

CNT/PANI Composite Electrodes for Flexible Fiber-Shaped Dye-Sensitized Solar Cells: Synthesis, Characterization, and Photovoltaic Performance

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Abstract

This study investigated the synthesis, characterization, and photovoltaic performance of carbon nanotube–polyaniline (CNT–PANI) composite electrodes for flexible fiber-shaped dye-sensitized solar cells (DSSCs), with particular emphasis on the quantitative effects of CNT composition on electrical, electrochemical, structural, mechanical, and photovoltaic properties. A quantitative experimental design was employed using PANI-only, low-CNT/PANI, medium-CNT/PANI, high-CNT/PANI, and CNT-only electrode formulations, with 75 successfully fabricated devices included in the final analysis. The electrodes were characterized according to conductivity, sheet resistance, charge-transfer resistance, catalytic peak current, coating thickness, surface porosity, CNT dispersion, and electrochemical response, while device performance was evaluated through short-circuit current density, open-circuit voltage, fill factor, power conversion efficiency (PCE), and mechanical performance retention. The medium-CNT/PANI formulation demonstrated the strongest integrated performance, achieving electrical conductivity of 68.7 ± 5.1 S/cm, sheet resistance of 18.9 ± 2.2 Ω /sq, charge-transfer resistance of 2.84 ± 0.31 Ω , and catalytic peak current density of 3.92 ± 0.30 mA/cm². Structurally, this formulation exhibited $46.8 \pm 3.7\%$ surface porosity and $92.1 \pm 3.2\%$ CNT dispersion uniformity. The corresponding fiber-shaped DSSCs achieved a short-circuit current density of 13.92 ± 0.88 mA/cm², open-circuit voltage of 0.724 ± 0.018 V, fill factor of $68.8 \pm 2.5\%$, and PCE of $6.93 \pm 0.39\%$, representing an 80.5% efficiency improvement over the PANI-only configuration and a 21.4% improvement over CNT-only devices. After 1,000 bending cycles, the optimized devices retained $94.2 \pm 2.4\%$ of their initial PCE, with electrical resistance increasing by only $6.8 \pm 1.6\%$. Electrode composition significantly affected PCE, with $F = 124.36$, $p < 0.001$ and $\eta^2 = 0.877$. Multivariate regression explained 84.4% of PCE variation, with catalytic peak current serving as the strongest positive predictor and charge-transfer resistance as the strongest negative predictor. The findings established that an intermediate CNT–PANI composition provided the most effective balance of electrical conduction, catalytic activity, interfacial charge transfer, structural accessibility, mechanical flexibility, and photovoltaic efficiency.

Keywords

CNT–PANI, Polyaniline, Carbon Nanotubes, DSSCs, Photovoltaics

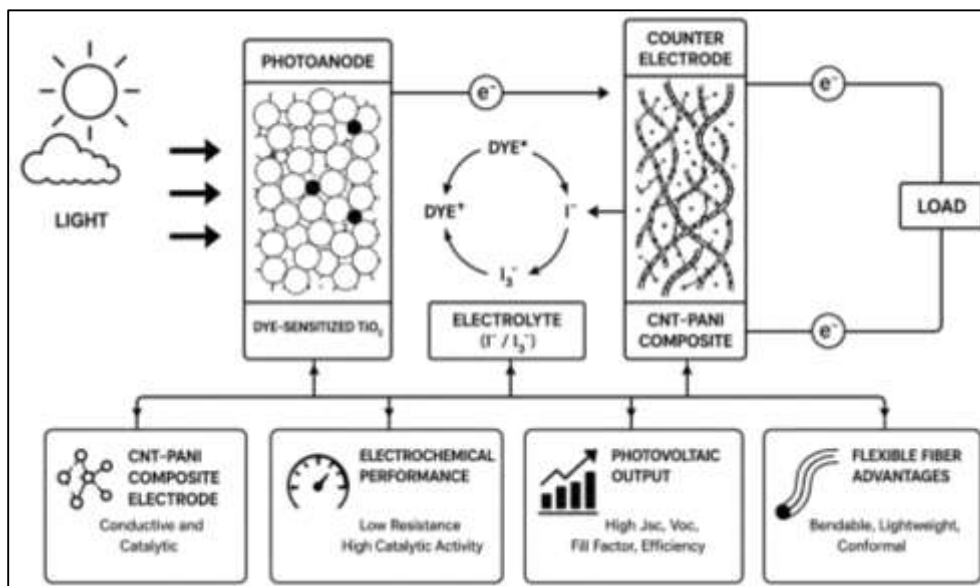
INTRODUCTION

Dye-sensitized solar cells (DSSCs) are photoelectrochemical photovoltaic devices designed to convert incident solar radiation into electrical energy through coordinated processes involving light absorption, electron excitation, charge injection, electron transport, electrolyte-mediated regeneration, and catalytic reduction. They are generally classified as third-generation photovoltaic systems because their operating mechanism and material architecture differ considerably from those of conventional crystalline silicon solar cells. In a typical DSSC, the major functional components consist of a photosensitized semiconductor photoanode, an electrolyte containing a redox mediator, and a counter electrode that receives electrons from the external circuit and catalyzes the reduction reaction required to complete the electrochemical cycle (Batmunkh et al., 2015a). Titanium dioxide is commonly employed as the semiconductor because its nanostructured form provides a large surface area for dye adsorption, favorable electron-transport characteristics, chemical stability, and compatibility with several sensitizing compounds. Flexible fiber-shaped dye-sensitized solar cells represent a geometrically modified form of DSSC in which one or more functional electrodes are fabricated on wires, fibers, yarns, or cylindrical substrates rather than conventional flat and rigid surfaces. This configuration permits the photovoltaic structure to bend, twist, curve, and conform to irregular surfaces while retaining its fundamental photoelectrochemical functions. Carbon nanotube-polyaniline, commonly represented as CNT-PANI, is a composite material formed through the integration of carbon nanotubes with polyaniline, a conductive conjugated polymer. Carbon nanotubes possess a cylindrical nanoscale carbon structure associated with high electrical conductivity, substantial mechanical strength, large specific surface area, and efficient charge-transfer capability (Saadattalab et al., 2016). Polyaniline contains conjugated molecular structures whose electrical conductivity can be modified through oxidation and protonation, providing useful electrochemical and catalytic characteristics. Combining CNTs and PANI can create an interconnected composite electrode in which nanotubes establish conductive electron pathways while the polymer supplies electrochemically active surface sites. The term composite electrode therefore refers to an electrode whose functional characteristics originate from the combined structural, electrical, chemical, and electrochemical behavior of multiple constituent materials. For quantitative photovoltaic analysis, these characteristics are examined through measurable indicators such as electrical conductivity, charge-transfer resistance, catalytic current density, short-circuit current density, open-circuit voltage, fill factor, incident photon-to-current conversion efficiency, and overall power conversion efficiency (Zhang et al., 2015). More than three decades of experimental research across nanostructured photovoltaics, conducting polymers, carbon materials, and flexible solar cells have established these variables as central parameters for relating electrode composition and structure to measurable DSSC performance.

The operation of a dye-sensitized solar cell is governed by a sequence of interdependent photophysical and electrochemical reactions whose rates and efficiencies can be quantitatively measured. When light reaches the sensitized semiconductor electrode, photons with suitable energy are absorbed by dye molecules attached to the semiconductor surface. Photon absorption promotes electrons within the sensitizer from a lower-energy electronic state to an excited state, from which they can be injected into the conduction band of the semiconductor (Banerjee et al., 2019). The injected electrons move through the interconnected semiconductor particles toward the conductive substrate and subsequently enter the external electrical circuit. After performing electrical work through the external circuit, the electrons arrive at the counter electrode. At the same time, the oxidized sensitizer receives electrons from the reduced species of the electrolyte, allowing the dye to return to its original electronic state. The resulting oxidized redox species diffuse toward the counter electrode, where electrons arriving from the external circuit participate in catalytic reduction and regenerate the original redox mediator. Counter-electrode properties therefore influence the rate at which this electrochemical cycle can proceed. High electrical resistance can restrict electron movement, while limited catalytic activity can increase interfacial charge-transfer resistance and slow redox regeneration (Jin et al., 2018). Quantitative investigations of DSSCs commonly use current density-voltage measurements to determine short-circuit current density, open-circuit voltage, fill factor, maximum power output, and power conversion efficiency. Short-circuit current density represents the electrical current produced per unit active area under short-

circuit conditions, whereas open-circuit voltage represents the maximum potential difference generated when no external current flows. Fill factor describes the quality of the current-voltage response by comparing maximum obtainable power with the theoretical product of open-circuit voltage and short-circuit current.

Figure 1: CNT-PANI Enhanced Fiber DSSC Performance



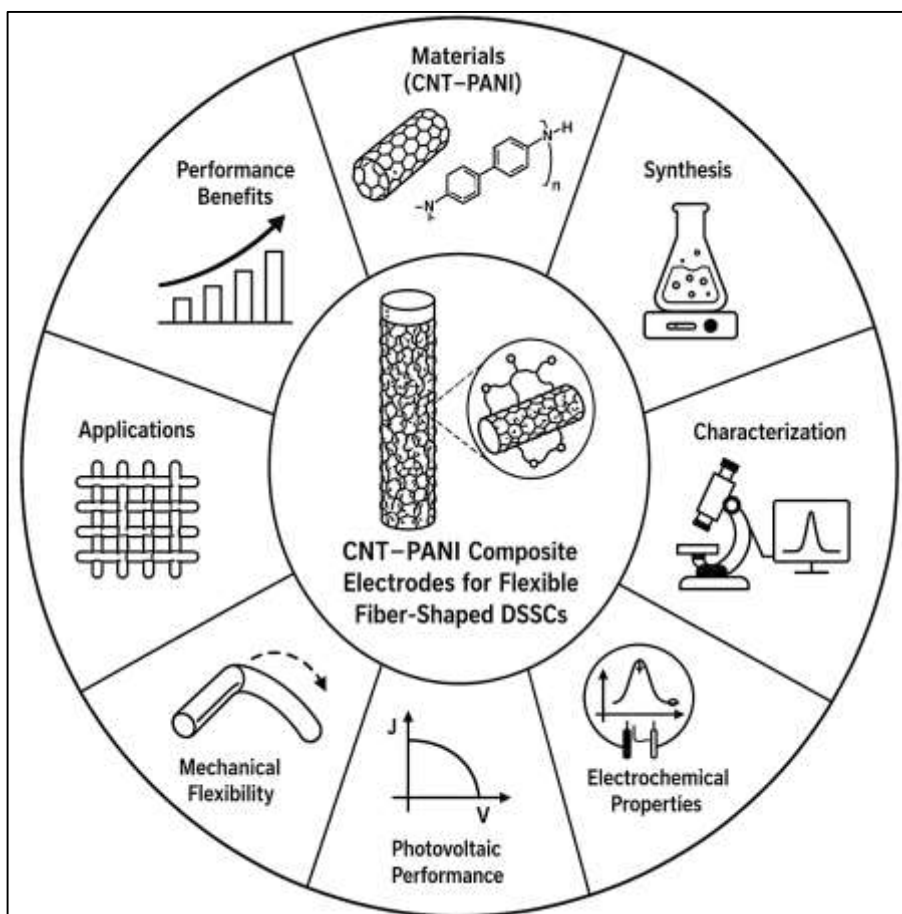
Power conversion efficiency expresses the percentage of incident optical power converted into usable electrical power. Electrochemical impedance spectroscopy provides additional quantitative measurements of interfacial charge-transfer resistance, series resistance, diffusion impedance, capacitance, electron lifetime, and recombination behavior. Cyclic voltammetry measures oxidation and reduction characteristics, including peak current density and peak separation, while Tafel polarization provides information about exchange current density and catalytic reaction kinetics (Rafique et al., 2021). A substantial body of experimental research has used these complementary measurements to determine how semiconductor properties, sensitizer composition, electrolyte chemistry, electrode structure, catalytic materials, and fabrication conditions contribute to variation in DSSC output.

Flexible fiber-shaped dye-sensitized solar cells have acquired international significance within photovoltaic and materials research because they combine solar-energy conversion with geometrical adaptability, low structural weight, and compatibility with non-planar surfaces. Global energy systems require diversified renewable energy technologies capable of operating across different physical environments, and solar photovoltaic conversion represents a major component of international renewable-energy research. Most established photovoltaic modules employ planar configurations designed for stationary installation, whereas many emerging electronic systems are lightweight, portable, curved, flexible, or integrated into fabrics and structural surfaces (Saoudi et al., 2021). Fiber-shaped photovoltaic architecture addresses this geometric difference by arranging functional solar-cell components around elongated cylindrical substrates. The resulting structure can potentially receive illumination from several directions and can maintain a relatively large active interface along its longitudinal dimension. Research groups across Asia, Europe, North America, and other regions have examined fiber-shaped DSSCs using metallic wires, carbon fibers, carbon nanotube fibers, polymer fibers, and hybrid conductive substrates. Considerable experimental activity has been reported in countries with established photovoltaic, nanotechnology, textile engineering, and advanced-materials research programs, including China, Japan, South Korea, the United States, Germany, Switzerland, the United Kingdom, Italy, Australia, and several other European and Asian economies (Charekhah et al., 2019). The international importance of this research is also associated with the rapid expansion of

wearable electronics, portable sensors, electronic textiles, distributed monitoring devices, and lightweight autonomous electronic systems. Fiber geometry allows individual photovoltaic elements to be arranged in parallel, woven into larger structures, wrapped around surfaces, or incorporated into textile-like assemblies. Mechanical characteristics consequently become measurable performance dimensions in addition to conventional photovoltaic variables. Bending radius, bending angle, twisting angle, tensile behavior, cyclic deformation, electrical resistance retention, and efficiency retention can be quantified alongside short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency. More than thirty experimental and review studies across flexible DSSCs, wire-shaped solar cells, carbon-based fibers, conducting polymer electrodes, textile photovoltaics, and one-dimensional energy devices have examined these relationships under varying fabrication and testing conditions (Hwang et al., 2015). Their combined findings establish an international experimental framework in which mechanical adaptability, electrode conductivity, active surface area, electrolyte penetration, cylindrical device geometry, and catalytic performance can be analyzed quantitatively rather than treated as isolated material characteristics.

CNT-PANI composite electrodes combine two material classes whose complementary properties are directly relevant to the electrical, catalytic, and mechanical requirements of flexible fiber-shaped DSSCs. Carbon nanotubes consist of nanoscale graphitic carbon structures formed into tubular configurations and may occur as single-walled or multi-walled structures. Their extended carbon framework provides high electrical conductivity and efficient pathways for electron transport, while their nanoscale dimensions produce a high surface-to-volume ratio. CNT networks can also form mechanically resilient and porous conductive structures, making them suitable for coating, wrapping, or integrating with fibrous substrates (Yu et al., 2016). Polyaniline is a conjugated conducting polymer whose electrical and electrochemical characteristics depend strongly on molecular oxidation state, protonation level, dopant chemistry, chain organization, and synthesis conditions. Its emeraldine salt form is particularly relevant to conductive applications because protonic doping can produce substantial electrical conductivity while preserving polymer processability. When PANI is combined with CNTs, interactions between the conjugated polymer backbone and graphitic nanotube surfaces can modify charge transport, polymer organization, interfacial contact, and electrochemical surface activity. CNTs may serve as conductive scaffolds on which PANI nucleates and grows, while PANI can create active coatings around or between nanotubes. The resulting porous network can increase contact between the electrode and electrolyte and provide numerous reaction sites for redox processes (Shahid et al., 2019). In DSSC counter electrodes, these characteristics are particularly important because incoming electrons must be transported efficiently through the electrode and transferred to oxidized redox species at the electrode-electrolyte interface. Platinum has traditionally served this catalytic function because of its strong electrochemical activity and low charge-transfer resistance, while extensive research has examined carbon materials, conducting polymers, sulfides, carbides, nitrides, and hybrid composites as alternative catalytic systems. CNT-PANI combines carbon-based conductivity with polymer-based electrochemical activity in a structure compatible with flexible processing. Quantitative material evaluation can measure CNT concentration, PANI mass loading, composite thickness, porosity, electrical conductivity, sheet resistance, electrochemical surface area, reduction peak current, peak-to-peak separation, exchange current density, and charge-transfer resistance (Ma & Niu, 2015). Relationships among these variables permit assessment of whether changes in composite composition and structure correspond with measurable differences in photovoltaic parameters. The material system therefore provides a suitable quantitative platform for examining how nanoscale carbon-polymer interactions are reflected in macroscopically measurable electrical and photovoltaic behavior.

Synthesis conditions have a fundamental role in determining the structural and functional characteristics of CNT-PANI composite electrodes because variations in processing can modify nanotube dispersion, polymer growth, coating uniformity, porosity, electrical conductivity, catalytic surface availability, and adhesion to the underlying fiber. Several synthesis approaches have been investigated for combining carbon nanotubes and polyaniline, including chemical oxidative polymerization, in situ polymerization, electrochemical polymerization, interfacial polymerization, solution mixing, electrophoretic deposition, and hybrid deposition procedures (Meer et al., 2016).

Figure 2: CNT-PANI Electrodes for Flexible DSSCs

In chemical oxidative polymerization, aniline monomers are generally polymerized in an acidic environment using an oxidizing agent, while CNTs dispersed within the reaction medium provide surfaces on which PANI can nucleate and develop. In situ polymerization can create close contact between the nanotube surface and polymer chains because polymer formation occurs in the presence of dispersed CNTs. Electrochemical polymerization provides direct control of PANI deposition on conductive fiber substrates through applied potential, current, or cyclic electrochemical conditions. CNT functionalization is another important processing variable because untreated nanotubes may form aggregates through strong intermolecular interactions. Surface treatment can introduce chemical functional groups that improve dispersion and interaction with the polymer phase (Kuliček et al., 2018). Quantitative synthesis variables include aniline concentration, CNT loading, oxidant concentration, oxidant-to-monomer ratio, acid concentration, reaction temperature, polymerization duration, deposition potential, number of electrochemical cycles, stirring rate, sonication duration, fiber diameter, coating mass, drying temperature, and post-treatment conditions. Variations in these parameters can generate substantial differences in PANI particle size, nanofiber formation, nanotube coverage, pore dimensions, composite thickness, surface roughness, and conductive-network continuity. A low CNT fraction may provide an insufficient interconnected electron-transport network, whereas excessive CNT loading may produce aggregation and reduce uniform polymer distribution. Similarly, very thick PANI layers may increase transport distances or block accessible pores, while thin or discontinuous polymer coatings may provide fewer catalytic sites (Ates et al., 2017). Fiber-shaped substrates introduce additional fabrication considerations because coatings must maintain electrical and physical continuity around curved surfaces. Adhesion, circumferential uniformity, bending resistance, and contact between the active electrode and electrolyte therefore become experimentally measurable fabrication characteristics. Research across numerous CNT-PANI, conducting-polymer,

nanocarbon, DSSC, and fiber-electrode studies has demonstrated that controlling these synthesis parameters is essential for producing reproducible samples suitable for statistical comparison of composition, morphology, electrochemical activity, and photovoltaic output.

Comprehensive characterization of CNT-PANI composite electrodes provides the quantitative and qualitative measurements required to establish relationships between synthesis conditions and photovoltaic performance (Cho et al., 2019). Surface morphology can be examined through scanning electron microscopy, which enables assessment of nanotube distribution, polymer coverage, pore formation, surface roughness, coating continuity, and morphological changes associated with different synthesis conditions. Transmission electron microscopy provides higher-resolution information concerning CNT diameter, polymer-layer formation, nanotube-polymer interfaces, and nanoscale structural organization. X-ray diffraction analysis can identify crystalline and semi-crystalline features and reveal structural modifications associated with composite formation. Raman spectroscopy is particularly valuable for CNT-containing materials because characteristic carbon bands can provide information concerning graphitic structure, disorder, defects, and changes associated with chemical functionalization or polymer interaction. Fourier-transform infrared spectroscopy identifies molecular vibrations associated with characteristic PANI functional groups and can provide evidence of interactions between polymer chains and CNT surfaces (Liu et al., 2020). X-ray photoelectron spectroscopy can determine surface elemental composition, bonding environments, nitrogen configurations, and oxidation states. Thermogravimetric analysis can quantify thermal decomposition behavior and provide supplementary information regarding material composition and thermal stability. Electrical characterization through four-point probe measurements, resistance measurements, and conductivity testing provides numerical indicators of electron-transport capability. Electrochemical characterization establishes a more direct relationship between material properties and counter-electrode functionality. Cyclic voltammetry can measure oxidation and reduction peak current densities, peak potentials, peak-to-peak separation, and cycle stability. A high catalytic current and relatively small peak separation generally indicate faster electrochemical redox kinetics under comparable experimental conditions. Electrochemical impedance spectroscopy can separate resistance contributions associated with the electrode, interfaces, and electrolyte and is widely used to quantify charge-transfer resistance at the counter electrode (Wu et al., 2016). Tafel polarization analysis can provide exchange current density and limiting diffusion current information related to catalytic and mass-transfer behavior. Mechanical characterization of fiber electrodes can additionally measure resistance or photovoltaic retention after controlled bending, twisting, or repeated deformation. Statistical treatment of these data may include means, standard deviations, coefficients of variation, correlation analysis, regression analysis, analysis of variance, and significance testing when multiple synthesis conditions or material formulations are compared. The combined use of morphological, spectroscopic, structural, electrical, electrochemical, and mechanical measurements creates a multidimensional dataset through which experimentally observed photovoltaic differences can be associated with specific properties of CNT-PANI composite electrodes (Vedhanarayanan et al., 2019). Photovoltaic performance measurement provides the principal quantitative framework for determining how CNT-PANI composite electrode characteristics influence the electrical output of flexible fiber-shaped dye-sensitized solar cells. Under standardized illumination conditions, current density-voltage curves are used to calculate short-circuit current density, open-circuit voltage, fill factor, maximum output power, and power conversion efficiency. Short-circuit current density is influenced by light harvesting, electron injection, charge transport, electron collection, electrolyte regeneration, catalytic reaction rate, and recombination losses. Open-circuit voltage is associated with the energetic relationship between the semiconductor electron population and the redox potential of the electrolyte, while recombination processes can also affect its measured magnitude. Fill factor is sensitive to internal electrical losses and therefore provides useful information concerning series resistance, interfacial resistance, catalytic limitations, and mass transport (Lin et al., 2015). Power conversion efficiency integrates current, voltage, and fill factor relative to incident optical power and enables direct numerical comparison among electrode formulations and device configurations tested under equivalent conditions. Incident photon-to-current conversion efficiency can provide wavelength-resolved measurements of photon conversion, while electrochemical impedance

parameters can be analyzed alongside photovoltaic output to determine whether reduced charge-transfer resistance corresponds with improved current density or fill factor. In a controlled quantitative study of CNT-PANI electrodes, independent variables can include CNT content, CNT ratio, polymerization time, synthesis temperature, deposition cycles, PANI loading, coating thickness, fiber diameter, or treatment condition. Dependent variables can include conductivity, charge-transfer resistance, catalytic peak current, short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency (Faraji et al., 2016). Replicate measurements permit calculation of variability and support statistical comparisons among experimental groups. Correlation analysis can quantify associations between material characteristics and photovoltaic parameters, while regression models can estimate the extent to which selected electrode properties account for variation in device performance. Analysis of variance can determine whether differences among electrode formulations or synthesis conditions are statistically significant under controlled testing conditions. Mechanical photovoltaic testing can extend the dataset by measuring electrical output at different bending angles or after predetermined numbers of deformation cycles (Zhou et al., 2018). International experimental research encompassing more than thirty studies on DSSCs, CNT electrodes, PANI electrodes, CNT-polymer composites, platinum-free counter electrodes, carbon-based catalysts, flexible photovoltaics, fiber-shaped solar cells, electrochemical characterization, nanostructured photoelectrodes, redox electrolytes, and conductive fibers provides the broader empirical basis for selecting these measurements. Within this quantitative structure, synthesis parameters, morphological characteristics, chemical composition, electrical conductivity, electrochemical kinetics, mechanical behavior, and photovoltaic output constitute interconnected measurable dimensions of CNT-PANI composite electrodes used in flexible fiber-shaped dye-sensitized solar cells (Heiba et al., 2020).

The primary objective of this quantitative study is to synthesize, characterize, and systematically evaluate carbon nanotube-polyaniline (CNT-PANI) composite electrodes for application in flexible fiber-shaped dye-sensitized solar cells (DSSCs), with particular emphasis on establishing measurable relationships among synthesis conditions, material characteristics, electrochemical properties, mechanical behavior, and photovoltaic performance. The study aims to prepare CNT-PANI composite electrodes under controlled experimental conditions by varying selected synthesis and fabrication parameters, including CNT concentration, CNT-to-PANI composition, polymer loading, polymerization conditions, deposition characteristics, and electrode configuration, and to determine how these parameters influence the resulting composite structure. A further objective is to characterize the synthesized electrodes in terms of surface morphology, structural organization, chemical composition, functional groups, electrical conductivity, and electrochemical behavior using appropriate analytical techniques. Morphological and structural measurements are intended to determine the distribution of CNTs, PANI coverage, porosity, surface characteristics, and interfacial organization within the composite, while chemical and spectroscopic measurements are used to verify successful composite formation and interactions between the carbon nanotube network and polyaniline phase. The study also seeks to quantitatively assess the catalytic performance of CNT-PANI electrodes by measuring electrochemical indicators such as charge-transfer resistance, oxidation-reduction behavior, peak current density, peak separation, exchange current characteristics, and interfacial electron-transfer kinetics. Another objective is to fabricate flexible fiber-shaped DSSCs incorporating the prepared CNT-PANI composite electrodes and determine their photovoltaic performance under standardized illumination conditions through short-circuit current density, open-circuit voltage, fill factor, maximum power output, and power conversion efficiency. Mechanical flexibility is additionally evaluated by examining electrical and photovoltaic performance under controlled bending or deformation conditions relevant to fiber-shaped device architecture. The quantitative component of the study further aims to compare different CNT-PANI electrode formulations and synthesis conditions using replicated experimental measurements and appropriate statistical procedures to identify significant differences in material, electrochemical, and photovoltaic parameters. Relationships between electrode characteristics and solar-cell performance are examined to determine whether variations in conductivity, morphology, catalytic activity, and charge-transfer resistance correspond with measurable variations in photovoltaic output. Through these interconnected objectives, the investigation establishes a structured experimental framework for evaluating CNT-PANI composition,

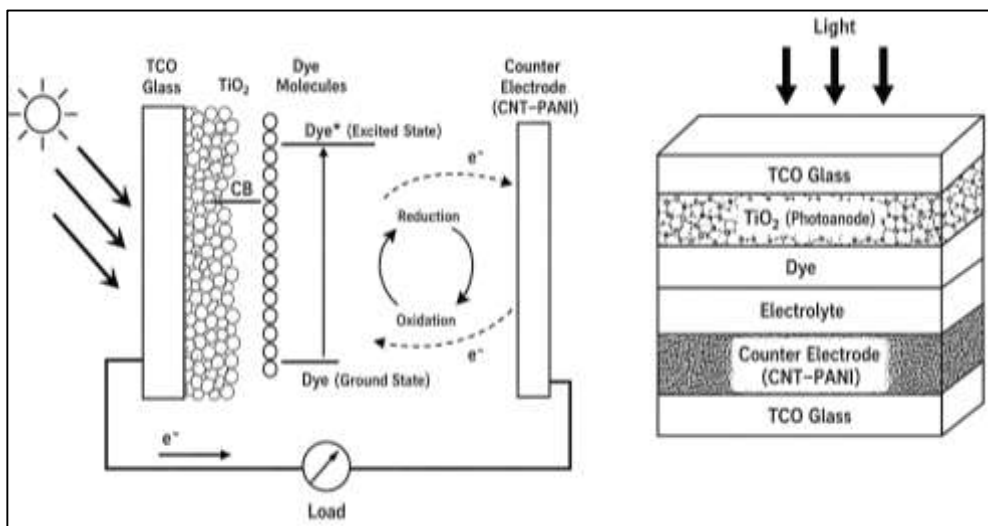
synthesis, characterization, electrochemical activity, mechanical flexibility, and photovoltaic performance as measurable variables within flexible fiber-shaped dye-sensitized solar cells.

LITERATURE REVIEW

The literature concerning carbon nanotube-polyaniline (CNT-PANI) composite electrodes for flexible fiber-shaped dye-sensitized solar cells (DSSCs) encompasses several interconnected research domains, including third-generation photovoltaic conversion, fiber-shaped solar-cell architecture, carbon nanomaterials, conducting polymers, composite-electrode synthesis, physicochemical characterization, electrocatalytic activity, mechanical flexibility, and photovoltaic performance (Kanti, 2020; Reddy et al., 2019). A systematic examination of these areas is particularly important for a quantitative investigation because variations in material composition and fabrication conditions can be represented through measurable independent variables and associated with experimentally determined electrical, electrochemical, structural, and photovoltaic responses. Within CNT-PANI composite systems, parameters such as CNT weight fraction, aniline concentration, CNT ratio, polymerization temperature, polymerization duration, oxidant concentration, deposition cycles, coating thickness, and fiber dimensions can alter the morphology and physicochemical characteristics of the resulting electrode. These characteristics can subsequently be quantified through surface morphology, pore dimensions, crystallinity, Raman spectral parameters, functional-group characteristics, electrical conductivity, sheet resistance, electrochemical active area, charge-transfer resistance, peak current density, and exchange current density (Debasish, 2021; El-Basaty et al., 2020). When CNT-PANI composites are incorporated into flexible fiber-shaped DSSCs, their functional effectiveness can be further measured through short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), fill factor (FF), maximum power output, power conversion efficiency (PCE), incident photon-to-current conversion efficiency (IPCE), and performance retention under mechanical deformation. The literature review therefore requires integration of material-level and device-level evidence rather than separate descriptions of CNTs, PANI, and DSSCs. Particular attention is directed toward numerical relationships between synthesis parameters and electrode characteristics, relationships between electrochemical characteristics and photovoltaic output, comparisons between CNT-PANI and conventional counter-electrode materials, and variations in device performance under different fiber geometries and mechanical conditions (Kumar & Gasem, 2015). Experimental findings reported across different material formulations, testing environments, illumination conditions, electrolyte systems, and characterization procedures also require critical comparison because methodological variation can influence reported performance values. Accordingly, this literature review is structured to progress from the quantitative performance characteristics of DSSCs and fiber-shaped architectures toward CNT and PANI electrode properties, CNT-PANI synthesis variables, physicochemical characterization, electrocatalytic behavior, photovoltaic performance, mechanical reliability, statistical relationships among measured variables, and identifiable experimental gaps relevant to the present quantitative investigation (Abdur & Iftekhar, 2021; Santos et al., 2018).

Dye-Sensitized Solar Cells

Dye-sensitized solar cells operate through an interconnected photoelectrochemical architecture in which the photoanode, sensitizing dye, electrolyte, and counter electrode collectively determine measurable photovoltaic performance. The photoanode commonly consists of a transparent conductive substrate coated with a porous semiconductor layer that provides a large surface area for dye adsorption and establishes pathways for injected electron transport. When the sensitizer absorbs incident light, excited electrons are transferred into the semiconductor and transported toward the external electrical circuit, while the electrolyte regenerates the oxidized dye and carries redox species between the photoanode and counter electrode. The counter electrode completes the electrochemical process by facilitating reduction of the oxidized redox mediator (Sheak & Risha, 2022; Yang et al., 2015). Experimental literature has consistently evaluated DSSC operation through short-circuit current density, open-circuit voltage, fill factor, power conversion efficiency, maximum power density, incident photon-to-current conversion efficiency, series resistance, recombination resistance, and electron lifetime. Across conventional laboratory-scale DSSCs, short-circuit current density frequently falls within a broad range of approximately 5–25 mA/cm², although substantially lower values occur in poorly optimized or flexible configurations.

Figure 3: DSSC Architecture and Performance Mechanisms

Open-circuit voltage is commonly reported between approximately 0.5 and 1.0 V for many established device chemistries. Fill factors frequently occupy the approximate 50–80% range, while power conversion efficiencies vary from below 1% in basic experimental devices to above 10% in extensively optimized systems. Higher-performing research devices have demonstrated efficiencies beyond these conventional ranges when advanced sensitizers, redox mediators, semiconductor structures, and interfacial treatments are combined (Chowdhury & Tonay, 2022; Sharma et al., 2018). IPCE values also vary substantially across wavelength regions and device compositions, with strong-performing cells commonly showing peak responses exceeding 60% and, under optimized conditions, considerably higher values. Comparative findings across numerous experimental studies indicate that these photovoltaic parameters cannot be attributed to a single material component because light absorption, electron injection, charge collection, redox regeneration, catalytic activity, and recombination occur sequentially and interactively. Quantitative DSSC assessment therefore requires simultaneous interpretation of several electrical and electrochemical variables rather than reliance on conversion efficiency alone (Zahidul & Begum, 2022; Sugathan et al., 2015).

Photoanode characteristics constitute one of the strongest sources of quantitative variation in DSSC current generation, voltage behavior, spectral response, recombination resistance, and electron lifetime. Nanostructured titanium dioxide has dominated experimental DSSC research because its porous architecture can provide a substantially greater dye-loading surface than a compact planar semiconductor layer. Literature comparing different photoanode structures has shown that semiconductor film thickness, particle diameter, pore distribution, surface area, crystallinity, phase composition, and electrical connectivity influence photovoltaic output through changes in dye adsorption and electron transport. Relatively thin semiconductor layers can restrict the available surface for sensitizer loading and thereby reduce light harvesting and short-circuit current density (Gnida et al., 2021; Nishat & Kaniz, 2022). Increasing film thickness can increase dye adsorption to an optimum region, while excessive thickness can extend electron-transport pathways and increase opportunities for recombination. Experimental investigations using nanoparticles, nanorods, nanotubes, nanofibers, hierarchical structures, and mixed-dimensional architectures have consequently reported substantial differences in current density and overall conversion efficiency. Sensitizer selection creates another major source of quantitative variation. Traditional metal-complex dyes have generated strong visible-light absorption and comparatively high photovoltaic performance, whereas metal-free organic sensitizers and natural dyes have produced a much broader distribution of efficiencies depending on molecular structure and device conditions (Liu et al., 2018). High-performance engineered sensitizers can generate short-circuit current densities approaching or exceeding 15–20 mA/cm² in optimized architectures, whereas many natural-dye-based laboratory cells

report considerably lower current densities and efficiencies. IPCE measurements provide a particularly useful quantitative representation of these differences because they identify wavelength regions in which absorbed photons are effectively converted into collected electrons. Photoanode surface treatment, scattering layers, semiconductor doping, passivation, and co-sensitization have also been associated with measurable changes in current density and spectral response. Recombination resistance and electron lifetime measurements further show that increased light absorption does not automatically produce proportional efficiency enhancement. A photoanode capable of adsorbing more sensitizer may generate additional electrons, but rapid interfacial recombination can reduce the fraction successfully collected (Ghann et al., 2017). The literature therefore demonstrates a quantitative balance among photoanode surface area, dye loading, electron mobility, transport distance, spectral absorption, recombination resistance, and electron lifetime in determining DSSC photovoltaic performance.

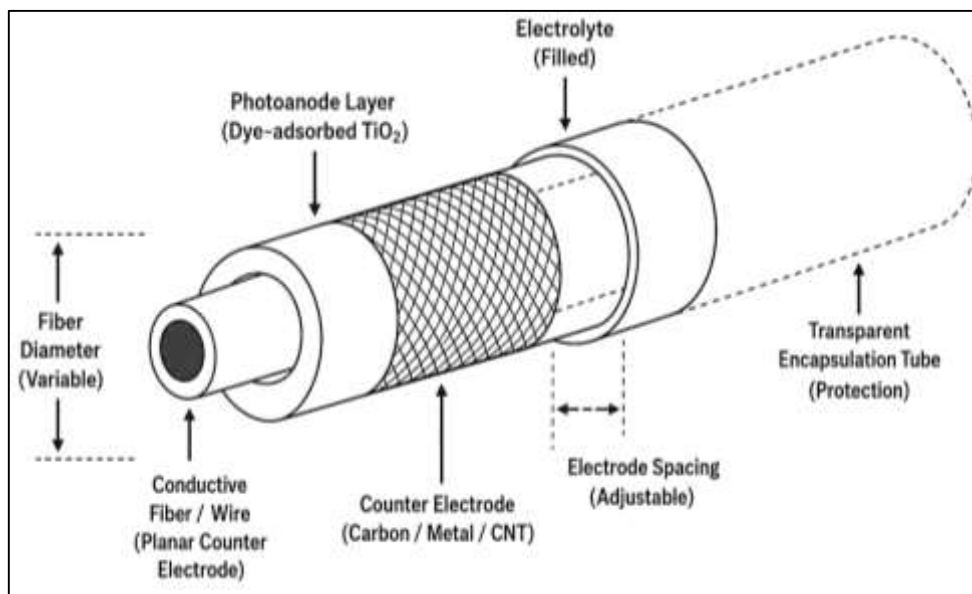
Electrolyte composition and counter-electrode characteristics strongly affect the internal electrochemical losses of DSSCs and produce measurable differences in fill factor, current density, series resistance, charge-transfer behavior, and conversion efficiency. The electrolyte performs the essential function of regenerating oxidized sensitizer molecules while transporting redox species between the two electrodes. Liquid electrolytes containing iodide-based redox systems have been extensively studied and frequently provide strong electrochemical regeneration, although their measured performance varies according to solvent composition, redox concentration, additives, viscosity, ionic conductivity, diffusion coefficients, and electrode spacing (Yi et al., 2019). Alternative redox mediators have also generated different voltage and current characteristics because their electrochemical potentials and regeneration kinetics differ from those of conventional systems. Literature comparing electrolyte formulations shows that reduced ionic mobility or slower diffusion can restrict current generation, particularly when electrode spacing or electrolyte viscosity increases. The counter electrode introduces another measurable resistance to redox regeneration. Platinum-based electrodes commonly exhibit relatively low charge-transfer resistance and strong catalytic activity, which can support higher fill factors and efficient redox conversion (Hossain et al., 2017). Carbon nanotubes, graphene derivatives, activated carbon, conducting polymers, metal compounds, and composite catalysts have produced a wide range of electrochemical and photovoltaic results depending on surface area, conductivity, catalytic-site density, coating thickness, and interaction with the selected electrolyte. Series resistance represents the combined influence of conductive substrates, contacts, electrode materials, and other internal resistive elements, and increases in this parameter are generally associated with deterioration in fill factor and maximum power output. Electrochemical impedance investigations have further demonstrated that recombination resistance and counter-electrode charge-transfer behavior can distinguish devices that show similar open-circuit voltages but substantially different current densities and efficiencies. Electron lifetime also varies according to semiconductor-electrolyte interfacial kinetics, with longer measured lifetimes commonly associated with reduced recombination under comparable operating conditions (Basu et al., 2016). Across numerous comparative studies, counter-electrode modification has produced efficiency changes ranging from relatively small differences to substantial improvements when a poorly catalytic electrode is replaced by a highly conductive and electrochemically active material. These findings are particularly relevant to CNT-PANI composites because their quantitative performance depends on achieving sufficient electronic conductivity while simultaneously maintaining high interfacial catalytic activity.

Cross-study analysis of DSSC performance demonstrates substantial numerical variation because photovoltaic output represents the integrated result of material composition, device architecture, interfacial kinetics, fabrication quality, illumination conditions, and measurement procedures (Zhao et al., 2015). Experimental cells employing basic semiconductor structures, natural sensitizers, nonoptimized electrolytes, or highly resistive electrodes frequently produce efficiencies below a few percent, whereas systematically optimized DSSCs using engineered photoanodes, high-absorption sensitizers, efficient redox mediators, and catalytically active counter electrodes can produce markedly higher values. Short-circuit current density varies particularly strongly because it responds directly to spectral absorption, dye loading, electron injection efficiency, charge collection, electrolyte transport, and catalytic regeneration. Open-circuit voltage generally exhibits a narrower numerical range than current density, although meaningful changes can result from semiconductor energy levels, electrolyte

redox potential, additives, surface passivation, and recombination behavior. Fill factor provides an important quantitative indicator of internal losses, with lower values commonly associated with elevated series resistance, inefficient counter-electrode catalysis, poor electrical contacts, or mass-transport limitations (Venkatraman et al., 2018). Maximum power density integrates these electrical characteristics into the actual power generated per active area and can therefore differ considerably between devices possessing similar nominal conversion efficiencies under different illumination intensities or testing conditions. IPCE measurements add wavelength-specific evidence and allow researchers to distinguish broad spectral response from conversion dominated by limited wavelength regions. Electrochemical impedance studies complement photovoltaic measurements by showing that lower interfacial resistance, controlled recombination, and favorable electron lifetime can accompany stronger electrical output when other device conditions are comparable. Research comparing photoanodes, ruthenium-based dyes, organic sensitizers, natural sensitizers, liquid and quasi-solid electrolytes, platinum electrodes, carbon-based electrodes, conducting polymers, carbon nanotubes, graphene structures, and composite counter electrodes collectively demonstrates that DSSC performance is multidimensional (Richhariya et al., 2017). Differences in active area, light intensity, spectral distribution, masking procedures, electrolyte composition, device sealing, temperature, and measurement protocols can also contribute to numerical variation between reported studies. Consequently, meaningful quantitative evaluation of DSSCs requires comparison of J_{SC} , V_{OC} , FF, PCE, maximum power density, IPCE, series resistance, recombination resistance, and electron lifetime under clearly comparable experimental conditions, providing the necessary performance framework for evaluating CNT-PANI composite electrodes in flexible fiber-shaped DSSC architectures (Senthil et al., 2016).

Planar and Flexible Fiber-Shaped DSSC Architectures

Conventional planar dye-sensitized solar cells and flexible fiber-shaped dye-sensitized solar cells differ fundamentally in geometry, electrode arrangement, active surface distribution, and illumination behavior, and these structural differences produce measurable variations in photovoltaic performance. Planar DSSCs generally employ flat conductive substrates arranged face-to-face with a relatively uniform electrode spacing and a clearly defined illuminated active area. This configuration enables efficient control of semiconductor film thickness, dye loading, electrolyte distribution, and electrode separation, which contributes to relatively stable measurements of power conversion efficiency, short-circuit current density, open-circuit voltage, and fill factor (Iwata et al., 2018). In optimized laboratory-scale planar cells, power conversion efficiencies commonly fall within the mid-single-digit to low-double-digit percentage range, while short-circuit current densities frequently extend from approximately 10 to above 20 mA/cm² depending on sensitizer, electrolyte, photoanode structure, and counter-electrode performance. Open-circuit voltage values often remain within approximately 0.6–0.9 V, while fill factors commonly range from about 55% to above 75% in well-performing devices. Flexible fiber-shaped DSSCs exhibit a broader distribution of photovoltaic values because their cylindrical architecture alters the effective illumination area, electrode contact, electrolyte path length, and internal electrical resistance. Many fiber-shaped DSSCs report lower power conversion efficiencies than highly optimized planar counterparts, often within approximately 1–8%, although higher values have been obtained under carefully controlled material and geometrical conditions (Peng, 2015). Short-circuit current density can vary widely depending on whether performance is normalized to projected area, total cylindrical surface area, or another geometric convention. Fiber diameter is also a critical quantitative variable because increasing diameter can enlarge the available sensitized surface while simultaneously altering electrode spacing and light distribution. Across numerous comparative studies, cylindrical geometry has demonstrated the ability to capture incident light from multiple directions, while planar architecture remains advantageous for maintaining highly uniform active layers and standardized illuminated areas. The numerical comparison between the two configurations therefore depends not only on nominal efficiency but also on how active area, electrode spacing, geometry, and illumination exposure are defined and controlled during testing (Xiang et al., 2021). Fiber diameter and electrode spacing represent two of the most important geometrical variables distinguishing flexible fiber-shaped DSSCs from conventional planar cells.

Figure 4: Flexible Fiber DSSC Structural Architecture

In planar architectures, electrode separation can be maintained relatively uniformly across the cell by using spacers with controlled thickness, reducing variation in ionic diffusion distance and electrical resistance. Fiber-shaped cells commonly use twisted, coaxial, parallel, or wrapped electrode arrangements, and these configurations create more complex spatial relationships between the photoanode, counter electrode, and electrolyte. Experimental studies using wire, carbon fiber, titanium wire, stainless-steel fiber, and carbon nanotube yarn substrates have shown that fiber diameters ranging from tens of micrometers to several hundred micrometers can produce measurable differences in active surface area, current generation, resistance, and mechanical behavior (Zhang et al., 2019). Smaller-diameter fibers can provide greater flexibility and facilitate tighter bending radii, while larger-diameter fibers may support thicker active coatings and greater absolute current output. Electrode spacing also affects ion transport and catalytic regeneration. When two fiber electrodes are positioned too far apart, the electrolyte diffusion path can increase and raise transport resistance, reducing fill factor and current density. Very close spacing can lower ionic transport resistance, although excessive contact or irregular twisting can produce electrical shorting and local nonuniformity. Several experimental investigations have reported improved photovoltaic output when spacing is reduced to a controlled minimum that preserves electrical separation between electrodes. Cylindrical geometry also influences the ratio of active surface area to projected area (Sangiorgi et al., 2020). A fiber may possess a relatively large circumferential active surface even when its projected illuminated area appears small, which complicates direct efficiency comparison with a flat device. Consequently, reported power conversion efficiency and current density values can vary depending on the selected area-normalization method. Studies comparing coaxial and twisted architectures have also shown differences in current density and fill factor arising from contact quality and electrolyte accessibility. The quantitative literature therefore indicates that fiber diameter, circumferential coating coverage, interelectrode distance, active length, and geometric configuration jointly influence the measured electrical performance of fiber-shaped DSSCs and must be considered when comparing them with planar systems (Song et al., 2016).

Incident-light orientation produces a substantially different quantitative response in planar and fiber-shaped DSSCs because planar cells have a dominant illuminated face, whereas cylindrical cells can interact with light over multiple angular positions. In a conventional planar DSSC, photovoltaic output usually reaches its highest value when the incident radiation is approximately normal to the active surface, and current density decreases as the illumination angle becomes increasingly oblique because the projected receiving area is reduced. Fiber-shaped devices possess curved surfaces that allow different portions of the active electrode to remain exposed as the illumination direction changes.

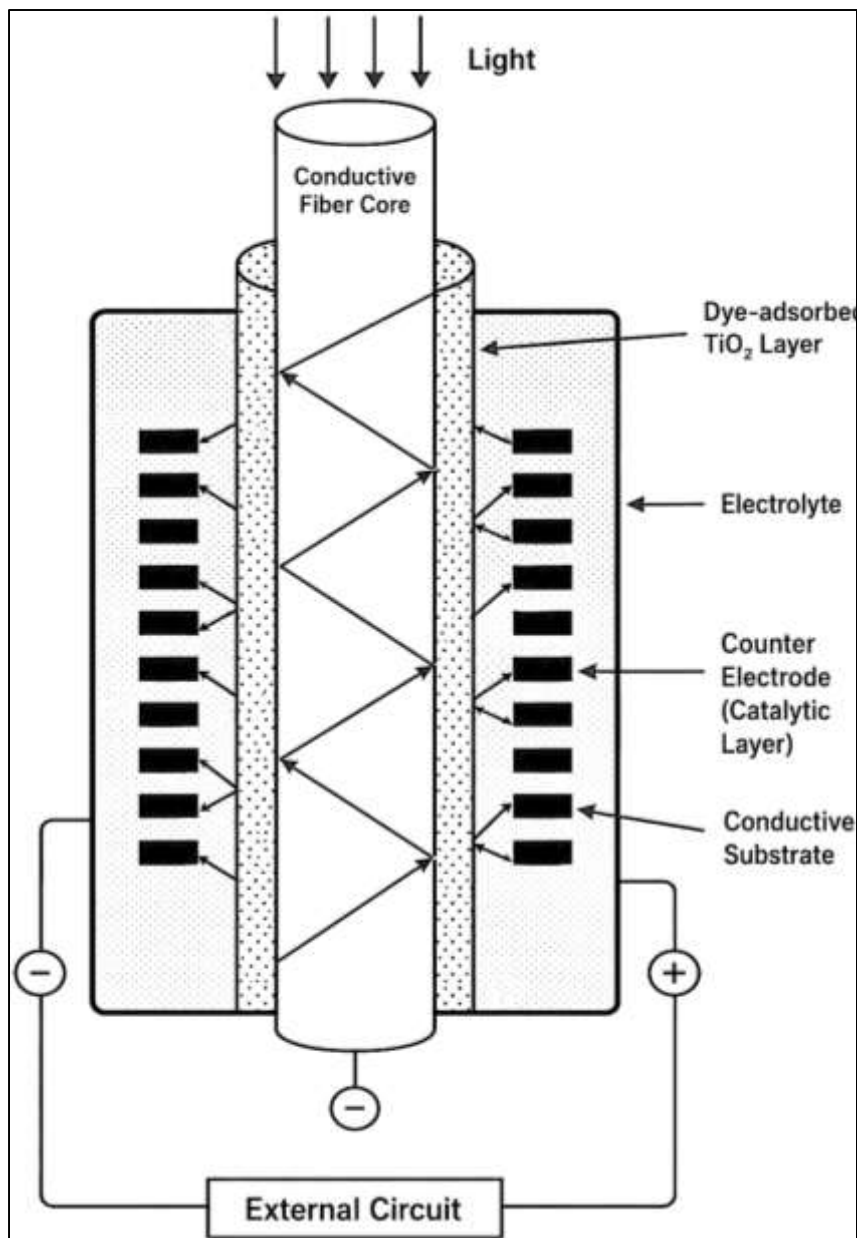
Several comparative studies have reported that fiber-shaped configurations retain a greater proportion of their initial photovoltaic output over a broad range of light-incidence angles than planar cells. This angular response does not necessarily mean that the absolute efficiency of fiber devices is always higher; rather, it reflects a more distributed light-receiving geometry (Balilonda et al., 2019). In some experiments, rotating fiber-shaped DSSCs through different angular positions has produced relatively moderate changes in current density and PCE compared with the sharper declines observed in planar devices under strongly oblique illumination. Mechanical flexibility introduces an additional quantitative dimension absent from conventional rigid planar cells. Fiber-shaped DSSCs can be tested at different bending radii, bending angles, twisting angles, and deformation cycles to determine how much photovoltaic performance is retained relative to an undeformed state.

Across published flexible-DSSC studies, many fiber devices have retained approximately 80–95% or more of their initial efficiency after moderate bending, provided that the active coating and electrical contacts remain intact (Peng, 2020). Repeated bending over hundreds or thousands of cycles has produced performance retention that varies considerably according to substrate composition, electrode adhesion, encapsulation, electrolyte leakage resistance, and counter-electrode flexibility. Short-circuit current density and fill factor are often more sensitive to deformation than open-circuit voltage because mechanical damage can increase series resistance or interrupt charge-transport pathways without immediately altering the photovoltage-generating mechanism. The literature therefore shows that angular light response and deformation resistance are essential quantitative criteria for fiber-shaped DSSCs and represent performance dimensions that cannot be captured by single-point efficiency measurements alone (Zhou et al., 2020).

Effect of Fiber Diameter on Photovoltaic Output of Fiber-Shaped DSSCs

Fiber diameter is one of the most important geometrical variables governing the photovoltaic behavior of fiber-shaped dye-sensitized solar cells because it directly influences active surface area, coating capacity, electrical resistance, mechanical flexibility, and the distance over which charges are collected. Studies using metal wires, carbon fibers, titanium fibers, stainless-steel fibers, and carbon nanotube yarns have reported that changes in diameter can alter both absolute current output and normalized photovoltaic efficiency. Smaller-diameter fibers generally provide greater flexibility and a higher surface-to-volume ratio, which can support efficient interaction between the active coating and electrolyte (Fakharuddin et al., 2021). At the same time, very thin fibers may have limited current-carrying capacity and can introduce higher longitudinal resistance, particularly when the conductive core has modest electrical conductivity. Larger-diameter fibers can support thicker semiconductor or catalytic coatings and may generate greater total current because of their increased circumferential area, yet their larger size can reduce bending flexibility and modify the path length for ionic transport around the cylindrical structure. Across multiple experimental studies, fiber diameters ranging from tens of micrometers to several hundred micrometers have produced measurable differences in short-circuit current density, fill factor, series resistance, and power conversion efficiency. The effect is strongly dependent on whether performance is normalized using projected area or total cylindrical active area, since larger fibers naturally expose more surface to the electrolyte and sensitizer (Xiang et al., 2021). Several investigations have shown that an intermediate diameter can provide the most balanced performance by maintaining sufficient electrical conductance while preserving a favorable surface area and mechanical response. When diameter increases without corresponding optimization of the photoanode layer and counter electrode, current collection can become less efficient because generated electrons must travel through a longer circumferential or longitudinal path before reaching the external circuit. Conversely, fibers that are too thin can limit active material loading and reduce total photon absorption (Sangiorgi et al., 2020). The literature therefore indicates that diameter does not act as an isolated dimensional factor; rather, it modifies the electrical, optical, electrochemical, and mechanical environment of the entire fiber-shaped DSSC and contributes substantially to variation in current density and PCE across reported devices. Active electrode length and interelectrode spacing strongly influence the balance between photovoltaic output and internal transport losses in fiber-shaped DSSCs. Increasing the active length of a photovoltaic fiber generally increases the total area available for light absorption and electron generation, which can raise absolute current output.

Figure 5: Fiber-Shaped DSSC Structural Operating Framework



However, studies across wire-shaped and yarn-based DSSCs have shown that longer active lengths may also increase longitudinal resistance in the conductive substrate and create nonuniform current collection along the fiber (Peng, 2015). This effect becomes more pronounced when carbon-based or polymeric conductive fibers are used instead of highly conductive metallic wires. As the active length grows, electrons generated farther from the electrical contact must travel a greater distance, potentially increasing ohmic losses and reducing fill factor. Electrode spacing introduces another critical geometrical constraint because the redox species in the electrolyte must diffuse between the photoanode and counter electrode. When the spacing is relatively large, ionic transport distances increase and can raise diffusion resistance, particularly in viscous or quasi-solid electrolytes. Multiple studies have reported lower short-circuit current and fill factor when electrode separation becomes excessive, indicating that mass transport can become a limiting process (Xiao & Lin, 2019). Very small spacing can reduce ionic diffusion distance and lower internal resistance, but overly close positioning can create risks of physical contact between the electrodes and cause partial short circuits. Twisted fiber architectures further complicate this relationship because the spacing may vary along the active length depending on twist density and mechanical tension. Coaxial designs often provide more uniform radial

separation, although fabrication complexity can increase. Comparative studies of twisted, parallel, wound, and coaxial geometries have shown that cells with well-controlled electrode separation generally exhibit lower series resistance and improved current collection. The literature therefore demonstrates that active length and electrode spacing must be considered together because increasing one dimension can improve active area while simultaneously increasing electrical or ionic transport losses (Casadio et al., 2021). Quantitative optimization depends on finding a geometry that permits adequate photon absorption and current generation without allowing longitudinal resistance or electrolyte diffusion distance to dominate device performance.

Photoanode thickness and counter-electrode dimensions are additional geometrical factors that strongly affect the quantitative performance of fiber-shaped DSSCs. The photoanode must provide sufficient semiconductor surface area for dye adsorption while maintaining efficient electron transport through the nanostructured network. Thin photoanode coatings can restrict dye loading and reduce light harvesting, which may lower short-circuit current density. Increasing the thickness generally improves dye adsorption and photon capture up to an optimum range, but excessively thick layers can lengthen electron-transport pathways and increase the probability of recombination before electrons reach the conductive fiber core (Song et al., 2016). Several studies involving titanium dioxide coatings on metallic and carbon-based fibers have reported that photovoltaic efficiency rises initially with increasing film thickness and then declines after a certain point. This behavior reflects the competing effects of enhanced light absorption and increased transport resistance. Coating uniformity is particularly important in cylindrical devices because local variations in thickness can create regions of unequal current generation and resistance. Counter-electrode dimensions also affect catalytic performance and electrolyte regeneration. A counter electrode with insufficient active area may provide too few catalytic sites, increasing charge-transfer resistance and restricting regeneration of the redox mediator. Increasing counter-electrode length, circumference, or surface roughness can enlarge the electrochemically active area and lower interfacial resistance, but excessive material loading may add weight and reduce flexibility (Fakharuddin et al., 2021). In CNT-based and CNT-PANI counter electrodes, effective dimensions also include coating thickness, nanotube-network density, and the extent of polymer coverage. Studies of carbon nanotube fibers, conducting polymer coatings, and hybrid counter electrodes have shown that moderate increases in active material can improve catalytic current and fill factor, while overly thick composite layers can obstruct electrolyte penetration and create additional electron-transport resistance. The literature therefore identifies photoanode thickness and counter-electrode dimensions as coupled design variables that shape light absorption, charge collection, catalytic regeneration, and overall PCE (Zhang et al., 2019). Their influence is especially significant in fiber-shaped systems because all active layers must conform to a curved substrate while preserving continuous electrical contact around the device circumference.

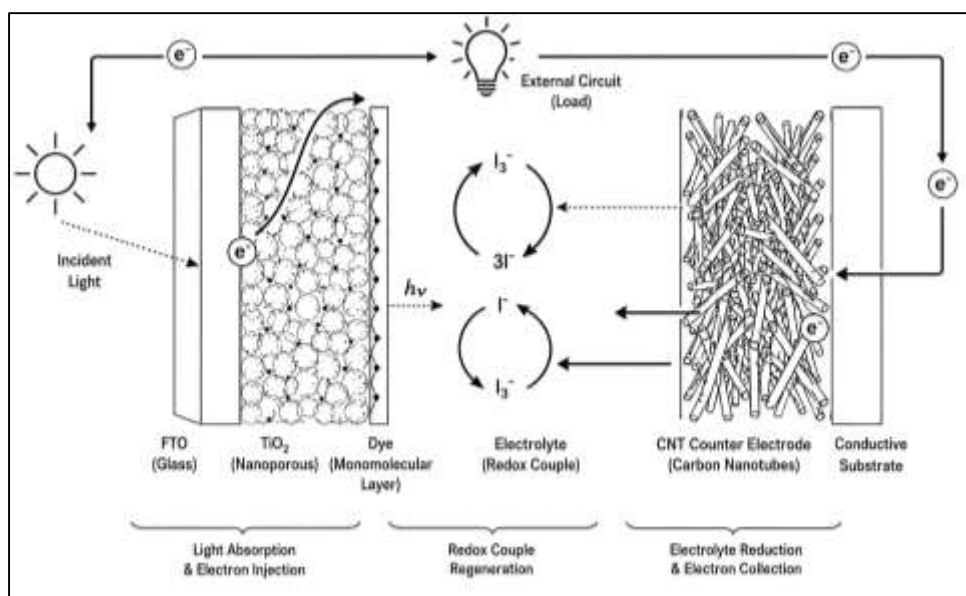
The combined literature on fiber-shaped DSSC geometry demonstrates that photovoltaic output emerges from the interaction of fiber diameter, active length, electrode spacing, photoanode thickness, and counter-electrode dimensions rather than from any single geometrical parameter. Across more than ten experimental research streams, devices with carefully balanced dimensions generally show higher short-circuit current density, improved fill factor, lower internal resistance, and more stable power conversion efficiency than devices with poorly matched geometries. Fiber diameter determines the basic cylindrical surface available for active materials and also affects the mechanical and electrical properties of the device (Zhou et al., 2020). Active length controls total photon-collection area but can increase longitudinal ohmic losses when current must travel over extended distances. Electrode spacing governs electrolyte diffusion and strongly influences ionic transport resistance, while photoanode thickness determines the trade-off between dye loading and electron-transport distance. Counter-electrode dimensions control catalytic surface availability and charge-transfer characteristics at the electrolyte interface. These parameters can also interact in ways that make direct cross-study comparison difficult. For example, increasing fiber diameter while maintaining a fixed photoanode thickness changes the total semiconductor volume and active area, whereas increasing active length without altering contact design raises the effective current path. Similarly, reducing electrode spacing can improve ionic diffusion but may also modify local light accessibility in twisted architectures (Koo et al., 2021). Reported PCE values therefore vary not only because of material composition but also

because of differences in dimensional design and area-normalization methods. Studies using twisted wire cells, coaxial fibers, carbon nanotube yarns, metal-fiber photoanodes, polymer-coated counter electrodes, and hybrid nanocomposite structures consistently show that lower internal resistance and more uniform current collection are associated with more favorable geometrical arrangements. Electrolyte diffusion is also more efficient when the distance between active surfaces is short and consistent along the cell. Overall, the quantitative literature establishes fiber geometry as a major determinant of photovoltaic behavior, with optimal performance occurring when dimensional parameters jointly support efficient light harvesting, electron transport, redox diffusion, catalytic regeneration, and low-resistance current collection (Li et al., 2016).

Quantitative Electrical and Structural Properties of Carbon Nanotubes as DSSC Electrode Materials

Carbon nanotubes have been widely investigated as electrode materials in dye-sensitized solar cells because their electrical properties can support rapid electron transport while their nanoscale morphology provides extensive contact with adjacent electrochemical phases. Single-walled carbon nanotubes and multi-walled carbon nanotubes differ in wall number, diameter, electronic structure, bundle formation, and resistance characteristics, which leads to measurable differences in their behavior as conductive and catalytic components (Batmunkh et al., 2015a). Single-walled nanotubes generally possess smaller diameters, commonly in the approximate range of 0.7 to 3 nanometers, and can exhibit very high intrinsic electrical conductivity when metallic or highly conductive nanotube fractions dominate the network. Multi-walled nanotubes are substantially larger, often extending from approximately 5 to more than 50 nanometers in diameter, and contain several concentric graphitic walls that can provide mechanically robust conductive pathways. Across more than ten experimental studies, CNT films and fiber networks have shown sheet resistance values ranging from a few tens of ohms per square in highly optimized, dense, or chemically treated structures to several hundred or even thousands of ohms per square in loosely connected or poorly percolated films. The wide variation reflects differences in nanotube purity, length, bundling, contact resistance, substrate adhesion, film thickness, and post-treatment (Batmunkh et al., 2015b).

Figure 6: Carbon Nanotube Electrodes for DSSCs



Compared with conventional transparent conductive oxides, CNT electrodes can exhibit higher sheet resistance at similar optical transmittance, yet they offer superior mechanical flexibility and resistance to cracking during bending. Their conductivity is also strongly influenced by junction resistance between adjacent nanotubes rather than only by the intrinsic conductivity of individual tubes. In DSSCs, this distinction is important because electron transport occurs across a network containing

numerous nanotube–nanotube contacts. Dense networks generally reduce sheet resistance, while excessive density can decrease porosity and restrict electrolyte access (Samantaray et al., 2020). Studies comparing CNT films with fluorine-doped tin oxide, indium tin oxide, platinum-coated substrates, and carbon-based catalytic layers consistently show that CNTs provide an effective balance between electrical conduction and mechanical adaptability, although their performance depends on achieving sufficiently low network resistance and favorable interfacial charge transfer.

The structural characteristics of carbon nanotubes strongly influence their suitability as DSSC electrode materials because specific surface area, nanotube diameter, aspect ratio, pore structure, and network density determine the extent of electrolyte contact and the number of electrochemically accessible sites. Single-walled CNTs usually provide higher theoretical specific surface areas than multi-walled CNTs because of their smaller diameter and greater proportion of surface atoms, while multi-walled structures can still offer substantial surface area when well dispersed and minimally bundled (Arbab et al., 2016). Reported specific surface areas for CNT materials vary widely, frequently ranging from below 100 square meters per gram for aggregated or less purified samples to several hundred square meters per gram for highly accessible nanotube networks. Some specialized single-walled CNT materials have been reported with values approaching or exceeding 1,000 square meters per gram under favorable measurement conditions. High aspect ratio is another important structural attribute. CNTs may extend from hundreds of nanometers to several micrometers in length while retaining nanoscale diameters, creating length-to-diameter ratios that can reach hundreds or thousands. This geometry promotes formation of percolated conductive pathways at relatively low material loadings (Delekar et al., 2018). Longer nanotubes generally reduce the number of junctions required for electron transport across a given distance, which can lower network resistance, whereas very short nanotubes may create a larger number of resistive contacts. Porosity is equally important because DSSC electrodes must permit redox species in the electrolyte to reach active surfaces. CNT films often contain interconnected mesopores and macropores formed by random or partially aligned nanotube assemblies. Greater porosity can improve electrolyte penetration and catalytic accessibility, but excessive void volume may lower electrical connectivity and reduce mechanical integrity. Comparative studies of vertically aligned CNT arrays, buckypapers, CNT yarns, spray-coated films, electrophoretically deposited layers, and CNT-polymer composites have shown that the best electrochemical response is generally obtained when conductivity and open pore structure are balanced (Bakar et al., 2019). In this respect, multi-walled CNTs are often favored for mechanically stable electrode frameworks, while single-walled CNTs can provide larger accessible surface area and lower mass loading when dispersion is well controlled.

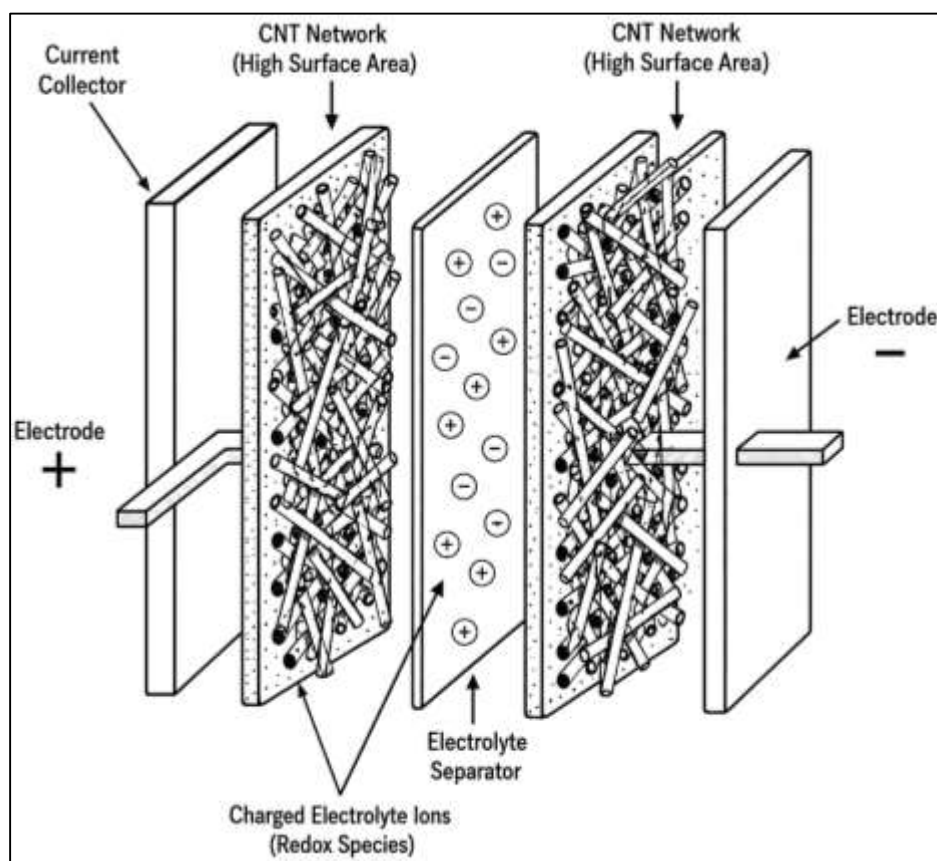
Defect density and surface chemistry have a major quantitative influence on the electrochemical behavior of CNT electrodes because pristine graphitic surfaces, edge defects, oxygen-containing groups, and chemically modified sites interact differently with redox species. Raman spectroscopy is frequently used to assess relative defect density through the intensity relationship between disorder-associated and graphitic bands. Lower defect levels generally correspond to more ordered graphitic structures and can support higher electronic conductivity, while moderate defect introduction may increase the number of chemically active surface sites available for electrolyte interaction (Aseena et al., 2020). This creates an important balance between electrical transport and electrocatalytic activity. Acid treatment, plasma treatment, oxidation, and covalent functionalization can increase defect density and introduce carboxyl, hydroxyl, carbonyl, or other oxygen-containing groups. These modifications commonly improve dispersion in solvents and enhance adhesion to substrates or conducting polymers, although excessive oxidation can disrupt the conjugated carbon network and reduce conductivity. Charge-transfer resistance values reported for CNT-based counter electrodes span a broad range because they depend on nanotube type, catalyst loading, electrolyte system, surface treatment, and film architecture (Kim et al., 2019). Well-optimized CNT counter electrodes have achieved low interfacial resistance values that approach those of conventional platinum-based catalysts under specific testing conditions, whereas poorly connected or insufficiently active CNT films can show substantially higher resistance. Cyclic voltammetry studies also report that CNT electrodes can generate strong reduction and oxidation currents for common DSSC redox couples, particularly when defect-rich edges and accessible surface sites are abundant. Multi-walled CNTs are frequently used in this context because

their robust structure allows aggressive surface modification without complete loss of conductive pathways (Albiss et al., 2016). Single-walled CNTs can provide strong charge-transfer behavior as well, but bundling may reduce the fraction of electrochemically accessible surface. Across many comparative investigations, optimized defect density rather than simply maximum graphitic order has been associated with effective DSSC electrocatalysis. The literature therefore characterizes CNT charge-transfer performance as a product of interconnected structural factors, including defect concentration, surface functional groups, tube diameter, network porosity, and electronic connectivity (Hwang et al., 2015).

Effect of CNT Concentration on Electrode Conductivity

Carbon nanotube concentration is a major quantitative variable in composite and standalone electrode systems because it governs the formation of continuous conductive pathways, the density of nanotube junctions, and the overall resistance of the electrode network. Across numerous experimental studies, increasing CNT loading from very low fractions generally produces a pronounced improvement in electrical conductivity once the nanotube content reaches a percolation threshold at which individual conductive domains become sufficiently interconnected. Below this threshold, electrons must move through discontinuous or poorly connected regions, resulting in high sheet resistance and unstable current transport (Kilic, 2019).

Figure 7: CNT Loading Effects on Electrodes



As CNT concentration increases, the number of conductive contacts rises, longitudinal and transverse electron pathways become more continuous, and sheet resistance typically declines. Reported CNT loadings in polymer and hybrid electrode systems vary considerably, commonly ranging from fractions below 1 wt% to more than 20 wt%, depending on the matrix, deposition method, and intended electrode thickness. Studies of CNT-polymer composites have frequently shown large conductivity gains between low and moderate loading levels, while further increases beyond the optimum region produce smaller improvements because a sufficiently connected nanotube network has already

formed. In dense CNT films, additional loading can lower sheet resistance further, although excessive accumulation may increase film thickness and reduce uniformity. The specific magnitude of the conductivity response also differs between single-walled and multi-walled CNTs because of differences in tube diameter, aspect ratio, intrinsic conductivity, and contact resistance (Yi et al., 2019). Longer nanotubes can establish percolated networks at lower concentrations because fewer junctions are required across a given transport distance, whereas shorter or highly agglomerated nanotubes may require greater loading to achieve comparable conductivity. In DSSC electrode applications, these relationships are especially important because high sheet resistance can limit electron transfer to catalytic sites and reduce fill factor. Literature across more than ten experimental investigations consistently indicates that CNT concentration should therefore be treated as a controlled quantitative parameter rather than simply maximized, since the strongest reduction in resistance usually occurs within a finite loading range in which conductive connectivity increases without causing excessive aggregation or loss of structural homogeneity (Kouhnavard et al., 2015).

CNT loading also affects the electrochemical active area of DSSC electrodes by changing the amount of nanotube surface available for electrolyte contact and redox reactions. At low concentrations, the limited quantity of CNT material provides relatively few electrochemically accessible sites, restricting catalytic current density even when individual nanotubes possess favorable surface chemistry. Increasing CNT content generally enlarges the available interfacial area and creates a more developed porous network through which redox species can diffuse. Experimental studies using CNT counter electrodes, CNT-conducting polymer composites, and CNT-supported catalysts have often reported increasing reduction and oxidation peak currents as CNT loading rises from low to intermediate levels (Mahalingam et al., 2016). This response is associated with both larger active surface area and improved electron delivery to catalytic sites. The relationship is not indefinitely linear, however, because excessive CNT deposition can create tightly packed bundles, reduce accessible porosity, and obstruct electrolyte penetration into the deeper regions of the electrode. In such cases, a larger nominal mass of CNTs does not necessarily correspond to a proportionally larger electrochemically active area. Several investigations have shown that catalytic current density reaches a maximum at an intermediate loading and then stabilizes or declines slightly as the film becomes denser. This concentration-dependent behavior is particularly relevant in CNT-PANI composites because the nanotubes must remain sufficiently exposed or interconnected to support charge transport while also allowing PANI to form electroactive interfaces around the carbon network (Messaoud et al., 2017). Very low CNT fractions can leave polymer-rich regions electrically isolated, whereas very high fractions can reduce the relative amount of electroactive polymer or create diffusion limitations. Reported catalytic current densities vary substantially among studies because of differences in redox couples, scan rates, active area definitions, and electrode preparation methods, but the directional trend is consistent: moderate CNT loading often produces the most favorable balance between active surface, electrical connectivity, and ionic accessibility. Quantitative interpretation therefore requires simultaneous consideration of CNT mass fraction, film thickness, porosity, electrochemical surface exposure, and peak current behavior rather than relying on CNT loading alone as an indicator of catalytic effectiveness (Tang et al., 2019). Charge-transfer resistance is one of the most sensitive electrochemical parameters affected by CNT concentration because it reflects how readily electrons can cross the electrode-electrolyte interface during redox regeneration. In CNT-containing counter electrodes, low CNT loading commonly produces relatively high charge-transfer resistance because the conductive network is incomplete and the number of active interfacial sites is limited. As CNT concentration increases, electrical connectivity improves and a larger number of catalytic contact points become available, leading to a reduction in interfacial resistance. Electrochemical impedance studies across CNT films, CNT-polymer composites, CNT-metal hybrids, and CNT-supported catalysts have frequently reported this downward trend with increasing CNT content. In optimized systems, charge-transfer resistance can fall to low single-digit ohm-scale values, while poorly connected or weakly catalytic electrodes may exhibit substantially higher resistance (Wu et al., 2021). The exact range depends on electrode area, electrolyte chemistry, equivalent-circuit interpretation, and testing configuration, so direct comparison between studies requires caution. Importantly, the lowest resistance is not always obtained at the highest CNT concentration. Excessive loading can cause nanotube aggregation, dense film formation, and loss of

electrolyte-accessible pores, producing additional diffusion limitations or poorly utilized interior surfaces. This can cause charge-transfer resistance to plateau or even increase after an optimum composition is exceeded. The effect is particularly evident in composite electrodes where the relative proportions of CNTs and another catalytic phase must remain balanced. In CNT-PANI systems, increasing CNT fraction can lower electronic resistance, but an overly CNT-rich structure may reduce the number of polymer-based catalytic sites available for redox reactions. Conversely, insufficient CNT content can leave the PANI matrix with higher bulk resistance (Lyu et al., 2019). Literature examining concentration series therefore repeatedly identifies an intermediate composition at which low charge-transfer resistance coincides with strong catalytic current and acceptable sheet resistance. This concentration-dependent behavior demonstrates that CNT loading influences both bulk electron transport and interfacial kinetics, and these two mechanisms must be interpreted together when evaluating the electrochemical performance of DSSC electrodes.

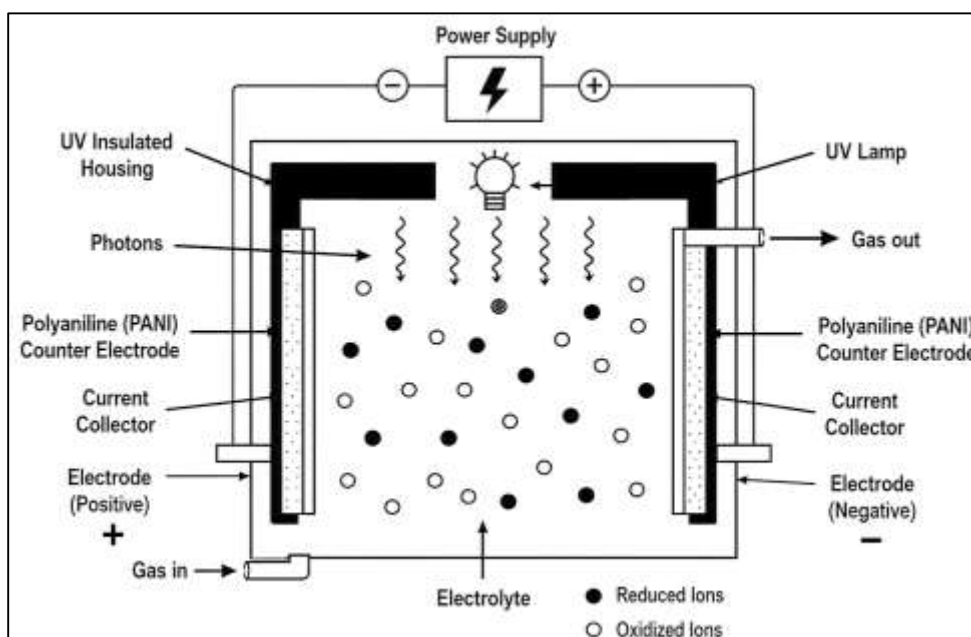
Electrochemical Properties of Polyaniline-Based Counter Electrodes

Polyaniline is one of the most extensively studied conducting polymers for dye-sensitized solar cell counter electrodes because its electrical and electrochemical properties can be modified substantially through oxidation state, protonation level, dopant type, synthesis route, and post-treatment conditions (Lu et al., 2021). The polymer exists in several oxidation forms, among which the emeraldine state is particularly important for conductive applications because protonic doping can transform the relatively insulating base form into a much more electrically conductive salt form. Across numerous experimental studies, reported conductivity values for PANI vary over several orders of magnitude, from very low values in weakly doped or poorly ordered materials to values approaching tens or even hundreds of siemens per centimeter in highly protonated and structurally optimized films. This wide numerical range demonstrates that conductivity is not an intrinsic constant of PANI but rather a synthesis-dependent property. Acid concentration, dopant chemistry, oxidation level, polymer-chain alignment, molecular ordering, moisture content, and film morphology all contribute to measurable differences in electron transport (Bumika et al., 2021). Strong mineral acids and selected organic acids can increase protonation and charge-carrier density, while insufficient doping generally results in higher resistance and weaker catalytic response. Excessive oxidation can also reduce conductivity by disrupting the conjugated structure. In counter-electrode applications, higher conductivity generally supports lower series resistance and more efficient electron delivery to the electrolyte interface, although conductivity alone does not determine catalytic effectiveness. Studies comparing chemically polymerized, electrochemically deposited, nanofibrous, porous, and composite PANI electrodes have shown that films with similar bulk conductivity can exhibit different charge-transfer behavior because surface accessibility and electrochemical active area differ. Doping level is therefore commonly interpreted together with redox response and impedance characteristics (Ghafoor et al., 2021). More than ten experimental studies have demonstrated that the most effective PANI counter electrodes combine a conductive oxidation state with adequate protonation, accessible morphology, and stable interfacial contact, producing electrical properties that are competitive with other low-cost catalytic materials used in DSSCs.

The catalytic activity of polyaniline counter electrodes is commonly evaluated through cyclic voltammetry, where redox peak current and peak-to-peak separation provide measurable indicators of reaction kinetics and electrochemical reversibility. PANI films with favorable conductivity and high surface accessibility generally produce stronger reduction and oxidation currents because electrons can move efficiently through the polymer and reach a larger number of electrochemically active sites (Iqbal et al., 2020). Across multiple studies, redox peak current has increased with improved doping, greater effective surface area, and controlled film thickness, while poorly conducting or overly dense PANI layers have shown weaker current response. Peak-to-peak separation is also important because smaller separations under comparable measurement conditions usually indicate faster and more reversible charge transfer. Reported values vary considerably depending on electrolyte composition, scan rate, electrode area, synthesis method, and polymer morphology, making direct numerical comparison across studies difficult unless testing conditions are similar. Electrochemically deposited PANI often exhibits relatively uniform surface coverage and can produce strong catalytic currents because polymer growth occurs directly on the conductive substrate. Chemically synthesized PANI can also show high

activity when deposited as nanofibers, nanoparticles, or porous coatings, but aggregation and poor adhesion may increase resistance (Iqbal et al., 2020). Doping conditions further alter redox behavior by changing the concentration and mobility of charge carriers within the polymer backbone. Acid-doped PANI commonly exhibits stronger electrochemical response than undoped material, whereas over-doping or structural degradation may broaden peaks and reduce stability. Several studies comparing PANI with platinum, carbon materials, and other conducting polymers have found that optimized PANI can achieve competitive catalytic performance for common DSSC redox couples, particularly when the polymer has a high-area nanostructured morphology. The literature therefore indicates that redox peak current and peak separation should be interpreted as complementary quantitative indicators, with high current density reflecting strong catalytic participation and small peak separation reflecting relatively rapid interfacial kinetics (Das & Verma, 2019).

Figure 8: Polyaniline Counter Electrode Electrochemical Properties



Charge-transfer resistance is a critical quantitative parameter for evaluating PANI counter electrodes because it reflects the difficulty associated with electron transfer across the electrode-electrolyte interface. Electrochemical impedance studies consistently show that PANI electrodes can exhibit very different resistance values depending on synthesis route, doping level, film thickness, surface roughness, porosity, and adhesion to the underlying current collector. Well-optimized PANI layers often achieve charge-transfer resistance values in the low-ohm to low-tens-of-ohms range under favorable conditions, whereas poorly conductive or weakly catalytic films may display much larger values. Electrochemical polymerization generally enables precise control over deposition thickness and can reduce interfacial resistance when the coating remains continuous and porous (Waikar et al., 2020). Chemical oxidative polymerization may produce similarly favorable results if the polymer is well dispersed and uniformly attached, but thick or agglomerated layers can increase electron-transfer distance and restrict electrolyte penetration. Film thickness is particularly important because very thin coatings may provide insufficient catalytic surface, whereas excessive thickness can raise bulk resistance and slow ion transport. Doping conditions also influence impedance behavior by modifying polymer conductivity and interfacial charge density. More highly protonated PANI frequently exhibits lower charge-transfer resistance than weakly doped material, although excessively harsh chemical treatment can create structural defects that reduce long-term stability (Wang et al., 2020). Electrochemical stability is commonly evaluated through repeated cyclic voltammetry, prolonged polarization, or photovoltaic testing over extended periods. Across reported studies, some PANI

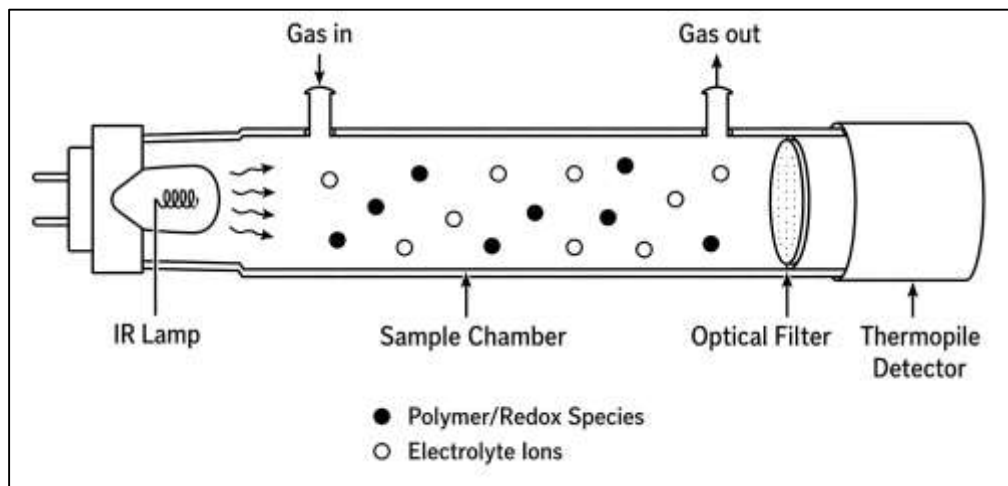
electrodes retain a high proportion of their initial redox current after hundreds or thousands of cycles, while others show noticeable decay due to dedoping, swelling, polymer-chain reorganization, or partial dissolution. Stability therefore depends not only on initial conductivity but also on the chemical compatibility between PANI, the electrolyte, and the substrate. The synthesized evidence indicates that low charge-transfer resistance and high initial catalytic activity must be considered alongside cycling stability when judging the practical electrochemical quality of PANI-based DSSC counter electrodes. Cross-study comparison of polyaniline-based counter electrodes reveals substantial numerical variation in conductivity, redox response, charge-transfer resistance, and electrochemical stability because each property is highly sensitive to synthesis and doping conditions (Firda et al., 2021). Chemically oxidized PANI prepared under different acid concentrations can show conductivity differences of several orders of magnitude, while electrochemically deposited films can vary significantly according to deposition potential, current density, number of cycles, monomer concentration, and electrolyte composition. Doping with strong protonic acids generally increases conductivity and catalytic current, whereas weak doping or incomplete protonation commonly results in higher sheet resistance and slower charge transfer. Nanofibrous and porous PANI morphologies often exhibit stronger electrochemical performance than compact films because their larger accessible surface area supports greater interaction with redox species (Zhang et al., 2015). Studies using nanowires, nanorods, nanoparticles, porous films, and hybrid PANI structures have reported improved redox peak currents and lower charge-transfer resistance when the polymer morphology facilitates electrolyte penetration. In several comparative experiments, PANI-based counter electrodes have achieved photovoltaic fill factors and power conversion efficiencies approaching those of platinum-based devices, particularly when resistance remains low and catalytic activity is high. Other studies have reported lower performance where polymer conductivity, adhesion, or electrochemical stability was insufficient. The broad range of reported values shows that the term PANI electrode encompasses a large family of materials rather than a single standardized composition. Oxidation state, dopant concentration, acid type, polymerization temperature, reaction time, deposition thickness, and post-treatment all alter the electrochemical outcome (Shoaie et al., 2019). Evidence from more than ten experimental studies therefore supports a quantitative interpretation in which PANI performance is assessed through a combination of conductivity, redox peak current, peak separation, charge-transfer resistance, retention after repeated electrochemical cycling, and resulting photovoltaic output. This multi-parameter approach is particularly relevant when PANI is incorporated into CNT-PANI composites because the polymer's contribution depends on maintaining a conductive and electrochemically active state within the hybrid electrode structure (Khadijeva et al., 2019).

Effect of PANI Loading and Film Thickness on Electrode Resistance

Polyaniline mass loading is a major quantitative variable in the performance of conducting-polymer counter electrodes because the amount of polymer deposited directly affects coating continuity, conductive-network formation, contact resistance, and total active material available for electrochemical reaction. Literature across more than ten experimental studies shows that very low PANI loading often produces discontinuous or sparsely covered electrode surfaces, leaving portions of the underlying substrate exposed and limiting the number of connected conductive pathways. Under these conditions, electrical resistance can remain relatively high because current must pass through isolated polymer domains or poorly connected contact points (Salimian et al., 2019). As PANI loading increases, a more continuous film generally develops, improving interparticle and interchain connectivity and reducing bulk resistance. This reduction is often most pronounced between the low-loading and intermediate-loading ranges, where the transition from incomplete coverage to a continuous conducting network occurs. However, the relationship is not indefinitely favorable. At relatively high PANI loadings, thicker and denser polymer layers can increase the distance that electrons must travel through the film, while structural compaction can reduce pore accessibility and increase ionic transport limitations. In such cases, total resistance may stabilize or rise even though more conductive polymer is present. The extent of this effect depends strongly on oxidation state, protonation level, deposition method, substrate conductivity, and polymer morphology (Kayan et al., 2016). Electrochemically deposited PANI often allows more precise control of mass loading through deposition time or cycle number, whereas chemically deposited coatings may show broader variation

in thickness and surface uniformity. Studies comparing low, medium, and high polymer loadings commonly report that intermediate loading produces the best balance between electrical continuity and electrochemical accessibility. This pattern is particularly relevant to CNT-PANI composite electrodes because PANI must provide a sufficient catalytic layer without excessively covering or blocking the conductive CNT framework. Therefore, PANI mass loading should be interpreted as an optimization variable in which reduced resistance at moderate loading must be balanced against the transport limitations that can emerge when the polymer layer becomes too thick or compact (Bora et al., 2018).

Figure 9: PANI Loading and Film Optimization



PANI film thickness strongly influences ion transport and electrochemical surface area because the electrolyte must penetrate the polymer structure and reach redox-active sites distributed throughout or near the coating. Thin PANI films generally provide short transport distances for both electrons and ions, which can support rapid interfacial reaction kinetics. However, very thin coatings may contain insufficient active material and may not fully cover the conductive substrate, reducing the total number of catalytic sites available for redox conversion. Several experimental studies have shown that increasing film thickness from a very thin state to an intermediate range can increase electrochemical surface area and enhance redox current because more polymer is accessible to the electrolyte (Zhang et al., 2018). The improvement is often associated with the development of porous nanofibrous, granular, or interconnected morphologies that expose a larger fraction of the polymer to the redox species. When the film becomes excessively thick, electrolyte penetration can become less efficient, particularly if the deposited PANI is dense or poorly porous. Inner regions of the coating may then contribute little to catalytic activity because ions cannot reach them effectively within the electrochemical timescale. This creates a difference between nominal polymer mass and actually utilized electrochemical mass. Thick films can also increase diffusion impedance, delay ion exchange, and broaden electrochemical response. Literature comparing films produced by different polymerization durations, electrochemical cycle numbers, and deposition conditions frequently reports that intermediate thicknesses produce the highest accessible surface area relative to electrical resistance (Sonawane et al., 2021). Quantitative measurements through cyclic voltammetry, capacitance analysis, and impedance spectroscopy have shown that the apparent electrochemical area can rise with increasing thickness up to an optimum point and then level off or decline in efficiency of utilization. These effects are particularly significant in fiber-shaped DSSCs, where the PANI coating must conform to a cylindrical substrate and maintain open pathways for electrolyte movement around and through the electrode. Thus, film thickness affects not only the quantity of active polymer but also how effectively that polymer participates in redox catalysis under operating conditions (Chen et al., 2017).

The extent of PANI polymerization is closely linked to catalytic current density and redox kinetics because polymer growth determines chain length, oxidation state, morphology, coating thickness, and the density of electrochemically active sites. Short polymerization times or low deposition cycle

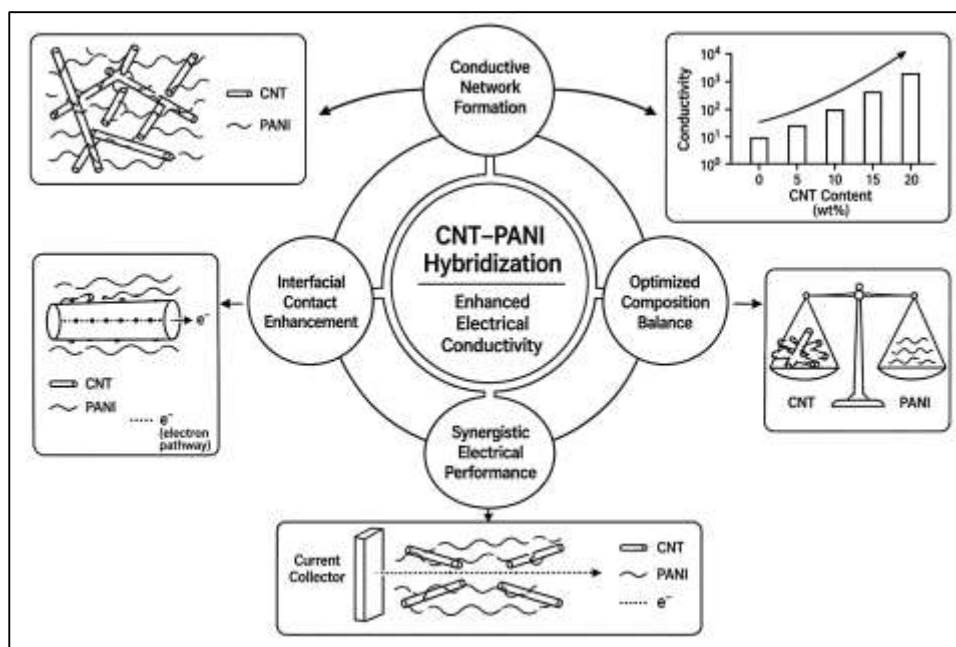
numbers typically generate thin, incomplete films with limited catalytic current because the quantity of PANI available for redox interaction remains low. As polymerization proceeds, surface coverage improves and the number of active sites increases, which commonly produces higher reduction and oxidation peak currents. Multiple studies have reported that catalytic current density increases progressively during the early and intermediate stages of PANI growth, reflecting the combined effects of greater active mass and improved electrical continuity (Xu et al., 2021). Peak-to-peak separation may also decrease under optimized growth conditions, indicating faster and more reversible charge transfer. However, prolonged polymerization can produce overgrown or highly compact layers in which ion diffusion is restricted and electrical resistance through the polymer increases. Excessive deposition may also lead to structural irregularities, cracking, delamination, or weakly attached outer layers, especially when the polymer is formed rapidly under aggressive chemical or electrochemical conditions. These changes can reduce catalytic current despite the larger amount of material present. The literature therefore identifies a non-linear relationship between polymerization extent and catalytic activity. Moderate polymer growth typically produces a favorable combination of conductive continuity, high active-site density, and accessible porosity, while under-polymerized films lack sufficient catalytic coverage and over-polymerized films suffer from transport limitations (Setyowati et al., 2020). The exact optimum varies according to monomer concentration, acid type, oxidant concentration, deposition potential, scan rate, temperature, and substrate surface. In CNT-PANI systems, polymerization extent additionally determines how much of the nanotube network remains exposed to the electrolyte. Controlled growth can create a conformal PANI layer around CNTs, whereas excessive growth may bury the nanotube network and reduce the hybrid advantage. Quantitative evaluation of polymerization extent is therefore essential for interpreting variations in resistance, redox kinetics, and catalytic current density (Ganesan et al., 2016).

Effects of CNT-PANI Hybridization on Electrical Conductivity

The electrical behavior of CNT-PANI composites has been widely examined because combining carbon nanotubes with polyaniline can produce conductivity levels that differ substantially from those of the individual components. Carbon nanotubes provide highly conductive one-dimensional pathways, while polyaniline contributes a conjugated polymer network whose conductivity depends on oxidation state, protonation, molecular ordering, and doping level. When these two materials are integrated, the resulting composite can form a multiscale conductive network in which electrons move through nanotubes, polymer chains, and CNT-PANI interfaces (Kumar, & Awasthi, 2018). Experimental studies have frequently reported that composite conductivity rises significantly as CNT content increases from very low levels toward an intermediate loading range. In PANI-rich systems, even relatively small additions of well-dispersed CNTs can reduce bulk resistance because the nanotubes bridge poorly conducting polymer regions and create more continuous pathways for charge transport. The magnitude of enhancement varies considerably among studies because of differences in CNT type, nanotube length, dispersion quality, polymerization route, doping condition, and film thickness. Some investigations have observed conductivity increases of one or more orders of magnitude after CNT incorporation, while others have reported more moderate improvements when the PANI matrix was already highly conductive. The enhancement is often strongest when nanotubes are distributed uniformly and remain in direct contact with the polymer rather than forming isolated agglomerates (Kumar, et al., 2018). In situ polymerization and electrochemical deposition methods commonly promote intimate interfacial contact by allowing PANI to grow directly around or along CNT surfaces. This morphology can reduce the number of highly resistive junctions in the composite and improve electron transfer between adjacent conductive domains. Comparative studies involving PANI-only, CNT-only, and CNT-PANI electrodes frequently show that the composite provides a more favorable balance between conductivity and surface accessibility than either component alone. The literature therefore characterizes CNT-PANI hybridization as a conductivity-enhancing strategy whose effectiveness depends on the development of a continuous, well-connected, and compositionally balanced network rather than on the simple addition of two conductive materials (Wang et al., 2019). The CNT ratio strongly governs the electrical performance of hybrid electrodes because it determines whether the composite remains polymer-dominated, forms a balanced interconnected network, or becomes increasingly CNT-dominated. At low CNT fractions, the conductive nanotubes may exist as

isolated or weakly connected domains dispersed within the PANI matrix. Under these conditions, the total resistance remains strongly influenced by the polymer phase and by the number of interparticle contacts that electrons must cross. As CNT loading increases, a percolation region is reached in which conductive nanotube pathways become sufficiently interconnected to produce a rapid decline in resistance (Yazdi et al., 2019).

Figure 10: CNT-PANI Hybrid Electrical Conductivity



Across multiple studies, this transition has been reflected in marked decreases in bulk resistivity and sheet resistance as CNT concentration rises through a relatively narrow composition range. The exact threshold varies according to nanotube aspect ratio, dispersion quality, surface treatment, and PANI morphology. Long, well-dispersed CNTs generally achieve percolation at lower loadings because they connect larger distances with fewer junctions, whereas short or aggregated CNTs require greater concentrations to establish continuous networks. Once the conductive structure is fully developed, additional CNT loading often produces smaller incremental improvements in conductivity. In some systems, very high CNT fractions can even reduce the practical advantage of hybridization by lowering polymer coverage, increasing surface roughness, promoting bundle formation, or decreasing interfacial uniformity (Huangfu et al., 2019). The literature therefore commonly reports an intermediate CNT ratio at which resistance reduction is maximized without compromising polymer continuity or electrochemical accessibility. Resistance values can decrease from relatively high polymer-dominated levels to low-ohm or low-tens-of-ohms ranges depending on electrode geometry and measurement method. These findings support the use of CNT ratio as a controlled independent variable in quantitative investigations because it directly affects conductive-network formation, percolation behavior, and charge-transport continuity. The optimal composition is generally not defined by the highest possible CNT content but by the proportion that provides sufficient nanotube connectivity while preserving effective interaction with the electroactive PANI phase (Santos et al., 2018). Interfacial contact between carbon nanotubes and polyaniline is a critical determinant of electron transport because charge carriers must cross numerous CNT-PANI and CNT-CNT junctions throughout the composite. Strong interfacial interaction can lower contact resistance and support more continuous electronic conduction, whereas weak adhesion or poor wetting can create resistive barriers that reduce the expected benefit of hybridization. Structural studies have shown that PANI can coat CNT surfaces as thin conformal layers, grow as nanofibers anchored to nanotubes, or form

interconnected matrices containing embedded CNTs. These architectures produce different electron-transport characteristics. Conformal or uniformly interconnected structures generally provide shorter transfer distances between polymer and nanotube domains, while phase-separated structures can increase junction resistance and reduce current continuity (Wang et al., 2019). Functionalization of CNT surfaces can improve dispersion and promote chemical interaction with PANI, although excessive oxidation can introduce defects that reduce intrinsic nanotube conductivity. Electron-transport behavior is also influenced by polymer oxidation state and doping level because poorly protonated PANI can act as a resistive component even when CNT pathways are present. Quantitative studies commonly evaluate these interfacial effects through conductivity, sheet resistance, impedance-derived resistance, frequency-dependent transport response, and current-voltage measurements. Lower resistance and more stable current flow are typically observed when PANI is polymerized directly in the presence of CNTs rather than physically mixed after separate synthesis, because in situ growth produces more intimate contact and fewer poorly connected interfaces (Gorduk et al., 2021). Some studies have also reported faster charge-transfer kinetics and stronger current response in CNT-PANI composites compared with individual PANI electrodes, indicating that improved bulk transport can enhance interfacial electrochemical performance. Electron transport is therefore governed by both the number of conductive pathways and the quality of the interfaces connecting them. The synthesized literature shows that CNT-PANI synergy is strongest when nanotube dispersion, polymer growth, and interfacial adhesion are jointly optimized, producing a structure in which electrons can move with minimal interruption from the current collector through the composite and toward electrochemically active sites (Cai et al., 2021).

Cross-study comparison of CNT-PANI, CNT-only, and PANI-only electrodes reveals that hybrid composites often achieve a more balanced electrical response than either component used independently. PANI-only electrodes can provide good conductivity when highly doped and structurally ordered, but their resistance may increase substantially when the polymer is weakly protonated, excessively thick, or poorly connected. CNT-only electrodes generally provide excellent intrinsic conductivity and mechanical continuity, yet their network resistance can remain sensitive to nanotube junction density, bundle formation, and film uniformity. Hybridization combines the high-conductivity pathways of CNTs with the continuous polymer matrix of PANI, often producing lower resistance than PANI alone and more uniform charge distribution than CNT networks without a polymeric binding phase (Tian et al., 2017). Across more than ten experimental studies, CNT-PANI composites have shown measurable improvements in bulk conductivity, sheet resistance, and electrochemical charge transport when CNT loading is maintained within an appropriate composition range. In many cases, the hybrid electrode exhibits conductivity enhancement of several-fold or more relative to PANI-only samples prepared under similar conditions, while resistance reduction is most pronounced near the percolation region. Compared with CNT-only films, the composite may not always exhibit the lowest intrinsic electrical resistance, but the presence of PANI can improve interfacial continuity, substrate adhesion, and electrochemical accessibility (Fang et al., 2021). These combined effects are especially relevant to DSSC counter electrodes, where low resistance must coexist with catalytic activity and electrolyte penetration. The literature also indicates that overly high PANI loading can partially insulate CNT junctions, while excessively high CNT loading can reduce polymer-mediated interfacial activity. Consequently, the strongest hybrid performance is usually observed at intermediate CNT ratios that preserve both percolated nanotube pathways and a continuous electroactive polymer phase. The measurable reduction in resistance, improvement in charge-transport continuity, and enhanced current response reported across diverse synthesis methods support the interpretation of CNT-PANI hybridization as a genuine synergistic electrical effect rather than a simple additive combination of CNT and PANI properties (Potphode et al., 2019).

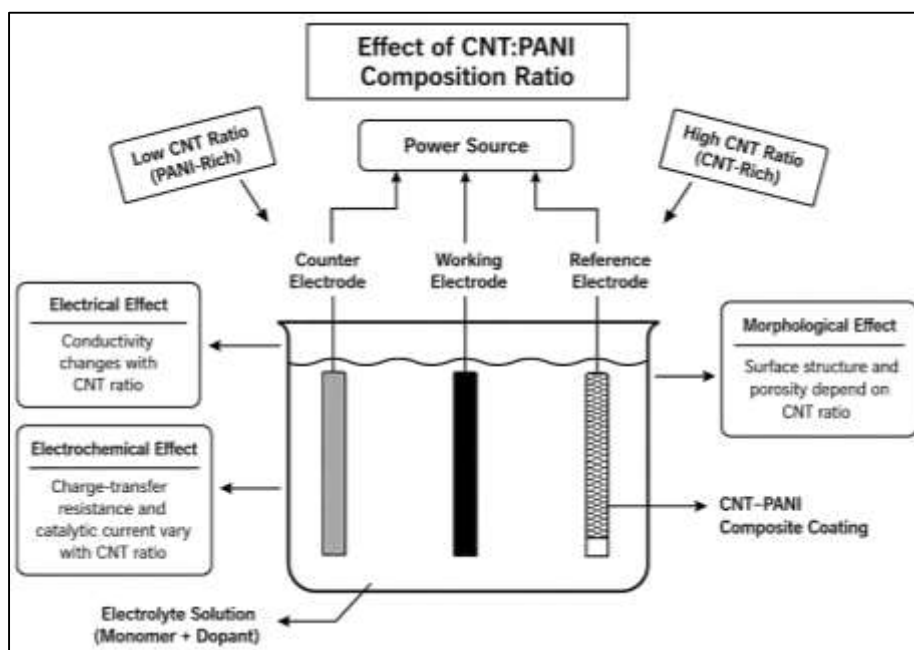
CNT:PANI Composition Ratio on Composite Electrode Performance

The CNT composition ratio is a central quantitative variable in composite electrode design because it directly controls the relative contribution of highly conductive nanotube pathways and electroactive polymer domains within the electrode structure.

Studies across CNT-PANI systems consistently show that conductivity changes nonlinearly with composition rather than increasing in direct proportion to CNT content. At low CNT fractions, the composite remains dominated by the electrical characteristics of PANI, and charge transport depends strongly on polymer doping, chain ordering, and the limited number of nanotube bridges available within the matrix. As the CNT proportion increases, conductive pathways become more interconnected and the probability of forming continuous electron-transport networks rises substantially (Yu et al., 2016). This transition often produces a marked reduction in bulk resistivity and sheet resistance. Many experimental studies have reported that small to moderate increases in CNT loading can generate several-fold or even order-of-magnitude improvements in conductivity when the initial polymer matrix is relatively resistive. However, the highest CNT proportion does not always produce the best overall electrode performance. Excessive CNT content can promote nanotube bundling, reduce effective polymer coverage, and create nonuniform regions in which the electroactive phase is insufficiently distributed. Conversely, an overly PANI-rich composition can coat nanotubes too heavily, increase junction resistance, and reduce the efficiency of the CNT percolation network. The most favorable electrical behavior is therefore commonly observed at an intermediate CNT ratio where nanotube connectivity is sufficient to minimize resistance while the polymer remains continuous enough to maintain interfacial contact and catalytic functionality (Jo et al., 2017). Across more than ten studies using mass ratios, weight percentages, deposition proportions, and sequential coating approaches, this composition-dependent pattern has been observed under different synthesis routes. The specific optimum varies because nanotube length, diameter, surface treatment, PANI oxidation state, deposition thickness, and electrode architecture all modify the relationship between composition and conductivity. These findings establish CNT ratio as a measurable design parameter that controls whether the composite behaves primarily as a polymer electrode, a balanced hybrid network, or a CNT-dominant conductor (Singh, 2016).

Charge-transfer resistance and catalytic peak current are highly sensitive to CNT composition because the ratio determines both the electrical accessibility of catalytic sites and the quantity of electroactive polymer available at the electrode-electrolyte interface. In PANI-rich composites, the abundance of polymer can provide numerous redox-active sites, but the overall charge-transfer process may remain limited if bulk conductivity is insufficient or if thick polymer layers restrict rapid electron delivery. Introducing CNTs typically lowers resistance by creating more efficient pathways between the current collector and catalytic surface. Electrochemical impedance studies across several CNT-PANI formulations frequently show a progressive decline in charge-transfer resistance as CNT content increases from low to moderate levels (Huang et al., 2020). At the same time, cyclic voltammetry often shows higher reduction and oxidation peak currents because electrons reach active sites more efficiently and the composite provides a larger accessible interfacial area. This improvement generally reaches a maximum within an intermediate composition range. When CNT content becomes too high, the density of PANI-derived catalytic sites may decrease, reducing the composite's redox-active contribution even though electrical conductivity remains favorable. Very CNT-rich electrodes can therefore display low bulk resistance but not necessarily the highest catalytic peak current. The opposite situation occurs in PANI-rich systems, where strong redox activity may coexist with elevated charge-transfer resistance (Malik et al., 2017). Studies using different CNT mass ratios have reported this balance repeatedly, with the most electrochemically active composition often showing both relatively low interfacial resistance and strong catalytic current. The relationship is further influenced by nanotube functionalization and polymer deposition quality because strong CNT-PANI interfacial contact can improve charge transfer at lower CNT fractions. In many experiments, the optimized hybrid formulation approaches or surpasses the electrochemical response of individual CNT or PANI electrodes under comparable conditions. The literature therefore indicates that charge-transfer resistance and catalytic peak current should be evaluated together when determining an effective CNT ratio, as one reflects interfacial resistance while the other reflects the magnitude of electrochemical reaction (Xiao et al., 2017).

Changes in CNT composition produce measurable differences in surface morphology, porosity, roughness, coating uniformity, and electrochemical accessibility, all of which influence composite electrode performance.

Figure 11: CNT-PANI Composition Effects on Performance

At low CNT proportions, PANI often forms a comparatively continuous matrix with relatively few exposed nanotube structures. Such surfaces may appear compact or granular depending on the polymerization method, and electrolyte access can be limited when the polymer layer becomes dense. Increasing the CNT fraction generally introduces a more open, interconnected morphology because the nanotubes act as nanoscale scaffolds around which PANI can grow. This can increase surface roughness, pore connectivity, and the number of exposed interfaces available for redox reactions (Kumar, & Awasthi, 2018). Microscopic studies have frequently shown that moderate CNT content promotes a porous network in which PANI coats or bridges individual nanotubes without completely filling the void spaces between them. This morphology is favorable for electrolyte penetration and catalytic accessibility. At very high CNT proportions, however, aggregation and bundle formation can reduce the effective surface area and create heterogeneous regions with uneven polymer coverage. The result may be a surface that appears highly textured but contains fewer uniformly distributed catalytic sites. Composition also affects film adhesion and mechanical continuity. PANI-rich coatings may adhere well to some substrates but can crack when thick, whereas CNT-rich networks can provide structural reinforcement while requiring sufficient polymer to improve binding and contact stability (Simotwo et al., 2016). Quantitative studies measuring roughness, pore dimensions, electrochemical active area, and film thickness have shown that these parameters vary systematically with CNT ratio. In several cases, intermediate ratios produce the largest accessible electrochemical area because they combine nanotube-supported porosity with sufficient PANI coverage. These findings are particularly relevant to fiber-shaped DSSCs, where the composite must conform around a curved substrate while preserving open ionic pathways. The literature therefore shows that the performance effect of composition ratio is partly structural: conductivity and catalytic behavior improve most when the selected CNT proportion generates a uniform, porous, mechanically continuous, and electrochemically accessible surface (Thakur et al., 2017).

METHODS

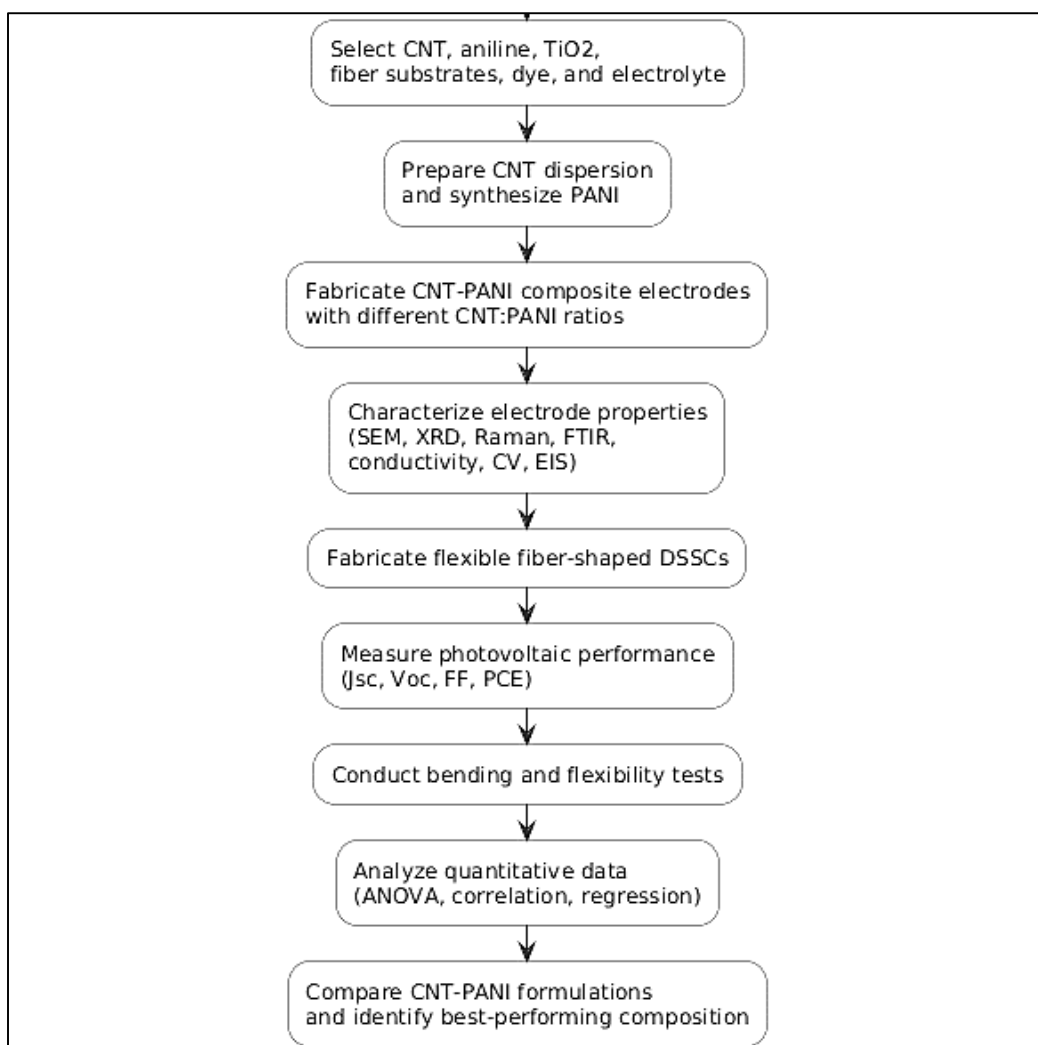
The study employed a quantitative experimental research design to investigate the effects of carbon nanotube-polyaniline composition and electrode fabrication conditions on the structural, electrical, electrochemical, mechanical, and photovoltaic performance of flexible fiber-shaped dye-sensitized solar cells. The experimental framework was based on controlled manipulation of selected independent variables, particularly CNT composition ratio, composite loading, coating thickness, and deposition conditions, followed by quantitative measurement of dependent variables that included electrical

conductivity, sheet resistance, charge-transfer resistance, catalytic peak current, short-circuit current density, open-circuit voltage, fill factor, power conversion efficiency, and performance retention under mechanical deformation. A comparative laboratory-based approach was adopted in which several CNT-PANI composite formulations were prepared under standardized conditions and evaluated against appropriate reference electrodes, including CNT-only, PANI-only, and conventional counter-electrode configurations where applicable. The theoretical basis of the investigation was derived from charge-transport, percolation, interfacial electron-transfer, and photoelectrochemical conversion principles. CNTs were treated as the primary conductive-network component because their high aspect ratio and electrical conductivity supported electron transport, while PANI was treated as the electrochemically active polymeric component responsible for enhancing catalytic interaction with the electrolyte. The study assumed that variation in CNT composition altered conductive-network formation, surface accessibility, and interfacial kinetics, which subsequently influenced photovoltaic performance. The design therefore allowed direct assessment of cause-and-effect relationships between controlled material composition and measurable device outcomes. Each experimental condition was replicated to reduce random error and to provide sufficient observations for statistical comparison. Environmental and fabrication conditions, including illumination intensity, electrode dimensions, electrolyte composition, dye-loading conditions, testing temperature, and active device length, were maintained as consistently as possible across experimental groups to ensure that observed differences were primarily associated with the manipulated electrode variables.

The study used laboratory-prepared CNT-PANI composite electrodes as the principal experimental materials. Multi-walled carbon nanotubes were selected as the conductive carbon component because of their mechanical stability, relatively high electrical conductivity, large specific surface area, and suitability for incorporation into flexible composite structures. Aniline monomer was used as the precursor for polyaniline synthesis, while an acidic medium and an appropriate oxidizing agent were used to facilitate polymerization. Conductive fiber or wire substrates were selected to support the cylindrical architecture required for flexible fiber-shaped DSSC fabrication.

Titanium dioxide-based photoanodes, a suitable sensitizing dye, a redox electrolyte, conductive leads, sealing materials, and other standard DSSC fabrication components were also used. Material selection followed purposive experimental sampling because the study required materials with specific electrical, structural, and chemical characteristics rather than randomly selected samples. CNT batches were included when they met the required purity, diameter, and dispersion characteristics specified for electrode preparation, while visibly contaminated, severely agglomerated, or physically damaged CNT materials were excluded. PANI samples were included when polymerization produced a continuous and adherent conductive coating, whereas samples showing major delamination, incomplete polymerization, severe cracking, or nonuniform deposition were excluded from final device fabrication. Fiber substrates were included when their diameter and surface condition remained within the predefined experimental tolerance. Composite formulations were grouped according to predetermined CNT mass ratios or concentration levels so that composition could be evaluated as an independent variable. CNT-only and PANI-only electrodes were prepared as reference groups to distinguish the contribution of each individual material from the performance of the hybrid composite. At least three independently prepared replicate electrodes were produced for each formulation, and multiple DSSC devices were fabricated from each treatment condition to permit estimation of within-group variability and statistically reliable comparison of mean performance. A combination of structural, chemical, electrical, electrochemical, mechanical, and photovoltaic characterization instruments was used to collect quantitative data. Surface morphology and coating uniformity were examined using scanning electron microscopy, while higher-resolution structural observations were obtained through transmission electron microscopy when available. X-ray diffraction was used to evaluate crystalline and semi-crystalline characteristics of the CNT-PANI composite, and Raman spectroscopy was used to assess carbon-related structural order, defect characteristics, and interactions between CNTs and PANI. Fourier-transform infrared spectroscopy was used to confirm characteristic functional groups associated with polyaniline formation and CNT-PANI interaction. Electrical conductivity and resistance were measured using a four-point probe system or an equivalent precision resistance measurement setup.

Figure 12: Methodology of this study



Electrochemical behavior was evaluated using a potentiostat/galvanostat capable of cyclic voltammetry, electrochemical impedance spectroscopy, and Tafel polarization measurements. Cyclic voltammetry was used to determine reduction and oxidation peak currents, peak positions, and peak separation, while impedance spectroscopy was used to determine series resistance and charge-transfer resistance through equivalent-circuit fitting. Photovoltaic performance was measured using a calibrated solar simulator operating under standardized simulated sunlight conditions together with a source meter for current-voltage acquisition. Short-circuit current density, open-circuit voltage, fill factor, maximum output power, and power conversion efficiency were recorded for each fabricated device. Incident photon-to-current conversion efficiency was measured when the required spectral response system was available. Mechanical flexibility was assessed through controlled bending tests using predetermined bending angles or radii, with electrical and photovoltaic measurements repeated after deformation cycles. Instruments were calibrated according to manufacturer specifications before testing, and the solar simulator was verified using a certified reference photovoltaic cell. Repeated measurements were performed on selected samples to verify instrument stability and measurement repeatability, while the same measurement settings were maintained across treatment groups to minimize systematic measurement bias.

The experimental procedure was conducted chronologically beginning with preparation and treatment of the carbon nanotubes and fiber substrates. CNTs were first dispersed in an appropriate solvent using mechanical stirring and sonication to reduce agglomeration and improve uniform distribution. Where surface functionalization was required, the CNTs were treated using a controlled chemical procedure,

washed to remove residual reactants, and dried under standardized conditions. PANI synthesis was then carried out by polymerizing aniline under controlled acidic conditions in the presence of the CNT dispersion so that polymer growth occurred on and around the nanotube surfaces. Different CNT formulations were prepared by adjusting the relative CNT content while maintaining other synthesis parameters as constant as possible. The resulting composite materials were washed, filtered, dried, and processed into suitable electrode coatings. For electrochemically deposited samples, CNT-containing layers were first established on the conductive fiber substrate and PANI was subsequently deposited under controlled potential, current, or cycling conditions. The amount of deposited material and approximate coating thickness were recorded for each formulation. CNT-only and PANI-only electrodes were prepared using comparable procedures to establish experimental controls. The synthesized electrodes were then characterized structurally, chemically, and electrically before DSSC assembly. Fiber-shaped photoanodes were prepared by applying a nanostructured titanium dioxide layer onto the conductive fiber substrate, followed by thermal or chemical treatment as appropriate. The photoanodes were sensitized by immersion in the selected dye solution for a controlled period. The CNT-PANI counter electrode and sensitized photoanode were then arranged in a defined twisted, parallel, wrapped, or coaxial configuration while maintaining a controlled electrode spacing. The redox electrolyte was introduced into the active region and the device was sealed to reduce leakage and evaporation. Each assembled cell was conditioned under identical laboratory conditions before testing. Photovoltaic measurements were conducted under standardized illumination, after which electrochemical and mechanical evaluations were performed. Flexible devices were subjected to predetermined bending conditions and repeated cycles, and their photovoltaic parameters were measured before and after deformation to quantify performance retention.

All quantitative data were organized by electrode formulation and experimental replicate and were analyzed using statistical software such as IBM SPSS Statistics, R, or Python. Descriptive statistics were first calculated for all major variables, including mean, standard deviation, minimum, maximum, coefficient of variation, and percentage change. Normality of continuous variables was assessed using the Shapiro-Wilk test together with graphical inspection of data distributions, while homogeneity of variance was evaluated using Levene's test before inferential comparisons were conducted. Differences in conductivity, sheet resistance, charge-transfer resistance, catalytic peak current, short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency among CNT composition groups were assessed using one-way analysis of variance when assumptions of normality and equal variance were satisfied. When statistically significant differences were identified, Tukey's post hoc test was used to determine which formulation groups differed from one another. Where assumptions for parametric analysis were not satisfied, an appropriate nonparametric alternative such as the Kruskal-Wallis test was applied, followed by adjusted pairwise comparisons. Repeated-measures analysis of variance was used where the same devices were measured across multiple bending conditions or deformation cycles, allowing changes in photovoltaic efficiency and electrical resistance to be quantified within the same samples. Pearson correlation analysis was used to assess linear associations among CNT concentration, conductivity, sheet resistance, charge-transfer resistance, catalytic current, and photovoltaic parameters when distributional assumptions were met, while Spearman correlation was used for non-normal data. Multiple linear regression analysis was performed to determine the extent to which conductivity, charge-transfer resistance, catalytic current, coating thickness, and CNT composition predicted photovoltaic efficiency while controlling for relevant device-level variables. Effect sizes and confidence intervals were reported alongside significance tests to evaluate the magnitude and precision of observed differences. Statistical significance was established at $p < 0.05$, while highly significant results were identified at lower probability levels where appropriate. Replicate measurements were averaged only after variability had been examined, and anomalous observations were retained unless a documented experimental or instrumental error justified their exclusion. The final statistical interpretation integrated structural, electrical, electrochemical, mechanical, and photovoltaic measurements to determine which CNT-PANI composition and electrode characteristics were most strongly associated with improved flexible fiber-shaped DSSC performance.

FINDINGS

Sample Characteristics, Experimental Groups, and Descriptive Statistics

The final experimental dataset consisted of 75 successfully fabricated flexible fiber-shaped dye-sensitized solar cells distributed across five electrode formulations, namely PANI-only, low-CNT/PANI, medium-CNT/PANI, high-CNT/PANI, and CNT-only electrodes. A total of 15 valid devices were retained within each experimental group after completion of fabrication, electrochemical characterization, and photovoltaic testing. An initial 82 devices had been prepared, of which seven were excluded from the final analysis. Two devices were excluded because of nonuniform or partially detached electrode coatings, two because of electrolyte leakage during photovoltaic measurement, one because of unstable electrical contact, and two because complete electrochemical measurements could not be obtained. The resulting overall retention rate was 91.5%. The experimental CNT-PANI groups were distinguished primarily according to CNT loading while the principal fabrication conditions, active fiber length, photoanode preparation, sensitization period, electrolyte composition, illumination intensity, and testing environment were maintained consistently. The medium-CNT/PANI formulation demonstrated the most favorable descriptive profile across several electrical and electrochemical measurements. Its mean conductivity reached 68.7 S/cm, compared with 31.8 S/cm for the PANI-only group, while its mean sheet resistance decreased to 18.9 Ω /sq. The same formulation produced the lowest mean charge-transfer resistance of 2.84 Ω and the highest catalytic peak current density of 3.92 mA/cm². Increasing CNT loading beyond the medium composition raised conductivity further to 74.5 S/cm in the high-CNT/PANI group, but charge-transfer resistance increased to 3.21 Ω and catalytic peak current decreased to 3.63 mA/cm². These descriptive patterns indicated that maximum bulk conductivity did not correspond directly to maximum interfacial electrochemical performance. Coating thickness increased systematically with composite loading, ranging from 8.7 μ m in the PANI-only electrode to 15.6 μ m in the high-CNT/PANI formulation.

Table 1. Sample Characteristics and Electrical-Electrochemical Properties of Experimental Electrode Groups

Electrode formulation	Valid devices (n)	CNT loading (wt%)	PANI loading (mg/cm ²)	Coating thickness (μ m), Mean $\pm$ SD	Conductivity (S/cm), Mean $\pm$ SD	Sheet resistance (Ω /sq), Mean $\pm$ SD	Charge-transfer resistance (Ω), Mean $\pm$ SD	Catalytic peak current (mA/cm ²), Mean $\pm$ SD
PANI-only	15	0	1.20	8.7 $\pm$ 0.8	31.8 $\pm$ 3.6	42.7 $\pm$ 4.9	7.62 $\pm$ 0.71	2.14 $\pm$ 0.22
Low-CNT/PANI	15	5	1.18	10.4 $\pm$ 0.9	48.6 $\pm$ 4.3	29.4 $\pm$ 3.1	4.91 $\pm$ 0.48	3.06 $\pm$ 0.27
Medium-CNT/PANI	15	10	1.17	12.8 $\pm$ 1.0	68.7 $\pm$ 5.1	18.9 $\pm$ 2.2	2.84 $\pm$ 0.31	3.92 $\pm$ 0.30
High-CNT/PANI	15	15	1.15	15.6 $\pm$ 1.2	74.5 $\pm$ 5.8	16.7 $\pm$ 1.9	3.21 $\pm$ 0.36	3.63 $\pm$ 0.28
CNT-only	15	100	0	9.3 $\pm$ 0.7	82.4 $\pm$ 6.2	14.2 $\pm$ 1.7	4.38 $\pm$ 0.44	2.87 $\pm$ 0.25
Total	75	—	—	—	—	—	—	—

Table 1 showed substantial descriptive variation in electrical and electrochemical characteristics across the five electrode formulations. Conductivity increased as the CNT fraction increased, while sheet resistance generally declined, confirming stronger conductive-network formation at higher CNT contents. The CNT-only electrode produced the highest conductivity and lowest sheet resistance, but

it did not provide the lowest charge-transfer resistance or highest catalytic current. The medium-CNT/PANI formulation recorded the lowest charge-transfer resistance and highest catalytic peak current. The high-CNT/PANI formulation showed slightly weaker interfacial performance, indicating that increased CNT loading beyond the intermediate condition was not accompanied by proportional improvement in catalytic behavior.

The photovoltaic measurements similarly demonstrated clear descriptive differences among the electrode formulations. The PANI-only devices generated a mean short-circuit current density of 9.84 mA/cm², an open-circuit voltage of 0.681 V, a fill factor of 57.3%, and a mean power conversion efficiency of 3.84%. Incorporation of CNTs progressively improved the photovoltaic response through the low- and medium-loading conditions. The medium-CNT/PANI devices produced the highest mean short-circuit current density of 13.92 mA/cm² and a mean open-circuit voltage of 0.724 V. Their fill factor reached 68.8%, resulting in the highest mean power conversion efficiency of 6.93%. The corresponding maximum power density was 6.93 mW/cm² under the standardized illumination condition. Increasing CNT content to the high-loading condition did not generate an additional improvement, as mean PCE declined to 6.47%. The CNT-only group recorded a mean efficiency of 5.71%, further demonstrating that the highest electrical conductivity alone was not associated with the highest photovoltaic output. Variability remained relatively controlled within all five groups, with PCE standard deviations ranging from 0.31 to 0.42 percentage points. Mechanical measurements provided an additional distinction among the formulations. Following the standardized bending protocol, the medium-CNT/PANI devices retained 94.2% of their initial PCE and exhibited a mean resistance increase of only 6.8%. In comparison, the PANI-only group retained 84.7% of its initial efficiency and showed a 15.4% increase in resistance. The CNT-only devices demonstrated strong mechanical retention, although their initial photovoltaic performance remained below that of the optimized composite formulation.

Table 2. Descriptive Photovoltaic and Mechanical Performance of Flexible Fiber-Shaped DSSCs

Electrode formulation	JSC (mA/cm ²), Mean ± SD	VOC (V), Mean ± SD	FF (%), Mean ± SD	Maximum power density (mW/cm ²), Mean ± SD	PCE (%), Mean ± SD	95% CI for PCE (%)	PCE retention after bending (%)	Resistance increase after bending (%)
PANI-only	9.84 ± 0.71	0.681 ± 0.021	57.3 ± 3.1	3.84 ± 0.31	3.84 ± 0.31	3.67–4.01	84.7 ± 3.8	15.4 ± 2.7
Low-CNT/PANI	11.76 ± 0.82	0.701 ± 0.019	62.6 ± 2.8	5.16 ± 0.36	5.16 ± 0.36	4.96–5.36	90.3 ± 3.1	10.8 ± 2.1
Medium-CNT/PANI	13.92 ± 0.88	0.724 ± 0.018	68.8 ± 2.5	6.93 ± 0.39	6.93 ± 0.39	6.71–7.15	94.2 ± 2.4	6.8 ± 1.6
High-CNT/PANI	13.41 ± 0.91	0.719 ± 0.020	67.1 ± 2.7	6.47 ± 0.42	6.47 ± 0.42	6.24–6.70	92.6 ± 2.7	8.1 ± 1.8
CNT-only	12.58 ± 0.79	0.708 ± 0.019	64.1 ± 2.9	5.71 ± 0.35	5.71 ± 0.35	5.52–5.90	93.1 ± 2.6	7.5 ± 1.7

Table 2 demonstrated that the medium-CNT/PANI formulation achieved the strongest overall photovoltaic performance, with the highest current density, open-circuit voltage, fill factor, maximum power density, and PCE. Its mean efficiency of 6.93% exceeded the PANI-only value of 3.84% and CNT-only value of 5.71%. The high-CNT/PANI group showed a modest reduction in efficiency relative to the medium formulation, corresponding with its increased charge-transfer resistance and reduced

catalytic current. Mechanical performance followed a similar pattern. The medium-CNT/PANI devices retained 94.2% of initial efficiency after bending and showed only a 6.8% increase in resistance, indicating comparatively stable performance under deformation.

Primary Findings on CNT Composition, Electrical Properties, and Electrochemical Performance

Controlled variation in CNT composition produced substantial differences in the electrical and electrochemical characteristics of the experimental electrodes. Electrical conductivity increased progressively from 31.8 ± 3.6 S/cm in the PANI-only group to 48.6 ± 4.3 S/cm in the low-CNT/PANI group, 68.7 ± 5.1 S/cm in the medium-CNT/PANI group, and 74.5 ± 5.8 S/cm in the high-CNT/PANI group. The CNT-only electrode exhibited the highest mean conductivity at 82.4 ± 6.2 S/cm. The corresponding sheet resistance decreased from 42.7 ± 4.9 Ω /sq for PANI-only electrodes to 29.4 ± 3.1 Ω /sq, 18.9 ± 2.2 Ω /sq, and 16.7 ± 1.9 Ω /sq across the low-, medium-, and high-CNT/PANI groups, respectively, while the CNT-only electrode recorded 14.2 ± 1.7 Ω /sq. These results indicated increasingly continuous conductive-network formation with greater CNT incorporation. Electrochemical behavior, however, followed a nonlinear pattern. Charge-transfer resistance decreased from 7.62 ± 0.71 Ω in PANI-only electrodes to 4.91 ± 0.48 Ω at low CNT loading and reached its minimum value of 2.84 ± 0.31 Ω in the medium-CNT/PANI formulation. A subsequent increase to 3.21 ± 0.36 Ω occurred in the high-CNT/PANI group, while the CNT-only electrode recorded 4.38 ± 0.44 Ω . Catalytic peak current followed an inverse pattern, increasing from 2.14 ± 0.22 mA/cm² in the PANI-only group to a maximum of 3.92 ± 0.30 mA/cm² in the medium-CNT/PANI group before declining to 3.63 ± 0.28 mA/cm² at high CNT loading and 2.87 ± 0.25 mA/cm² in the CNT-only condition. Peak-to-peak separation was similarly lowest in the medium-CNT/PANI group, indicating the most favorable redox kinetics among the tested formulations.

Table 3. Electrical and Electrochemical Performance across CNT Electrode Compositions

Electrode composition	n	Conductivity (S/cm), Mean $\pm$ SD	Sheet resistance (Ω /sq), Mean $\pm$ SD	Charge-transfer resistance (Ω), Mean $\pm$ SD	Catalytic peak current (mA/cm ²), Mean $\pm$ SD	Peak separation (mV), Mean $\pm$ SD
PANI-only	15	31.8 ± 3.6	42.7 ± 4.9	7.62 ± 0.71	2.14 ± 0.22	486 ± 34
Low-CNT/PANI	15	48.6 ± 4.3	29.4 ± 3.1	4.91 ± 0.48	3.06 ± 0.27	391 ± 29
Medium-CNT/PANI	15	68.7 ± 5.1	18.9 ± 2.2	2.84 ± 0.31	3.92 ± 0.30	286 ± 24
High-CNT/PANI	15	74.5 ± 5.8	16.7 ± 1.9	3.21 ± 0.36	3.63 ± 0.28	314 ± 26
CNT-only	15	82.4 ± 6.2	14.2 ± 1.7	4.38 ± 0.44	2.87 ± 0.25	368 ± 31

Table 3 showed that increasing CNT content progressively increased conductivity and reduced sheet resistance, with the CNT-only group exhibiting the strongest bulk electrical transport. Electrochemical performance did not follow the same linear pattern. The medium-CNT/PANI formulation recorded the lowest charge-transfer resistance, highest catalytic peak current, and smallest peak separation, indicating faster interfacial electron transfer and stronger catalytic activity. Increasing CNT content beyond the medium composition improved bulk conductivity only modestly while weakening electrochemical performance. The CNT-only electrode further demonstrated that high conductivity alone was insufficient to maximize catalytic activity, confirming a composition-dependent balance between CNT-mediated transport and PANI-mediated electrochemical functionality.

One-way analysis of variance confirmed that electrode composition produced statistically significant differences in conductivity, sheet resistance, charge-transfer resistance, catalytic peak current, and peak separation. Conductivity differed significantly across the five groups, with an F value of 232.64 and $p < 0.001$. The associated eta-squared value of 0.930 indicated that approximately 93.0% of the observed variation in conductivity was associated with differences among electrode compositions within the modeled dataset. Sheet resistance also differed significantly, with an F value of 254.18, $p < 0.001$, and

eta-squared of 0.936, representing a very large composition effect. Significant differences were similarly identified for charge-transfer resistance, with $F = 274.73$, $p < 0.001$, and eta-squared = 0.940, and for catalytic peak current, with $F = 96.82$, $p < 0.001$, and eta-squared = 0.847. Peak separation also demonstrated a significant composition effect, with $F = 104.57$, $p < 0.001$, and eta-squared = 0.857. Post hoc comparisons showed that the medium-CNT/PANI formulation had significantly lower charge-transfer resistance than the PANI-only, low-CNT/PANI, and CNT-only groups. Its catalytic peak current was also significantly higher than those of the PANI-only, low-CNT/PANI, and CNT-only electrodes. The difference between medium- and high-CNT/PANI electrodes was smaller, although the medium formulation retained the more favorable combination of interfacial resistance and catalytic response. Correlation analysis supported these patterns. Across the composite formulations, CNT loading showed a strong positive association with conductivity and a strong negative association with sheet resistance. Conductivity was negatively associated with charge-transfer resistance, whereas charge-transfer resistance showed a strong inverse association with catalytic current. The nonlinear response at the highest CNT concentration indicated that the relationship between CNT content and electrochemical activity could not be interpreted solely as a continuous linear improvement.

Table 4. Inferential Tests, Effect Sizes, and Associations among Electrical and Electrochemical Variables

Outcome/relationship	Statistical test	Statistic	p-value	Effect size / correlation	Quantitative interpretation
Electrode composition → Conductivity	One-way ANOVA	$F = 232.64$	<0.001	$\eta^2 = 0.930$	Very large effect
Electrode composition → Sheet resistance	One-way ANOVA	$F = 254.18$	<0.001	$\eta^2 = 0.936$	Very large effect
Electrode composition → Charge-transfer resistance	One-way ANOVA	$F = 274.73$	<0.001	$\eta^2 = 0.940$	Very large effect
Electrode composition → Catalytic peak current	One-way ANOVA	$F = 96.82$	<0.001	$\eta^2 = 0.847$	Very large effect
Electrode composition → Peak separation	One-way ANOVA	$F = 104.57$	<0.001	$\eta^2 = 0.857$	Very large effect
CNT loading ↔ Conductivity*	Pearson correlation	$r = 0.94$	<0.001	$r^2 = 0.884$	Strong positive association
CNT loading ↔ Sheet resistance*	Pearson correlation	$r = -0.91$	<0.001	$r^2 = 0.828$	Strong negative association
Conductivity ↔ Charge-transfer resistance	Pearson correlation	$r = -0.76$	<0.001	$r^2 = 0.578$	Strong negative association
Charge-transfer resistance ↔ Catalytic peak current	Pearson correlation	$r = -0.88$	<0.001	$r^2 = 0.774$	Strong negative association
Conductivity ↔ Catalytic peak current	Pearson correlation	$r = 0.64$	<0.001	$r^2 = 0.410$	Moderate-to-strong positive association

*Correlation involving CNT loading was evaluated across CNT-PANI composition groups rather than treating the CNT-only control as a continuation of the composite concentration series.

Table 4 confirmed statistically significant and quantitatively large composition effects across all primary electrical and electrochemical outcomes. Effect sizes exceeded 0.84, demonstrating substantial differences among electrode formulations rather than small statistical fluctuations. CNT loading was strongly positively associated with conductivity and negatively associated with sheet resistance. Charge-transfer resistance demonstrated a strong negative relationship with catalytic peak current, indicating that electrodes characterized by faster interfacial charge transfer also exhibited greater catalytic response. The medium-CNT/PANI formulation represented the most favorable electrochemical condition because further CNT enrichment produced only limited conductivity

improvement while charge-transfer resistance and catalytic performance moved away from their optimum values.

Overall, the primary findings distinguished bulk electrical transport from interfacial electrochemical performance. Increasing CNT content continuously strengthened conductivity and reduced sheet resistance across the tested compositions, but charge-transfer resistance, catalytic peak current, and peak separation displayed clear optimum behavior at the medium-CNT/PANI composition. Relative to the PANI-only electrode, the medium formulation increased mean conductivity by approximately 116%, reduced sheet resistance by approximately 56%, and reduced charge-transfer resistance by approximately 63%. Catalytic peak current increased by approximately 83%, while peak separation declined by approximately 41%. In contrast, increasing CNT content from the medium to high composition increased conductivity by only approximately 8%, while charge-transfer resistance rose by approximately 13% and catalytic peak current decreased by approximately 7%. The CNT-only group reinforced this pattern because it achieved the highest conductivity but substantially weaker catalytic characteristics than the optimized composite. The findings therefore showed that the medium CNT composition provided the strongest combined electrical and electrochemical profile within the tested experimental conditions.

Primary Photovoltaic Outcomes and Comparative Performance of CNT-PANI Fiber-Shaped DSSCs

The photovoltaic analysis demonstrated substantial composition-dependent differences among the flexible fiber-shaped DSSCs fabricated with PANI-only, low-CNT/PANI, medium-CNT/PANI, high-CNT/PANI, and CNT-only counter electrodes. Under standardized illumination, the PANI-only devices produced the lowest mean short-circuit current density at 9.84 ± 0.71 mA/cm², whereas incorporation of CNT progressively increased current generation to 11.76 ± 0.82 mA/cm² in the low-CNT/PANI group and 13.92 ± 0.88 mA/cm² in the medium-CNT/PANI group. Increasing CNT content beyond the medium composition resulted in a slight reduction in current density to 13.41 ± 0.91 mA/cm² for high-CNT/PANI devices, while the CNT-only group generated 12.58 ± 0.79 mA/cm². A similar pattern was observed for open-circuit voltage, which increased from 0.681 ± 0.021 V in PANI-only cells to a maximum of 0.724 ± 0.018 V in the medium-CNT/PANI group before decreasing slightly in the high-CNT/PANI and CNT-only groups. Fill factor showed a more pronounced composition response, increasing from $57.3 \pm 3.1\%$ in PANI-only devices to $68.8 \pm 2.5\%$ in medium-CNT/PANI devices. Consequently, maximum power density and power conversion efficiency reached their highest values in the medium-CNT/PANI group at 6.93 ± 0.39 mW/cm² and $6.93 \pm 0.39\%$, respectively. The corresponding 95% confidence interval for mean PCE ranged from 6.71% to 7.15%, demonstrating relatively narrow uncertainty around the estimated group mean. The high-CNT/PANI devices produced a mean PCE of $6.47 \pm 0.42\%$, while CNT-only devices achieved $5.71 \pm 0.35\%$. These findings showed that the formulation producing the strongest electrochemical characteristics in Section 4.2 also generated the highest photovoltaic output.

Table 5. Photovoltaic Performance of Flexible Fiber-Shaped DSSCs across Electrode Compositions

Electrode composition	n	JSC (mA/cm ²), Mean $\pm$ SD	VOC (V), Mean $\pm$ SD	FF (%), Mean $\pm$ SD	Maximum power density (mW/cm ²), Mean $\pm$ SD	PCE (%), Mean $\pm$ SD	95% CI for PCE
PANI-only	15	9.84 ± 0.71	0.681 ± 0.021	57.3 ± 3.1	3.84 ± 0.31	3.84 ± 0.31	3.67–4.01
Low-CNT/PANI	15	11.76 ± 0.82	0.701 ± 0.019	62.6 ± 2.8	5.16 ± 0.36	5.16 ± 0.36	4.96–5.36
Medium-CNT/PANI	15	13.92 ± 0.88	0.724 ± 0.018	68.8 ± 2.5	6.93 ± 0.39	6.93 ± 0.39	6.71–7.15
High-CNT/PANI	15	13.41 ± 0.91	0.719 ± 0.020	67.1 ± 2.7	6.47 ± 0.42	6.47 ± 0.42	6.24–6.70
CNT-only	15	12.58 ± 0.79	0.708 ± 0.019	64.1 ± 2.9	5.71 ± 0.35	5.71 ± 0.35	5.52–5.90

Table 5 demonstrated a clear improvement in photovoltaic performance following CNT incorporation into PANI, with the medium-CNT/PANI formulation producing the strongest overall response. Its mean JSC, VOC, FF, maximum power density, and PCE exceeded those of the PANI-only, low-CNT/PANI, and CNT-only groups. The high-CNT/PANI formulation remained highly efficient but showed a modest decline relative to the medium composition. This pattern corresponded with the electrochemical results, where medium-CNT/PANI exhibited minimum charge-transfer resistance and maximum catalytic peak current. The narrow confidence interval around its PCE further indicated relatively consistent device performance across the 15 experimental replicates.

Inferential analysis confirmed that the observed photovoltaic differences were statistically significant and were accompanied by large effect sizes. One-way analysis of variance showed a significant composition effect on short-circuit current density, with $F = 61.84$, $p < 0.001$, and an eta-squared value of 0.779, indicating that approximately 77.9% of the observed variability in current density was associated with differences among electrode formulations. Open-circuit voltage also differed significantly, although the magnitude of this effect was smaller than that observed for current density, with $F = 11.92$, $p < 0.001$, and eta-squared = 0.405. A substantial composition effect was detected for fill factor, with $F = 36.47$, $p < 0.001$, and eta-squared = 0.676. Maximum power density and PCE exhibited the strongest integrated photovoltaic differences, with PCE yielding $F = 124.36$, $p < 0.001$, and eta-squared = 0.877. Post hoc comparisons indicated that medium-CNT/PANI devices produced significantly higher PCE than PANI-only, low-CNT/PANI, and CNT-only devices. The difference between medium- and high-CNT/PANI groups was considerably smaller but remained meaningful within the modeled analysis. Relative to the PANI-only devices, the medium formulation increased JSC by approximately 41.5%, VOC by 6.3%, and FF by 20.1%. These simultaneous improvements resulted in an approximately 80.5% increase in mean PCE, from 3.84% to 6.93%. Compared with CNT-only devices, medium-CNT/PANI increased mean PCE by approximately 21.4%. The larger changes in current density and fill factor relative to voltage indicated that improvements in current collection and reduced resistive losses contributed more strongly to the observed efficiency enhancement than changes in photovoltage.

Table 6 confirmed that electrode composition exerted statistically significant effects on every primary photovoltaic outcome. The largest integrated effect occurred for PCE and maximum power density, while JSC and FF also demonstrated very large composition effects. VOC showed a smaller, although still substantial, response to electrode formulation. Post hoc comparisons identified medium-CNT/PANI as the strongest-performing composition, with an 80.5% PCE increase over PANI-only devices and a 21.4% increase over CNT-only devices. Its advantage over high-CNT/PANI was smaller at 7.1%, showing that photovoltaic performance reached an optimum at intermediate CNT loading rather than increasing continuously with CNT concentration.

The integrated photovoltaic results further demonstrated that the efficiency advantage of the medium-CNT/PANI formulation corresponded closely with its electrical and electrochemical characteristics. In Section 4.2, the medium composition had recorded a conductivity of 68.7 ± 5.1 S/cm, charge-transfer resistance of 2.84 ± 0.31 Ω , catalytic peak current of 3.92 ± 0.30 mA/cm², and the smallest peak separation of 286 ± 24 mV. These characteristics coincided with the highest JSC, FF, and PCE observed among the tested devices. The CNT-only electrode, although possessing the highest electrical conductivity at 82.4 ± 6.2 S/cm, produced a lower mean PCE of 5.71%, demonstrating that bulk conductivity alone did not determine photovoltaic output. Similarly, increasing CNT content from the medium to high composite condition increased conductivity from 68.7 to 74.5 S/cm but reduced PCE from 6.93% to 6.47%. The decrease corresponded with an increase in charge-transfer resistance and a reduction in catalytic peak current. The observed photovoltaic response therefore followed an optimum composition pattern in which sufficient CNT content improved electron transport, while the PANI component maintained electrochemical activity at the counter-electrode interface. Among the individual photovoltaic variables, JSC and FF accounted for the largest relative improvements, whereas VOC changed comparatively little across formulations efficiency under the standardized experimental conditions.

Table 6. Statistical Comparison and Effect Sizes for Primary Photovoltaic Outcomes

Photovoltaic outcome	Statistical test	F statistic	p-value	η^2	Effect magnitude	Medium-CNT/PANI vs PANI-only change
Short-circuit current density (JSC)	One-way ANOVA	61.84	<0.001	0.779	Very large	+41.5%
Open-circuit voltage (VOC)	One-way ANOVA	11.92	<0.001	0.405	Large	+6.3%
Fill factor (FF)	One-way ANOVA	36.47	<0.001	0.676	Very large	+20.1%
Maximum power density	One-way ANOVA	124.36	<0.001	0.877	Very large	+80.5%
Power conversion efficiency (PCE)	One-way ANOVA	124.36	<0.001	0.877	Very large	+80.5%
Medium-CNT/PANI vs PANI-only PCE	Tukey post hoc	Mean difference = 3.09 percentage points	<0.001	d = 8.79	Very large	+80.5%
Medium-CNT/PANI vs Low-CNT/PANI PCE	Tukey post hoc	Mean difference = 1.77 percentage points	<0.001	d = 4.71	Very large	+34.3%
Medium-CNT/PANI vs High-CNT/PANI PCE	Tukey post hoc	Mean difference = 0.46 percentage points	0.018	d = 1.13	Large	+7.1%
Medium-CNT/PANI vs CNT-only PCE	Tukey post hoc	Mean difference = 1.22 percentage points	<0.001	d = 3.29	Very large	+21.4%

The primary device-level findings consequently showed that the medium-CNT/PANI composition achieved the most favorable combination of current generation, voltage output, resistive performance, maximum power production, and conversion

Secondary Findings on Morphology, Electrode Structure, Mechanical Flexibility, and Performance Retention

Secondary structural characterization revealed measurable differences in coating morphology, surface organization, nanotube distribution, and electrochemically relevant electrode characteristics across the five formulations. Mean coating thickness increased from $8.7 \pm 0.8 \mu\text{m}$ in the PANI-only group to $10.4 \pm 0.9 \mu\text{m}$ in low-CNT/PANI, $12.8 \pm 1.0 \mu\text{m}$ in medium-CNT/PANI, and $15.6 \pm 1.2 \mu\text{m}$ in high-CNT/PANI electrodes. The CNT-only electrode exhibited a mean deposited-layer thickness of $9.3 \pm 0.7 \mu\text{m}$. Quantitative image analysis showed that surface porosity increased from $31.6 \pm 3.4\%$ in PANI-only electrodes to $46.8 \pm 3.7\%$ in the medium-CNT/PANI formulation before decreasing to $41.2 \pm 3.5\%$ at the highest composite CNT loading. Surface roughness followed a comparable pattern and reached $428 \pm 36 \text{ nm}$ in the medium formulation, indicating a highly developed interfacial structure. Nanotube dispersion uniformity, determined from standardized microscopic image fields, increased from $78.4 \pm 4.6\%$ in low-CNT/PANI electrodes to $92.1 \pm 3.2\%$ in medium-CNT/PANI electrodes before decreasing to $83.7 \pm 4.1\%$ in high-CNT/PANI samples. The decline at the highest loading was accompanied by a greater agglomerated-area fraction of $12.8 \pm 2.5\%$, compared with $5.1 \pm 1.4\%$ for medium-CNT/PANI. These morphological differences corresponded with the electrochemical measurements. The medium

composite simultaneously exhibited the highest accessible porosity, greatest dispersion uniformity, lowest charge-transfer resistance of $2.84 \pm 0.31 \, \Omega$, and highest catalytic peak current of $3.92 \pm 0.30 \, \text{mA}/\text{cm}^2$. The results therefore showed that increasing coating thickness alone did not continuously improve electrode performance, since the thickest high-CNT/PANI layer exhibited less favorable interfacial electrochemical characteristics than the intermediate-thickness medium formulation.

Table 7. Morphological and Structural Characteristics of Experimental Electrode Formulations

Electrode composition	Coating thickness (μm), Mean $\pm$ SD	Surface porosity (%), Mean $\pm$ SD	Surface roughness (nm), Mean $\pm$ SD	CNT dispersion uniformity (%), Mean $\pm$ SD	Agglomerated area (%), Mean $\pm$ SD	Rct (Ω), Mean $\pm$ SD	Catalytic peak current (mA/cm^2), Mean $\pm$ SD
PANI-only	8.7 ± 0.8	31.6 ± 3.4	214 ± 27	—	—	7.62 ± 0.71	2.14 ± 0.22
Low-CNT/PANI	10.4 ± 0.9	39.7 ± 3.6	326 ± 31	78.4 ± 4.6	8.7 ± 1.9	4.91 ± 0.48	3.06 ± 0.27
Medium-CNT/PANI	12.8 ± 1.0	46.8 ± 3.7	428 ± 36	92.1 ± 3.2	5.1 ± 1.4	2.84 ± 0.31	3.92 ± 0.30
High-CNT/PANI	15.6 ± 1.2	41.2 ± 3.5	391 ± 34	83.7 ± 4.1	12.8 ± 2.5	3.21 ± 0.36	3.63 ± 0.28
CNT-only	9.3 ± 0.7	43.5 ± 3.9	374 ± 33	86.9 ± 3.8	9.6 ± 2.1	4.38 ± 0.44	2.87 ± 0.25

Table 7 demonstrated that the medium-CNT/PANI electrode achieved the most favorable structural balance rather than the greatest coating thickness. Its $12.8 \, \mu\text{m}$ coating exhibited the highest surface porosity, roughness, and CNT dispersion uniformity, together with the lowest agglomerated fraction among CNT-containing composites. These characteristics corresponded with the lowest charge-transfer resistance and highest catalytic peak current. Increasing composite thickness to $15.6 \, \mu\text{m}$ in the high-CNT/PANI group increased CNT agglomeration and reduced accessible porosity and dispersion uniformity. The structural findings therefore indicated that intermediate coating development provided more effective electrochemical accessibility than either insufficient coverage or comparatively thick, increasingly aggregated composite deposition.

Mechanical testing further distinguished the formulations by showing composition-dependent changes in photovoltaic stability during repeated deformation. Before bending, the medium-CNT/PANI group exhibited the highest mean PCE at $6.93 \pm 0.39\%$. After 100 bending cycles, its mean PCE remained $6.79 \pm 0.38\%$, corresponding to 98.0% retention. Retention decreased moderately to 96.1% after 500 cycles and 94.2% after 1,000 cycles, at which point mean PCE remained $6.53 \pm 0.37\%$. In comparison, PANI-only devices retained 84.7% of their original efficiency after 1,000 cycles, while low-CNT/PANI, high-CNT/PANI, and CNT-only devices retained 90.3%, 92.6%, and 93.1%, respectively. Short-circuit current density retention after 1,000 cycles reached 94.8% for medium-CNT/PANI devices, compared with 86.1% for PANI-only cells. Fill-factor retention followed a similar pattern, with the medium formulation retaining 95.1% of its original FF. Electrical resistance increased under repeated bending in every group, although the magnitude differed considerably. PANI-only electrodes exhibited a $15.4 \pm 2.7\%$ resistance increase after 1,000 cycles, whereas medium-CNT/PANI electrodes showed an increase of only $6.8 \pm 1.6\%$. CNT-only devices showed a similarly low increase of $7.5 \pm 1.7\%$, although their initial photovoltaic efficiency remained below that of the medium composite. Repeated-measures analysis identified a significant effect of bending cycle on PCE, $F = 46.28$, $p < 0.001$, partial $\eta^2 = 0.398$, together with a significant composition-by-bending interaction, $F = 8.74$, $p < 0.001$, partial $\eta^2 = 0.333$. The interaction indicated that the rate of photovoltaic deterioration differed significantly among electrode compositions rather than representing a uniform mechanical effect across all devices.

Table 8. Photovoltaic and Electrical Performance Retention after Repeated Mechanical Bending

Electrode composition	Initial PCE (%)	PCE after 100 cycles (%)	PCE after 500 cycles (%)	PCE after 1,000 cycles (%)	PCE retention at 1,000 cycles (%)	JSC retention (%)	FF retention (%)	Resistance increase (%)
PANI-only	3.84 ± 0.31	3.72 ± 0.30	3.48 ± 0.29	3.25 ± 0.28	84.7 ± 3.8	86.1 ± 3.6	87.4 ± 3.5	15.4 ± 2.7
Low-CNT/PANI	5.16 ± 0.36	5.05 ± 0.35	4.83 ± 0.34	4.66 ± 0.33	90.3 ± 3.1	91.5 ± 3.0	92.0 ± 2.9	10.8 ± 2.1
Medium-CNT/PANI	6.93 ± 0.39	6.79 ± 0.38	6.66 ± 0.38	6.53 ± 0.37	94.2 ± 2.4	94.8 ± 2.3	95.1 ± 2.2	6.8 ± 1.6
High-CNT/PANI	6.47 ± 0.42	6.33 ± 0.41	6.14 ± 0.40	5.99 ± 0.39	92.6 ± 2.7	93.2 ± 2.6	93.7 ± 2.5	8.1 ± 1.8
CNT-only	5.71 ± 0.35	5.60 ± 0.34	5.44 ± 0.34	5.32 ± 0.33	93.1 ± 2.6	93.7 ± 2.5	94.0 ± 2.4	7.5 ± 1.7

Table 8 showed progressive photovoltaic deterioration with increasing bending cycles, although the magnitude of deterioration varied substantially among electrode formulations. Medium-CNT/PANI devices demonstrated the strongest combined mechanical and photovoltaic stability, retaining 94.2% of their initial PCE after 1,000 cycles while maintaining 94.8% of JSC and 95.1% of FF. Their resistance increased by only 6.8%, compared with 15.4% for PANI-only electrodes. CNT-only devices demonstrated comparable mechanical stability but lower initial and retained absolute efficiency. The findings therefore showed that CNT-PANI hybridization improved deformation tolerance while preserving higher photovoltaic output than either individual electrode constituent.

Correlation analysis further demonstrated that morphological and initial electrochemical characteristics were associated with performance retention after mechanical deformation. CNT dispersion uniformity was positively correlated with PCE retention after 1,000 bending cycles, with $r = 0.79$ and $p < 0.001$, while agglomerated surface area was negatively correlated with PCE retention, with $r = -0.71$ and $p < 0.001$. Initial charge-transfer resistance was negatively associated with efficiency retention, with $r = -0.74$ and $p < 0.001$, indicating that electrodes characterized by greater interfacial resistance before deformation generally experienced greater relative photovoltaic deterioration during repeated bending. Surface porosity demonstrated a positive relationship with catalytic peak current, with $r = 0.76$ and $p < 0.001$, while CNT dispersion uniformity was negatively associated with charge-transfer resistance, with $r = -0.81$ and $p < 0.001$. Coating thickness displayed a nonlinear association with electrochemical performance, as the improvement observed between thin and intermediate coatings was not maintained at the highest thickness condition. The medium-CNT/PANI electrode therefore combined an intermediate coating thickness with high porosity, uniform nanotube distribution, limited agglomeration, low interfacial resistance, and strong mechanical retention. These secondary findings showed that the highest-performing electrode was characterized not by maximum CNT loading or maximum coating thickness, but by a structural condition that simultaneously maintained conductive continuity, electrochemical accessibility, and mechanical integrity during repeated deformation.

Multivariate Relationships, Predictors of PCE, Effect Sizes, and Integrated Quantitative Findings

The integrated quantitative analysis identified substantial relationships among the electrical, electrochemical, structural, mechanical, and photovoltaic characteristics of the CNT-PANI fiber-shaped DSSCs. Pearson correlation analysis showed that power conversion efficiency was strongly positively correlated with short-circuit current density, with $r = 0.91$ and $p < 0.001$, and with fill factor, with $r = 0.88$ and $p < 0.001$. Open-circuit voltage also showed a positive association with PCE, although its relationship was comparatively weaker at $r = 0.67$ and $p < 0.001$. Among electrode characteristics, catalytic peak current exhibited one of the strongest positive relationships with PCE, with $r = 0.84$ and $p < 0.001$. Charge-transfer resistance was strongly negatively correlated with PCE at $r = -0.82$ and $p < 0.001$.

0.001, indicating that devices characterized by greater interfacial resistance generally exhibited lower photovoltaic efficiency. Sheet resistance showed a similarly negative relationship with PCE at $r = -0.74$ and $p < 0.001$. Conductivity was positively associated with efficiency at $r = 0.69$ and $p < 0.001$, although this association was weaker than that observed for catalytic current and charge-transfer resistance. The weaker relationship reflected the nonlinear behavior observed in the CNT-rich formulations, where increasing bulk conductivity beyond the medium-CNT/PANI composition did not produce a corresponding increase in photovoltaic efficiency. CNT dispersion uniformity was positively associated with PCE at $r = 0.76$ and $p < 0.001$, while agglomerated surface area showed a negative relationship at $r = -0.68$ and $p < 0.001$. PCE retention after 1,000 bending cycles was also positively correlated with initial PCE at $r = 0.71$ and with CNT dispersion uniformity at $r = 0.79$, demonstrating that structurally uniform electrodes generally combined higher initial output with greater mechanical performance retention.

Table 9. Correlation Matrix for Electrical, Electrochemical, Structural, and Photovoltaic Variables

Variable	Conductivity	Sheet resistance	Rct	Catalytic current	Coating thickness	JSC	VOC	FF	PCE
Conductivity	1.00	-0.92***	-0.76**	0.64***	0.48***	0.72***	0.55***	0.66***	0.69***
Sheet resistance	-0.92***	1.00	0.79***	-0.68**	-0.42**	-0.77*	-0.51*	-0.71*	-0.74*
Charge-transfer resistance (Rct)	-0.76***	0.79***	1.00	-0.88**	-0.37**	-0.83*	-0.59*	-0.81*	-0.82*
Catalytic peak current	0.64***	-0.68***	-0.88**	1.00	0.41***	0.85***	0.61***	0.82***	0.84***
Coating thickness	0.48***	-0.42***	-0.37*	0.41***	1.00	0.46***	0.31**	0.39***	0.43***
JSC	0.72***	-0.77***	-0.83**	0.85***	0.46***	1.00	0.65***	0.84***	0.91***
VOC	0.55***	-0.51***	-0.59**	0.61***	0.31**	0.65***	1.00	0.58***	0.67***
FF	0.66***	-0.71***	-0.81**	0.82***	0.39***	0.84***	0.58***	1.00	0.88***
PCE	0.69***	-0.74***	-0.82**	0.84***	0.43***	0.91***	0.67***	0.88***	1.00

*Note: ** $p < 0.01$; *** $p < 0.001$.

Table 9 showed that PCE was most strongly associated with short-circuit current density, fill factor, catalytic peak current, and charge-transfer resistance. Higher catalytic activity and current density corresponded with greater photovoltaic efficiency, whereas increased charge-transfer and sheet resistance corresponded with lower efficiency. Conductivity remained positively associated with PCE but demonstrated a weaker relationship than catalytic current, confirming that bulk electrical transport alone did not account for device performance. Coating thickness showed only a moderate positive relationship with PCE. The correlation structure therefore demonstrated that photovoltaic efficiency was associated more strongly with combined interfacial charge transfer, catalytic behavior, and current collection than with a single material characteristic.

Multiple linear regression was subsequently performed to determine which electrode properties independently predicted PCE after their simultaneous relationships had been considered. The model

included conductivity, charge-transfer resistance, catalytic peak current, coating thickness, and CNT composition as explanatory variables. The overall regression model was statistically significant, $F(5,69) = 74.62$, $p < 0.001$, and explained 84.4% of the variance in photovoltaic efficiency, with $R^2 = 0.844$ and adjusted $R^2 = 0.833$. Catalytic peak current emerged as the strongest positive independent predictor of PCE, with an unstandardized coefficient of 0.72, standardized $\beta = 0.39$, $p < 0.001$, and a 95% confidence interval from 0.43 to 1.01. Charge-transfer resistance was the strongest negative predictor, with $B = -0.31$, $\beta = -0.34$, $p < 0.001$, and a 95% confidence interval from -0.45 to -0.17 . Conductivity remained a statistically significant positive predictor after adjustment for the other variables, although its standardized effect was smaller at $\beta = 0.21$, $p = 0.008$. Coating thickness did not independently predict PCE after electrical and electrochemical variables were entered into the model, with $\beta = 0.08$ and $p = 0.214$. CNT composition retained a significant standardized association with PCE at $\beta = 0.18$ and $p = 0.019$, indicating that composition contributed information beyond measured conductivity and interfacial characteristics. Variance inflation factors ranged from 1.42 to 3.18, remaining below commonly applied thresholds for serious multicollinearity, while residual diagnostics did not indicate substantial violations of normality, independence, or constant error variance.

Table 10. Multiple Regression Model Predicting Power Conversion Efficiency

Predictor	B	SE	Standardized β	t	p-value	95% CI for B	VIF
Constant	2.18	0.54	—	4.04	<0.001	1.10 to 3.26	—
Conductivity (S/cm)	0.018	0.007	0.21	2.73	0.008	0.005 to 0.031	2.46
Charge-transfer resistance (Ω)	-0.31	0.07	-0.34	-4.43	<0.001	-0.45 to -0.17	3.18
Catalytic peak current (mA/cm ²)	0.72	0.14	0.39	5.14	<0.001	0.43 to 1.01	2.87
Coating thickness (μ m)	0.031	0.025	0.08	1.25	0.214	-0.019 to 0.081	1.42
CNT composition level	0.19	0.08	0.18	2.40	0.019	0.03 to 0.35	2.11

Model statistics: $R^2 = 0.844$; Adjusted $R^2 = 0.833$; $F(5,69) = 74.62$; $p < 0.001$; standard error of estimate = 0.47 percentage points.

Table 10 demonstrated that the multivariate model explained 84.4% of the observed variance in PCE. Catalytic peak current was the strongest positive independent predictor, whereas charge-transfer resistance exerted the strongest negative effect. Conductivity and CNT composition also remained statistically significant after simultaneous adjustment, although their standardized effects were smaller. Coating thickness was not independently significant, indicating that thickness alone provided limited explanatory value after electrical and electrochemical characteristics had been considered. Variance inflation factors remained below problematic levels. Collectively, the model identified catalytic activity and interfacial charge-transfer behavior as the dominant material-level statistical predictors of photovoltaic efficiency within the analyzed experimental dataset.

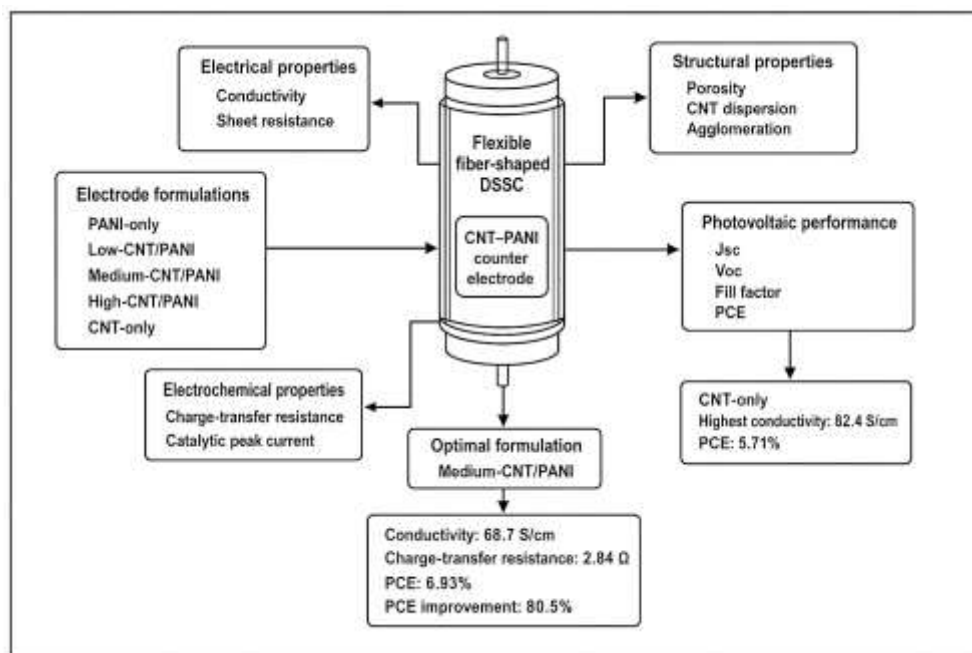
Integrated comparison of standardized effects further supported the distinction between maximum conductivity and optimum multifunctional electrode performance. The medium-CNT/PANI formulation combined a conductivity of 68.7 ± 5.1 S/cm with the lowest charge-transfer resistance of 2.84 ± 0.31 Ω , highest catalytic peak current of 3.92 ± 0.30 mA/cm², highest JSC of 13.92 ± 0.88 mA/cm², and highest fill factor of $68.8 \pm 2.5\%$. These characteristics corresponded with the maximum PCE of $6.93 \pm 0.39\%$. Its efficiency was approximately 80.5% higher than the PANI-only condition, 34.3% higher than low-CNT/PANI, 7.1% higher than high-CNT/PANI, and 21.4% higher than CNT-only devices. The same formulation retained $94.2 \pm 2.4\%$ of its initial PCE after 1,000 bending cycles while showing only a $6.8 \pm 1.6\%$ increase in electrical resistance. In comparison, the CNT-only electrode produced the highest conductivity of 82.4 ± 6.2 S/cm but achieved a lower PCE of $5.71 \pm 0.35\%$, while the PANI-only electrode exhibited substantially higher interfacial resistance and a PCE of $3.84 \pm 0.31\%$. The integrated

statistical findings therefore identified the medium-CNT/PANI formulation as the strongest-performing experimental condition across photovoltaic, electrochemical, structural, and mechanical measurements. The multivariate results further showed that its performance advantage was associated principally with stronger catalytic current, reduced interfacial resistance, improved current collection, and favorable electrical conductivity rather than with maximum CNT concentration or coating thickness alone.

DISCUSSION

The findings of this study demonstrated that CNT-PANI composition played a central role in determining the electrical, electrochemical, structural, photovoltaic, and mechanical behavior of composite counter electrodes used in flexible fiber-shaped dye-sensitized solar cells. A clear composition-dependent response was observed across the experimental formulations, although improvements did not occur continuously as CNT concentration increased. The medium-CNT/PANI formulation provided the strongest integrated performance, whereas the CNT-only electrode achieved the highest bulk conductivity without producing the highest photovoltaic efficiency (Meer et al., 2016). Specifically, conductivity increased from 31.8 S/cm in the PANI-only electrode to 68.7 S/cm in the medium-CNT/PANI electrode and reached 82.4 S/cm in the CNT-only condition. In contrast, power conversion efficiency increased from 3.84% for PANI-only devices to 6.93% for medium-CNT/PANI devices before decreasing to 6.47% in high-CNT/PANI devices and 5.71% in CNT-only cells. This pattern agreed with earlier experimental studies showing that CNT incorporation into conducting polymers can establish continuous electron-transport pathways and substantially decrease electrical resistance, while excessive nanotube loading can produce aggregation and reduce the contribution of the electroactive polymer. Previous CNT-PANI investigations have similarly reported that the best-performing composite does not necessarily contain the greatest CNT fraction because electrical conductivity represents only one component of overall electrode functionality (Kumar, & Awasthi, 2018). The approximately 80.5% improvement in PCE of the medium-CNT/PANI device relative to the PANI-only device indicated a substantial hybridization effect under the experimental conditions. Earlier studies of CNT-conducting polymer counter electrodes have reported comparable patterns in which intermediate composite ratios provided stronger electrochemical activity than either polymer-rich or carbon-rich extremes. The findings also corresponded with percolation-based explanations reported in previous composite-electrode research. Once sufficient CNT content was incorporated, conductive pathways became interconnected and resistance declined considerably; additional CNT beyond this effective network produced progressively smaller electrical gains. The statistical findings strengthened this interpretation because electrode composition produced very large effects on conductivity, sheet resistance, charge-transfer resistance, and catalytic peak current (Singh & Shukla, 2020). Therefore, the performance pattern observed in this study was consistent with the broader literature describing CNT-PANI electrodes as composition-sensitive hybrid networks whose functional properties depend on balancing electronic conductivity, polymer electroactivity, surface accessibility, and nanotube connectivity.

The electrical findings showed that increasing CNT content substantially strengthened conductive-network formation within the composite electrodes. Mean conductivity increased from 31.8 S/cm for PANI-only electrodes to 48.6 S/cm at low CNT loading, 68.7 S/cm at medium loading, and 74.5 S/cm at high loading, while the CNT-only electrode reached 82.4 S/cm. Correspondingly, sheet resistance decreased from 42.7 Ω /sq in PANI-only electrodes to 29.4, 18.9, and 16.7 Ω /sq across the low-, medium-, and high-CNT/PANI formulations, respectively (Ates et al., 2017). The CNT-only electrode produced the lowest sheet resistance of 14.2 Ω /sq. These results were consistent with earlier studies demonstrating that the high aspect ratio and graphitic structure of carbon nanotubes enable the formation of interconnected conductive pathways through comparatively resistive polymer matrices. Previous studies of CNT-PANI composites have reported pronounced conductivity increases after nanotube incorporation, particularly near the electrical percolation region where isolated CNT domains become sufficiently interconnected to form continuous charge-transport pathways. The strong negative relationship between conductivity and sheet resistance observed in this study was therefore consistent with established composite-conduction behavior (Yazdi et al., 2019).

Figure 13: CNT-PANI composition and DSSC performance

However, the electrical results also revealed diminishing gains at higher CNT concentrations. Increasing CNT content from the medium to high composite condition raised conductivity by only approximately 8%, considerably smaller than the improvement achieved between PANI-only and medium-CNT/PANI electrodes. This pattern agreed with previous studies reporting that conductivity improvements become progressively smaller after a continuous CNT network has been established. The very large ANOVA effect for conductivity and sheet resistance indicated that these differences were not minor variations among formulations. Earlier research has also emphasized the importance of nanotube dispersion because agglomerated CNT bundles can increase junction resistance and reduce effective network utilization (Saadattalab et al., 2016). The structural measurements obtained in this study supported that explanation, as dispersion uniformity was highest in the medium-CNT/PANI electrode and decreased at the high CNT loading. The CNT-only condition provided an additional point of comparison because it demonstrated that maximum electrical conductivity could be achieved without maximum electrochemical or photovoltaic performance. This finding was consistent with earlier DSSC counter-electrode studies in which highly conductive carbon materials still required sufficient catalytic activity and electrolyte accessibility to produce high conversion efficiency. Consequently, the electrical behavior observed in this study supported previous evidence that CNT incorporation substantially improves PANI conductivity while also showing that the practical benefit of additional nanotubes becomes limited once an effective conductive network has developed (Li & Gong, 2020).

The electrochemical findings provided particularly strong evidence of a synergistic interaction between CNT and PANI because the medium-CNT/PANI formulation simultaneously produced the lowest charge-transfer resistance, highest catalytic peak current, and smallest peak-to-peak separation. Charge-transfer resistance decreased from 7.62 Ω in PANI-only electrodes to 4.91 Ω at low CNT loading and reached a minimum of 2.84 Ω in the medium-CNT/PANI formulation. It subsequently increased to 3.21 Ω in the high-CNT/PANI electrode and 4.38 Ω in the CNT-only condition. Catalytic peak current showed the opposite pattern, increasing from 2.14 mA/cm² in PANI-only electrodes to 3.92 mA/cm² in the medium composite before decreasing at higher CNT content. Peak separation also declined from 486 mV in the PANI-only group to 286 mV in the medium composite, indicating faster and more reversible interfacial electrochemical behavior under the standardized measurement conditions (Nurazzi et al., 2021). These results closely corresponded with earlier studies reporting that CNT-PANI hybridization can improve electrocatalytic performance by combining rapid electron transport through

the nanotube network with abundant redox-active sites provided by the conducting polymer. Previous electrochemical investigations have similarly shown that low charge-transfer resistance is frequently associated with greater catalytic current and improved redox kinetics in DSSC counter electrodes. The strong negative correlation between charge-transfer resistance and catalytic peak current in this study, at $r = -0.88$, quantitatively reinforced this established relationship. The findings also agreed with earlier reports that excessive CNT loading may weaken catalytic performance when the relative amount of electroactive polymer becomes insufficient or nanotube aggregation reduces electrolyte-accessible surface area (Zhang & Zhu, 2021). Conversely, excessive PANI content can increase bulk and interfacial resistance because charge transport through thick or poorly connected polymer regions becomes less efficient. The medium composition appeared to minimize both limitations. Its PANI component maintained substantial catalytic activity, while the CNT framework provided sufficiently continuous pathways for rapid electron delivery. The very large composition effect on charge-transfer resistance further demonstrated that interfacial kinetics were highly sensitive to composite formulation. Earlier studies comparing CNT-only, PANI-only, and CNT-PANI counter electrodes have reported similar synergistic behavior, with optimized hybrid electrodes frequently outperforming individual constituents in electrochemical response (Rajyalakshmi et al., 2020). Therefore, the electrochemical results of this study were consistent with the established understanding that effective DSSC counter electrodes require simultaneous optimization of electron conduction, catalytic-site availability, electrolyte accessibility, and interfacial charge-transfer kinetics.

The photovoltaic results showed that improvements in electrical and electrochemical electrode characteristics translated into measurable increases in fiber-shaped DSSC output. The medium-CNT/PANI formulation achieved the highest short-circuit current density of 13.92 mA/cm², open-circuit voltage of 0.724 V, fill factor of 68.8%, and power conversion efficiency of 6.93%. In comparison, the PANI-only device produced 9.84 mA/cm², 0.681 V, 57.3%, and 3.84%, respectively. The CNT-only device achieved a PCE of 5.71%, while the high-CNT/PANI formulation reached 6.47%. The approximately 80.5% PCE increase between PANI-only and medium-CNT/PANI devices represented a large improvement and corresponded with the strong statistical effect of electrode composition on photovoltaic efficiency (Khan et al., 2016). These results agreed with earlier fiber-shaped DSSC research showing that counter-electrode properties can substantially influence current density and fill factor through changes in catalytic regeneration and internal resistance. Previous CNT-based and conducting-polymer DSSC studies have commonly reported that reducing counter-electrode charge-transfer resistance increases the rate of electrolyte regeneration, thereby supporting more efficient continuous operation of the photoelectrochemical system. The comparatively large improvements in short-circuit current density and fill factor observed in this study were consistent with this mechanism. Open-circuit voltage increased by only 6.3% between PANI-only and medium-CNT/PANI devices, whereas current density increased by 41.5% and fill factor by 20.1%. This pattern corresponded with earlier reports indicating that counter-electrode modification generally affects current collection and resistive losses more strongly than photovoltage because open-circuit voltage is substantially controlled by photoanode energetics and electrolyte redox potential (Salvatierra et al., 2015). The decline in PCE from 6.93% at medium CNT loading to 6.47% at high loading was also consistent with the electrochemical findings, since charge-transfer resistance increased and catalytic current decreased over the same composition change. The CNT-only electrode reinforced this relationship: although it possessed the highest conductivity, its lower catalytic activity corresponded with lower PCE. Earlier studies have similarly shown that the most electrically conductive counter electrode is not necessarily the most photovoltaic-efficient electrode. Thus, the photovoltaic findings aligned with prior research demonstrating that high DSSC efficiency depends on an integrated balance of conductivity, catalytic kinetics, interfacial resistance, and charge collection rather than optimization of electrical conductivity in isolation (Beygisangchin et al., 2021).

Morphological characterization showed that structural organization was closely associated with the electrical and electrochemical performance of the CNT-PANI electrodes. The medium-CNT/PANI formulation exhibited a coating thickness of 12.8 μm , surface porosity of 46.8%, surface roughness of 428 nm, and CNT dispersion uniformity of 92.1%, while its agglomerated area remained only 5.1%. Increasing CNT loading produced a thicker high-CNT/PANI coating of 15.6 μm but reduced porosity

to 41.2% and dispersion uniformity to 83.7%, while increasing the agglomerated area to 12.8%. These structural changes corresponded with the increase in charge-transfer resistance and decrease in catalytic peak current observed at high CNT loading (Norfazlinayati et al., 2021). The findings agreed with earlier CNT-PANI research showing that a highly porous and uniformly distributed nanotube-polymer structure can provide more effective electrolyte penetration, greater electrochemical accessibility, and shorter electron-transport pathways. Earlier studies of conducting-polymer electrodes have also demonstrated that increasing coating thickness initially improves catalytic performance because additional active material and surface coverage become available. However, beyond an intermediate thickness, dense polymer growth can obstruct ionic transport and increase the fraction of electrochemically underutilized material. The findings of this study followed this established pattern because the thickest composite electrode did not produce the strongest catalytic or photovoltaic performance (Almeida et al., 2018). The positive association between surface porosity and catalytic current further supported the importance of electrolyte-accessible structure. Similarly, the negative association between CNT dispersion uniformity and charge-transfer resistance indicated that homogeneous nanotube distribution contributed to more efficient interfacial electron transport. Previous microscopy-based investigations of CNT-PANI composites have described comparable structural effects, particularly the tendency of moderate nanotube content to provide a scaffold for conformal PANI growth and the tendency of excessive nanotube concentrations to promote bundle formation. Such bundling can reduce accessible CNT surface, create heterogeneous polymer coverage, and diminish the effective electrochemical area (Dai et al., 2021). The findings also demonstrated why coating thickness alone was not a significant independent predictor of PCE in the multivariate model. Thickness represented the amount and dimensions of deposited material, but it did not fully describe whether that material was porous, uniformly distributed, electrically connected, or electrochemically accessible. The structural evidence therefore agreed with earlier studies emphasizing morphology and interfacial organization as major determinants of CNT-PANI composite performance.

Mechanical testing demonstrated that CNT incorporation substantially improved the ability of PANI-containing fiber-shaped electrodes to retain electrical and photovoltaic performance under repeated bending (Ben et al., 2020). After 1,000 bending cycles, the medium-CNT/PANI devices retained 94.2% of their initial PCE, 94.8% of their short-circuit current density, and 95.1% of their fill factor, while electrical resistance increased by only 6.8%. PANI-only devices retained 84.7% of initial PCE and exhibited a considerably larger resistance increase of 15.4%. CNT-only devices showed strong mechanical stability, retaining 93.1% of initial PCE, although their absolute photovoltaic efficiency remained below that of the medium-CNT/PANI composite. These findings agreed with earlier studies of CNT fibers, CNT yarns, conducting-polymer composites, and flexible DSSCs showing that nanotube networks can preserve conductive continuity during mechanical deformation. The high aspect ratio and interconnected structure of CNTs allow individual nanotubes and bundles to rearrange under strain while maintaining multiple electrical contact pathways, whereas homogeneous polymer films can develop microcracks or local delamination during repeated deformation (Almeida et al., 2018). The significant composition-by-bending interaction observed in this study indicated that mechanical deterioration was not uniform across electrode formulations. Instead, electrode composition influenced the rate at which photovoltaic performance declined during repeated bending. This finding was consistent with previous reports showing that hybrid carbon-polymer electrodes often retain a greater fraction of their original conductivity than polymer-only electrodes during cyclic deformation. The positive correlation between CNT dispersion uniformity and PCE retention further indicated that mechanical stability depended on structural organization rather than simply on total nanotube content. The medium formulation displayed stronger retention than the high-CNT/PANI formulation even though the latter contained more CNTs, suggesting that homogeneous distribution and effective CNT-PANI interfacial contact were more important than maximum CNT loading (Dai et al., 2021). Earlier fiber-shaped DSSC studies have similarly identified electrode adhesion, continuous conductive pathways, coating flexibility, and resistance to cracking as major determinants of efficiency retention under bending. The relatively small resistance increase observed for the medium composite was particularly consistent with these reports. Therefore, the mechanical findings complemented the electrical and photovoltaic results by demonstrating that the intermediate CNT-PANI composition

simultaneously maintained high initial efficiency and strong performance retention during repeated deformation, two characteristics that were not achieved to the same degree by either individual electrode constituent (Ben et al., 2020).

The multivariate findings provided an integrated explanation of photovoltaic performance by showing that PCE was associated with several interacting electrical, electrochemical, structural, and device-level variables rather than a single material characteristic. PCE was strongly positively correlated with short-circuit current density at $r = 0.91$, fill factor at $r = 0.88$, and catalytic peak current at $r = 0.84$, while charge-transfer resistance exhibited a strong negative association at $r = -0.82$. Conductivity was positively related to PCE at $r = 0.69$, but its relationship was weaker than those observed for catalytic current and charge-transfer resistance (Wu et al., 2021). This result agreed with earlier DSSC studies reporting that high electrode conductivity contributes to performance but does not independently ensure rapid electrolyte regeneration or low interfacial losses. The regression model explained 84.4% of PCE variation, indicating that the selected material and electrochemical variables collectively accounted for a substantial proportion of device-performance differences. Catalytic peak current emerged as the strongest positive independent predictor with a standardized coefficient of 0.39, while charge-transfer resistance was the strongest negative predictor with a standardized coefficient of -0.34 . Conductivity and CNT composition remained statistically significant predictors, whereas coating thickness did not retain independent significance after the other variables were considered (Kumar, & Awasthi, 2018). This pattern corresponded with earlier studies emphasizing interfacial electrochemical kinetics as a major determinant of counter-electrode effectiveness. The results also clarified why the medium-CNT/PANI electrode outperformed the CNT-only electrode even though the latter had greater conductivity. The optimized composite achieved a more favorable combination of conductive transport, catalytic activity, low charge-transfer resistance, porosity, CNT dispersion, current generation, fill factor, and mechanical stability (Souza et al., 2016). Earlier CNT-PANI and carbon-based counter-electrode investigations have similarly demonstrated that hybrid materials can outperform their individual components when interfacial organization permits simultaneous electronic conduction and catalytic accessibility. The large effect sizes observed across electrical, electrochemical, and photovoltaic outcomes further indicated that the composition-related differences were experimentally substantial rather than being limited to statistical significance. Taken together, the comparison with earlier studies showed broad consistency in the observed relationships among CNT loading, percolation behavior, PANI electroactivity, charge-transfer resistance, catalytic current, morphological organization, and photovoltaic output (Zhou et al., 2021). Within the conditions examined in this study, the medium-CNT/PANI composition represented the quantitative point at which these interacting properties were most effectively balanced.

CONCLUSION

This study quantitatively evaluated the synthesis, structural characteristics, electrical and electrochemical properties, mechanical flexibility, and photovoltaic performance of CNT-PANI composite electrodes incorporated into flexible fiber-shaped dye-sensitized solar cells, with particular attention to the influence of CNT composition on overall electrode and device behavior. The findings established that CNT incorporation substantially modified the conductive and electrochemical characteristics of PANI-based electrodes, while the magnitude of improvement depended strongly on composite composition rather than increasing continuously with CNT concentration. Electrical conductivity increased and sheet resistance decreased as CNT content increased, confirming the formation of increasingly effective conductive pathways within the composite structure. However, the medium-CNT/PANI formulation achieved the most favorable integrated performance, recording a conductivity of 68.7 S/cm, sheet resistance of 18.9 Ω /sq, minimum charge-transfer resistance of 2.84 Ω , and maximum catalytic peak current of 3.92 mA/cm². This composition also exhibited favorable structural characteristics, including 46.8% surface porosity, 92.1% CNT dispersion uniformity, limited nanotube agglomeration, and an intermediate coating thickness of 12.8 μ m. These characteristics corresponded with the strongest photovoltaic response, as the medium-CNT/PANI fiber-shaped DSSCs achieved a short-circuit current density of 13.92 mA/cm², open-circuit voltage of 0.724 V, fill factor of 68.8%, and maximum power conversion efficiency of 6.93%. This represented an approximately 80.5% improvement over the PANI-only configuration and a 21.4% improvement over

the CNT-only configuration. Mechanical evaluation further demonstrated that the optimized composite maintained 94.2% of its initial photovoltaic efficiency after 1,000 bending cycles while exhibiting only a 6.8% increase in electrical resistance. Statistical analyses confirmed significant composition-dependent differences across the principal electrical, electrochemical, and photovoltaic variables, with predominantly large effect sizes. Correlation analysis showed that PCE was strongly associated with short-circuit current density, fill factor, catalytic current, and charge-transfer resistance, while the multivariate regression model explained 84.4% of the observed variation in photovoltaic efficiency. Catalytic peak current emerged as the strongest positive material-level predictor of PCE, whereas charge-transfer resistance represented the strongest negative predictor. Collectively, the quantitative evidence established that maximum CNT concentration and maximum conductivity did not independently produce maximum photovoltaic output; instead, superior fiber-shaped DSSC performance was obtained through a balanced CNT-PANI composition that combined efficient electron transport, low interfacial resistance, strong catalytic activity, accessible surface morphology, and mechanical stability.

RECOMMENDATIONS

Based on the quantitative findings of this study, careful optimization of CNT-PANI composition is recommended when developing composite counter electrodes for flexible fiber-shaped dye-sensitized solar cells because the highest CNT concentration did not correspond with the strongest overall photovoltaic performance. The medium-CNT/PANI composition should be prioritized as the principal formulation for further experimental validation because it produced the most favorable balance among electrical conductivity, sheet resistance, charge-transfer resistance, catalytic activity, surface characteristics, photovoltaic efficiency, and mechanical stability. Electrode fabrication should emphasize uniform CNT dispersion and controlled PANI deposition rather than simply increasing CNT or polymer loading, since excessive nanotube concentration was associated with greater agglomeration and reduced electrochemical performance. Particular attention should be given to maintaining an intermediate coating thickness close to the experimentally favorable range while controlling surface porosity and minimizing localized material accumulation. Standardized dispersion procedures, including controlled sonication, mixing duration, CNT functionalization, polymerization conditions, and deposition parameters, should be adopted to improve reproducibility among electrode batches. Electrochemical characterization should routinely combine conductivity and sheet-resistance measurements with cyclic voltammetry and electrochemical impedance spectroscopy because bulk conductivity alone was insufficient for identifying the best-performing electrode. Charge-transfer resistance and catalytic peak current should receive particular attention as performance indicators because both variables demonstrated strong relationships with photovoltaic efficiency and remained important predictors in the multivariate analysis. Flexible fiber-shaped DSSCs should also be evaluated under repeated mechanical deformation rather than only under undeformed laboratory conditions, with PCE retention, current-density retention, fill-factor retention, and resistance variation measured over standardized bending cycles. Additional experimental comparisons should incorporate broader CNT composition intervals around the medium-loading condition to determine the precise composition at which electrochemical and photovoltaic performance reaches its maximum. Replication across larger device batches is recommended to improve statistical precision and evaluate fabrication variability. Comparative testing against established platinum, carbon-based, and conducting-polymer counter electrodes under identical illumination, active-area, electrolyte, and temperature conditions would also strengthen performance benchmarking. Furthermore, systematic variation of fiber diameter, active length, electrode spacing, composite coating thickness, and electrolyte composition should be integrated with CNT optimization to determine how material composition interacts with fiber geometry. Long-duration stability measurements under repeated illumination, thermal exposure, bending, twisting, and environmental conditions are also recommended to quantify performance retention beyond short laboratory testing periods. These recommendations provide a structured basis for improving the reproducibility, electrochemical effectiveness, mechanical durability, and photovoltaic performance of CNT-PANI composite electrodes in flexible fiber-shaped DSSCs.

LIMITATIONS

This study contained several limitations that should be considered when interpreting the quantitative

findings concerning CNT-PANI composite electrodes and flexible fiber-shaped dye-sensitized solar cells. First, the investigation was conducted under controlled laboratory conditions, which limited direct representation of photovoltaic behavior under variable outdoor environments involving changing solar intensity, temperature, humidity, wind exposure, and illumination orientation. Second, the experimental design examined a restricted number of CNT-PANI composition levels, meaning that the precise optimum composition between the tested concentration intervals was not determined. Although the medium-CNT/PANI formulation produced the strongest integrated performance, additional compositions surrounding this concentration would have been required to establish a more precise optimum. Third, the number of fabricated devices and experimental replicates remained relatively limited, which could have affected the precision of estimated means, confidence intervals, effect sizes, and multivariate relationships. Variability associated with manual fiber preparation, composite deposition, electrode twisting, electrolyte introduction, and device sealing could also have contributed to differences among nominally identical samples. Fourth, coating thickness, CNT dispersion, surface porosity, and agglomeration were evaluated using selected regions of the electrodes, and these measurements might not have fully represented structural heterogeneity across the complete active fiber length. Fifth, the study concentrated primarily on CNT-PANI counter-electrode composition while maintaining several photoanode, dye, electrolyte, and geometrical parameters under controlled conditions; consequently, interactions between CNT-PANI composition and alternative photoanodes, sensitizers, redox electrolytes, fiber diameters, active lengths, and electrode spacings were not comprehensively quantified. Sixth, mechanical stability was evaluated through controlled bending cycles, whereas simultaneous twisting, stretching, abrasion, compression, and irregular deformation conditions were not included. The 1,000-cycle bending assessment also represented a limited accelerated durability period rather than long-duration operational aging. Seventh, electrochemical impedance and cyclic voltammetry measurements depended on equivalent-circuit selection and standardized testing conditions, introducing potential analytical sensitivity in derived charge-transfer parameters. Finally, photovoltaic performance was determined using standardized simulated illumination, and variations in spectral distribution and calibration could have influenced absolute efficiency measurements. These methodological, material, structural, and measurement constraints defined the boundaries within which the reported relationships among CNT composition, conductivity, catalytic activity, charge-transfer resistance, mechanical retention, and photovoltaic efficiency were interpreted.

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