports this behavior, reflecting kinetic limitations in electron transfer and ion transport within the PANI/CV matrix [23].

The anodic peak observed around 0.5–0.6 V corresponds to the oxidation of the leucoemeraldine to the emeraldine state, whereas the cathodic peak around 0.2–0.3 V represents the reverse reduction process. The increasing peak current and the area under the CV curve also indicate good electrochemical activity and stability of the PANI film over successive cycles, which is essential for applications as electrode material in SCs, as will be illustrated in the following sections.

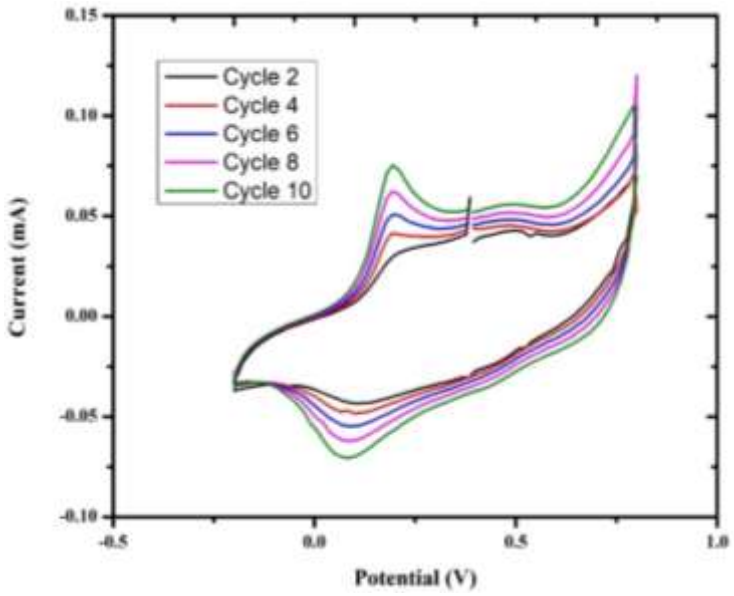

Figure 1: Cyclic voltammetry of 0.2M PANI in 0.5M H_2SO_4 at scan rate 50 mV/s

3.1.2. Synthesis of PANI using pulse chronopotentiometry (PANI/PC):

Figure 2 illustrates the **pulse** chronopotentiometric response of the electrode material under a series of current pulses. The working electrode potential (E_{we}) is recorded as a function of time, revealing periodic and reproducible potential transients corresponding to each applied current step. Each sharp increase in potential is attributed to the immediate response of the electrode to the onset of the current pulse, followed by a gradual decay, which is characteristic of ion diffusion and charge transfer processes at the electrode–electrolyte interface [24].

The observed potential decay after each peak suggests capacitive behavior superimposed with faradaic reactions, typical for conducting polymer-coated electrodes or pseudocapacitive materials. The relatively stable baseline between pulses indicates good reversibility and electrochemical stability of the system during repeated cycling.

The increasing peak heights or slight potential shift with successive pulses may be indicative of ion accumulation or gradual changes in the electrochemical environment near the electrode surface, such as dopant redistribution or incomplete recovery between pulses. This behavior is commonly observed in redox-active polymer systems like polyaniline (PANI), where ion exchange with the electrolyte accompanies the redox transitions.

Overall, the reproducibility and shape of the transients suggest that (PANI/PC) exhibits reliable electrochemical switching behavior and charge storage capabilities, highlighting its potential application as electrode material in supercapacitors [25]. "On" phase, during which aniline undergoes electrochemical oxidation to form radical cations. The subsequent decay in current represents the "off" phase, during which the electrode potential relaxes. The repetitive spiking pattern illustrates the process of nucleation and polymer growth.

During each pulse, aniline monomers are oxidized at the electrode surface, generating radical cations that couple to form oligomers, thereby initiating the growth of the (PANI/PC) film. In the off-time, aniline diffusion from the bulk solution replenishes the electrode interface, allowing the film to reorganize and reducing the risk of uncontrolled over-oxidation. The electrochemical response observed in Figure 2 strongly supports the proposed polymerization mechanism, where each potential spike reflects the oxidative coupling of aniline monomers and subsequent film formation dynamics.

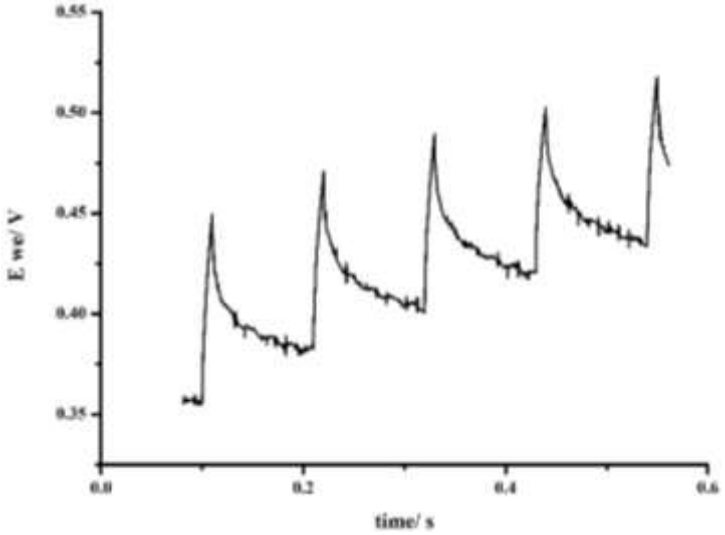

Figure 2: Pulse polymerization 10ms (PANI/PC)

3.2. Characterization:

After electrochemical polymerization, the prepared films of PANI/CV and PANI/PC were characterized using cyclic voltammetry (CV) and galvanostatic charge–discharge (GCD) techniques to evaluate their performance as pseudocapacitor materials. All electrochemical measurements were carried out at room temperature in 0.5 M H_2SO_4 aqueous solution, which is widely used due to its excellent ionic conductivity, economic viability, and compatibility with various electrode materials. The electrochemical tests were conducted within a potential window ranging from –0.2 to 0.8 V (vs. SCE), which was chosen based on the stability of the electrolyte and the electroactive behavior of the materials. In addition, the surface morphology of the prepared electrodes was investigated using scanning electron microscopy (SEM) and atomic force microscopy (AFM) to correlate structural features with electrochemical performance.

3.2.1. Cyclic Voltammetry at Different Scan Rates:

Figure 3 shows CV curves of 0.2M PANI in 0.5M H_2SO_4 at different scan rate 200, 100, 70, 50, 30 and 10 mV/s which were prepared by CV(PANI/CV) at 50 mV/s and pulse polymerization, duration time 10 ms (PANI/PC).

From Figure 3 both CV curves in case of PANI/CV and PANI/PC clearly show that current response increases with scan rate. At high scan rates the redox peaks become broader and shift slightly due to increased polarization, kinetic limitations and Peak currents are higher due to faster charge transfer and

ion diffusion dynamics. At lower scan rates the redox peaks are sharper and Electron transfer processes occur more reversibly and reflect intrinsic pseudocapacitive behavior.

By comparing both CV curves, we observe that the curves in the case of PANI/PC are smoother and have a larger area suggesting that the pulse made the curve more rectangular than CV and the peaks less sharp which means PANI/PC has more capacitive properties. The rectangular CV curves can be preserved demonstrating the good electrochemical rate capability of the material.

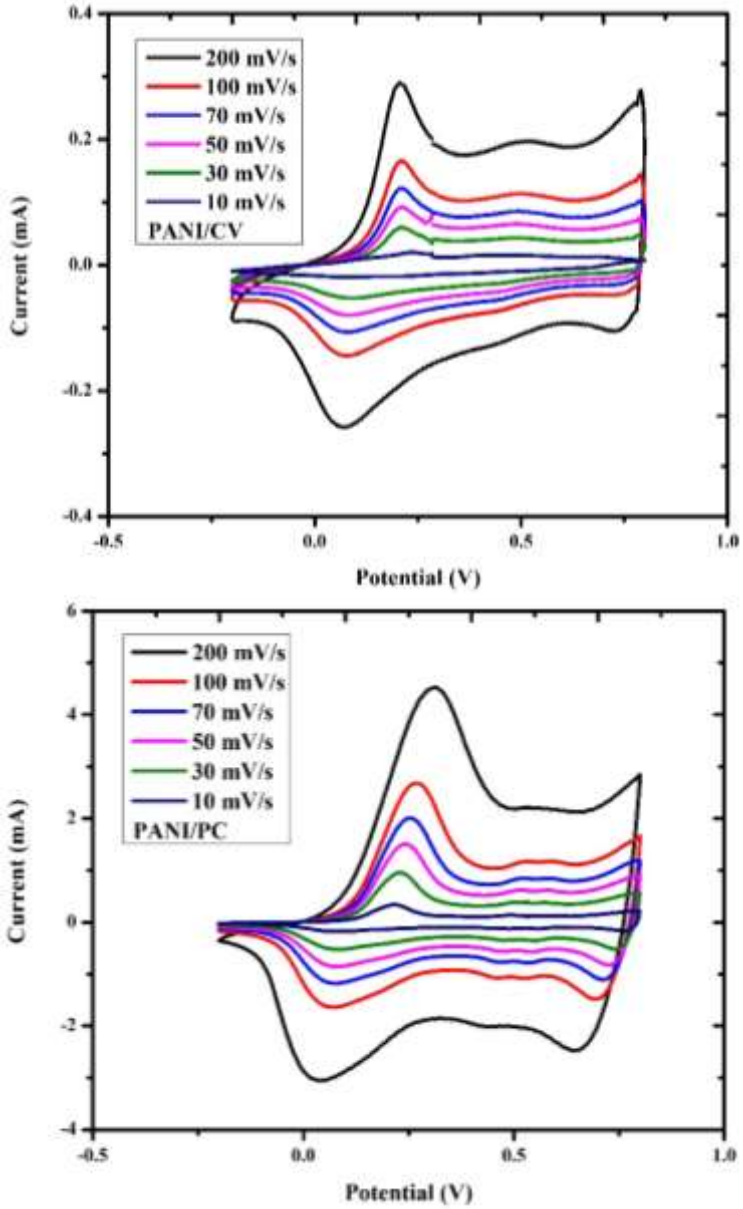

Figure 3. Cyclic voltammetry (CV) curves of PANI/CV and PANI/PC electrodes recorded at various scan rates (10, 30, 50, 70, 100, and 200 mV/s), demonstrating the electrochemical behavior and rate capability of the materials.

The specific capacitances of PANI/CV and PANI/PC electrodes are calculated using the CV curves at different scan rates using Eq. 1 to assess their electrochemical performance [26-27].

$$Sc = \frac{1}{mv\Delta v} \int_{v1}^{v2} i(V)dV \qquad \text{Eq. 1}$$

Where **SC** = specific capacitance (F/g), **m** = mass of the active material (g), **v** = scan rate (V/s), $\mathbf{\Delta V = V_2 - V_1}$ = potential window (V), **i(V)** = current as a function of potential (A) and the integral $\int_{v1}^{v2} i(V)dV$ represents the total charge (Q) from the CV curve.

Table 1. Specific capacitances for PANI/CV and PANI/PC with different scan rates

Scan Rate (mV/s)	Cs from CV (F/g)	Cs from Pulse (F/g)
200	276.1	536.3
100	307.1	565.7
70	324.8	579.5
50	342.7	589.5
30	375.95	602.9
10	427.7	640.9

As shown in Figure 4, both PANI/CV and PANI/PC electrode exhibit a clear increase in specific capacitance with decreasing scan rate, which is attributed to enhanced ion diffusion and more efficient utilization of the electroactive surface at lower scan rates.

At high scan rates (e.g., 200 mV/s), the PANI electrode prepared via the pulse method demonstrates superior performance (536.3 F/g) compared to that prepared by CV (276.1 F/g), indicating better rate capability, this improvement can be linked to the more porous and accessible structure typically formed through pulsed electropolymerization, which facilitates rapid charge transfer and ion transport, interestingly, as the scan rate decreases to 10 mV/s, the difference in capacitance values becomes less pronounced, with the PANI/CV reaching 427.7 F/g compared to 640.9 F/g for PANI/PC. This convergence suggests that, under slower scan conditions, both morphologies allow sufficient time for complete redox processes and full penetration of electrolyte ions into the electrode bulk.
Overall, the pulse deposition method appears to offer enhanced performance at higher scan rates, making it favorable method for fabricating PANI electrodes, while the CV method may provide slightly higher capacitance under slower scan conditions due to its possibly thicker or denser polymer film.

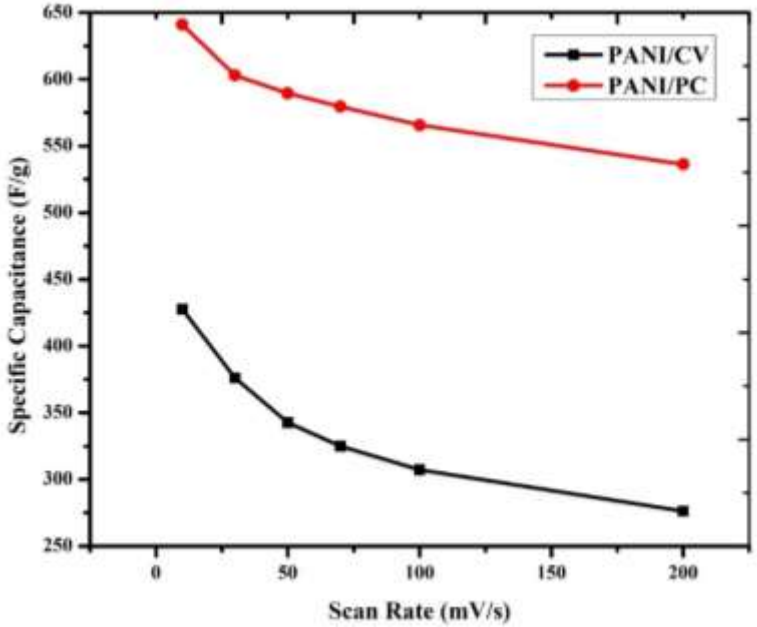

Figure 4: The variation in the specific capacitance of PANI/CV and PANI/PC as a function of scan rates.

By plotting the relationship between peak current and the square root scan rate, it is found linear relationship which indicates a surface-controlled (capacitive) process. The peak current (i_p) is related to the scan rate (ν) according to the Randles-Sevcik equation [28] , if the temperature is assumed to be 25 ℃ [29-30]:

$$i_p = 2.65x10^5 n^{\frac{3}{2}} A\, D^{\frac{1}{2}} C\, v^{\frac{1}{2}}$$

Where i_p = current maximum in A, n is the number of electrons, A is the surface area of the electrode (cm^2), D is the diffusion constant (cm^2/s), C is the bulk concentration of electroactive species (mol/cm^3), and v is the scan rate (V/s). Therefore, for a diffusion-controlled process, the peak current is proportional to the square root of the scan rate. For pseudo capacitors, a square root relationship suggests a diffusion-controlled process [31]. Figure 5 shows mixed behavior, common in PANI, where faradaic (redox) and capacitive (electric double-layer) contributions coexist, **Stable redox behavior** across varying scan rates.

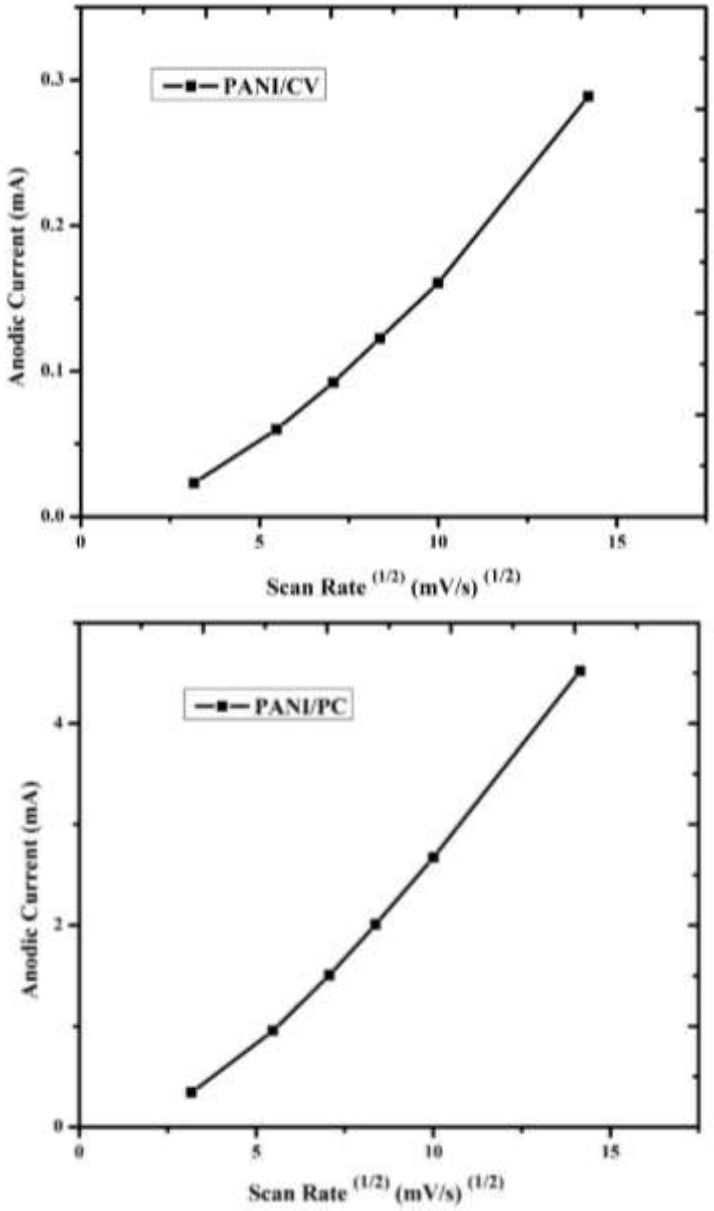

Figure 5: relationship between peak current (mA) with square root of scan rate for PANI/CV and PANI/PC

3.2.2. Scanning Electron Microscope (SEM):

The electrochemical performance of the conducting polymers like PANI is strongly dependent on their surface morphology, which governs ion diffusion, active surface area, and mechanical integrity during redox cycling.

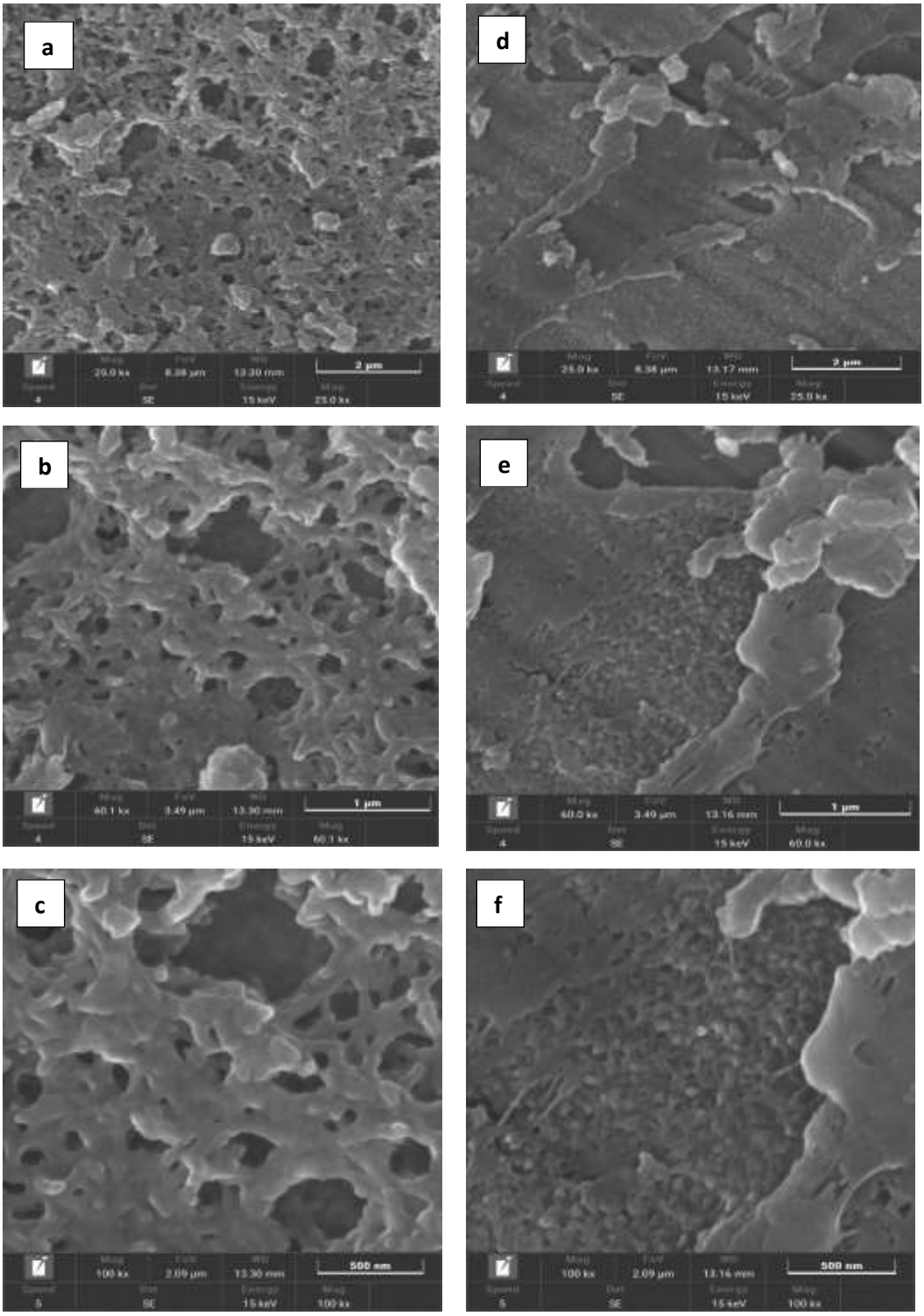

Figure 6: a, b and c: SEM for PANI/PC. & d, e and f: SEM for PANI/CV at different magnifications.

Figure 6 (a, b and c) SEM of PANI/PC shows a highly porous, sponge-like structure containing numerous interconnected pores and nano-sized cavities are visible that making PANI/PC ideal for ease for electrolyte ion diffusion and Maximizing electrochemically active surface area. The pore sizes are in the submicron range (~100–500 nm), as indicated by the scale bar, suggesting a hierarchical porous structure.

The distinct electrochemical behaviors observed for PANI/CV and PANI/PC can be closely linked to differences in their morphological characteristics, which are strongly influenced by the employed synthesis method. These morphological differences are further supported by SEM analysis (Figure 6), which reveals that the film structure of PANI is highly dependent on the polymerization technique. The pulse electropolymerization method promotes the formation of a more porous and nanostructured surface due to the alternating on/off current application, allowing for better organization and relaxation of the growing polymer chains. In contrast, SEM image (Fig. 6: d, e and f) shows a denser and more compact surface with reduced porosity and a more aggregated appearance. The structure seems to consist of granular and nodular particles with limited inter-particle spacing. This morphology is typical for polymers synthesized via cyclic voltammetry, where the continuous redox cycling results in layer-by-layer growth without the rest periods that favor pore formation.

Thus, the SEM findings confirm that the synthesis method plays a crucial role in defining the surface morphology, which in turn governs the electrochemical performance of the resulting PANI electrodes.

The intermittent nature of pulse electropolymerization allows for controlled nucleation and growth, resulting in a more open, nanostructured, and porous film. During the pulse deposition process, the alternating "on" and "off" phases enable controlled polymer growth. In the "on" phase, aniline monomers are oxidized to form radical cations, initiating nucleation and chain propagation. The subsequent "off" phase allows for monomer diffusion from the bulk solution to the electrode surface, relaxation of the electrode potential, and structural reorganization of the growing polymer film. This periodic modulation facilitates the formation of a more porous and uniformly distributed polymer network with enhanced ion accessibility. In contrast, the continuous potential cycling employed in the cyclic voltammetry (CV) method leads to uninterrupted polymer growth, which may result in the formation of denser and less organized films with lower porosity. The limited time for relaxation and structural adjustment during CV deposition can hinder effective ion diffusion within the polymer matrix, especially at high scan rates [32].

PC Polymerization method gives refined and nanostructure surface which excellent electrochemical accessibility and good specific capacitance and rate performance. Finally, SEM confirms results from cyclic at different scan rate, these results summarize that PANI-PC suitable for pseudocapacitor applications than the cyclic voltammetry method. The SEM images directly support the electrochemical data, confirming that morphological control is key to optimizing energy storage materials.

3.2.3. Electrochemical cyclic stability:

The cyclic stability of polyaniline (PANI) electrodes (PANI/CV and PANI /PC) was evaluated over 1000 cycles using CV, as shown in Figure 7. The specific capacitance values were recorded at various intervals to assess retention performance [33–34].

The PANI/PC electrode exhibited an initially higher specific capacitance (**536.3 F/g**) compared to the PANI/CV electrode (**276.1 F/g**) at the second cycle. This superior initial performance of the pulse-polymerized sample can be attributed to its highly porous nanostructure (as observed in the SEM images), which facilitates better ion diffusion and greater electroactive surface area.

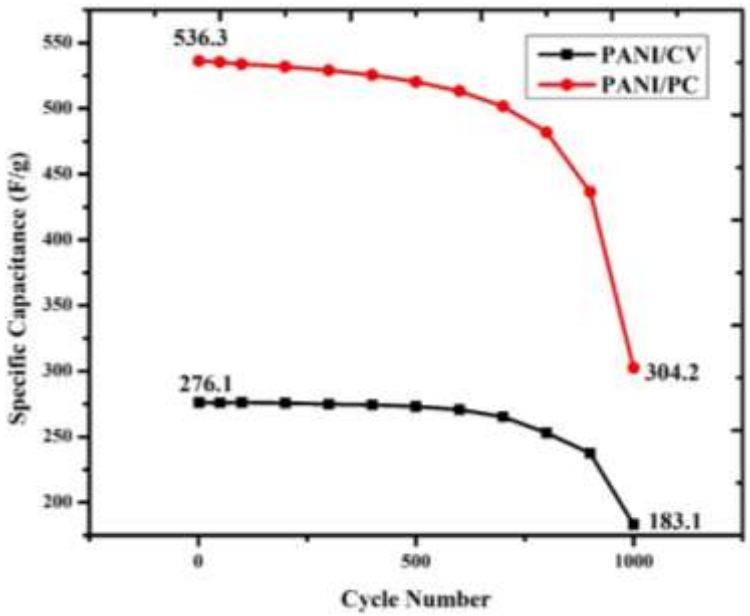

Figure 7: Cyclic stability of PANI/CV and PANI /PC as a function of cycle number.

However, with increasing cycle number, a significant difference in capacitance retention behavior was observed between the two electrodes. After 1000 cycles, the PANI/PC sample retained only **56.73%** of its initial capacitance, dropping to **304.2 F/g**, whereas the PANI/CV electrode retained **66.42%**, maintaining a capacitance of **183.3 F/g**. These results are summarized in Table 2:

Table 2: Specific Capacitance of PANI/CV and PANI/PC and their retentions

Electrode	Capacitance at Cycle 2 (F/g)	Capacitance at Cycle 1000 (F/g)	Retention (%)
PANI/CV	276.1	183.3	66.4%
PANI/PC	536.3	304.2	56.7%

This contrasting behavior highlights a common trade-off between initial performance and long-term stability. The superior cycling stability of the CV-prepared PANI is likely due to its denser and more compact morphology, which offers enhanced mechanical integrity during repetitive swelling and contraction processes. In contrast, the highly porous structure of the pulse-polymerized PANI, while advantageous for initial charge storage, may be more prone to structural degradation and delamination under prolonged cycling.

These findings underscore the importance of tailoring the electropolymerization method based on the intended application—where high initial capacitance is desired (e.g., for short-lifetime supercapacitors), pulse deposition may be preferred, while CV offers better durability for long-term energy storage.

3.2.4. Atomic Force Microscopy (AFM)

To ensure the shape of the resulting polymer, Atomic Force Microscopy (AFM) was performed to study the surface morphology, roughness, and topography of the film [35]. As shown from Figure 8, the film surface is highly rough and porous, which increases the effective surface area that provide fast redox reactions, Additionally roughness increases the electrode/electrolyte interface area which reflect high specific capacitance [36]. The three-dimensional AFM image (fig. illustrates the surface morphology of the PANI/PC electrode. The height profile ranges from approximately –253 nm to +123 nm, indicating

significant surface roughness and the presence of nanostructured features. The film shows a significantly more porous and open structure with numerous surface features and well-developed micro/nano-textures. This enhanced porosity is attributed to the periodic nature of the pulse technique, which allows for controlled chain propagation and relaxation during the OFF cycles. The intermittent current flow facilitates more uniform nucleation and the formation of a more porous, sponge-like network.

As shown from Figure 8 (b), the surface of PANI/CV exhibits a relatively dense and compact structure with lower porosity and fewer surface voids. The morphology is characterized by tightly packed, rough nodules with less pronounced vertical features. This indicates a continuous and uncontrolled polymer growth process without interruption, resulting in compact agglomerates and low surface area.

The highly porous morphology observed in the PANI/PC film (Figure 8 (a)) is directly correlated with enhanced specific capacitance values. The increased surface area and more accessible active sites facilitate efficient ion diffusion and charge storage. As a result, the PANI/PC electrode demonstrates superior charge storage capability, making it advantageous for supercapacitor applications.

Despite its higher capacitance, PANI/PC structure exhibits slightly lower electrochemical stability compared to the PANI/CV film. The increased porosity, while beneficial for ion transport, may also lead to structural fragility and degradation under repeated charge/discharge cycling. In contrast, the denser morphology of the PANI/CV provides greater mechanical integrity, leading to improved long-term cycling stability.

These topographical characteristics confirm the successful formation of a nanostructured PANI/PC, suitable for use as a high-performance electrode material in supercapacitor devices.

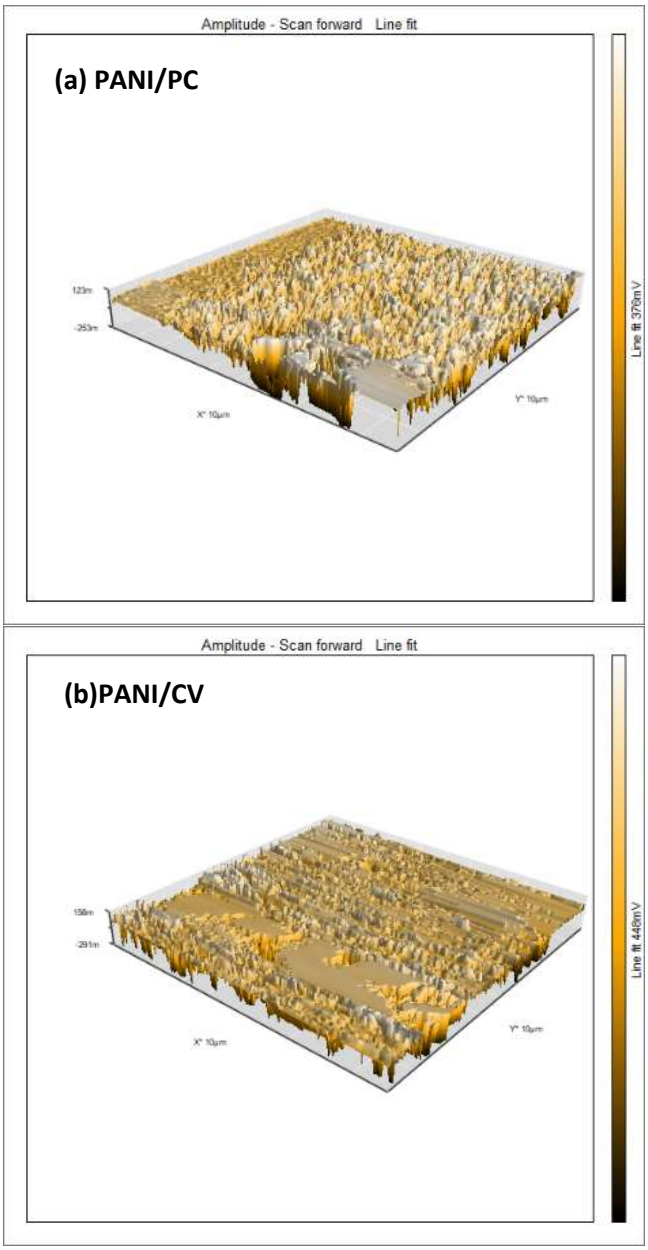

Figure 8: (a) AFM of PANI/PC (b) AFM of PANI /CV.

3.2.5. Galvanostatic charge–discharge (GCD):

The electrochemical performance of the synthesized polyaniline (PANI) electrodes was evaluated using galvanostatic charge–discharge (GCD) measurements at various current densities. Figure 9 represent the GCD curves of the PANI/CV and PANI/PC electrodes, respectively, recorded at current densities of 3, 6, 8, 12, and 15 A/g in 0.5 M H_2SO_4.

The measurements were carried out within a potential window of 0–0.8 V in a three-electrode system. The GCD curves of both PANI/CV and PANI/PC exhibit a quasi-triangular shape, indicating typical capacitive behavior with pseudo-capacitive contributions attributed to the redox activity of PANI. The curves remain symmetric with increasing current density, suggesting good electrochemical reversibility and stability [37–38]. The linear and sloped nature of the curves also suggests good ion transport and reversibility of redox reactions [39]. Notably, the discharge time significantly decreases as the current

density increases, which is consistent with typical capacitive behavior due to limited ion diffusion and charge transfer at higher current rates. The PANI/PC electrode demonstrates significantly longer discharge times than the PANI/CV electrode across all current densities, suggesting enhanced charge storage capability. This superior performance is attributed to the enhanced ion diffusion kinetics of the PANI/PC. The improved electrochemical response of PANI/PC is attributed to better-controlled nucleation and growth, which may result in more porous and conductive morphologies enhancing electrolyte accessibility.

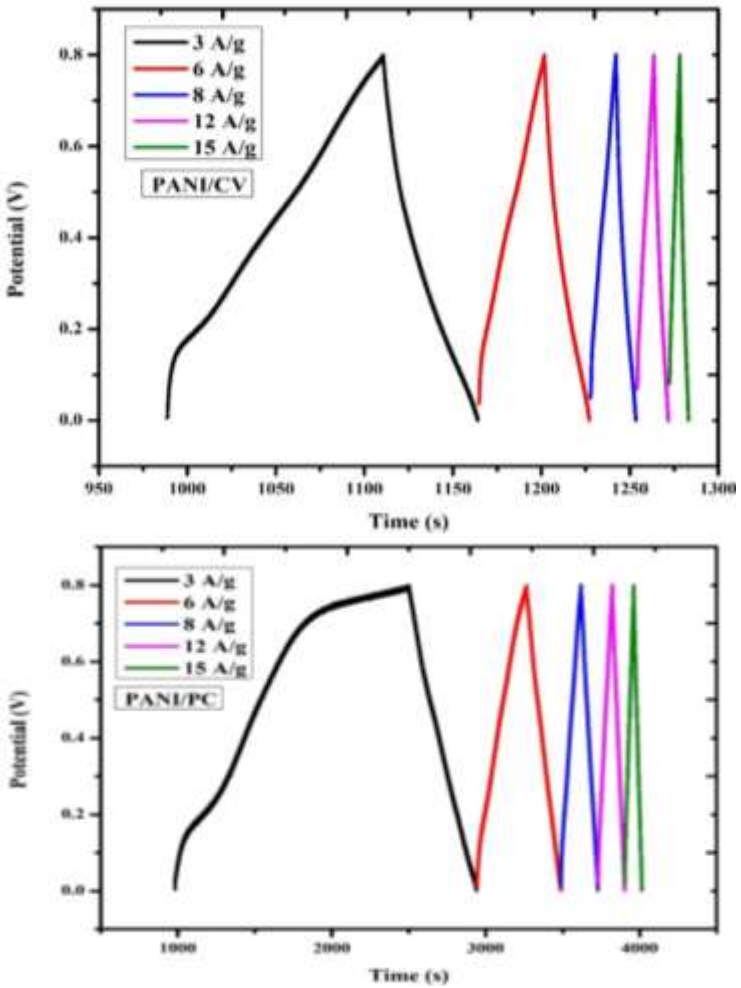

Figure 9 : a Charge–discharge curves of PANI/CV and PANI/PC at current densities of 3, 6, 8, 12, and 15 Ag^{-1} in 0.5 M H_2SO_4

4. CONCLUSION

This study highlights the significant impact of the synthesis method on the electrochemical performance of polyaniline (PANI). The electrode fabricated via pulse chronopotentiometry (PANI/PC) exhibited enhanced capacitive behavior due to its porous morphology, which provides greater ion-accessible surface area and leads to higher specific capacitance. In contrast, the cyclic voltammetry-based PANI electrode (PANI/CV) showed lower capacitance but better electrochemical stability, attributed to its denser structure. These findings underscore the importance of tailoring electropolymerization conditions to optimize the morphology and performance of conducting polymers for energy storage, with PANI synthesized by the pulse technique emerging as a promising electrode material for supercapacitor applications.

Conflict of interest: There is no conflict of interest.

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