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Electrochemical sensing of dopamine in hydrochloride injection using SWCNT@PANI hydrogel-modified electrode

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Abstract

A single-walled carbon nanotube (SWCNT)-polyaniline (PANI) hydrogel-modified screen-printed carbon electrode (SPCE), denoted as SWCNT@PANI/SPCE, was developed for the electrochemical detection of dopamine (DA). The electrochemical performance of the fabricated sensor was systematically investigated using cyclic voltammetry (CV) and differential pulse voltammetry (DPV) techniques. The CV studies revealed a remarkable enhancement in the oxidation current response for DA at the SWCNT@PANI hydrogel/SPCE, attributed to the synergistic interaction between the highly conductive SWCNT network and the redox-active PANI hydrogel matrix. The incorporation of the PANI hydrogel not only provided a three-dimensional porous structure for analyte diffusion but also offered superior ionic conductivity, mechanical flexibility, and biocompatibility to enhance the interfacial electron transfer kinetics. The DPV analysis demonstrated a well-defined linear response over the DA concentration range of 10-300 μM with a low limit of detection (LOD) of 0.24 μM. The SWCNT@PANI hydrogel/SPCE exhibited excellent reproducibility, stability, and selectivity toward DA oxidation. Furthermore, the practical applicability of the developed sensor was validated using a commercial dopamine hydrochloride injection as the real sample. The analysis showed excellent recovery, with a value of 105.22%, confirming that the sensor was suitable for detecting dopamine in real samples for pharmaceutical and clinical applications.

Keywords: Single-walled carbon nanotubes; Polyaniline; Hydrogel; Electrochemical Sensors; Dopamine Hydrochloride Injection

1. Introduction

Dopamine (DA), a key catecholamine neurotransmitter, plays an indispensable role in regulating neuronal signalling, cardiovascular activity, renal function, immune modulation, and blood pressure control [1]. Dysregulated DA levels are closely associated with pathological conditions, where deficiency contributes to neurodegenerative and psychiatric disorders such as Parkinson's disease, Alzheimer's disease, and depression, while excess leads to cardiotoxic manifestations including hypertension and heart failure [2,3]. Therefore, accurate measurement of DA is very important to understand its role in the body and to diagnose related diseases. For the determination of DA, traditional analytical techniques such as enzyme assays, HPLC-MS/MS, and capillary electrophoresis offer high accuracy and reliability. However, these methods are costly, time-consuming, and involve complex instrumentation. In comparison, electrochemical sensing provides a simple, rapid, and cost-effective alternative, utilizing the facile oxidation of DA at the electrode surface to enable sensitive and selective detection, even in the presence of interfering species like ascorbic acid [4–6].

Polymeric hydrogels have emerged as promising functional materials in electrochemical sensing owing to their unique three-dimensional cross-linked network and tunable physicochemical properties [7]. Their highly porous and hydrated structure provides an excellent microenvironment for the diffusion and adsorption of target analytes, facilitating efficient mass transport toward the electrode surface. This interconnected network not only enhances the accessibility of electroactive sites but also improves the stability and reproducibility of the sensing interface [8]. Furthermore, hydrogels can be engineered to possess desirable mechanical strength, ionic conductivity, and biocompatibility, enabling them to serve as effective matrices for immobilizing biomolecules or nanomaterials. The synergistic combination of high-water content, porosity, and functional versatility allows polymeric hydrogels to significantly improve the sensitivity and selectivity of electrochemical sensors, making them ideal platforms for real-time and label-free detection of a wide range of analytes.

Recent advancements in nanotechnology have greatly accelerated the development of high-performance electrochemical sensors by incorporating nanomaterials with superior electrical, structural, and catalytic properties [9,10]. Nanomaterials are significantly used in electrochemical sensing application [11–16] such as single-walled carbon nanotubes (SWCNTs) and conducting polymers like polyaniline (PANI) have attracted considerable attention due to their ability to enhance electron transfer kinetics, increase electroactive surface area, and improve overall sensor sensitivity [17,18]. PANI, a well-known intrinsically conducting polymer, offers good environmental stability, reversible redox behavior, and proton

conductivity, which are advantageous for electrochemical transduction. SWCNTs exhibit remarkable electrical conductivity, high surface-to-volume ratio, and excellent charge transfer capabilities, making them ideal candidates for electrode surface modification and bioreceptor immobilization [11]. Recent studies have demonstrated that integrating SWCNTs and PANI within a hydrogel framework further enhances electrical conductivity and provides a porous, hydrated environment that facilitates efficient analyte diffusion and electron transport. Although SWCNT-based electrode modifications are widely reported in the literature [19], the synergistic combination of SWCNT and PANI hydrogels for electrochemical sensing has only recently emerged, offering a promising pathway for developing next-generation, highly sensitive biosensing platforms [20].

In the present study, a single-walled carbon nanotube–polyaniline (SWCNT@PANI) hydrogel-based electrochemical sensor was developed for the sensitive detection of dopamine (DA). The hydrogel matrix provides a biocompatible and hydrated microenvironment that effectively stabilizes the embedded nanomaterials and prevents aggregation, while its interconnected porous network promotes efficient diffusion of analyte molecules toward the electrode surface. This facilitates rapid electron transfer and enhances the overall electrocatalytic performance of the sensor. The SWCNT@PANI hydrogel combines the high electrical conductivity and large surface area of SWCNTs with the redox activity and mechanical flexibility of PANI, resulting in superior sensitivity, selectivity, and operational stability. This work highlights the potential of SWCNT@PANI hydrogel as a promising sensing platform for rapid, on-site monitoring of biologically and environmentally relevant analytes, offering valuable insights into the design of next-generation electrochemical biosensors.

2. Materials and methods

2.1 Chemicals and characterizations

Signle walled carbon nanotube (SWCNT) and Polyaniline (PANI) were procured from XG Sciences, Inc. (USA). Hydrochloric acid (HCl, 37% v/v), Aniline hydrochloride (C6H5NH2.HCl, 99%), and sodium hydroxide (NaOH), were procured from Sigma-Aldrich (USA). Potassium chloride (KCl), ferric ferrocyanide ($Fe_4[Fe(CN)_6]_3$), and ammonium persulfate ((NH4)2S2O8) (APS) were sourced from Sigma-Aldrich (USA). Screen-printed carbon electrodes (SPCEs) were purchased from Zensor. A Fourier transform infrared spectrometer (FTIR- PerkinElmer) was used for spectroscopic characterization. Electrochemical performance of the fabricated sensor was evaluated using K-Lyte 1.0 Potentiostat.

2.2 Preparation of SWCNT@PANI Hydrogel

The SWCNT@PANI hydrogel was synthesized via an in-situ oxidative polymerization process. Briefly, single-walled carbon nanotubes (SWCNTs) were ultrasonically dispersed in deionized water containing 0.5 wt% sodium dodecyl sulfate (SDS) for 1 hour to obtain a stable suspension. Aniline monomer was dissolved separately in 1 M HCl under constant stirring, after which the SWCNT dispersion was slowly added to the aniline solution to ensure uniform interaction between the components. Polymerization was initiated by the dropwise addition of ammonium persulfate (APS) solution (aniline:APS = 1:1 molar ratio) at 0-5 °C, and the reaction was allowed to proceed for 12 hours. The resulting dark-green SWCNT@PANI hydrogel was washed several times with deionized water and ethanol to remove unreacted monomers and impurities, then stored at 4 °C for further use. For comparison, pure SWCNT and PANI hydrogels were synthesized under identical conditions without adding aniline or SWCNTs, respectively.

2.3 Modification of SPCE using SWCNT@PANI hydrogel

A screen-printed carbon electrode (SPCE) was utilized as the sensing platform in this study. Before modification, the electrode surface was carefully cleaned with distilled water to remove any adsorbed impurities and ensure a reproducible surface. Subsequently, 5 µL of the prepared SWCNT@PANI hydrogel was drop-cast onto the working electrode area. The modified electrode was then placed in a sealed glass chamber and incubated in a water bath at 50 °C for 6 hours to promote uniform gelation. Afterward, the electrode was air-dried at ambient temperature and conditioned for an additional 30 minutes to ensure complete stabilization of the hydrogel layer. The resulting SWCNT@PANI/SPCE was then subjected to electrochemical characterization using cyclic voltammetry (CV) and differential pulse voltammetry (DPV) techniques.

2.4 Electrochemical measurement of DA

All electrochemical measurements were carried out using a three-electrode system connected to an EmStat3 Blue potentiostat (PalmSens, The Netherlands). The screen-printed carbon electrode (SPCE) was modified with 5 µL of SWCNT@PANI hydrogel nanocomposite and used as the working electrode. Cyclic voltammetry (CV) was performed in 5 mM $[Fe(CN)_6]^{3-/4-}$ containing 0.1 M KCl over a potential range of -0.6 to 0.6 V at a scan rate of 50 mV s^{-1} to evaluate the electrochemical performance of the modified electrode. For dopamine sensing, cyclic voltammetry (CV) and differential pulse voltammetry (DPV) measurements were

carried out in 1.0 M phosphate-buffered saline (PBS, pH 7.0) containing different concentrations of dopamine (10, 30, 70, 100, 150, 200, and 300 μM).

2.5 Real sample analysis

The practical applicability of the developed SWCNT@PANI hydrogel nanocomposite electrode was evaluated by determining dopamine in a commercial dopamine hydrochloride injection using the standard addition (recovery) method [21]. Prior to analysis, the pharmaceutical formulation was appropriately diluted with 1 M phosphate-buffered saline (PBS, pH 7.0) to bring the analyte concentration within the linear detection range. Known concentrations of standard dopamine were subsequently spiked into the diluted sample, and the electrochemical response was recorded under the optimized experimental conditions. The dopamine concentration was quantified from the corresponding calibration curve, and the recovery values were calculated.

3. Results and discussion

3.1 Characterisation of SWCNT@PANI hydrogel

The synthesis procedure for the SWCNT@PANI hydrogel-modified SPCE is illustrated in **Schematic 1**. The chemical composition and functional group characteristics of the various hydrogels were analyzed using FTIR spectroscopy, as illustrated in **Figure 1**. The bare hydrogel exhibits broad -OH stretching around 3400 cm^{-1}, C=O stretching near 1640-1650 cm^{-1}, and C-O-C/C-O stretching in the 1200-1000 cm^{-1} range, confirming the formation of a hydrophilic polymer network. The SWCNT hydrogel shows minimal transmittance changes, with small peaks around 1600 cm^{-1} attributed to residual carboxyl or defect-associated C=C stretching, indicating well-dispersed nanotubes without significant new chemical groups. The PANI hydrogel displays characteristic peaks of polyaniline, including quinoid ring stretching at 1550-1500 cm^{-1}, benzenoid vibrations near 1480 cm^{-1}, broad N-H stretching at 3400 cm^{-1} from secondary amines, and C-N stretching at 1300-1250 cm^{-1}, consistent with the emeraldine salt form secondary amines [22]. The SWCNT@PANI hydrogel shows combined features of both SWCNTs and PANI, with slight shifts and intensity changes, indicating interactions between nanotubes and polymer matrix; the broad N-H stretching at 3400 cm^{-1} and quinoid/benzenoid peaks at 1550-1480 cm^{-1} confirm PANI presence, while subtle peaks near 1600 cm^{-1} reflect the SWCNT component, suggesting successful integration of PANI onto the SWCNT network to form a conductive nanocomposite hydrogel [23].

The swelling behavior of different hydrogels is illustrated in the **Figure 2**. All samples show a gradual increase in swelling percentage with time, indicating their ability to absorb water and expand. Among them, the SWCNT@PANI hydrogel (blue curve) exhibits the highest swelling capacity, reaching nearly 400% after 50 hours, which suggests a highly porous and flexible network structure that facilitates water uptake. The PANI hydrogel (red curve) shows moderate swelling behavior, attaining about 320% at 50 hours, reflecting its hydrophilic nature but comparatively denser structure. The SWCNT hydrogel (black curve) displays the lowest swelling ratio, approximately 270% at 50 hours, likely due to the rigid and graphitic characteristics of SWCNTs that limit water diffusion [24]. Overall, the enhanced swelling of the SWCNT@PANI hydrogel confirms the synergistic effect of SWCNT incorporation with PANI, leading to an interconnected network that improves water retention and structural flexibility.

3.2 Electrochemical characterisation of SWCNT@PANI hydrogel

The cyclic voltammetry (CV) and scan rate studies presented in the **Figure 3**, provide valuable insights into the electrochemical behavior of the hydrogel-modified electrodes. In **Figure 3(A)**, the CV curves of the Bare SPCE, PANI Hydrogel/SPCE, SWCNT Hydrogel/SPCE, and SWCNT@PANI Hydrogel/SPCE were recorded in 5 mM $[Fe(CN)_6]^{3-/4-}$ containing 0.1 M KCl at a scan rate of 50 mV/s. The bare SPCE exhibited the lowest anodic peak current (0.016 mA), while the peak current gradually increased to 0.023 mA for the PANI hydrogel/SPCE, 0.033 mA for the SWCNT hydrogel/SPCE, and reached the highest value of 0.039 mA for the SWCNT@PANI hydrogel/SPCE. This gradual increase indicates that each modification step improved the electrical conductivity and facilitated faster electron transfer at the electrode surface. The enhanced response of the SWCNT@PANI hydrogel can be attributed to the combined effect of the highly conductive SWCNT network and the conductive PANI matrix, which together provide more electroactive sites and efficient pathways for charge transport. The quantitative comparison of anodic peak currents for different electrodes is presented in **Figure 3(B)**. These results clearly demonstrate a progressive increase in electrochemical activity following each modification step. The gradual enhancement in peak current confirms the successful incorporation of conductive nanomaterials within the hydrogel matrix and the improved charge-transfer characteristics of the modified electrodes.

The electrochemical behavior of the SWCNT@PANI hydrogel/SPCE was further investigated at scan rates ranging from 10 to 200 mV/s, as shown in **Figure 3(C)**. As the scan rate increased

from 10, 20, 30, 50, 70, 100, 150, to 200 mV s^{-1}, both the anodic and cathodic peak currents increased progressively while maintaining well-defined oxidation and reduction peaks. The anodic peak current increased from approximately 0.05 mA at 10 mV s^{-1} to approximately 0.23 mA at 200 mV s^{-1}, whereas the cathodic peak current increased from approximately -0.05 mA to approximately -0.22 mA over the same scan-rate range. The increase in peak current with increasing scan rate indicates enhanced electron-transfer activity and rapid electrochemical kinetics at the modified electrode surface. To investigate the electrochemical mechanism, the anodic and cathodic peak currents were plotted against scan rate, as shown in **Figure 3(D)**. A good linear relationship was obtained for both oxidation and reduction processes. The anodic peak current exhibited a linear regression coefficient of $R^2 = 0.9523$, whereas the cathodic peak current showed a regression coefficient of $R^2 = 0.9510$. The strong linear dependence of peak current on scan rate indicates that the electrochemical reaction is predominantly adsorption-controlled rather than diffusion-controlled [25]. These results confirm that the SWCNT@PANI hydrogel provides an interconnected conductive network and enhanced electrochemical activity, making it a promising platform for sensing applications. Furthermore, the number of electrons (n) transferred during the electrochemical reaction was determined using the Bard–Faulkner equation (**Eq. 1**) [26] .

$$\Delta E_p = E_p - E_{\frac{p}{2}} = \frac{47.7}{\alpha n}\, mV \qquad (1)$$

Where $E_{p/2}$ is the half-peak potential and α is the electron transfer coefficient (0.5). The calculated electron transfer number (n = 1.96) indicates that dopamine oxidation follows a predominantly two-electron, two-proton transfer mechanism.

The electrochemically active surface area of the SWCNT@PANI hydrogel/SPCE was determined from cyclic voltammetry using the Randles-Sevcik equation **(Eq. 2)** [27].

$$I_{Pa} = 2.69 \times 10^5 \times \mathrm{A} \times D^{1/2} \times n^{3/2} \times v^{1/2} \times C \qquad (2)$$

where A is the electroactive surface area of the electrode (cm^2), D is the diffusion coefficient of dopamine ($cm^2\ s^{-1}$), n is the number of electrons transferred, ν is the scan rate ($V\ s^{-1}$), and **C** is the concentration of dopamine ($mol\ cm^{-3}$). The electroactive surface areas were calculated to be 0.035 cm^2 for the bare SPCE, 0.047 cm^2 for the bare hydrogel/SPCE, and 0.089 cm^2 for the SWCNT@PANI hydrogel/SPCE. The significantly larger electroactive surface area of the SWCNT@PANI hydrogel/SPCE indicates the successful incorporation of the conductive nanocomposite, providing abundant electroactive sites and enhanced electron-transfer

pathways. The synergistic interaction between SWCNTs and PANI improves the adsorption and oxidation of dopamine molecules at the electrode surface, thereby facilitating faster electron-transfer kinetics and enhancing the electrochemical sensing performance. Furthermore, the electrochemical kinetics of dopamine oxidation were investigated using Laviron's equation, which was employed to determine the charge transfer coefficient (**α**) and the heterogeneous electron transfer rate constant (k). The values of α and k were calculated from the slope of the plot of anodic peak potential (**Epa**) versus the logarithm of the scan rate (log ν) using **Eq. (3)** [28].

$$logk_s = \alpha \log(1-\alpha) + (1-\alpha)\ log\alpha - \log\frac{RT}{NFV} - \alpha nf\ (1-\alpha)\ \frac{\Delta E_p}{2.3RT} \quad (3)$$

The heterogeneous electron transfer rate constant (k) was found to be 0.986 s^{-1}, while the charge transfers coefficient (α) was found to be 0.5. A k value approaching 1 s^{-1} suggests a highly efficient electron transfer, which is essential for sensitive and responsive electrochemical sensing applications. Additionally, using the Randles-Sevick equation, the diffusion coefficient of DA was calculated to be 8.6×10^{-6} cm^2/s.

3.3 Electrochemical performance of SWCNT@PANI hydrogel/SPCE for DA detection

The CV responses of different modified electrodes toward dopamine (DA) are presented in **Figure 4**. In each case, the voltammograms recorded after the addition of DA (red curves) show distinct anodic and cathodic peaks compared to the baseline responses without DA (black curves), confirming the successful electrochemical oxidation and reduction of dopamine. For the bare SPCE **Figure 4(A),** a relatively weak redox response is observed, indicating limited electron transfer efficiency. The PANI hydrogel/SPCE **Figure 4(B)** exhibits a noticeable increase in current response, attributed to the conductive polymer network that facilitates charge transport and enhances active site availability. The SWCNT hydrogel/SPCE **Figure 4(C)** further improves the redox current due to the excellent electrical conductivity and large surface area of the SWCNTs, which promote electron transfer between DA molecules and the electrode surface. The SWCNT@PANI hydrogel/SPCE **Figure 4(D)** demonstrates the highest redox peak currents and the smallest potential separation between the oxidation and reduction peaks, reflecting superior electrocatalytic activity and faster electron-transfer kinetics. Overall, the results confirm that the synergistic combination of SWCNTs and PANI within the hydrogel

matrix significantly enhances dopamine sensing performance compared to the individual components or bare electrode.

To evaluate the optimum performance of the SWCNT@PANI hydrogel/SPCE toward DA detection, CV and DPV measurements were conducted across a range of DA concentrations. As illustrated in **Figure 5(A)**, the oxidation peak current exhibited a systematic and proportional increase with rising DA concentration, confirming a concentration-dependent electrochemical response. The corresponding calibration plot, shown in **Figure 5(B)**, demonstrates a well-defined linear relationship between peak current and DA concentration, indicating the electrode's reliable quantitative sensing capability represented as:

$$\mathrm{I}\ (\mu\mathrm{A}) = 0.02C_{\mathrm{DA}}\ (mA) + 2.44; R^2 = 0.9544 \qquad (4)$$

Similarly, the DPV profiles in **Figure 5(C)** reveal that the oxidation peak current increases progressively with increasing DA concentration under optimized experimental conditions. Furthermore, as depicted in (**Figure 5(D))**, the sensor displayed a strong linear relationship, with the corresponding linear regression equation represented as:

$$\mathrm{I}\ (\mu\mathrm{A}) = 0.09C_{\mathrm{DA}}\ (mA) + 2.00; R^2 = 0.9563 \qquad (5)$$

The limit of detection (LOD) for dopamine was calculated to be 0.24 µM using the standard equation LOD = 3.3s/m, where s represents the standard deviation of the regression line and m denotes the slope of the calibration curve. Although both CV and DPV techniques exhibited reliable electrochemical responses, DPV was chosen as the preferred analytical method for quantitative analysis due to its reduced susceptibility to charging current interference. Moreover, the pulse nature of DPV enhances signal resolution and sensitivity, enabling precise distinction of analyte peaks from background or interfering species. This characteristic makes DPV particularly advantageous for biosensing applications, as it offers improved selectivity and accuracy in detecting target analytes even in complex sample matrices. A comparative summary of previously reported electrochemical sensors for dopamine detection is presented in **Table 1**, highlighting the analytical performance and methodologies described in the literature.

3.4 Selectivity, Reproducibility Repeatability, and Stability Analysis

Interference from electroactive species commonly present in biological and pharmaceutical samples is a major challenge that can compromise the reliability and accuracy of electrochemical sensors. Therefore, the selectivity of the SWCNT@PANI hydrogel nanocomposite electrode toward dopamine (DA) was systematically evaluated using the differential pulse voltammetry (DPV) technique. In this study, the sensor response was examined in the presence of 100 μM of potential interfering species, including ascorbic acid (AA), uric acid (UA), acetaminophen (AC), glucose (GLU), and *p*-aminophenol (PAP), followed by the addition of 50 μM dopamine (DA) in 5 mM $[Fe(CN)_6]^{3-/4-}$ containing 0.1 M KCl at a scan rate of 50 mV/s (pH 7.0). As illustrated in **Figure 8A**, the presence of these interfering compounds caused only negligible changes in the electrochemical response, while the addition of DA produced a well-defined and distinct oxidation peak with a significant increase in peak current. The maximum variation in the dopamine response current due to the interfering species was less than 5%, indicating excellent resistance to interference. Therefore, we confirmed that SWCNT@PANI sensor exhibited an outstanding anti-interference property. The reproducibility of the proposed SWCNT@PANI hydrogel nanocomposite electrode was evaluated by fabricating five independently prepared electrodes and recording their differential pulse voltammetry (DPV) responses toward 50 μM dopamine (DA) in 5 mM $[Fe(CN)_6]^{3-/4-}$ containing 0.1 M KCl at a scan rate of 50 mV/s (pH 7.0). As shown in **Figure 8B**, only slight variations were observed in the oxidation peak currents among the five fabricated electrodes, indicating excellent fabrication consistency. The relative standard deviation (RSD) of the peak current responses was calculated to be 1.27%, demonstrating excellent reproducibility. The repeatability of the proposed SWCNT@PANI hydrogel nanocomposite electrode was evaluated by recording five consecutive differential pulse voltammetry (DPV) measurements for the detection of 50 μM dopamine (DA) in 5 mM $[Fe(CN)_6]^{3-/4-}$ containing 0.1 M KCl at a scan rate of 50 mV/s (pH 7.0) using the same electrode. As shown in **Figure 8C**, the oxidation peak currents remained highly consistent over the five successive measurements, indicating excellent operational stability. The relative standard deviation (RSD) of the recorded peak currents was found to be 0.43%, demonstrating outstanding repeatability. The stability of the proposed SWCNT@PANI hydrogel nanocomposite electrode was evaluated over 8 days by recording its differential pulse voltammetry (DPV) response toward 50 μM dopamine. As shown in **Figure 8D**, only a 3.62% decrease in the peak current was observed after 8 days compared to the initial response. This result indicates that the developed SWCNT@PANI hydrogel nanocomposite electrode possesses good stability for the electrochemical detection of dopamine.

3.5 Real sample analysis

Dopamine hydrochloride injection was employed to evaluate the practical applicability of the developed SWCNT@PANI hydrogel/SPCE sensor for the determination of DA. The injection sample was appropriately diluted with 0.2 mol L^{-1} phosphate-buffered saline (PBS, pH 7.0) to obtain a suitable concentration range for analysis. Several concentrations of the diluted injection solution were prepared, and the corresponding current responses were recorded using the DPV technique under identical experimental conditions. As summarized in **Table 2**, the obtained recovery values ranged from 95.10 % to 105.22 %, confirming the high accuracy and reliability of the fabricated electrochemical sensor for DA detection in real pharmaceutical samples.

4. Conclusions

In conclusion, the SWCNT@PANI hydrogel-modified SPCE was successfully developed for the sensitive and selective electrochemical determination of dopamine. The incorporation of SWCNT within the PANI hydrogel framework significantly enhanced the oxidation peak current of DA, attributed to the synergistic interplay between the large electroactive surface area and excellent electron transport characteristics of SWCNT and the superior redox conductivity of PANI. This hybrid architecture facilitated efficient charge transfer kinetics and provided abundant active sites for DA oxidation. The resulting SWCNT@PANI/SPCE sensor demonstrated excellent analytical performance, including high sensitivity, reproducibility, and a low detection limit. Owing to its robust electrochemical response, the sensor was further validated for practical DA detection in real samples, exhibiting reliable recovery and operational stability, underscoring its potential for biosensing applications.

Conflict of interest

There are no conflicts of interest associated with this work.

Funding declaration

The authors declare no competing financial interest.

Data availability

The data for this study are available from the corresponding author on request.

Author contributions

Deepak Kumar: Conceptualization, Methodology, Investigation, Writing- Original Draft; **Prashant Chechi:** Experimentation, and Schematic Preparation; **Dinesh Kumar:** Design and Validation**; Amika:** Resource, Editing, Validation.

Clinical trail

No clinical trials were conducted as part of this study.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

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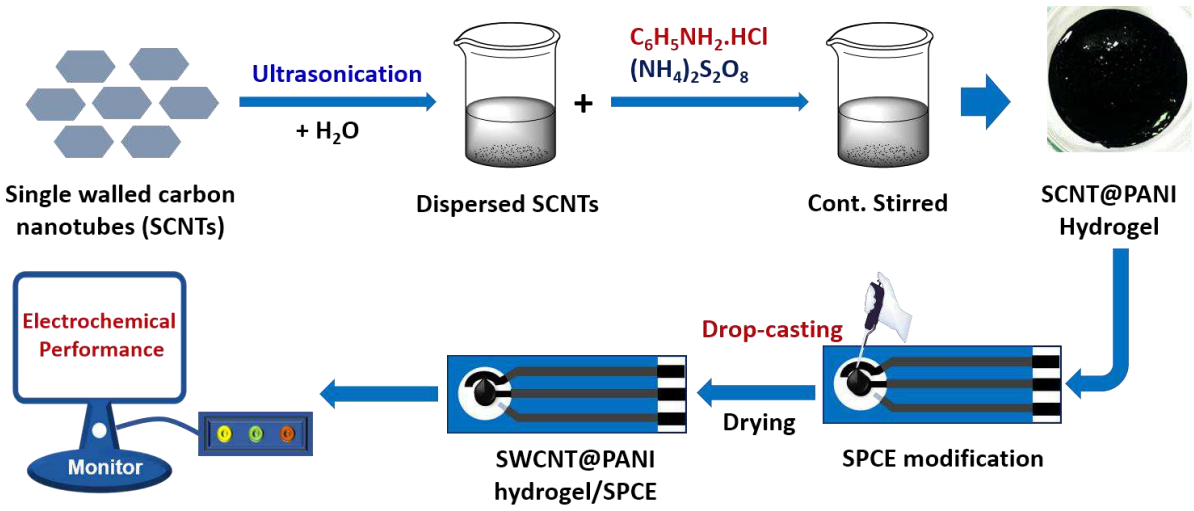
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List of Figures with Captions



Schematic 1. Schematic representation of SWCNT@PANI hydrogel modified screen-printed carbon electrode

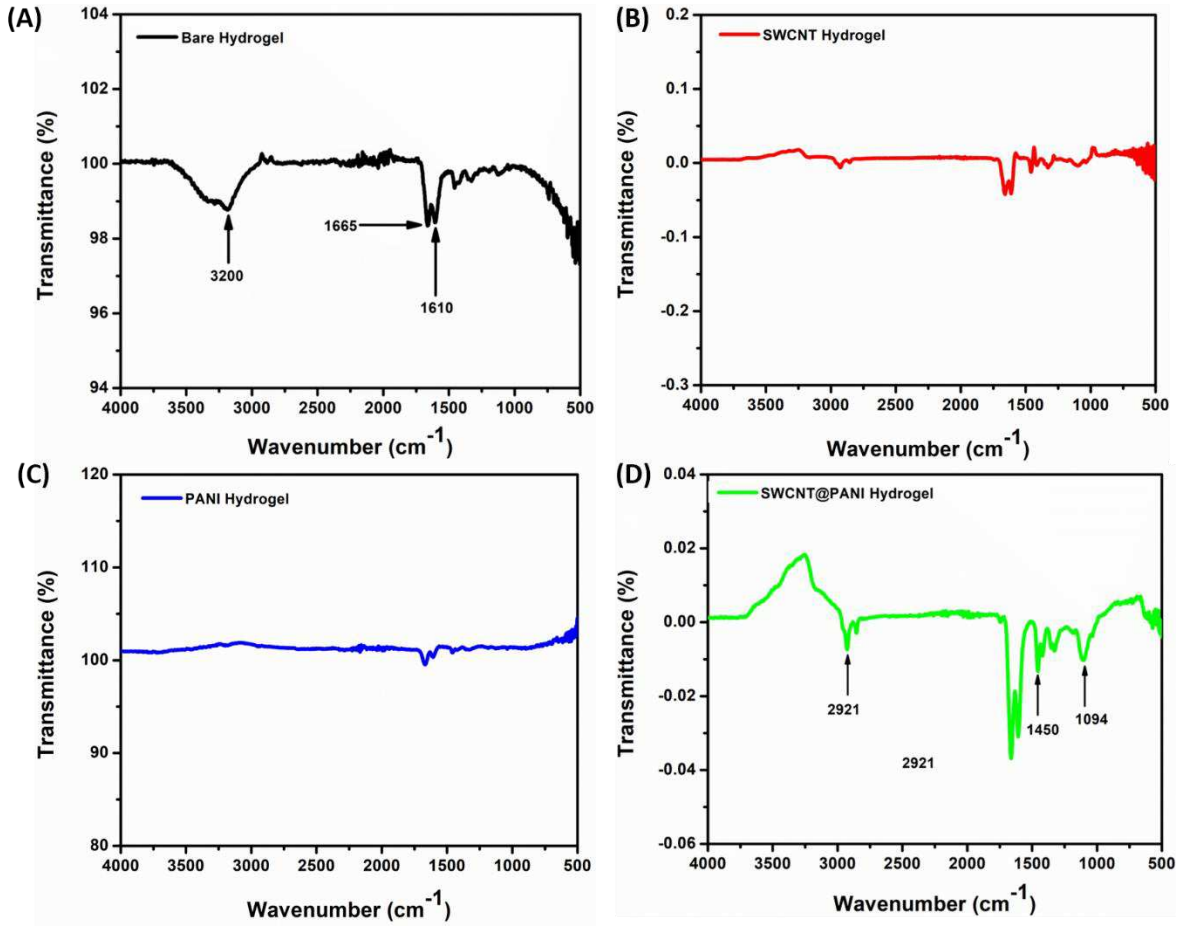


Figure 1. FTIR analysis of Bare hydrogel. SWCNT hydrogel, PANI hydrogel and SWCNT@PANI hydrogel.

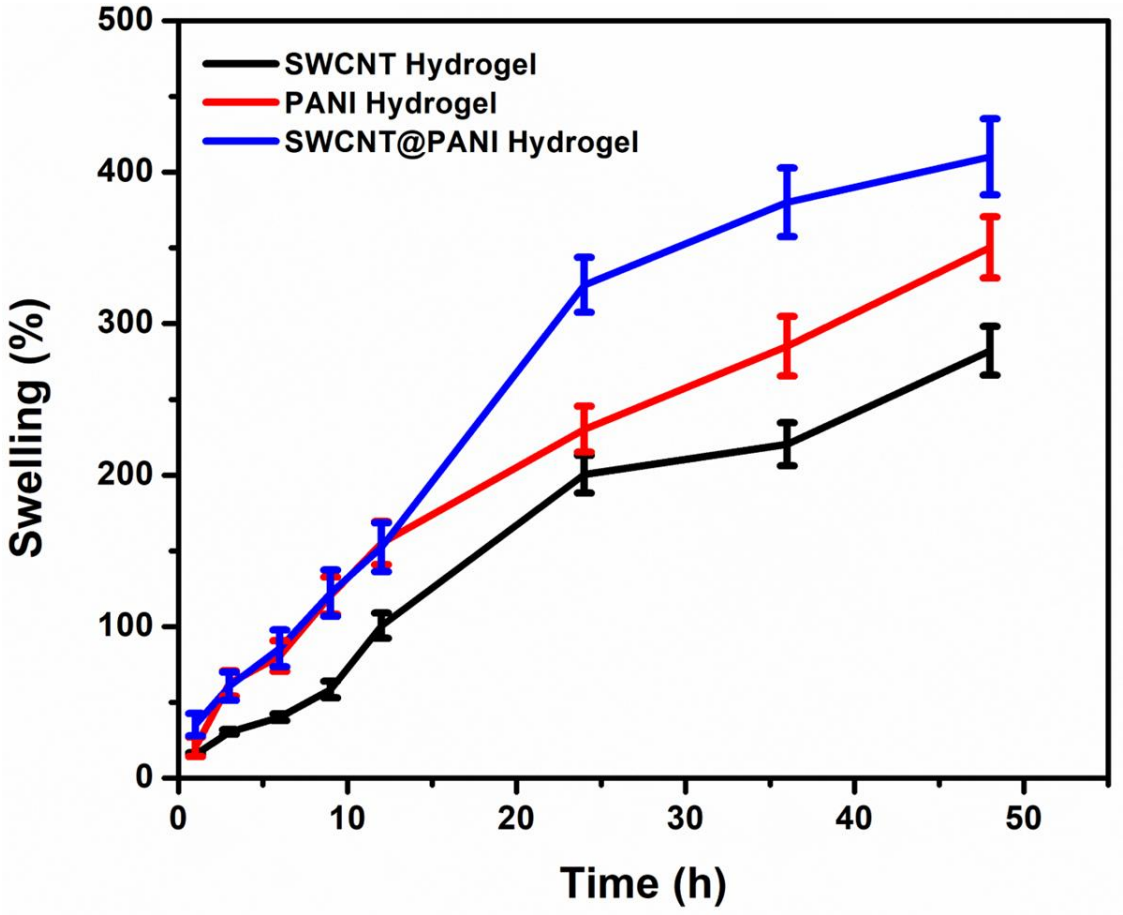


Figure 2: Percentage swelling ratios of SWCNT hydrogel, PANI hydrogel and SWCNT@PANI hydrogel.

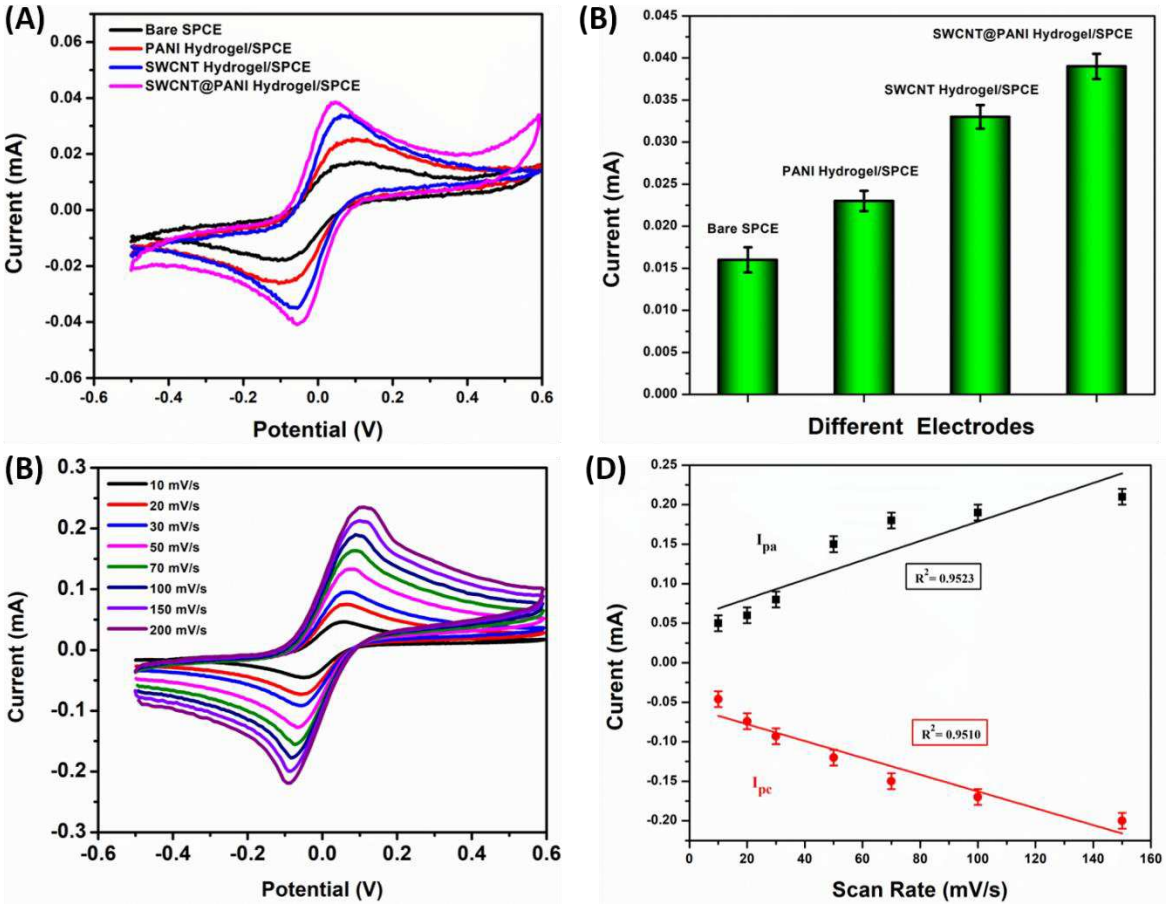


Figure 3. Electrochemical characterization of the fabricated electrodes. **(A)** CV of bare SPCE, PANI hydrogel/SPCE, SWCNT hydrogel/SPCE, and SWCNT@PANI hydrogel/SPCE. **(B)** CV responses of different electrodes. **(C)** SWCNT@PANI hydrogel/SPCE at different scan rates (10-200 mV/s). **(D)** Linear relationship between the anodic (Ipa) and cathodic (Ipc) peak currents and scan rate.

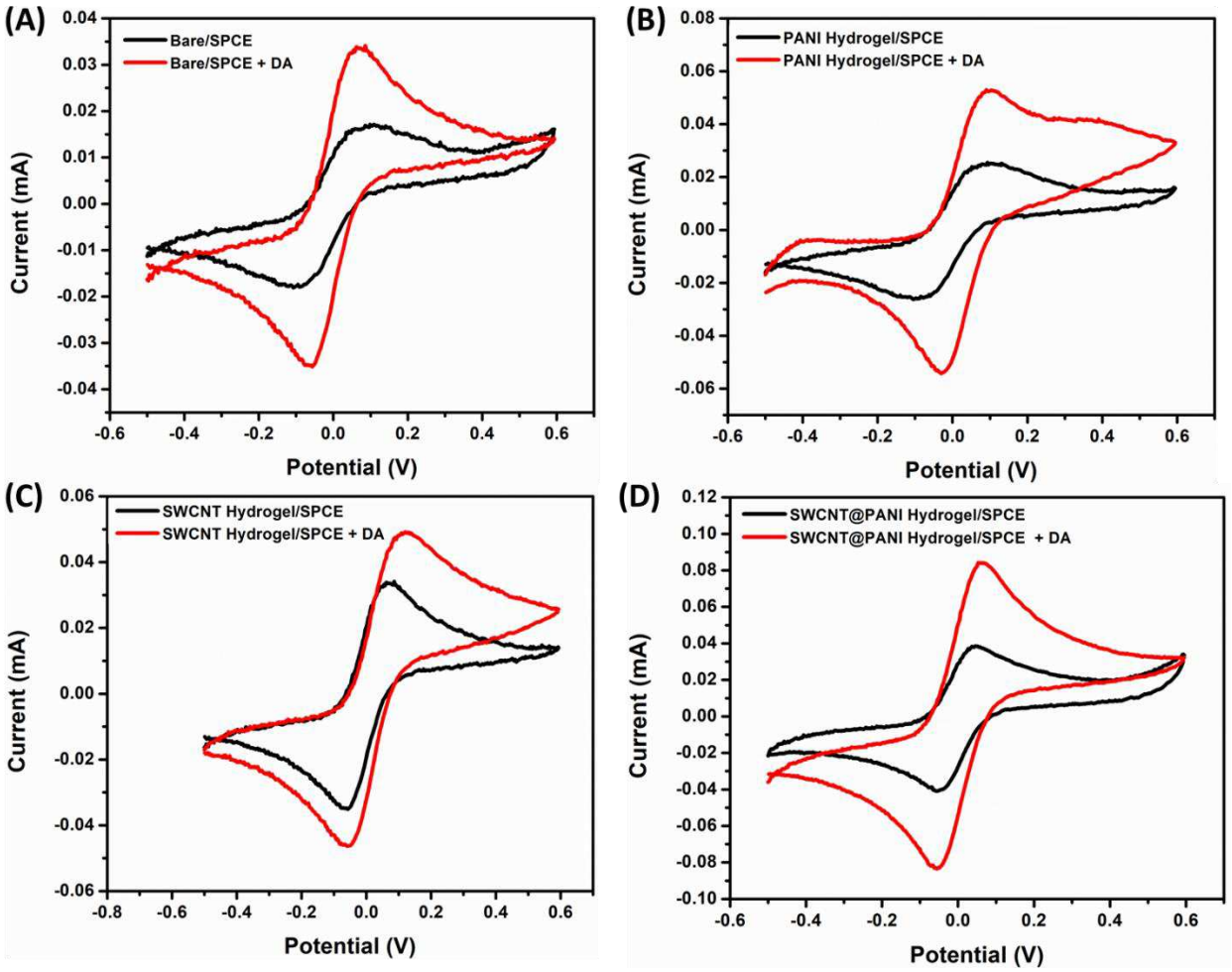


Figure 4. Cyclic voltammograms of different electrodes in the absence (black curve) and presence (red curve) of 100 µM DA. **(A)** SPCE, (B) PANI hydrogel/SPCE, (C) SWCNT hydrogel/SPCE, and (D) SWCNT@PANI hydrogel/SPCE at 50 mV/s.

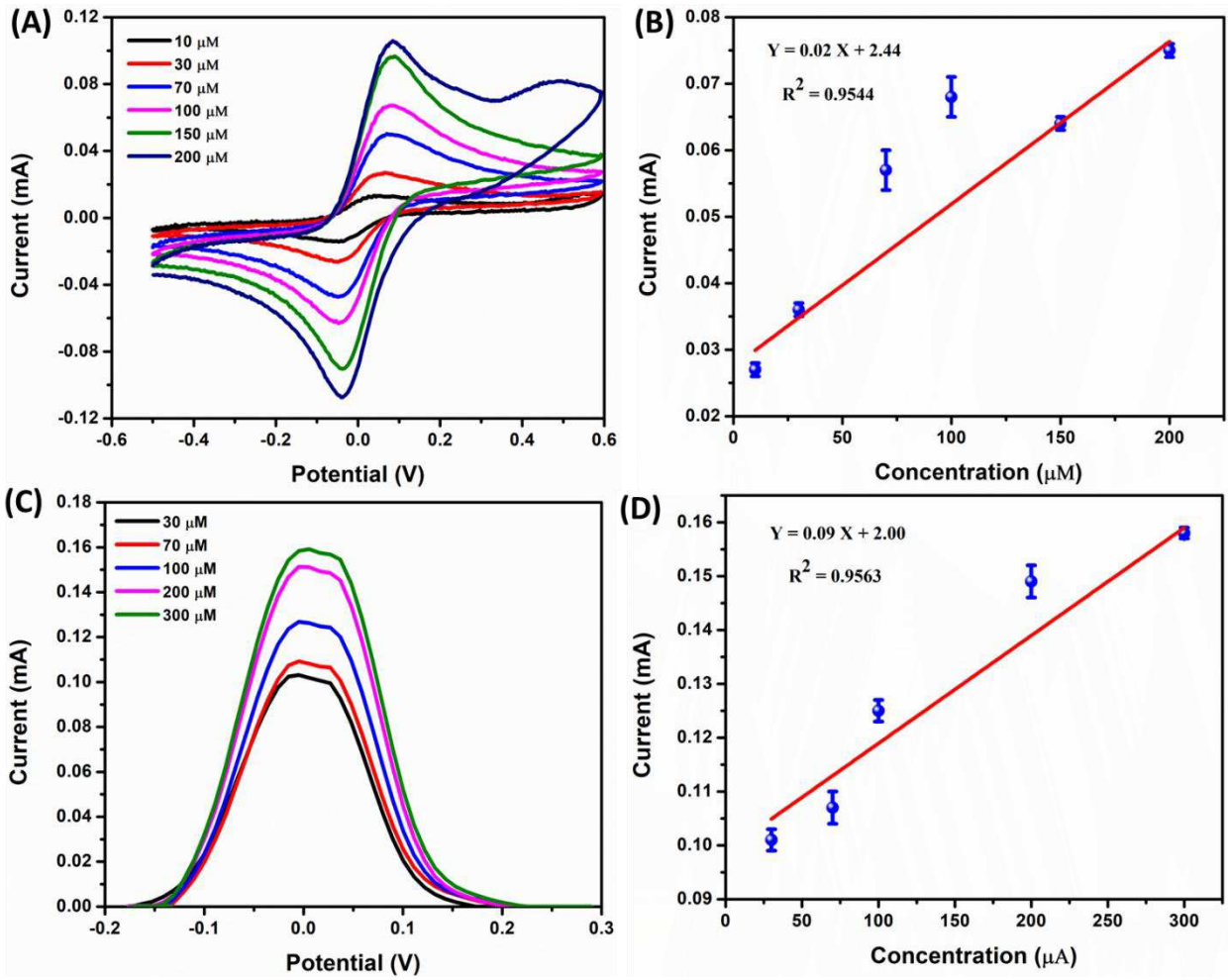


Figure 5. (**A**) CV and (C) DPV curve of SWCNT@PANI hydrogel/SPCE with various concentrations of DA (10, 30, 70, 100, 130, and 200 µM). (**B**) The linear calibration plots of peak (B) CV $Y = 0.02X_{\mathrm{DA}}\ (\mu\mathrm{M}) + 2.24; R^2 = 0.95]$ and (D) DPV $Y = 0.009X_{\mathrm{DA}}\ (\mu\mathrm{M}) + 2.00; R^2 = 0.95]$ depicting an increase in current response as a function of DA concentrations.

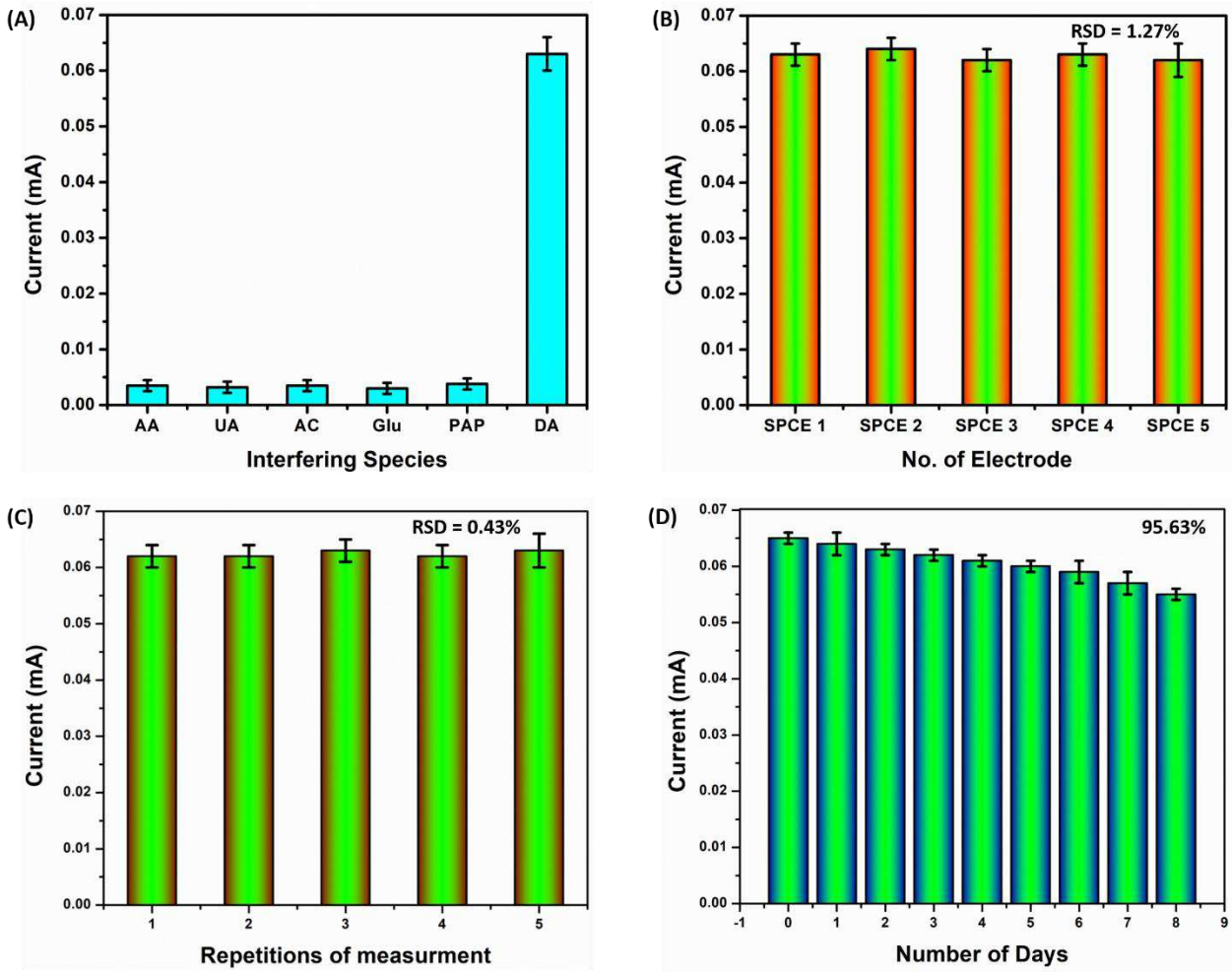


Figure 6. (A) Selectivity studies of SWCNT@PANI hydrogel/SPCE towards DA over various interfering species. **(B)** Reproducibility, **(C)** Selectivity, and **(D)** Stability plots of fabricated identical sensors against 50 µM DA at the surface of SWCNT@PANI hydrogel/SPCE.

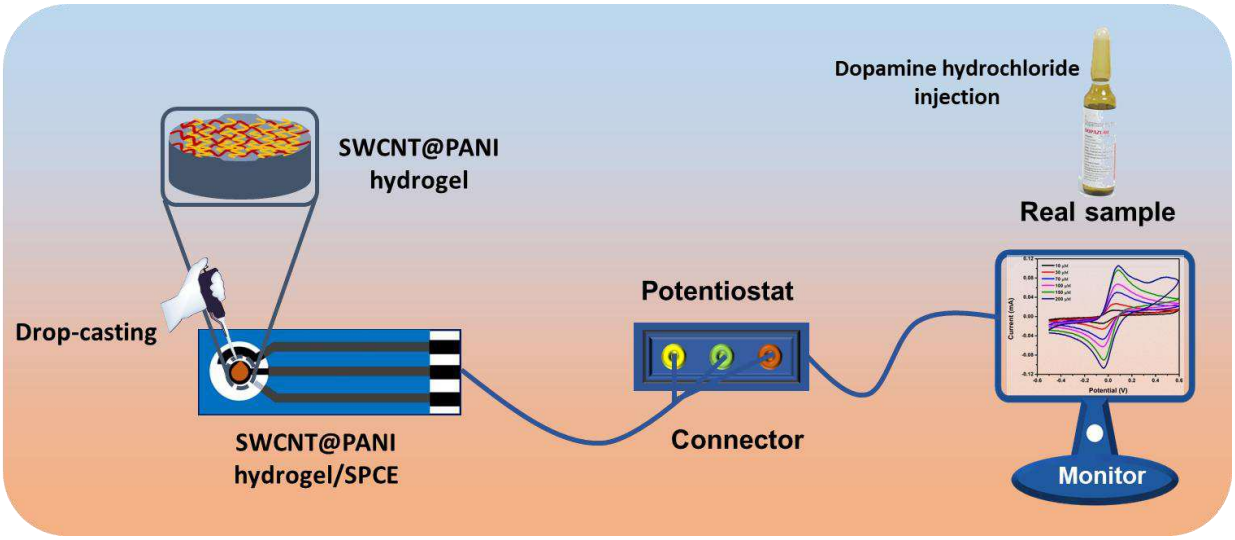
Electrode Materials	Method	Linear Range (µM)	LOD (µM)	Ref.
MWCNTs/ZIF-L/CPE	CV	0.001-900	0.007	[29]
AD/PGE	CV/ESI	10-0.1	0.032	[30]
ZIF- 8/CNTs/GCE	CV	0.1-400	0.04	[31]
MWCNTs-βCD-rGO/SPCE	DPV	0.25-16	0.08	[32]
Cu-MOF-CN/GCE	CV/DPV	0.5-100	0.13	[33]
Nb_2CTx/AuNPs/AgNPs	CV/DPV	32.64-424.33	8.98	[34]
AgNPs/f-MWCNT/Poly(L-Cyc)/PGE	DPV	10-1000	0.068	[35]
COF/MWCNT electrode	DPV	0.3-500	0.0316	[36]
Au@Ni-MOF (Ni(CH3CO2)2)/SPCE	DPV	0.1-2000	0.5	[37]
$CoMn_2O_4$/CQDs/CPE	CV	2.0-1000	0.087	[38]
Mo-ZIF-8@ZIF-67	DPV	50-300	0.55	[39]
SWCNT@PANI hydrogel/SPCE	CV/DPV	10-300	0.24	**This work**

Table 1. Comparison different types of biosensors for dopamine detection.

Content (μM)	Found (μM)	Recovery (%)	RDS (%)
5.00	5.26	105.22	1.06
10.0	9.62	96.20	0.72
20.0	19.02	95.10	0.65
30.0	29.24	97.46	0.54

Table 2. Real sample analysis of dopamine hydrochloride injection using SWCNT@PANI hydrogel electrode.

Graphical Abstract



Graphical Abstact: SWCNT@PANI hydrogel electrode for electrochemical detection of dopamine.

Supplementary Files

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