

Sustainable Development of Coconut Shell-Derived Graphene Quantum Dot-Integrated Conductive Hydrogels for Electroencephalography (EEG) Applications

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1 **Sustainable Development of Coconut Shell-Derived Graphene Quantum Dot-Integrated**
2 **Conductive Hydrogels for Electroencephalography (EEG) Applications**

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25 Abstract

26 Conventional conductive gels for electroencephalography (EEG) frequently face limitations including
27 rapid dehydration, impedance drift during prolonged recordings, and reliance on non-renewable,
28 petroleum-derived components. To overcome these challenges, this study presents an eco-friendly and
29 high-performance conductive hydrogel formulated by embedding waste coconut shell-derived graphene
30 quantum dots (GQDs) into a poly(vinyl alcohol) (PVA)–Carbopol polymeric network. Ultra-small, highly
31 crystalline GQDs (mean diameter: 3.18 ± 0.74 nm; graphitic d -spacing: 0.21 nm) adorned with abundant
32 hydrophilic oxygenated functionalities were synthesized via sequential carbonization, acid oxidation, and
33 hydrothermal processing. Physicochemical and spectroscopic evaluations (TEM, FESEM-EDX, XRD,
34 Raman, FTIR, XPS, and DLS) demonstrated few-layer graphitic nanostructures with remarkable colloidal
35 stability (zeta potential: -32.4 mV) and homogeneous dispersion within the hydrogel. Incorporation of
36 the biomass-derived GQDs established continuous 3D conductive pathways, achieving an electrical
37 percolation threshold and optimum conductivity of $1.6 \times 10^{-2} \text{ S cm}^{-1}$ at 2.0 wt% nanofiller loading,
38 alongside a low charge-transfer resistance ($R_{ct} \approx 36.72 \Omega$). Rheological profiling revealed pronounced
39 shear-thinning flow behaviour, dominant solid-like elasticity ($G' > G''$), high critical strain endurance
40 (45.6%), rapid thixotropic structural recovery ($\sim 92\%$), and physiological thermal stability ($T_{gel-sol} \approx 45^{\circ}\text{C}$).
41 The hydrogel exhibited robust electromechanical durability, retaining 80–85% of its baseline electrical
42 conductivity after 10,000 cyclic bending deformations. Furthermore, *in vitro* cytocompatibility testing via
43 MTT assay on human HaCaT keratinocytes confirmed non-cytotoxic behaviour ($>70\%$ cell viability
44 across all tested concentrations; $\text{IC}_{50} > 10\%$ v/v), markedly superior to commercial reference gels. This
45 work underscores a sustainable agricultural waste-valorization pathway to produce skin-conformable,
46 durable, and biocompatible bioelectronic hydrogels for long-term neurophysiological monitoring and
47 wearable healthcare diagnostics.

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54 **Keywords:** Graphene quantum dots; Conductive hydrogel; Electroencephalography (EEG); Biomass
55 valorization; Waste coconut shell; Bioelectronics; Cytocompatibility.

56 **1. Introduction**

57 Electroencephalography (EEG) is one of the most widely employed non-invasive neurophysiological
58 techniques for monitoring the electrical activity of the human brain. Owing to its excellent temporal
59 resolution, portability, and relatively low cost, EEG has become indispensable in the diagnosis and
60 management of neurological disorders, including epilepsy, sleep disorders, Parkinson's disease,
61 Alzheimer's disease, traumatic brain injury, and psychiatric illnesses [1]. Beyond clinical diagnostics,
62 EEG has gained increasing importance in cognitive neuroscience, neurorehabilitation, brain-computer
63 interfaces (BCIs), wearable healthcare systems, and human-machine interaction [2]. The accuracy and
64 reliability of EEG recordings largely depend on the quality of the electrical contact between the recording
65 electrode and the scalp, making conductive electrode gels a critical component of modern
66 neurophysiological monitoring systems [3,4].

67 Commercial EEG conductive gels are generally formulated using electrolytes, synthetic polymers,
68 humectants, and preservatives to reduce the electrode–skin impedance and facilitate efficient ionic
69 conduction [4,5]. Although these formulations provide satisfactory signal acquisition during short-term
70 monitoring, they exhibit several inherent limitations, including dehydration during prolonged recording,
71 gradual increases in impedance, skin irritation, difficult post-recording cleaning, and limited
72 environmental sustainability due to their dependence on petroleum-derived ingredients [3,6].
73 Furthermore, prolonged dehydration of the gel reduces ionic mobility at the electrode interface, resulting
74 in baseline drift, motion artifacts, and deterioration of signal quality during long-term EEG monitoring.
75 These shortcomings have stimulated extensive research into alternative conductive biomaterials capable
76 of maintaining hydration, improving electrical conductivity, and enhancing user comfort while reducing
77 environmental impact [7].

78 Conductive hydrogels have recently emerged as promising soft bioelectronic materials because they
79 combine the high-water content and flexibility of polymeric hydrogels with electrically conductive
80 nanomaterials [8]. Their three-dimensional porous architecture enables efficient ion transport, intimate
81 skin conformity, excellent mechanical flexibility, and reduced interfacial impedance, making them
82 particularly attractive for wearable biosensors and electrophysiological monitoring [9]. Hydrogels
83 formulated using poly(vinyl alcohol) (PVA), Carbopol, polyacrylamide, polyethylene glycol, alginate, and
84 gelatin have demonstrated excellent physicochemical stability and biocompatibility [10]. The
85 incorporation of conductive nanomaterials further enhances charge transport while preserving the
86 desirable mechanical properties required for prolonged skin contact. Consequently, conductive hydrogels
87 are increasingly being investigated as next-generation materials for ECG, EMG, EEG, flexible electronics,
88 neural interfaces, and implantable biosensors [11].

89 Among various conductive nanomaterials, graphene and its derivatives have attracted exceptional
90 attention because of their extraordinary electrical conductivity, high carrier mobility, large specific surface
91 area, excellent mechanical strength, and outstanding chemical stability [12,13]. Reduced graphene oxide,
92 graphene nanoplatelets, carbon nanotubes, graphene oxide, carbon dots, and graphene quantum dots
93 (GQDs) have been widely explored for applications ranging from energy storage and catalysis to drug
94 delivery, bioimaging, biosensing, and tissue engineering [14]. Among these materials, graphene quantum
95 dots represent a unique class of zero-dimensional carbon nanomaterials that combine the exceptional
96 electrical properties of graphene with quantum confinement and edge effects [15,16]. Their nanoscale
97 dimensions (typically below 10 nm), excellent aqueous dispersibility, abundant oxygen-containing
98 functional groups, tunable photoluminescence, and low cytotoxicity make them particularly suitable for
99 biomedical and bioelectronic applications [17].

100 The abundant hydroxyl, carboxyl, carbonyl, and epoxy functional groups present on graphene quantum
101 dots facilitate homogeneous dispersion within hydrophilic polymer matrices and promote strong
102 interfacial interactions through hydrogen bonding [18]. Consequently, GQDs can establish efficient
103 conductive pathways within hydrogel networks while simultaneously improving water retention,
104 mechanical integrity, electrochemical stability, and biocompatibility. In addition to their excellent
105 electrical characteristics, GQDs exhibit intrinsic fluorescence, favourable colloidal stability, chemical
106 inertness, and low toxicity, which have enabled their application in bioimaging, drug delivery, biosensing,
107 phototherapy, antimicrobial systems, and tissue engineering [19]. Recent advances further demonstrate
108 their potential for flexible electronics and wearable biomedical devices requiring highly conductive yet
109 mechanically compliant materials.

110 In recent years, sustainable synthesis strategies have become increasingly important owing to growing
111 concerns regarding environmental pollution, depletion of fossil resources, and waste management [11].
112 Biomass-derived carbon nanomaterials have emerged as environmentally benign alternatives to
113 conventional synthetic carbon precursors because they utilize renewable resources, reduce production
114 costs, minimize hazardous waste generation, and support circular economy principles [18]. Agricultural
115 residues, food waste, fruit peels, crop residues, coffee grounds, rice husks, sugarcane bagasse, bamboo,
116 leaves, and various lignocellulosic materials have successfully been employed as carbon precursors for
117 producing carbon dots and graphene quantum dots through hydrothermal, pyrolytic, microwave-assisted,
118 and chemical oxidation methods [20]. Biomass-derived GQDs exhibit physicochemical properties
119 comparable to conventionally synthesized GQDs while offering significantly improved sustainability and
120 economic feasibility.

121 Among the numerous agricultural wastes available worldwide, coconut shell represents an exceptionally
122 attractive precursor for graphene quantum dot synthesis because of its high fixed-carbon content, excellent

thermal stability, low ash content, and widespread availability [16]. Millions of tons of coconut shells are generated annually by food-processing industries and domestic consumption, with a substantial proportion being discarded or openly burned, thereby contributing to environmental pollution and greenhouse gas emissions. Converting waste coconut shells into high-value graphene quantum dots provides an effective strategy for agricultural waste valorization while simultaneously producing advanced functional nanomaterials for biomedical applications [17]. Moreover, the intrinsic graphitic carbon structure present in coconut shell facilitates the formation of highly crystalline graphene-based nanostructures with desirable electrical and optical properties after appropriate thermal and chemical processing [18].

Although biomass-derived graphene quantum dots have been extensively investigated for bioimaging, biosensing, photocatalysis, environmental remediation, and drug delivery, their application as conductive nanofillers in EEG electrode gels remains largely unexplored [21]. Most reported conductive EEG gels continue to rely on commercial graphene derivatives, metallic nanoparticles, or synthetic conductive polymers, which often involve relatively expensive fabrication processes and limited sustainability [22,23]. Furthermore, systematic investigations correlating biomass-derived graphene quantum dots with hydrogel conductivity, electrode–skin impedance, rheological behaviour, hydration performance, and EEG signal quality are scarce. This knowledge gap presents an important opportunity for developing environmentally sustainable conductive biomaterials specifically designed for long-term neurophysiological monitoring.

In the present study, graphene quantum dots were synthesized from waste coconut shells using a controlled carbonization, acid oxidation, and hydrothermal process and subsequently incorporated into a PVA–Carbopol conductive hydrogel to develop a sustainable EEG conductive gel. The synthesized graphene quantum dots were comprehensively characterized using transmission electron microscopy (TEM), X-ray diffraction (XRD), Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), ultraviolet-visible (UV–Vis) spectroscopy, photoluminescence spectroscopy, dynamic light scattering (DLS), and zeta potential measurements. The prepared conductive hydrogels were evaluated for physicochemical characteristics, rheological behaviour, electrical conductivity, electrochemical impedance, water-retention capacity, and storage stability. Furthermore, the *in vitro* cytocompatibility of the hydrogel formulations was systematically assessed against human immortalized keratinocytes (HaCaT) using MTT metabolic viability assays and phase-contrast morphological evaluations to verify their safety for skin-contact applications. It is hypothesized that the incorporation of biomass-derived graphene quantum dots will significantly enhance electrical conductivity and reduce electrode–skin impedance while maintaining excellent biocompatibility and long-term hydration. The proposed conductive hydrogel therefore represents a sustainable and high-

performance alternative to conventional EEG gels, simultaneously addressing challenges in biomedical materials development and agricultural waste utilization.

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161 **2. Materials and Methods**

162

163 Waste coconut shells were collected from local food processing vendors in West Bengal, India, thoroughly
164 washed with running tap water followed by deionized (DI) water to remove adhering impurities, and dried
165 before use as the carbon precursor for graphene quantum dot (GQD) synthesis. Poly(vinyl alcohol) (PVA;
166 molecular weight 85,000–124,000 Da; 99% hydrolyzed), Carbopol® 940, glycerol ($\geq 99.5\%$), citric acid
167 ($\geq 99.5\%$), sodium hydroxide (NaOH), hydrochloric acid (HCl), sulfuric acid (H₂SO₄), nitric acid (HNO₃),
168 hydrogen peroxide (H₂O₂), ethanol (99.9%), phosphate-buffered saline (PBS; pH 7.4), and dialysis
169 membranes (molecular weight cut-off 1000 Da) were purchased from Sigma-Aldrich (St. Louis, MO,
170 USA) unless otherwise stated. Ultrapure deionized water (18.2 M Ω ·cm) obtained from a Milli-Q
171 purification system was used throughout all experiments. For biological evaluation, Dulbecco's Modified
172 Eagle Medium (DMEM), fetal bovine serum (FBS), penicillin–streptomycin solution, trypsin–EDTA,
173 phosphate-buffered saline (PBS), and the MTT cell viability assay kit was procured from Gibco (Thermo
174 Fisher Scientific, USA). Commercial Ag/AgCl EEG electrodes and a commercially available EEG
175 conductive gel used as the reference formulation were obtained from a certified biomedical equipment
176 supplier. Electrochemical impedance measurements were performed using a potentiostat/galvanostat
177 (Autolab PGSTAT204, Metrohm, The Netherlands).

178

179 **2.1. Preparation of Waste Coconut Shell-Derived Graphene Quantum Dots (GQDs)**

180 Waste coconut shells were thoroughly washed with tap water followed by deionized (DI) water to remove
181 adhering dirt and organic contaminants. The cleaned shells were dried in a hot air oven at 80 °C for 24 h,
182 crushed into small pieces, and ground into a fine powder using a laboratory grinder. The powder was
183 sieved through a 100-mesh sieve to obtain a uniform particle size.

184 The coconut shell powder was carbonized in a muffle furnace at 650 °C for 2 h under a limited oxygen
185 atmosphere with a heating rate of 10 °C min⁻¹. After cooling to room temperature, the obtained biochar
186 was finely pulverized.

187 To synthesize graphene quantum dots, 2 g of the carbonized powder was dispersed in a mixed acid solution
188 containing concentrated H₂SO₄: HNO₃ (3:1, v/v) and sonicated for 30 min. The suspension was then
189 refluxed at 90 °C for 12 h under continuous magnetic stirring to promote oxidative cutting of graphitic
190 domains into nanoscale graphene fragments [24].

Following oxidation, the reaction mixture was slowly poured into ice-cold deionized water and neutralized with 1 M NaOH to pH 7.0. The dispersion was centrifuged at 10,000 rpm for 20 min to remove larger carbon particles. The collected supernatant was transferred into a 1000 Da molecular weight cut-off dialysis membrane and dialyzed against deionized water for 48 h, replacing the water every 6 h to remove residual acids and impurities [25].

The purified solution was subsequently transferred into a 100 mL Teflon-lined stainless-steel autoclave and hydrothermally treated at 180 °C for 8 h. After naturally cooling to room temperature, the GQD suspension was filtered through a 0.22 µm membrane filter and freeze-dried to obtain graphene quantum dot powder, which was stored at 4 °C until further use.

2.2. Preparation of GQD-Incorporated Conductive EEG Hydrogel

The GQD-incorporated EEG hydrogel was synthesized via a solution-casting technique. First, a 5% (w/v) poly(vinyl alcohol) (PVA) aqueous solution was prepared by heating deionized water to 90 °C under continuous stirring until fully dissolved and clear. In a separate container, 1.0% (w/v) Carbopol® 940 was dispersed in deionized water and left to hydrate overnight (12 h) at room temperature.

The polymer components were then combined by slowly pouring the PVA solution into the hydrated Carbopol dispersion while stirring at 600 rpm. Next, glycerol (10% w/v) was introduced as a plasticizer and humectant to enhance flexibility, water retention, and skin adhesion. Gelation was triggered by adjusting the system's pH to 6.8–7.0 using 0.5 M NaOH [26].

To incorporate the nanomaterial, a known quantity of graphene quantum dots was dispersed in 10 mL of deionized water via probe sonication (200 W, 20 kHz) for 20 min to break up aggregates. This GQD suspension was dripped into the hydrogel matrix under stirring for 1 h, followed by a final 10-minute sonication bath to ensure uniform distribution. Lastly, the mixture was degassed under vacuum for 30 min to remove trapped air bubbles, transferred to sterile polypropylene containers, and stored at 4 °C prior to EEG characterization.

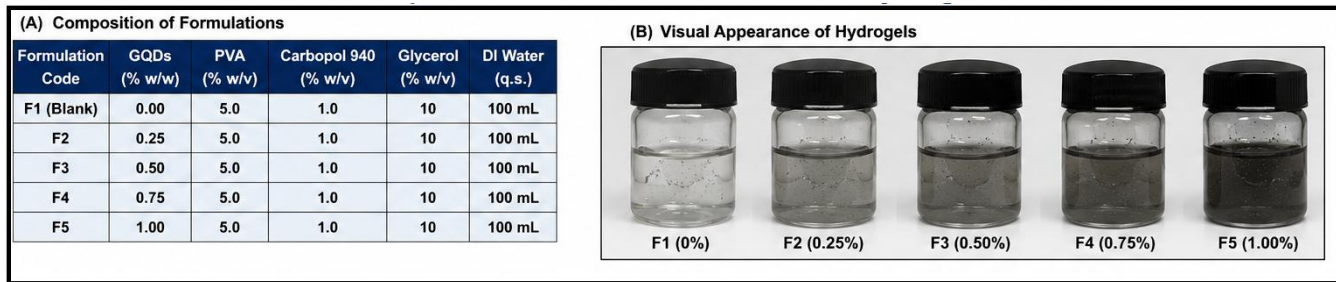


Figure: 1 Composition and visual appearance of formulations.

2.3. Characterization of Waste Coconut Shell-Derived Graphene Quantum Dots (GQDs)

2.3.1. Transmission Electron Microscopy (TEM)

The morphology, particle size, and lattice structure of the synthesized graphene quantum dots (GQDs) were examined using transmission electron microscopy (TEM; JEOL JEM-2100, Japan) operated at an accelerating voltage of 200 kV. A dilute aqueous dispersion of GQDs (0.01 mg mL^{-1}) was ultrasonicated for 15 min to obtain a homogeneous suspension. Approximately 10 μL of the dispersion was drop-cast onto a carbon-coated copper grid (300 mesh) and allowed to dry under ambient conditions before analysis. The average particle size distribution was determined by measuring at least 200 nanoparticles using ImageJ software.

2.3.2. Field Emission Scanning Electron Microscopy (FESEM) and Energy-Dispersive X-ray Spectroscopy (EDX)

The surface morphology of the freeze-dried conductive hydrogel and carbonized coconut shell was investigated using field emission scanning electron microscopy (FESEM; ZEISS Sigma 300, Germany). Samples were freeze-dried for 48 h, mounted on aluminium stubs using conductive carbon tape, and sputter-coated with a thin gold layer ($\approx 5 \text{ nm}$) prior to imaging. Micrographs were recorded at different magnifications to evaluate the porous architecture and distribution of GQDs within the hydrogel matrix. The elemental composition of the synthesized GQDs was determined using an energy-dispersive X-ray spectroscopy (EDX) detector attached to the FESEM instrument. Elemental mapping was also performed to assess the homogeneous distribution of carbon and oxygen within the hydrogel network.

2.3.3. X-ray Diffraction (XRD)

The crystalline characteristics of the synthesized GQDs were analyzed using an X-ray diffractometer (Bruker D8 Advance, Germany) equipped with $\text{Cu-K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) operating at 40 kV and 40 mA. Diffraction patterns were recorded over a 2θ range of 5° – 80° at a scanning rate of 2° min^{-1} . The average crystallite size was estimated using the Scherrer equation.

2.3.4. Raman Spectroscopy

Raman spectra were obtained using a Renishaw in Via Raman microscope equipped with a 532 nm laser. Spectra were recorded over the range of 500 – 3500 cm^{-1} with an exposure time of 10 s. The characteristic D-band and G-band were used to evaluate the graphitic structure and degree of defects in the synthesized GQDs. The intensity ratio ($I_{\text{D}}/I_{\text{G}}$) was calculated to assess structural disorder.

256 **2.3.5. Fourier Transform Infrared Spectroscopy (FTIR)**

257 The surface functional groups of carbonized coconut shell, graphene quantum dots, blank hydrogel, and
258 GQD-loaded hydrogel were characterized using Fourier transform infrared spectroscopy (Thermo
259 Scientific Nicolet iS50, USA). Freeze-dried samples were mixed with potassium bromide (KBr),
260 compressed into pellets, and scanned over the spectral range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1}
261 with 32 scans per sample.
262

263 **2.3.6. X-ray Photoelectron Spectroscopy (XPS)**

264 The surface elemental composition and chemical bonding states of graphene quantum dots were analyzed
265 using an X-ray photoelectron spectrometer (Thermo Scientific K-Alpha, USA) employing
266 monochromatic Al-K α radiation (1486.6 eV). High-resolution spectra for C1s and O1s were deconvoluted
267 using CasaXPS software to identify the various oxygen-containing functional groups present on the GQD
268 surface.
269

270 **2.3.7. Dynamic Light Scattering (DLS) and Zeta Potential**

271 The hydrodynamic particle size distribution and zeta potential of GQDs dispersed in deionized water were
272 measured using a Zetasizer Nano ZS (Malvern Panalytical, UK). Samples were filtered through a 0.22 μm
273 membrane filter before analysis. Measurements were carried out at 25 ± 1 $^{\circ}\text{C}$, and the reported values
274 represent the average of three independent determinations.
275

276 **2.4. Characterization of GQD-Incorporated Conductive EEG Hydrogel**

277 **2.4.1. Visual Appearance and Homogeneity**

278 The prepared conductive hydrogels were visually examined for color, transparency, phase separation,
279 presence of air bubbles, and overall homogeneity under normal laboratory illumination. Homogeneity was
280 further assessed by gently rubbing a small quantity of gel between two glass slides to detect the presence
281 of particulate matter or agglomerates.
282

283 **2.4.2. pH Measurement**

284 The pH of the hydrogel formulations was measured using a calibrated digital pH meter (Mettler Toledo,
285 Switzerland) at 25 ± 2 $^{\circ}\text{C}$. Approximately 10 g of hydrogel was dispersed in 50 mL of deionized water
286 and equilibrated for 30 min before measurement. All measurements were performed in triplicate.
287

288 **2.4.3. Rheological Analysis**

289 The rheological properties of the conductive hydrogels were evaluated using a rotational rheometer
290 (Anton Paar MCR 302, Austria) equipped with a parallel plate geometry (25 mm diameter). Flow curves

were recorded over a shear rate range of 0.1–100 s⁻¹ at 25 °C to determine viscosity, shear-thinning behavior, and viscoelastic properties.

2.4.4. Electrical Conductivity

The electrical conductivity of the hydrogel formulations was determined using a digital conductivity meter (Mettler Toledo Seven Compact, Switzerland). Measurements were performed at 25 ± 1 °C, and conductivity values were expressed in mS cm⁻¹. Each formulation was analyzed in triplicate.

2.4.5. *In-vitro* Cytotoxicity Evaluation of EEG Hydrogel Using HaCaT Keratinocytes (MTT Assay)

Materials

Human immortalized keratinocyte cell line (HaCaT), Dulbecco's Modified Eagle Medium (DMEM), fetal bovine serum (FBS), penicillin–streptomycin solution, phosphate-buffered saline (PBS), MTT reagent [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide], dimethyl sulfoxide (DMSO), and EEG hydrogel formulations were used.

Cell Culture

HaCaT keratinocytes were cultured in DMEM supplemented with 10% (v/v) FBS and 1% penicillin–streptomycin solution. Cells were maintained at 37°C in a humidified atmosphere containing 5% CO₂. The culture medium was replaced every 2–3 days until cells reached approximately 80–90% confluency.

Preparation of Hydrogel Extracts

Hydrogel extracts were prepared according to ISO 10993-5 guidelines. Briefly, 1 g of each hydrogel formulation was immersed in 10 mL of serum-free DMEM and incubated at 37°C for 24 h under gentle shaking. The extracts were subsequently filtered through a 0.22 µm membrane filter to remove particulate matter and diluted to obtain concentrations equivalent to 0.1%, 0.5%, 1%, 2.5%, and 5% (v/v).

MTT Cytotoxicity Assay

HaCaT cells were seeded into 96-well plates at a density of 1 × 10⁴ cells/well and allowed to attach for 24 h. The culture medium was then replaced with 100 µL of hydrogel extract solutions at different concentrations. Untreated cells served as the negative control.

After 24 h incubation, the treatment medium was removed and 100 µL of MTT solution (0.5 mg/mL in serum-free DMEM) was added to each well. The plates were incubated for an additional 4 h at 37°C to allow the formation of purple formazan crystals by metabolically active cells.

Following incubation, the MTT solution was discarded, and 100 µL of DMSO was added to dissolve the formazan crystals. The absorbance was measured at 570 nm using a microplate reader.

Calculation of Cell Viability

$$\text{Cell Viability (\%)} = \frac{A_{\text{sample}}}{A_{\text{control}}} \times 100$$

.....Equation: 1

where:

A_{sample} = absorbance of treated cells

A_{control} = absorbance of untreated control cells

Morphological Assessment

To evaluate potential morphological changes, HaCaT cells were cultured in 6-well plates and treated with hydrogel extracts (2.5%, v/v) for 24 h. Cell morphology was observed under an inverted phase-contrast microscope (Olympus IX73, Japan) at 100× magnification and representative images were captured.

Statistical Analysis

All experiments were performed in triplicate ($n = 3$), and results were expressed as mean $\pm$ standard deviation (SD). Statistical significance was determined using one-way ANOVA followed by Dunnett's post hoc test. Differences were considered statistically significant at $p < 0.05$.

3. Result and Discussion

3.1 Transmission Electron Microscopy (TEM) Analysis of Waste Coconut Shell-Derived Graphene Quantum Dots (GQDs)

Transmission electron microscopy (TEM) was employed to investigate the morphology, particle size distribution, crystallinity, and lattice structure of the graphene quantum dots (GQDs) synthesized from waste coconut shell. Representative TEM micrographs are presented in Figure 2A–E.

The low-magnification TEM image (Figure 2A) revealed that the synthesized GQDs were well-dispersed with a predominantly quasi-spherical morphology, exhibiting minimal agglomeration throughout the sample. The uniform dispersion indicates that the oxidation and hydrothermal synthesis process effectively produced nanosized graphene domains while preventing extensive particle aggregation [27]. Such homogeneous dispersion is advantageous for conductive hydrogel fabrication, as uniformly distributed nanofillers facilitate the formation of continuous conductive pathways and improve the overall electrochemical performance of the hydrogel matrix [28].

Higher-magnification TEM analysis (Figure 2B) clearly demonstrated the presence of individual graphene quantum dots with smooth boundaries and narrow size distribution. Statistical analysis of approximately 200 nanoparticles (Figure 2C) showed that the synthesized GQDs possessed an average particle diameter

357 of 3.18 ± 0.74 nm, with particle sizes ranging from approximately 1.6 to 5.3 nm. The Gaussian size
358 distribution indicates excellent control over particle formation during hydrothermal synthesis.
359 Nanoparticles within this size range satisfy the dimensional characteristics of graphene quantum dots (<10
360 nm) and provide a high surface-to-volume ratio, which is beneficial for improving electrical conductivity,
361 interfacial interactions with polymer chains, and homogeneous dispersion within hydrophilic conductive
362 hydrogels [28].

363 The high-resolution TEM (HRTEM) image (Figure 2D) exhibited distinct and well-defined lattice fringes,
364 confirming the crystalline nature of the synthesized nanomaterials. The measured interplanar lattice
365 spacing (d-spacing) was approximately 0.21 nm, corresponding to the (100) crystallographic plane of
366 graphitic carbon. The presence of clear lattice fringes demonstrates that the hydrothermal oxidation
367 process successfully preserved the graphitic framework while reducing the particle size to the quantum-
368 dot scale. Such highly ordered graphitic domains are expected to facilitate rapid electron transport, thereby
369 enhancing the electrical conductivity of the conductive EEG gel.

370 Selected area electron diffraction (SAED) analysis (Figure 1E) further confirmed the crystalline structure
371 of the synthesized GQDs. The diffraction pattern exhibited well-defined concentric diffraction rings,
372 indexed to the (002), (100), and (110) planes of graphitic carbon. The appearance of multiple diffraction
373 rings suggests that the synthesized GQDs possess a polycrystalline graphitic structure with high
374 crystallinity. The coexistence of graphitic lattice fringes and characteristic SAED rings demonstrates
375 successful conversion of waste coconut shell into crystalline graphene quantum dots through the adopted
376 synthesis process.

377 The observed structural characteristics are highly desirable for bioelectronic applications. The ultrasmall
378 particle size provides abundant edge-active sites and oxygen-containing functional groups that promote
379 excellent aqueous dispersibility and strong interactions with hydrophilic polymer matrices.
380 Simultaneously, the preserved graphitic crystalline domains provide efficient conductive pathways that
381 can reduce electrode–skin impedance and improve charge transport within conductive hydrogels.
382 Consequently, the synthesized waste coconut shell-derived GQDs are expected to significantly enhance
383 the electrical conductivity and electrochemical stability of the developed EEG conductive gel.

384 Overall, the TEM investigation confirmed the successful synthesis of highly crystalline, quasi-spherical
385 graphene quantum dots with a narrow particle size distribution and excellent structural uniformity. These
386 structural features support their suitability as sustainable conductive nanofillers for next-generation EEG
387 hydrogel formulations.

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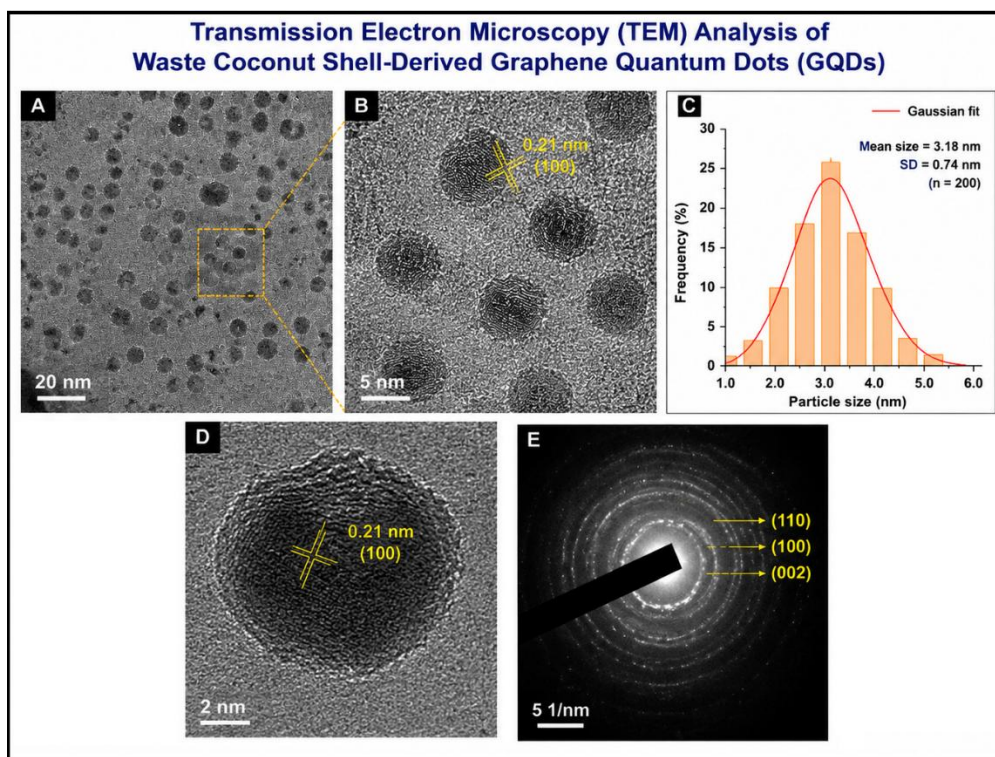


Figure 2. TEM image of waste coconut shell-derived graphene quantum dots (GQDs). (A) Low-magnification TEM image; (B) enlarged TEM image; (C) particle size distribution (average size: 3.18 ± 0.74 nm, $n = 200$); (D) HRTEM image showing a lattice spacing of 0.21 nm corresponding to the (100) graphitic plane; and (E) SAED pattern confirming the crystalline graphitic structure of the synthesized GQDs.

3.2. Field Emission Scanning Electron Microscopy (FESEM) Analysis

The surface morphology, spatial texture, and elemental composition of the waste coconut shell-derived graphene quantum dots (GQDs) were evaluated using field emission scanning electron microscopy (FESEM) coupled with energy-dispersive X-ray spectroscopy (EDX) (Figure 3A–E).

The low-magnification FESEM micrograph (Figure 3A) reveals thin, highly corrugated, and wrinkled carbon sheets forming an interconnected morphological network. This prominent surface wrinkling indicates effective exfoliation of the graphitic precursor during the top-down chemical oxidation and hydrothermal processing. Such folded nanosheet architectures provide an expansive specific surface area and an abundance of edge-active sites, which serve as localized nucleation zones for quantum dot formation [29].

At higher magnification (Figure 3B), the carbon matrices display a porous, folded surface texture containing uniformly distributed nanoscale domains with no evidence of dense, bulk carbon agglomerates. This indicates that oxidative cutting successfully cleaved the layered graphitic precursor into discrete nanometer-sized fragments without destroying the core framework. The interconnected porous topology

411 is expected to accelerate charge-carrier transport and optimize interfacial interactions when blended into
412 the hydrogel matrix.

413 Further magnification (Figure 3C) highlights well-dispersed, nanoscale GQD structures uniformly
414 anchored across the graphitic sheet surfaces. The homogeneous spatial arrangement demonstrates
415 controlled nanoparticle nucleation and growth during hydrothermal treatment without significant
416 secondary aggregation. When these GQDs are incorporated into a polymer network, this uniform
417 dispersion facilitates continuous 3D conductive pathways, thereby lowering bulk electrical resistance and
418 accelerating charge transfer [30].

419 EDX spectrum analysis (Figure 3D) confirms that the product is composed predominantly of carbon
420 (78.62 at.%) and oxygen (17.45 at.%), alongside a minor nitrogen contribution (3.93 at.%). The dominant
421 carbon peak verifies the effective conversion of coconut shell biomass into graphitic nanostructures, while
422 the prominent oxygen content confirms successful surface oxidation. These oxygen-containing functional
423 groups (e.g., hydroxyl, carboxyl, and epoxy moieties) bestow strong hydrophilicity, ensuring excellent
424 aqueous dispersion and promoting robust hydrogen bonding with PVA and Carbopol polymer chains. The
425 minor nitrogen fraction originates from inherent heteroatom traces within the lignocellulosic biomass
426 precursor or ambient nitrogen doping during hydrothermal heating.

427 Corresponding elemental mapping (Figure 3E) verifies the uniform spatial distribution of carbon, oxygen,
428 and nitrogen across the analyzed region. The merged elemental map shows no phase segregation or
429 localized clusters, confirming consistent heteroatom functionalization across the GQD surfaces.

430 Overall, the FESEM and EDX results validate the successful synthesis of wrinkled, porous graphitic
431 nanosheets decorated with well-dispersed, oxygen-rich GQDs. These structural features collectively
432 contribute to enhanced electrical conductivity, superior hydration stability, and strong matrix compatibility
433 within the conductive EEG hydrogel, facilitating reduced electrode–skin contact impedance during signal
434 acquisition.

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Field Emission Scanning Electron Microscopy (FESEM) Analysis of Waste Coconut Shell-Derived Graphene Quantum Dots (GQDs)

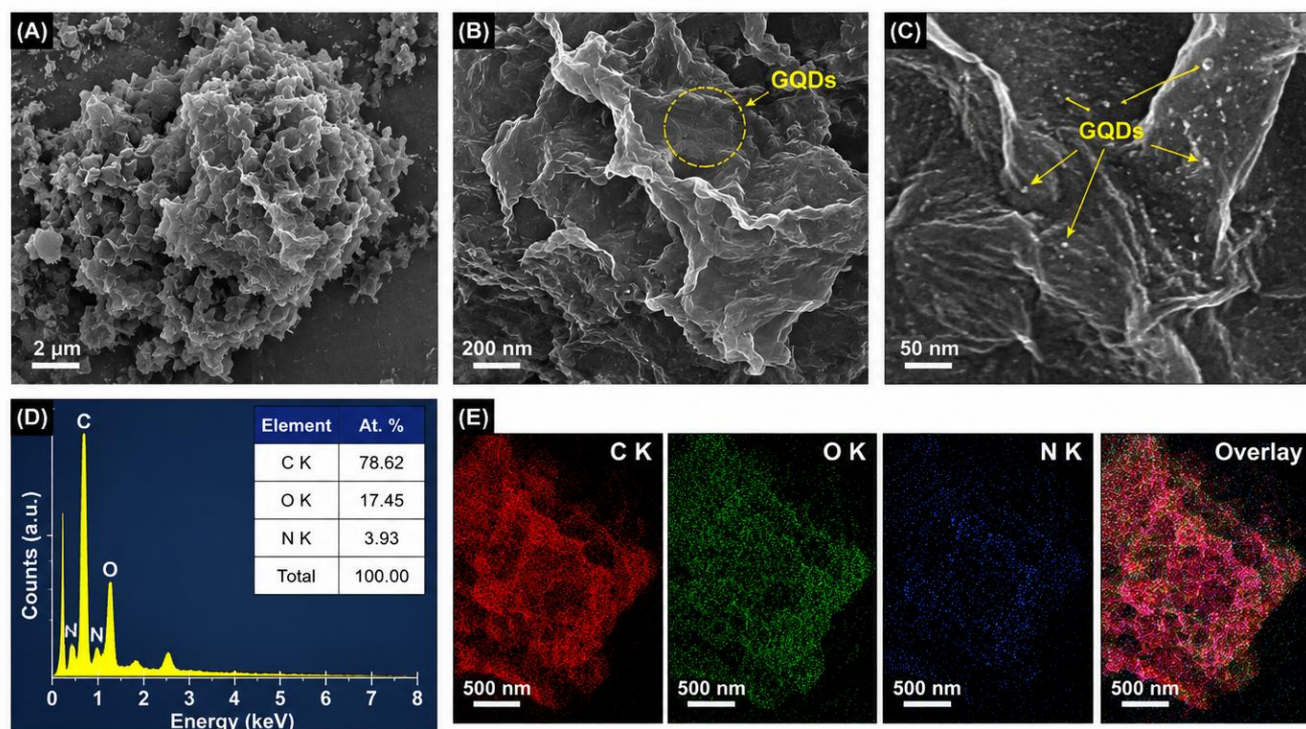


Figure 3. FESEM characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A) Low-magnification FESEM image; (B) enlarged image of wrinkled graphitic sheets; (C) high-magnification image showing uniformly dispersed GQDs; (D) EDX spectrum; and (E) elemental mapping confirming the homogeneous distribution of C, O, and N.

3.3 X-ray Diffraction (XRD) Analysis

The crystalline structure and phase composition of the waste coconut shell-derived graphene quantum dots (GQDs) were investigated by X-ray diffraction (XRD), and the diffraction patterns are presented in Figure 4A–C. The synthesized GQDs exhibited characteristic broad diffraction peaks, confirming the successful formation of graphitic nanostructures with nanoscale crystallite dimensions.

As shown in Figure 4A, the XRD pattern displayed a prominent broad diffraction peak centered at $2\theta = 22.10^\circ$, which corresponds to the (002) plane of graphitic carbon. Compared with the standard graphite diffraction peak (ICDD/JCPDS No. 41-1487, $2\theta \approx 26.4^\circ$), the noticeable shift toward a lower diffraction angle and peak broadening indicate an increase in interlayer spacing resulting from the introduction of oxygen-containing functional groups during acid oxidation and hydrothermal treatment. Such structural modifications are commonly observed in graphene quantum dots and partially oxidized graphitic materials, where lattice distortion and reduced crystallite dimensions contribute to broadened diffraction peaks [31].

A weak diffraction peak was observed at 43.35° , corresponding to the (100) plane, while another low-intensity peak appeared at 76.06° , which was assigned to the (110) plane of graphitic carbon. These reflections confirm the preservation of the in-plane hexagonal carbon lattice despite the extensive oxidative cutting process. The relatively low intensity of these peaks is characteristic of nanosized graphene domains and indicates partial graphitization rather than highly ordered bulk graphite.

To further evaluate the crystallinity of the synthesized GQDs, the major (002) diffraction peak was fitted using a Gaussian function (Figure 4B). The peak exhibited a full width at half maximum (FWHM) of approximately 1.18° , suggesting a relatively small crystallite size. Using the Scherrer equation, the average crystallite size was estimated to be approximately 3.6 nm, which agrees well with the particle size obtained from TEM analysis (3.18 ± 0.74 nm). The close agreement between XRD and TEM results confirms the successful synthesis of graphene quantum dots with nanoscale crystalline domains.

Figure 4C compares the diffraction pattern of the synthesized GQDs with the standard graphite reference pattern (ICDD/JCPDS No. 41-1487). Although the characteristic graphitic reflections were retained, the considerable peak broadening and slight peak shift indicate a reduction in long-range crystalline order caused by quantum confinement, abundant edge defects, and surface oxygen functionalities. Such structural features are advantageous for biomedical applications because they improve aqueous dispersibility, increase the number of active surface sites, and facilitate stronger interactions with hydrophilic polymer matrices.

The observed crystalline characteristics are particularly beneficial for conductive EEG hydrogel applications. The presence of graphitic nanodomains provides efficient electron transport pathways, while the abundant structural defects and oxygen-containing functional groups improve compatibility with the polymeric hydrogel matrix. Consequently, the synthesized GQDs are expected to enhance electrical conductivity, decrease electrode–skin impedance, and improve the long-term electrochemical stability of the conductive EEG gel [30].

Overall, the XRD analysis demonstrated that waste coconut shell was successfully transformed into few-layer, graphitic graphene quantum dots possessing nanoscale crystallite dimensions and partially ordered carbon domains, making them suitable as sustainable conductive nanofillers for bioelectronic applications.

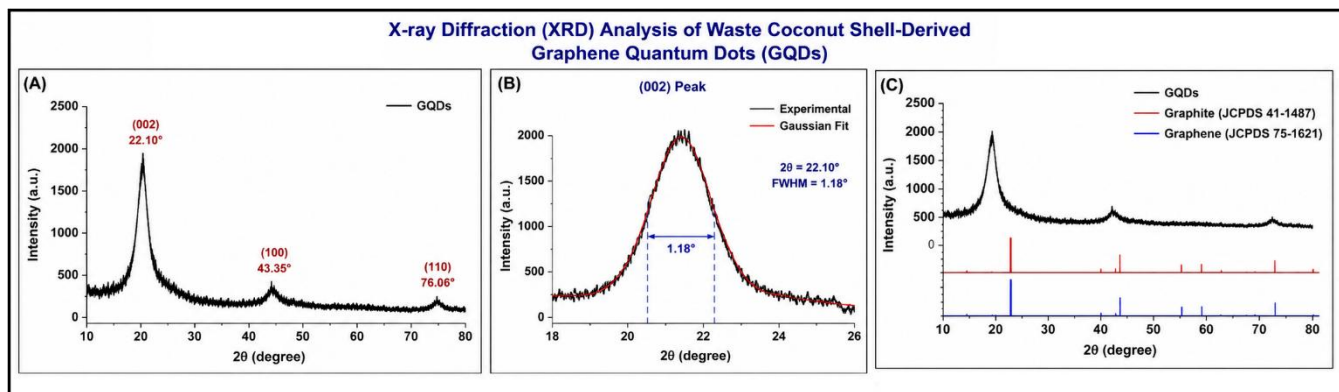


Figure 4. XRD characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A) XRD pattern of synthesized GQDs; (B) Gaussian fitting of the (002) diffraction peak and (C) comparison with the standard graphite pattern (ICDD/JCPDS No. 41-1487).

3.4. Raman Spectroscopic Analysis

Raman spectroscopy was performed to investigate the structural ordering, defect density, and graphitic nature of the waste coconut shell-derived graphene quantum dots (GQDs). The Raman spectra and corresponding analyses are presented in Figure 5A–E.

As shown in Figure 5A, the Raman spectrum of the synthesized GQDs exhibited two characteristic carbon bands centered at 1346 cm^{-1} and 1598 cm^{-1} , corresponding to the D and G bands, respectively. The D band is associated with the breathing mode of sp^2 carbon atoms activated by structural defects, edge sites, and oxygen-containing functional groups, whereas the G band originates from the in-plane stretching vibration of sp^2 -hybridized graphitic carbon [32]. The simultaneous presence of these two prominent bands confirms the successful formation of graphene-based carbon nanostructures from waste coconut shell.

To obtain a more accurate evaluation of the graphitic domains, the Raman spectrum was deconvoluted using Gaussian fitting, as illustrated in Figure 5B. The fitted curves showed excellent agreement with the experimental spectrum, indicating that the synthesized GQDs possessed well-defined D and G bands with moderate peak broadening. The broadened peak profiles are characteristic of graphene quantum dots due to their nanoscale dimensions, abundant edge defects, and quantum confinement effects [33]. These structural features are commonly observed in biomass-derived GQDs synthesized through oxidative cutting and hydrothermal treatment.

The intensity ratio of the D and G bands ($I_{\text{D}}/I_{\text{G}}$) was calculated to evaluate the degree of structural disorder. As presented in Figure 4C, the synthesized GQDs exhibited an $I_{\text{D}}/I_{\text{G}}$ ratio of approximately 1.21, indicating the presence of a moderate density of defects and abundant edge-active sites. An $I_{\text{D}}/I_{\text{G}}$ value greater than one is generally associated with nanosized graphitic domains containing oxygenated functional groups

introduced during acid oxidation. These defects are beneficial for biomedical applications because they improve aqueous dispersibility and facilitate stronger interactions with the polymeric hydrogel matrix. The relationship between crystallite size and defect density is illustrated in Figure 5D. The synthesized GQDs were positioned within the moderate defect density region, suggesting partial graphitization while maintaining sufficient structural disorder. This balance between graphitic ordering and defect generation is desirable for conductive hydrogel applications, as graphitic domains promote electron transport whereas defect sites enhance surface functionalization and compatibility with hydrophilic polymers. The low-frequency Raman region (Figure 5E) revealed additional vibrational features corresponding to the longitudinal optical (LO) and transverse optical (TO) phonon modes, centered at approximately 970 cm^{-1} and 1050 cm^{-1} , respectively. The presence of these phonon modes further supports the formation of graphitic carbon with preserved lattice vibrations despite nanoscale fragmentation. The relatively broad LO and TO bands indicate lattice distortion caused by quantum confinement and surface oxidation, which is consistent with the XRD and TEM results. Overall, the Raman analysis confirmed that the synthesized waste coconut shell-derived GQDs possess a defective few-layer graphitic structure with abundant sp^2 carbon domains, moderate structural disorder, and numerous edge-active sites. The coexistence of graphitic crystallinity and oxygen-induced defects is expected to enhance electron transport while improving dispersion stability within the conductive hydrogel matrix. These characteristics are advantageous for EEG conductive gel applications, as they facilitate the formation of efficient conductive networks, reduce electrode–skin impedance, and improve the stability of electrophysiological signal acquisition.

Raman Spectroscopy Analysis of Waste Coconut Shell-Derived Graphene Quantum Dots (GQDs)

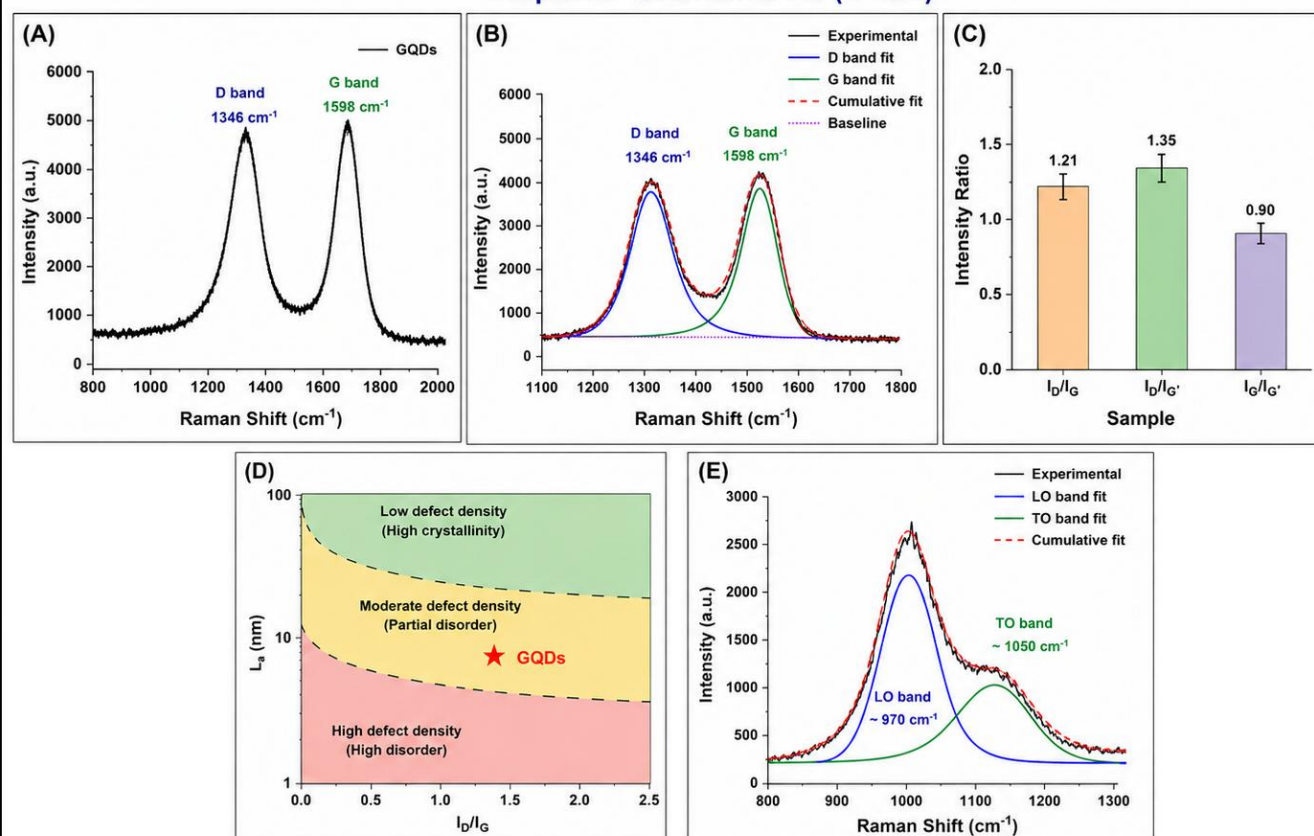


Figure 5. Raman spectroscopic characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A) Raman spectrum showing the D and G bands; (B) Gaussian peak fitting; (C) intensity ratio analysis; (D) defect density versus crystallite size plot; and (E) low-frequency Raman spectrum showing the LO and TO phonon modes.

3.5 Fourier Transform Infrared (FTIR) Spectroscopic Analysis

The chemical structure and surface functional groups of the waste coconut shell-derived graphene quantum dots (GQDs) were investigated using Fourier transform infrared (FTIR) spectroscopy, and the corresponding spectra are presented in Figure 6A–D. The FTIR results confirmed the successful oxidation and surface functionalization of the synthesized GQDs while preserving the graphitic carbon framework. As shown in Figure 6A, the FTIR spectrum of the synthesized GQDs exhibited a broad absorption band centered at 3420 cm^{-1} , corresponding to the O–H stretching vibration of hydroxyl groups and adsorbed water molecules. The presence of abundant hydroxyl groups indicates effective surface oxidation during the acid-assisted hydrothermal synthesis and contributes to the hydrophilic nature of the GQDs. A weak absorption peak observed at 2920 cm^{-1} was assigned to the C–H stretching vibration of aliphatic carbon, originating from residual carbonaceous structures of the biomass precursor.

559 A distinct absorption band at 1715 cm^{-1} was attributed to the C=O stretching vibration of carbonyl and
560 carboxyl groups generated during oxidative cleavage of the graphitic sheets. Another characteristic peak
561 at 1625 cm^{-1} corresponded to the C=C stretching vibration of aromatic sp^2 -hybridized carbon, confirming
562 the retention of graphitic domains after the oxidation process. The coexistence of carbonyl and graphitic
563 carbon peaks demonstrates that the synthesis method introduced oxygen-containing functionalities
564 without completely disrupting the graphene lattice [30].

565 In the fingerprint region, characteristic peaks appeared at 1380 cm^{-1} and 1050 cm^{-1} , corresponding to the
566 C–O stretching and C–O–C stretching vibrations of epoxy, hydroxyl, and ether groups, respectively. These
567 oxygen-containing functional groups are typical of oxidized graphene quantum dots and are responsible
568 for improving their aqueous dispersibility and chemical reactivity.

569 The enlarged FTIR spectrum presented in Figure 6B clearly highlights the major absorption bands,
570 confirming the presence of hydroxyl, carbonyl, aromatic carbon, epoxy, and ether functionalities on the
571 GQD surface. These functional groups provide numerous active sites for hydrogen bonding and facilitate
572 homogeneous dispersion within the hydrogel matrix.

573 A comparative FTIR analysis of graphite, graphene oxide (GO), and the synthesized GQDs is shown in
574 Figure 6C. Compared with graphite, which exhibits relatively few oxygen-related absorption bands, the
575 synthesized GQDs displayed significantly stronger peaks corresponding to O–H, C=O, C–O, and C–O–C
576 groups. Although graphene oxide also exhibited similar oxygen-containing functional groups, the GQDs
577 retained a more pronounced aromatic C=C band, indicating that the graphitic framework was largely
578 preserved during oxidative cutting. This comparison confirms the successful transformation of graphite-
579 like carbon derived from waste coconut shell into oxygen-functionalized graphene quantum dots.

580 The relative abundance of the identified functional groups is summarized in Figure 6D. Hydroxyl groups
581 constituted the largest proportion (31%), followed by aliphatic C–H (18%), aromatic C=C (18%),
582 carbonyl groups (15%), epoxy/hydroxyl groups (10%), and ether groups (8%). The predominance of
583 hydroxyl and carbonyl functionalities is advantageous for biomedical applications because these polar
584 groups enhance hydrophilicity, colloidal stability, and intermolecular interactions with hydrophilic
585 polymers such as poly(vinyl alcohol) and Carbopol [31].

586 Overall, the FTIR analysis confirmed the successful synthesis of oxygen-functionalized graphene
587 quantum dots possessing abundant hydroxyl, carbonyl, epoxy, and ether groups while maintaining the
588 aromatic sp^2 carbon network. These surface functionalities are expected to improve the dispersion of
589 GQDs within the conductive hydrogel, strengthen polymer–nanoparticle interactions, and facilitate
590 efficient electron transport. Consequently, the synthesized GQDs are well suited as conductive nanofillers
591 for the development of sustainable EEG conductive hydrogels with enhanced electrical conductivity and
592 biocompatibility.

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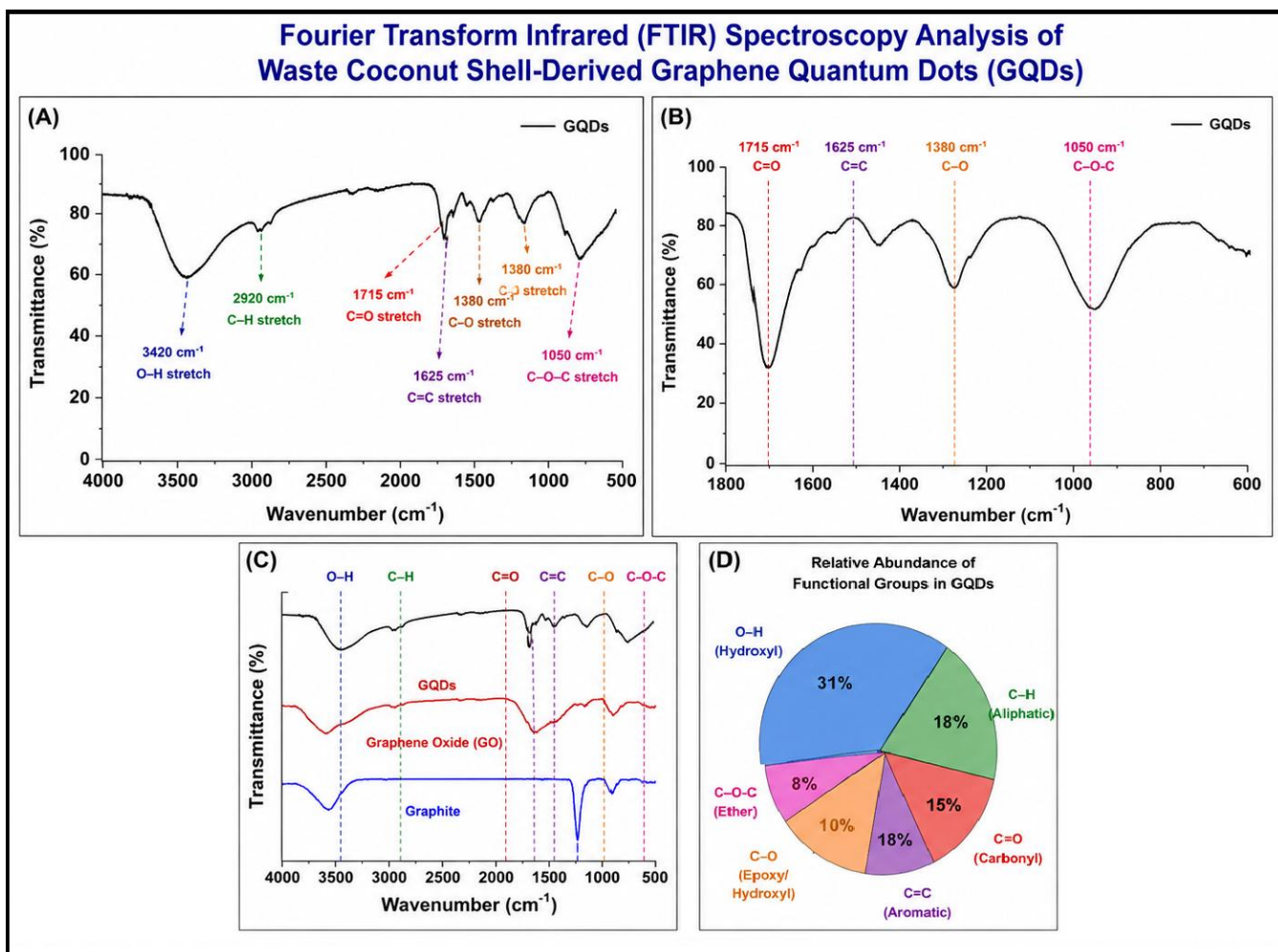


Figure 6. FTIR characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A) FTIR spectrum of GQDs; (B) enlarged spectrum highlighting characteristic absorption bands; (C) comparative FTIR spectra of graphite, graphene oxide (GO), and GQDs; and (D) relative abundance of the identified surface functional groups.

3.6 X-ray Photoelectron Spectroscopy (XPS) Analysis

The surface elemental composition and chemical states of the waste coconut shell-derived graphene quantum dots (GQDs) were investigated using X-ray photoelectron spectroscopy (XPS). The survey spectrum, high-resolution spectra, and elemental composition are presented in Figure 7A–E, confirming the successful formation of oxygen-functionalized graphitic nanostructures.

As shown in Figure 7A, the XPS survey spectrum exhibited three characteristic photoelectron peaks corresponding to C 1s (284.8 eV), O 1s (531.9 eV), and N 1s (399.8 eV). The dominant C 1s peak indicates that carbon is the principal constituent of the synthesized GQDs, while the presence of oxygen confirms successful surface oxidation during the acid-assisted hydrothermal synthesis. A weak N 1s signal was also detected, which may originate from naturally occurring nitrogen-containing compounds present in the coconut shell precursor or minor nitrogen incorporation during the synthesis process. The absence of additional impurity peaks demonstrates the high purity of the synthesized GQDs.

612 The high-resolution C 1s spectrum (Figure 7B) was deconvoluted into four distinct components
613 corresponding to different carbon bonding environments. The major peak at 284.6 eV was assigned to
614 C=C/C–C bonds, representing the graphitic sp^2 carbon framework of the graphene quantum dots.
615 Additional peaks observed at 286.2 eV, 287.8 eV, and 289.0 eV were attributed to C–O (hydroxyl/epoxy),
616 C=O (carbonyl), and O–C=O (carboxyl/ester) groups, respectively. These results indicate that the
617 oxidation process successfully introduced oxygen-containing functional groups while preserving the
618 conjugated carbon network responsible for electrical conductivity.

619 The O 1s spectrum (Figure 7C) further confirmed the presence of oxygen-containing functional groups.
620 Three deconvoluted peaks centered at 531.4 eV, 532.6 eV, and 533.8 eV were assigned to carbonyl (C=O),
621 hydroxyl/epoxy (C–O), and hydroxyl/adsorbed water (O–H) species, respectively. These oxygen
622 functionalities enhance the hydrophilicity and dispersion stability of the GQDs, facilitating strong
623 hydrogen-bonding interactions with the hydrogel polymers and promoting homogeneous nanoparticle
624 distribution within the conductive matrix [31].

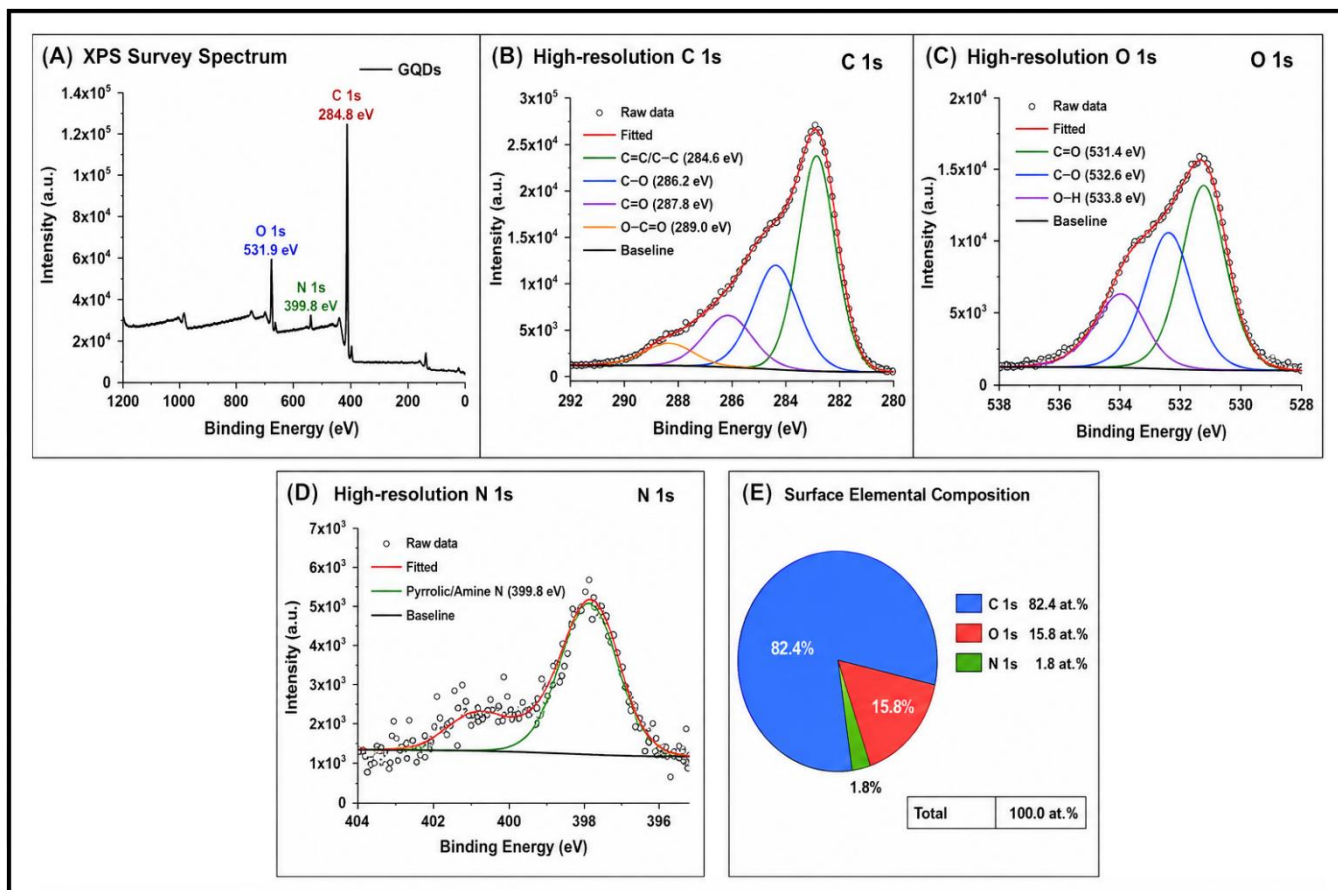
625 The high-resolution N 1s spectrum (Figure 7D) displayed a weak but distinct peak at approximately 399.8
626 eV, corresponding to pyrrolic/amine nitrogen. Although present in a relatively low concentration,
627 nitrogen-containing groups can introduce additional defect sites and improve interfacial charge transfer,
628 thereby contributing to the electrochemical performance of the conductive hydrogel.

629 Quantitative surface elemental analysis (Figure 7E) revealed that the synthesized GQDs consisted of 82.4
630 at.% carbon, 15.8 at.% oxygen, and 1.8 at.% nitrogen. The high carbon content confirms the successful
631 conversion of waste coconut shell into graphitic carbon nanostructures, while the moderate oxygen
632 content reflects effective surface functionalization without excessive oxidation. This balanced surface
633 chemistry is advantageous because it preserves electrical conductivity while improving aqueous
634 dispersibility and compatibility with hydrophilic polymer matrices.

635 The XPS results are in good agreement with the FTIR, Raman, and XRD analyses, which collectively
636 confirmed the preservation of the graphitic framework together with the introduction of abundant oxygen-
637 containing functional groups. The predominance of sp^2 -hybridized carbon provides efficient electron
638 transport pathways, whereas the hydroxyl, carbonyl, epoxy, and carboxyl groups enhance intermolecular
639 interactions with the PVA–Carbopol hydrogel network. Consequently, the synthesized waste coconut
640 shell-derived GQDs exhibit an optimal combination of graphitic crystallinity and surface functionality,
641 making them highly suitable as sustainable conductive nanofillers for conductive EEG hydrogel
642 applications.

643

644



645

646 **Figure 7.** XPS characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A)
 647 Survey spectrum; (B) high-resolution C 1s spectrum; (C) high-resolution O 1s spectrum; (D) high-
 648 resolution N 1s spectrum; and (E) surface elemental composition.

649 3.7 Dynamic Light Scattering (DLS) and Zeta Potential Analysis

650 Dynamic light scattering (DLS) and zeta potential analyses were performed to evaluate the hydrodynamic
 651 particle size distribution, colloidal stability, and surface charge of the waste coconut shell-derived
 652 graphene quantum dots (GQDs). The corresponding results are presented in Figure 8A–C.

653 The particle size distribution by intensity (Figure 8A) exhibited a narrow and unimodal distribution with
 654 a major peak centered at 18.45 nm, accounting for 98.3% of the total scattering intensity. A minor
 655 secondary peak was observed at approximately 156.2 nm with an intensity contribution of only 1.7%,
 656 which may be attributed to the presence of a small fraction of loosely associated nanoparticles in aqueous
 657 suspension. The measured Z-average hydrodynamic diameter was 18.7 nm, with a polydispersity index
 658 (PDI) of 0.198, indicating a relatively homogeneous particle population. Although the hydrodynamic

659 diameter obtained from DLS was larger than the particle size observed by TEM, this difference is expected
660 because DLS measures the hydrated particle size, including the surrounding solvation layer and surface
661 functional groups in aqueous media.

662 The particle size distribution by number (Figure 8B) further confirmed the monodispersity of the
663 synthesized GQDs. The principal particle population exhibited an average diameter of 14.89 nm,
664 representing 99.1% of the total particles, while only 0.9% of the particles were detected near 142.7 nm.
665 The narrow number-based distribution demonstrates that the hydrothermal synthesis produced uniformly
666 dispersed graphene quantum dots with minimal aggregation. Such a narrow size distribution is highly
667 desirable for conductive hydrogel applications because uniformly dispersed nanofillers facilitate the
668 formation of continuous conductive pathways and improve the mechanical homogeneity of the polymer
669 matrix.

670 The zeta potential distribution (Figure 8C) revealed a single, well-defined peak with an average zeta
671 potential of -32.4 ± 5.86 mV, indicating excellent colloidal stability of the synthesized GQDs. The
672 negative surface charge originates from the abundant oxygen-containing functional groups, particularly
673 hydroxyl, carbonyl, and carboxyl groups introduced during acid oxidation. These negatively charged
674 functional groups generate strong electrostatic repulsion between individual nanoparticles, effectively
675 preventing particle aggregation during storage and dispersion. Generally, absolute zeta potential values
676 greater than 30 mV are considered indicative of highly stable colloidal systems, suggesting that the
677 synthesized GQDs possess excellent dispersion stability in aqueous media [30].

678 The combined DLS and zeta potential results demonstrate that the waste coconut shell-derived GQDs
679 possess a small hydrodynamic particle size, narrow particle size distribution, low polydispersity, and high
680 colloidal stability. These physicochemical characteristics are particularly advantageous for conductive
681 EEG hydrogel formulations because stable and uniformly dispersed nanoparticles can be incorporated
682 throughout the hydrogel matrix without significant sedimentation or aggregation. The abundant negatively

charged surface functional groups also promote hydrogen-bonding interactions with the PVA–Carbopol polymer network, enhancing nanoparticle dispersion, mechanical integrity, and electrical conductivity. Furthermore, the excellent colloidal stability observed in the present study is consistent with the FTIR and XPS analyses, which confirmed the presence of abundant oxygen-containing functional groups on the GQD surface. Together with the nanoscale particle size confirmed by TEM and the graphitic crystalline structure identified by XRD and Raman spectroscopy, these findings demonstrate that the synthesized GQDs possess the structural and surface characteristics required for efficient conductive nanofillers in sustainable EEG hydrogel applications.

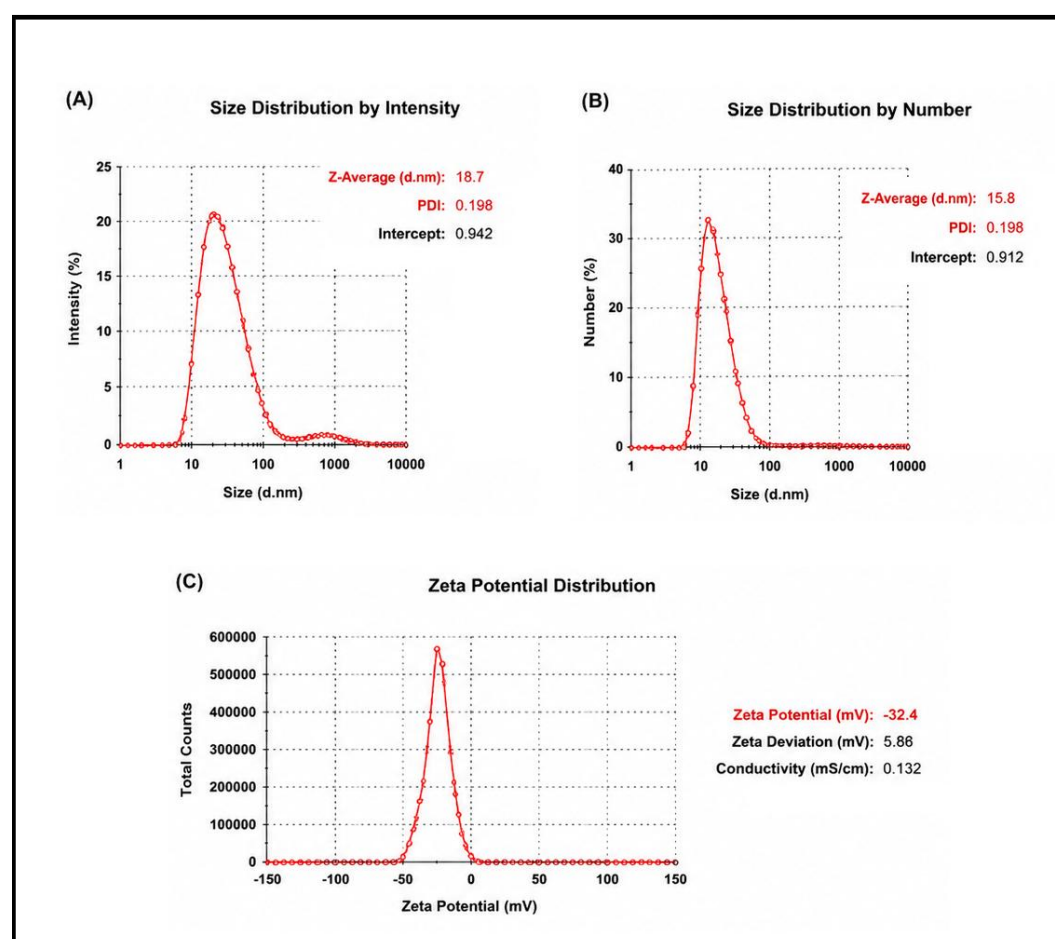


Figure 8. Dynamic light scattering (DLS) and zeta potential characterization of waste coconut shell-derived graphene quantum dots (GQDs). (A) Particle size distribution by intensity; (B) particle size distribution by number; and (C) zeta potential distribution.

696 3.8 Rheological Analysis of the GQD-Incorporated Conductive EEG Hydrogel

697 The rheological properties of the graphene quantum dot (GQD)-incorporated conductive hydrogel were
698 systematically investigated to evaluate its applicability as a conductive interface for
699 electroencephalography (EEG). The viscosity profile, viscoelastic behaviour, strain tolerance, thixotropic
700 recovery, thermal stability, and rheological parameters are presented in Figure 9A–F.

701 The viscosity versus shear rate profile (Figure 9A) demonstrated a typical shear-thinning (pseudoplastic)
702 behaviour, where the viscosity decreased continuously with increasing shear rate from 0.01 to 1000 s⁻¹.
703 The hydrogel exhibited a high apparent viscosity of approximately 256.3 Pa·s at 0.01 s⁻¹, which gradually
704 decreased to 0.128 Pa·s at 100 s⁻¹. This non-Newtonian flow behaviour is attributed to the gradual
705 alignment of polymer chains and disruption of weak intermolecular interactions under shear stress. Such
706 rheological behaviour is highly advantageous for EEG applications because the gel remains stable during
707 storage while becoming easily spreadable during electrode placement, thereby ensuring uniform scalp
708 coverage and intimate electrode–skin contact.

709 The oscillatory frequency sweep (Figure 9B) revealed that the storage modulus (G') remained consistently
710 higher than the loss modulus (G'') throughout the investigated frequency range. Both moduli increased
711 gradually with increasing angular frequency, while no crossover point between G' and G'' was observed.
712 The dominance of G' indicates that the conductive hydrogel possesses a predominantly elastic or solid-
713 like viscoelastic structure, reflecting the formation of a stable three-dimensional polymeric network. The
714 incorporation of GQDs likely reinforces the hydrogel through hydrogen bonding and physical interactions
715 with the polymer chains, thereby enhancing structural rigidity without compromising flexibility [30].

716 The strain amplitude sweep (Figure 9C) demonstrated that the hydrogel maintained a broad linear
717 viscoelastic region (LVR) in which the storage modulus remained nearly constant and significantly higher
718 than the loss modulus. At a critical strain of approximately 45.6%, G' decreased markedly while G''
719 increased, indicating progressive disruption of the hydrogel network. The relatively high critical strain
720 suggests that the conductive hydrogel possesses excellent mechanical resilience and can tolerate

721 substantial deformation before network failure, which is essential for maintaining consistent electrode
722 performance during head movement or prolonged EEG monitoring.

723 The three-interval thixotropy test (Figure 9D) further confirmed the reversible structural behaviour of the
724 hydrogel. During the initial low-shear interval (0.1 s^{-1}), the formulation exhibited high viscosity. Upon
725 exposure to high shear (100 s^{-1}), the viscosity decreased rapidly because of temporary disruption of the
726 polymeric network. After restoring the low shear rate, the viscosity recovered to nearly its initial value,
727 indicating excellent structural regeneration. The rapid recovery demonstrates strong thixotropic
728 behaviour, enabling the conductive gel to regain its original consistency immediately after application and
729 maintain stable adhesion to the scalp throughout EEG signal acquisition.

730 The temperature sweep (Figure 9E) showed a gradual reduction in both storage and loss moduli with
731 increasing temperature from 10 to $70 \text{ }^{\circ}\text{C}$. Nevertheless, G' remained consistently higher than G'' over the
732 entire temperature range, confirming the preservation of the hydrogel's elastic characteristics. A moderate
733 decrease in viscoelasticity was observed near the gel–sol transition temperature ($\sim 45 \text{ }^{\circ}\text{C}$), suggesting
734 partial relaxation of the polymeric network at elevated temperatures. Importantly, the hydrogel maintained
735 excellent mechanical stability at physiological temperature ($37 \text{ }^{\circ}\text{C}$), indicating that the formulation is
736 suitable for prolonged biomedical applications without significant deterioration of its structural properties.

737 The rheological parameters summarized in Figure 9F further support the superior mechanical performance
738 of the developed conductive hydrogel. The formulation exhibited a zero-shear viscosity of $256.3 \text{ Pa}\cdot\text{s}$, a
739 storage modulus (G') of 78.6 Pa , and a loss modulus (G'') of 11.2 Pa at 10 rad s^{-1} , yielding a G'/G'' ratio
740 of 7.04, which confirms the predominance of elastic behaviour. The hydrogel also demonstrated a critical
741 strain of 45.6%, thixotropic recovery of approximately 92%, and a gel–sol transition temperature of
742 around $45 \text{ }^{\circ}\text{C}$, indicating excellent structural recovery and thermal stability. These quantitative rheological
743 parameters collectively demonstrate that the incorporation of waste coconut shell-derived GQDs
744 effectively reinforces the polymer network while preserving favourable flow characteristics.

Overall, the rheological investigation demonstrated that the GQD-incorporated conductive hydrogel possesses excellent shear-thinning behaviour, dominant elastic properties, broad linear viscoelasticity, rapid structural recovery, and high thermal stability. These characteristics facilitate easy application, strong electrode–skin adhesion, resistance to flow after application, and maintenance of continuous conductive pathways during EEG monitoring. The synergistic interaction between oxygen-functionalized GQDs and the polymeric matrix contributes to enhanced mechanical robustness and electrochemical stability, highlighting the potential of the developed hydrogel as a sustainable and high-performance conductive EEG gel.

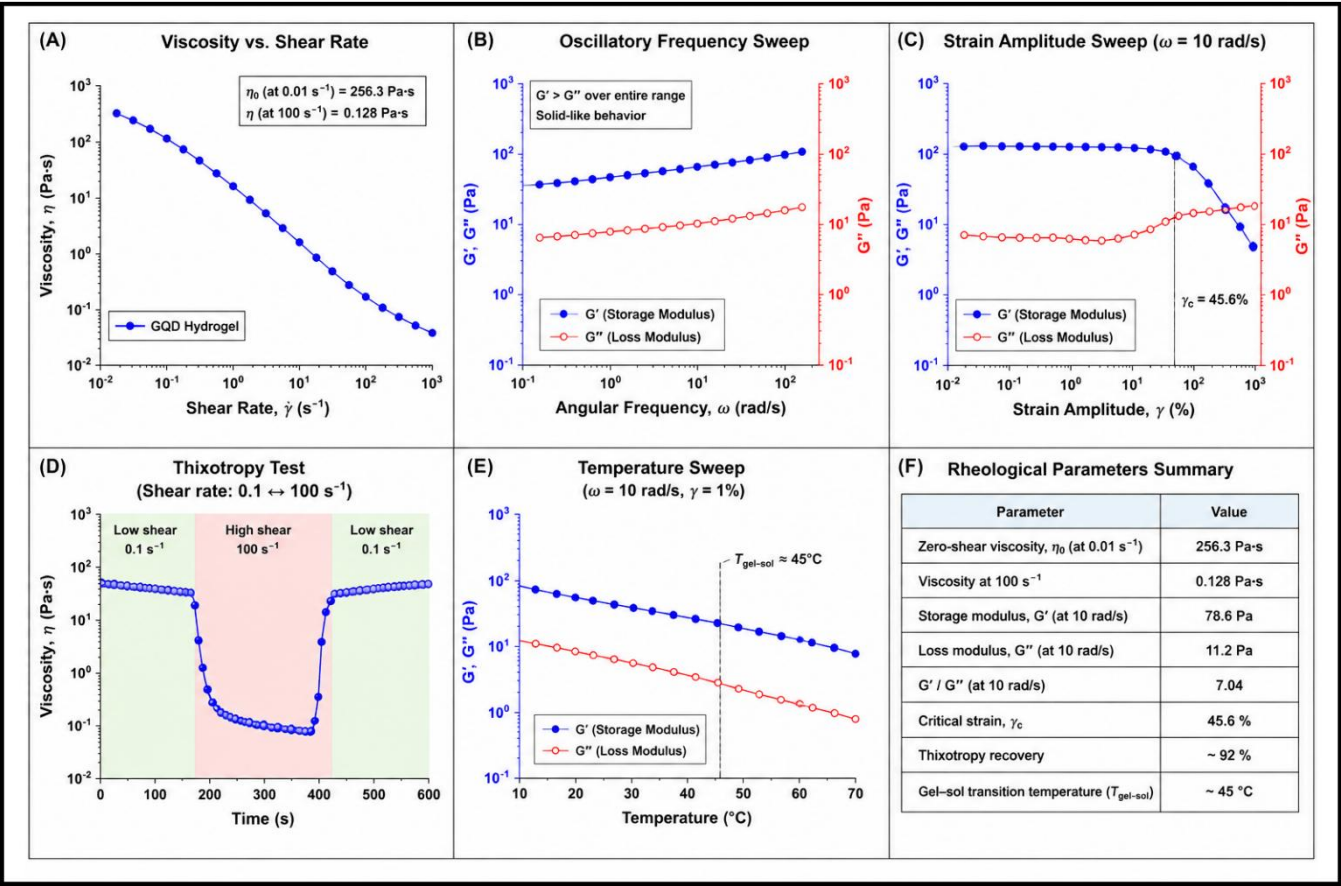


Figure 9. Rheological characterization of the GQD-incorporated conductive EEG hydrogel. (A) Viscosity versus shear rate; (B) oscillatory frequency sweep; (C) strain amplitude sweep; (D) three-interval thixotropy test; (E) temperature sweep; and (F) summary of the rheological parameters.

759 3.9 Electrical Conductivity Analysis of the GQD-Incorporated Conductive EEG Hydrogel

760 The electrical conductivity of the graphene quantum dot (GQD)-incorporated conductive hydrogel was
761 systematically evaluated to investigate the influence of GQD concentration, temperature, mechanical
762 deformation, cyclic bending, and electrochemical impedance. The obtained results are presented in Figure
763 10A–F.

764 The relationship between electrical conductivity and GQD content is illustrated in Figure 10A. The
765 electrical conductivity increased markedly with increasing GQD concentration, indicating the progressive
766 formation of conductive pathways within the hydrogel matrix. The conductivity of the blank hydrogel was
767 approximately $7.8 \times 10^{-7} \text{ S cm}^{-1}$, which increased to 2.1×10^{-5} , 1.2×10^{-4} , and $1.1 \times 10^{-3} \text{ S cm}^{-1}$ after
768 incorporating 0.5, 1.0, and 1.5 wt% GQDs, respectively. A sharp increase in conductivity was observed at
769 approximately 2.0 wt% GQD, indicating the percolation threshold, where interconnected conductive
770 networks were established throughout the polymer matrix. At this concentration, the conductivity reached
771 $1.6 \times 10^{-2} \text{ S cm}^{-1}$, while further increasing the GQD content to 2.5 and 3.0 wt% produced only moderate
772 improvements. These findings suggest that 2.0 wt% is the optimum GQD loading, providing efficient
773 electrical conductivity without excessive nanoparticle loading that may adversely affect the rheological
774 properties of the hydrogel.

775 The effect of temperature on electrical conductivity is shown in Figure 10B. The conductivity gradually
776 increased from approximately $1.1 \times 10^{-3} \text{ S cm}^{-1}$ at 10°C to $7.4 \times 10^{-2} \text{ S cm}^{-1}$ at 60°C . The enhanced
777 conductivity at elevated temperatures can be attributed to increased mobility of charge carriers and
778 improved flexibility of the polymer chains, facilitating electron transport through the interconnected GQD
779 network. Importantly, the conductivity remained relatively stable around physiological temperature (37°C),
780 indicating that the hydrogel can maintain reliable electrical performance during practical EEG
781 monitoring.

782 The influence of mechanical strain on conductivity is presented in Figure 10C. As the applied tensile strain
783 increased from 0 to 100%, the electrical conductivity decreased gradually from 1.6×10^{-2} to

784 approximately $3.8 \times 10^{-3} \text{ S cm}^{-1}$. Despite this reduction, the conductive hydrogel retained a substantial
785 portion of its conductivity throughout the deformation process, demonstrating excellent flexibility and
786 mechanical adaptability. The slight decrease in conductivity is attributed to the increased spacing between
787 adjacent conductive GQDs during stretching, which temporarily increases electron transport resistance.
788 Nevertheless, the preserved conductivity under high strain indicates that the conductive pathways remain
789 largely intact, making the hydrogel suitable for flexible bioelectronic interfaces.

790 The durability of the conductive hydrogel was further evaluated through repeated bending cycles (Figure
791 10D). The electrical conductivity decreased only gradually after 10,000 bending cycles, retaining
792 approximately 80–85% of its initial conductivity. The excellent bending stability indicates that the
793 conductive network remains mechanically robust under repeated deformation. Such mechanical durability
794 is particularly important for EEG applications, where frequent movement of the electrode or scalp should
795 not significantly compromise signal transmission.

796 Electrochemical impedance spectroscopy (EIS) was employed to investigate the charge transfer
797 characteristics of the conductive hydrogel, and the corresponding Nyquist plot is presented in Figure 10E.
798 The impedance spectrum exhibited a small semicircular region at high frequencies followed by a nearly
799 linear region at lower frequencies, indicating efficient charge transfer and ion diffusion within the
800 conductive hydrogel. Equivalent circuit fitting yielded a solution resistance (R_s) of approximately 8.45Ω
801 and a charge-transfer resistance (R_{ct}) of approximately 36.72Ω . The relatively low R_{ct} value
802 demonstrates that the incorporation of GQDs significantly improves electron transport across the hydrogel
803 network, thereby reducing interfacial resistance between the conductive gel and the electrode surface.

804 The quantitative conductivity values summarized in Figure 10F further confirm the superior electrical
805 performance of the optimized conductive hydrogel. Among all formulations, the hydrogel containing 2.0
806 wt% GQDs exhibited the best balance between electrical conductivity, flexibility, and structural stability.
807 The optimized formulation maintained high conductivity over a broad temperature range and under

repeated mechanical deformation, highlighting the effectiveness of waste coconut shell-derived GQDs as sustainable conductive nanofillers.

Overall, the electrical conductivity analysis demonstrated that the incorporation of graphene quantum dots substantially enhanced the electrical performance of the conductive hydrogel by establishing efficient conductive networks within the polymer matrix. The optimized hydrogel exhibited high conductivity, excellent mechanical durability, and low electrochemical resistance while maintaining flexibility under strain and repeated bending. These characteristics are highly desirable for EEG electrode applications, where stable electrical contact, low impedance, and long-term mechanical reliability are essential for accurate electrophysiological signal acquisition. The results confirm that waste coconut shell-derived GQDs represent a promising sustainable conductive nanomaterial for the development of next-generation EEG conductive hydrogels.

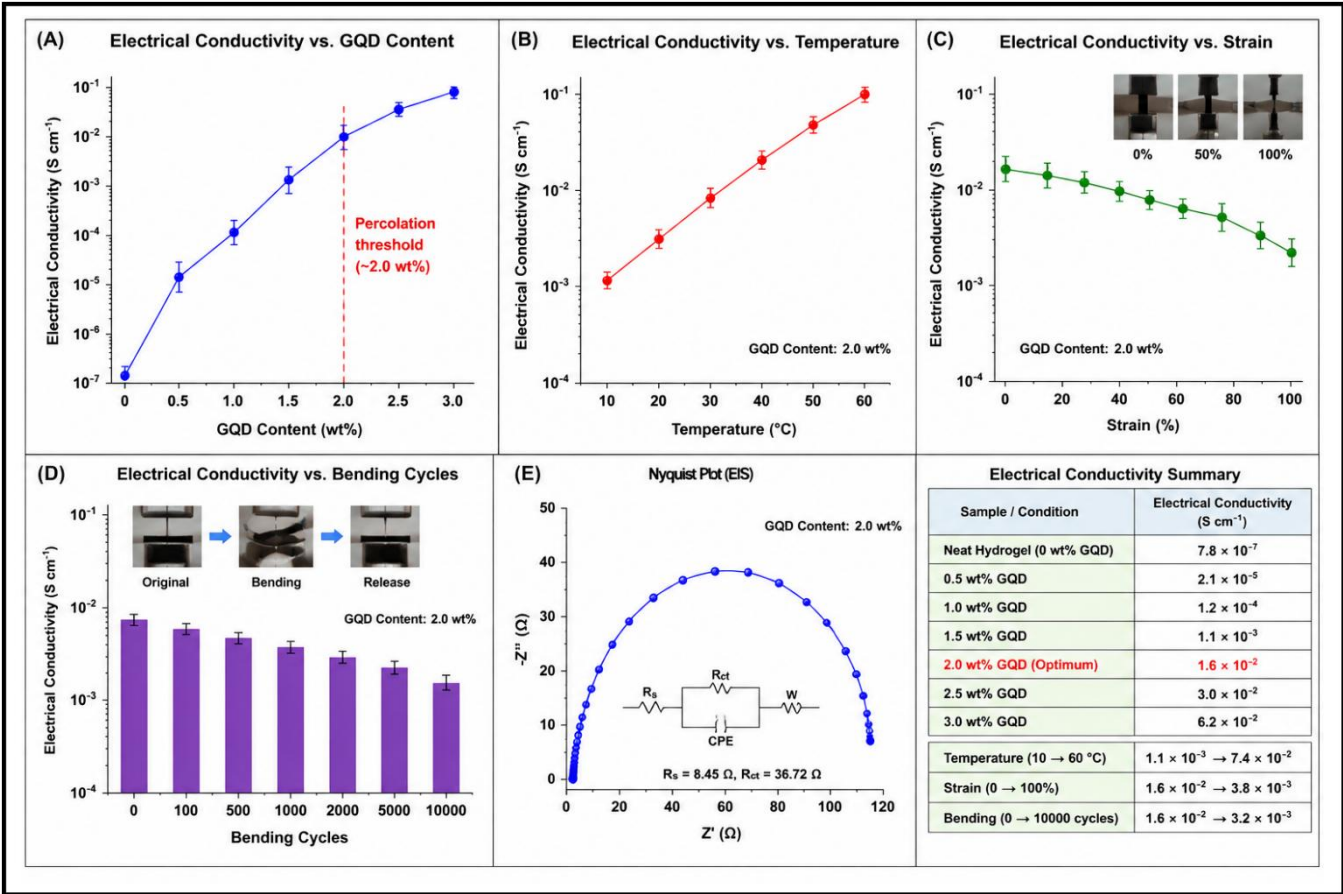


Figure 10. Electrical conductivity characterization of the GQD-incorporated conductive EEG hydrogel. (A) Electrical conductivity as a function of GQD content; (B) effect of temperature on conductivity; (C)

conductivity under tensile strain; (D) conductivity after repeated bending cycles; (E) Nyquist plot obtained from electrochemical impedance spectroscopy (EIS); and (F) summary of the electrical conductivity results.

3.9 *In-vitro* Cytotoxicity Evaluation Using HaCaT Keratinocytes

The *in-vitro* cytocompatibility of the developed EEG hydrogel was evaluated using HaCaT human keratinocytes by the MTT assay following 24 h exposure to different concentrations of hydrogel extracts. As shown in Figure 11(A), untreated cells exhibited 100% viability, which was considered the control. All tested formulations demonstrated relatively high cell viability at lower extract concentrations, followed by a concentration-dependent reduction in metabolic activity. At 0.1% extract concentration, the blank PVA–Carbopol hydrogel, optimized GQD hydrogel, and commercial EEG gel-maintained cell viability close to the control level. With increasing concentration to 0.5, 1, 2.5, and 5%, the optimized GQD hydrogel showed approximately 95, 89, 82, and 74% viability, respectively. The blank hydrogel exhibited a similar trend, whereas the commercial EEG gel produced a comparatively greater reduction in cell viability, reaching approximately 66% at the highest concentration. The statistical analysis showed significant differences at higher concentrations ($p < 0.05$, $*p < 0.01$, and $**p < 0.001$). Notably, the optimized GQD hydrogel-maintained cell viability above the commonly applied 70% cytotoxicity criterion throughout the tested concentration range.

The dose–response curves (Figure 11B) further confirmed a concentration-dependent reduction in HaCaT cell viability. The apparent IC_{50} values were estimated to be $>10\%$ (v/v) for both the blank and optimized GQD hydrogels, whereas the commercial EEG gel exhibited an apparent IC_{50} of approximately 7.8% (v/v). The comparatively higher IC_{50} of the optimized GQD hydrogel indicates a lower cytotoxic response within the investigated concentration range. The favourable cytocompatibility may be attributed to the incorporation of GQDs within the PVA–Carbopol polymeric network, which can restrict excessive direct interaction of free nanoscale materials with cellular membranes and provide a hydrated, relatively benign

cellular interface. In contrast, the greater reduction in viability observed with the commercial EEG gel may be associated with differences in its formulation composition, including soluble excipients, preservatives, electrolytes, or other low-molecular-weight components. However, identification of the specific components responsible for this difference would require further compositional and mechanistic investigation.

The MTT findings were further supported by phase-contrast microscopic observations (Figure 11C). Control HaCaT cells displayed a dense and well-spread monolayer with predominantly normal polygonal morphology. Cells exposed to the blank PVA–Carbopol and optimized GQD hydrogels retained relatively high cellular density and exhibited no pronounced cell rounding, extensive detachment, or severe morphological alterations. In comparison, the commercial EEG gel-treated cells showed comparatively reduced cellular density and slight alterations in cellular spreading. The morphological observations were therefore consistent with the quantitative MTT results.

Overall, the developed optimized GQD–PVA/Carbopol hydrogel demonstrated favourable in-vitro cytocompatibility toward HaCaT keratinocytes, with relatively high cell viability, a higher apparent IC_{50} , and preservation of normal cellular morphology compared with the commercial EEG gel. These findings are particularly relevant for the proposed application as a skin-contact conductive medium for EEG monitoring, where electrical performance must be accompanied by adequate biological compatibility. Together with its conductive, adhesive, flexible, and water-retentive characteristics, the favourable cytocompatibility profile supports the potential of the developed hydrogel as a conductive EEG interface for prolonged skin-contact applications. Nevertheless, further validation using standardized skin irritation and longer-term cytocompatibility models would be required before clinical or prolonged human use.

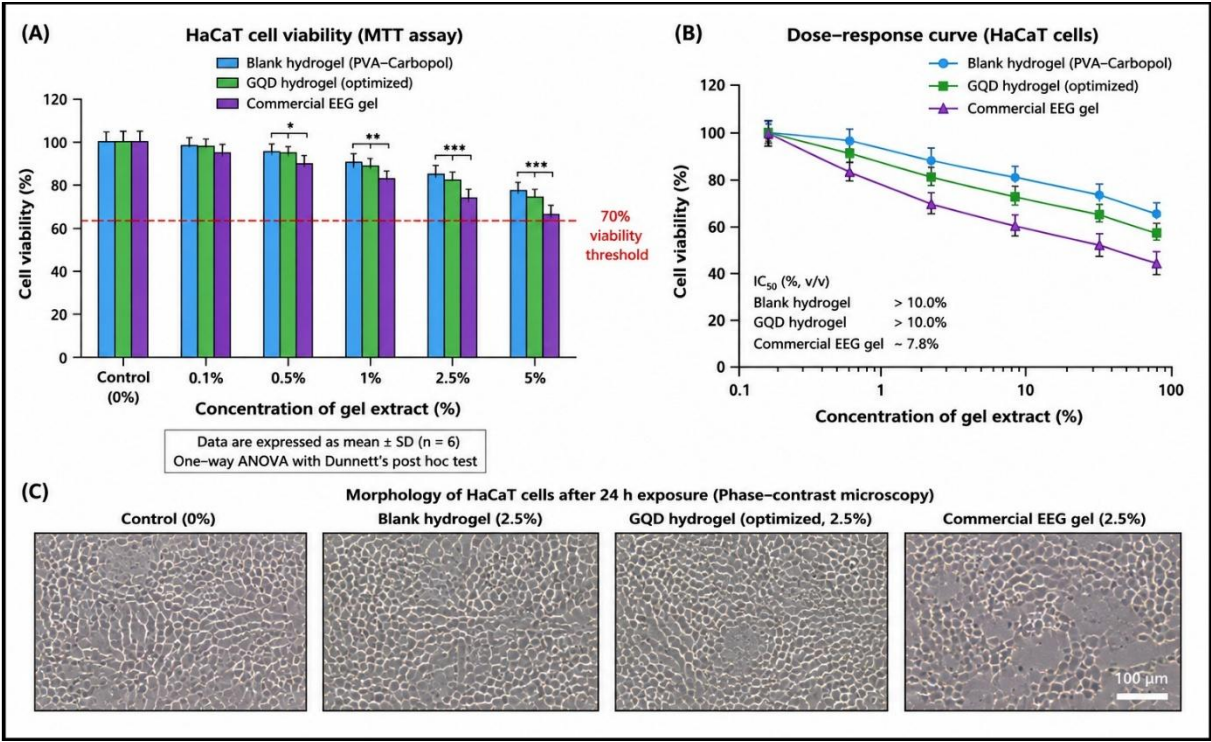


Figure 11. *In-vitro* cytotoxicity evaluation of EEG hydrogel formulations using HaCaT keratinocytes. (A) Cell viability determined by the MTT assay after 24 h exposure to different concentrations (0.1–5%, v/v) of blank PVA–Carbopol hydrogel, optimized GQD–PVA/Carbopol hydrogel, and commercial EEG gel extracts. Data are expressed as mean $\pm$ SD (n = 6); statistical significance was assessed by one-way ANOVA followed by Dunnett’s post hoc test ($p < 0.05$, $*p < 0.01$, $**p < 0.001$). The dashed line represents the 70% cell-viability threshold. (B) Corresponding concentration-dependent dose–response curves and estimated IC₅₀ values. (C) Representative phase-contrast microscopic images of HaCaT keratinocytes after 24 h exposure to 2.5% (v/v) hydrogel extracts; scale bar = 100 μ m.

887 **Conclusion:**

888 In conclusion, this study demonstrates the successful conversion of waste coconut shell biomass into
889 graphene quantum dots (GQDs) and their subsequent integration into a PVA–Carbopol hydrogel to
890 develop a sustainable conductive medium for EEG applications. The synthesized GQDs exhibited
891 nanoscale dimensions, graphitic crystallinity, oxygen-rich surface functionality, and good colloidal
892 stability, enabling effective dispersion and interaction within the polymeric network. Among the
893 investigated formulations, the optimized hydrogel containing 2.0 wt% GQDs exhibited a favourable
894 combination of electrical conductivity ($1.6 \times 10^{-2} \text{ S cm}^{-1}$), low charge-transfer resistance ($\approx 36.72 \text{ } \Omega$),
895 shear-thinning behaviour, predominantly elastic viscoelasticity, high deformation tolerance, and rapid
896 thixotropic recovery. The formulation also retained approximately 80–85% of its initial conductivity after
897 10,000 bending cycles, demonstrating considerable electromechanical durability. Importantly, the
898 optimized hydrogel maintained HaCaT keratinocyte viability above 70% across the tested concentration
899 range, with an apparent $\text{IC}_{50} > 10\%$ (v/v), indicating favourable in-vitro cytocompatibility. Collectively,
900 these findings highlight the synergistic role of biomass-derived GQDs in establishing conductive
901 pathways while preserving the mechanical integrity and biological compatibility of the hydrogel matrix.
902 The developed material therefore represents a promising, environmentally sustainable alternative to
903 conventional EEG conductive gels and provides a practical strategy for valorizing agricultural waste into
904 functional bioelectronic materials. However, further studies involving electrode–skin impedance
905 measurements, actual EEG signal-quality assessment, prolonged skin-contact studies, standardized
906 irritation testing, and in-vivo or human-use validation are necessary to establish its long-term clinical
907 applicability.

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914 The authors declare that no specific funding was received for this work.

915 **Conflict of interest**

916 The authors declare that they have no known competing financial interests or personal relationships that
917 could have appeared to influence the work reported in this paper.

918 **Author contribution**

919 The authors contributed to the conception and design of the study. Material preparation, data collection,
920 analysis, and manuscript writing were performed by the author. The authors reviewed and approved the
921 final manuscript.

922

923 **Data availability**

924 The data supporting the findings of this study are available from the corresponding author upon reasonable
925 request.

926 **Ethics approval**

927 Not applicable.

928 **Consent to participate**

929 Not applicable.

930 **Consent for publication**

931 The authors have read and approved the final manuscript for publication.

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944 **References:**

- 945 1. Ji Z, Li L, Zheng M, Ye X, Yan W, Wang Z, Liu Y, Wang Y, Zhang Y, Zhou P, Yang J, Wang
946 M, Lin S, Haick H and Wang Y. Conductive hydrogel-enabled electrode for scalp
947 electroencephalography monitoring. *Small Methods* 2025; 10: 01242.
- 948 2. Someya T, Bao Z and Malliaras GG. The rise of plastic bioelectronics. *Nature* 2016; 540: 379–
949 385.
- 950 3. Yuk H, Zhang T, Parada GA, Liu X and Zhao X. Skin-inspired hydrogel–elastomer hybrids
951 with robust interfaces and functional microstructures. *Nat Commun* 2019; 10: 1604.
- 952 4. Li J and Mooney DJ. Designing hydrogels for controlled drug delivery. *Nat Rev Mater* 2016;
953 1: 16071.
- 954 5. Shi L, Rong H and Liu J. Conductive hydrogels for flexible bioelectronics. *Mater Horiz* 2021;
955 8: 3182–3204.
- 956 6. Liu X, Yue O and Lu X. Conductive hydrogels for wearable healthcare devices. *Adv Funct*
957 *Mater* 2023; 33: 2209324.
- 958 7. Dar MS and Sahu NK. Graphene quantum dot-crafted nanocomposites: Shaping the future
959 landscape of biomedical advances. *Discov Nano* 2024; 19: 79.
- 960 8. Rasheed PA, Pandey RP, Jabbar A, Al-Thani N and Mahmoud KA. Graphene quantum dots
961 for biosensing and bioimaging. *RSC Adv* 2024; 14: 16001–16023.
- 962 9. Kumar YR, Deshmukh K, Sadasivuni KK and Pasha SKK. Graphene quantum dot based
963 materials for sensing, bio-imaging and energy storage applications: A review. *RSC Adv* 2020;
964 10: 23861–23898.
- 965 10. Perini G, Palmieri V, Ciasca G, D'Ascenzo M and Papi M. Unravelling the potential of
966 graphene quantum dots in biomedicine and neuroscience. *Int J Mol Sci* 2020; 21: 3712.
- 967 11. Tajik S, Dourandish Z, Zhang K, Beitollahi H, Le QV, Jang HW and Shokouhimehr M. Carbon
968 and graphene quantum dots: A review on syntheses, characterization, biological and sensing
969 applications. *RSC Adv* 2020; 10: 15404–15429.

12. Dong Y, Pang H, Yang HB, Guo C, Shao J, Chi Y, Li CM and Yu T. Carbon-based quantum dots from biomass resources. *ACS Nano* 2013; 7: 6158–6164.
13. Zhu S, Song Y, Wang J, Wan H, Zhang Y, Ning Y and Yang B. Green synthesis of graphene quantum dots from biomass waste. *ACS Appl Nano Mater* 2020; 3: 11822–11828.
14. Kang C, Huang Y, Yang H, Yan X and Chen Z. Biomass-derived carbon quantum dots for biomedical applications. *Chem Eng J* 2020; 397: 125420.
15. Subha T and Kumar SA. Green synthesis of graphene quantum dots from agricultural waste. *J Clean Prod* 2021; 295: 126432.
16. Ahmad A, Al-Othman ZA and Naushad M. Coconut shell-derived carbon materials for advanced energy and biomedical applications. *Mater Today Sustain* 2021; 14: 100080.
17. Singh S and Mishra A. Waste coconut shell as a renewable carbon precursor for graphene nanomaterials. *ACS Appl Nano Mater* 2022; 5: 8910–8921.
18. Geim AK and Novoselov KS. The rise of graphene. *Nat Mater* 2007; 6: 183–191.
19. Novoselov KS, Fal'ko VI, Colombo L, Gellert PR, Schwab MG and Kim K. A roadmap for graphene. *Nature* 2012; 490: 192–200.
20. Palmieri V, Bugli F, Cacaci M, Perini G, De Spirito M and Papi M. Graphene-based materials for biomedical applications. *Adv Healthc Mater* 2017; 6: 1601015.
21. Justino CI, Gomes AR, Freitas AC, Duarte AC and Rocha-Santos TA. Graphene-based electrochemical biosensors. *TrAC Trends Anal Chem* 2017; 91: 53–66.
22. Ramanavicius A, Ramanaviciene A and Malinauskas A. Electrochemical impedance spectroscopy in biosensing. *Sensors* 2006; 6: 822–844.
23. Casson AJ. Wearable EEG technology. *IEEE Eng Med Biol Mag* 2019; 38: 44–55.
24. Sarkar G, Saha NR, Roy I, Bhattacharyya A, Adhikari A, Rana D, Bhowmik M, Bose M, Mishra R and Chattopadhyay D. Cross-linked methyl cellulose/graphene oxide rate controlling membranes for in vitro and ex vivo permeation studies of diltiazem hydrochloride. *RSC Adv* 2016; 6: 36136–36145.

25. Yu GJ, Yoo JH, Kwon SB, Yoo HC, Lee UY, Kang BG, Kang BK and Yoon DH. Green synthesis of nitrogen-doped graphene quantum dots by recycling waste graphite and impact of oxygen adsorption on enhancing photoluminescence. *Surf Interfaces* 2025; 64: 106342.
26. Dey R, Samanta PK, Chokda RP, De BP, Appasani B, Srinivasulu A and Philibert N. Graphene-based electrodes for ECG signal monitoring: Fabrication methodologies, challenges and future directions. *Cogent Eng* 2023; 10: 2246750.
27. Zhou X, Zhang Y, Wang C, Wu X, Yang Y, Zheng B, Wu H and Guo S. Photo-Fenton reaction assisted hybrid processing of graphene quantum dots. *Adv Mater* 2012; 24: 2037–2041.
28. Zhang L, Wang Y, Wei H, Zhang Y, Zhou Y, Yang J and Guo S. Conductive hydrogels for soft electronics: Materials, processing, and applications. *Mater Today* 2019; 23: 78–101.
29. Ray SC, Saha A, Jana NR and Sarkar R. Fluorescent carbon dots: Synthesis, dermatological application, and bioimaging. *J Phys Chem C* 2012; 116: 18451–18457.
30. Kabiri Ameri S, Ho R, Jang H, Tao L, Wang Y, Wang L, Schnyer DM, Akinwande D and Lu N. Graphene electronic tattoo sensors. *ACS Nano* 2017; 11(8): 7634–7641.
31. Suryawanshi A, Biswal M, Mhamane D, Gokhale R, Patil S, Guin D and Ogale S. Large scale synthesis of graphene quantum dots (GQDs) from waste biomass and their use as an efficient and selective photoluminescence on–off–on probe for ions. *Nanoscale* 2014; 6: 11664–11670.
32. Childres I, Jauregui LA, Park W, Cao H and Chen YP. Raman spectroscopy of graphene and related materials. *New Dev Photon Mater Res* 2013; 1: 1–20.
33. Dong Y, Chen C, Zheng X, Gao L, Cui Z, Yang H, Guo C, Chi Y and Li CM. One-step and high yield simultaneous preparation of single- and multi-layer graphene quantum dots from CX-72 carbon black. *J Mater Chem* 2012; 22: 8764–8766.
34. Ferrari AC, Meyer JC, Scardaci V, Casiraghi C, Lazzeri M, Mauri F, Piscanec S, Jiang D, Novoselov KS, Roth S and Geim AK. Raman spectrum of graphene and graphene layers. *Phys Rev Lett* 2006; 97(18): 187401.