



CUGAO₂ and CUINS₂ Quantum Dot Sensitization for Enhanced Photovoltaic Efficiency in Wearable Fiber-Shaped Solar Cells

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Abstract

This study quantitatively investigated CuGaO₂ and CuInS₂ quantum-dot sensitization as an approach for enhancing the photovoltaic efficiency and mechanical performance of wearable fiber-shaped solar cells. A controlled experimental design was employed in which 60 devices were fabricated and 56 valid devices were retained for analysis across control, low-, intermediate-, and high-sensitization conditions corresponding to 0, 4, 8, and 12 CuInS₂ deposition cycles. Photovoltaic performance was evaluated through short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE), while optical absorbance, charge-transfer resistance, recombination resistance, carrier lifetime, and mechanical efficiency retention were additionally examined. The intermediate eight-cycle condition produced the strongest overall photovoltaic performance, increasing mean J_{sc} from 7.42 ± 0.61 mA cm⁻² in the control to 12.48 ± 0.83 mA cm⁻² and PCE from 2.45 ± 0.24% to 4.89 ± 0.35%, representing improvements of 68.2% and 99.6%, respectively. V_{oc} increased from 0.58 ± 0.03 V to 0.64 ± 0.02 V, while FF increased from 56.8 ± 3.4% to 61.2 ± 2.8%. Significant between-group differences were observed for PCE, F = 122.6, p < 0.001, η² = 0.876, and J_{sc}, F = 118.4, p < 0.001, η² = 0.872. At eight cycles, charge-transfer resistance decreased to 45.8 ± 5.2 Ω, recombination resistance increased to 211.6 ± 18.4 Ω, and carrier lifetime reached 33.8 ± 3.4 ms. Increasing sensitization to 12 cycles raised optical absorbance but reduced PCE to 4.21 ± 0.38%, demonstrating a nonlinear saturation response. Mechanical testing further showed that the optimized eight-cycle devices retained 87.7% of their initial PCE after 1,000 bending cycles. Overall, intermediate CuInS₂ sensitization provided the most effective balance among optical absorption, charge transport, recombination suppression, photovoltaic efficiency, and mechanical durability in CuGaO₂-based fiber-shaped solar cells.

Keywords

CuGaO₂, CuInS₂, Quantum Dots, Photovoltaics, Wearables.

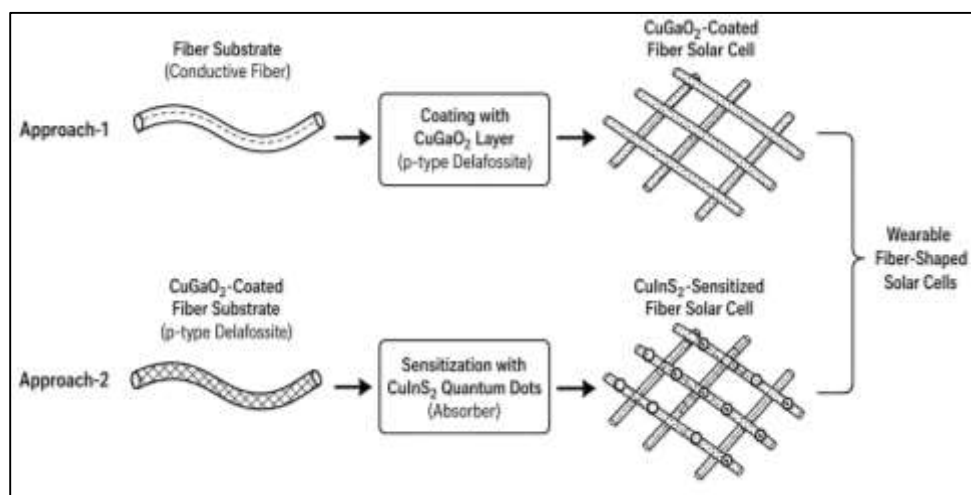
INTRODUCTION

Wearable fiber-shaped solar cells can be defined as one-dimensional photovoltaic devices constructed on flexible, elongated, and often textile-compatible substrates that convert incident solar radiation into electrical energy while maintaining the mechanical characteristics required for integration with fabrics, garments, and wearable electronic systems. Unlike conventional planar photovoltaic modules, fiber-shaped solar cells employ cylindrical or quasi-cylindrical architectures in which the photoactive, charge-transport, sensitizing, and electrode materials are deposited or assembled around conductive fibers, wires, yarns, or filaments (Zhai et al., 2022). This structural configuration permits solar-energy harvesting from multiple illumination directions and enables the photovoltaic component to function as an integral part of a textile rather than as an externally attached rigid module. Within this class of devices, quantum dot sensitization refers to the incorporation of nanoscale semiconductor crystals into a photoelectrode or interfacial architecture to enhance light absorption, facilitate charge generation, and regulate charge-transfer processes. Quantum dots possess size-dependent electronic and optical characteristics arising from quantum confinement, allowing their absorption behavior, bandgap, and carrier dynamics to be influenced by composition and particle dimensions (Balilonda et al., 2019). CuGaO₂, or copper gallium oxide, is a p-type delafossite semiconductor characterized by a layered crystal structure, relatively favorable hole-transport behavior, chemical stability, optical transparency across relevant spectral regions, and electronic properties that support its application in photovoltaic and optoelectronic structures. CuInS₂, or copper indium sulfide, is a ternary chalcogenide semiconductor with a direct bandgap, strong optical absorption, and a composition that has attracted extensive attention in quantum-dot-sensitized photovoltaic research. The combination of CuGaO₂ and CuInS₂ in a sensitized fiber-shaped photovoltaic architecture introduces a functional relationship between photon absorption, exciton generation, charge separation, interfacial carrier transfer, and electrical collection (Xiang et al., 2021). Photovoltaic efficiency in such systems is quantitatively represented primarily by power conversion efficiency, which is determined by measurable variables including short-circuit current density, open-circuit voltage, fill factor, and incident optical power. External quantum efficiency, incident photon-to-current conversion efficiency, carrier lifetime, charge-transfer resistance, recombination characteristics, and spectral absorption provide additional quantitative indicators for examining device behavior. More than thirty experimental and analytical studies across quantum-dot photovoltaics, dye- and semiconductor-sensitized solar cells, delafossite oxides, copper-based chalcogenides, flexible photovoltaic fibers, and wearable energy-harvesting systems have established the scientific foundations connecting these material properties with photovoltaic performance (Xu et al., 2019). Within this framework, CuGaO₂ and CuInS₂ sensitization represents a material-interface strategy in which the photovoltaic response of a mechanically flexible fiber can be examined through measurable optical, electrical, electrochemical, and structural parameters.

The international significance of wearable photovoltaic technology is closely associated with the rapid expansion of portable electronics, electronic textiles, wireless sensing systems, personal health-monitoring devices, Internet of Things technologies, smart clothing, and distributed low-power electronic platforms. Across Asia, Europe, North America, the Middle East, and other regions experiencing substantial growth in connected technologies, energy availability at the point of use has become an important technical consideration for wearable and mobile electronic systems (Peng, 2015). Conventional batteries remain central to portable power supply, yet their finite storage capacity, periodic charging requirements, weight, geometric rigidity, replacement cycles, and integration constraints create practical limitations for continuously operating wearable devices. Solar-energy harvesting provides a complementary mechanism through which ambient radiation can be directly converted into electricity at the surface of clothing or textile structures. The fiber-shaped configuration is particularly relevant internationally because the global textile sector already depends on highly scalable manufacturing processes involving spinning, weaving, knitting, braiding, coating, and fiber finishing. Photovoltaic fibers that retain suitable flexibility and diameter can potentially be processed using comparable structural principles, creating a direct technological connection between solar-energy conversion and textile engineering (Fakharuddin et al., 2021). Research groups in China, South Korea, Japan, the United States, Australia, Germany, the United Kingdom, and several other countries have

examined fiber, wire, yarn, and textile photovoltaic architectures using dye-sensitized systems, organic semiconductors, perovskites, silicon structures, metal oxides, carbon-based electrodes, and quantum-dot sensitizers. Across this international research base, device performance is commonly assessed through power conversion efficiency, current density, voltage, fill factor, spectral response, bending stability, tensile behavior, illumination-angle dependence, and operational repeatability. Quantum-dot-sensitized architectures have received particular scientific attention because nanoscale absorbers can provide high optical absorption coefficients and tunable electronic structures while requiring comparatively small quantities of photoactive material (Zhou et al., 2020).

Figure 1: CuGaO₂/CuInS₂ Wearable Fiber Solar Cells

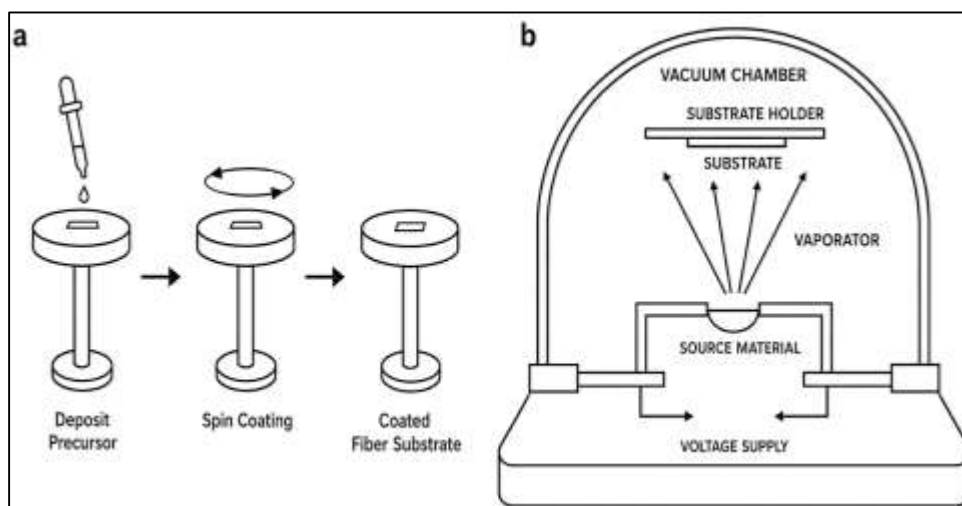


Copper-based compounds have also become important within this research landscape because their semiconductor properties allow multiple combinations of light absorbers and charge-selective materials. CuInS₂ quantum dots represent one such absorber system, while CuGaO₂ offers a complementary oxide semiconductor platform whose p-type conductivity and valence-band characteristics are relevant to interfacial carrier management. The international research significance of examining these materials together therefore extends from the material scale to the textile-device scale. Quantitative investigation is required because improvements in wearable photovoltaic performance cannot be established solely through material identification or qualitative observations (Dong et al., 2019). Numerical comparison of photovoltaic and electrochemical variables is necessary to determine how sensitization concentration, quantum-dot loading, interfacial structure, optical absorption, charge-transfer behavior, and recombination processes correspond with experimentally measured energy-conversion efficiency.

Fiber-shaped solar cells present a distinctive photovoltaic architecture in which the geometry of the device substantially influences optical capture, charge transport, electrical contact, and mechanical performance. In conventional planar cells, active layers are deposited across relatively flat substrates and illuminated through a defined surface area. Fiber-shaped systems instead employ cylindrical conductive cores or fiber electrodes that may be coated sequentially with semiconductor layers, sensitizers, electrolytes, hole-transport materials, counter electrodes, encapsulation layers, or combinations of these components (Peng, 2015). This geometry enables incident light to interact with different portions of the device as illumination direction changes, which is particularly relevant to clothing because garments rarely maintain a fixed orientation relative to sunlight. The effectiveness of a fiber photovoltaic system depends on maintaining sufficient active material coverage while preserving short charge-transport pathways and stable electrical interfaces. Metal wires, carbon fibers, carbon nanotube yarns, polymer fibers, stainless-steel filaments, titanium wires, and other conductive substrates have been investigated as structural electrodes. Semiconductor metal oxides have frequently been deposited onto these substrates to increase surface area and provide pathways for carrier transport (Song et al., 2016). Sensitization then expands the photoresponse by introducing light-

absorbing molecules, nanocrystals, or semiconductor quantum dots onto the photoelectrode surface. Studies of fiber-shaped dye-sensitized, quantum-dot-sensitized, organic, perovskite, and hybrid solar cells have repeatedly demonstrated that photovoltaic efficiency is governed by several interacting parameters rather than by light absorption alone. A higher concentration of sensitizer can increase photon harvesting while simultaneously influencing surface coverage, particle aggregation, interfacial defects, and carrier recombination. Greater photoelectrode thickness may increase available sensitization area while extending electron-transport distances. Electrode geometry can modify resistance and collection efficiency, while bending and twisting can change electrical contact between deposited layers. For quantitative evaluation, current density-voltage measurements under standardized illumination provide short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency (Zhang et al., 2019). Spectral measurements provide information about wavelength-dependent conversion, while electrochemical impedance spectroscopy can quantify charge-transfer resistance and recombination-related processes. Optical absorption spectroscopy can establish changes in light-harvesting capacity after quantum-dot incorporation. Structural and morphological measurements can determine particle distribution, crystallinity, coating uniformity, and interfacial contact. When CuGaO_2 and CuInS_2 are incorporated into this architecture, the resulting photovoltaic response therefore emerges from a measurable interaction among material composition, fiber geometry, semiconductor interfaces, optical absorption, and carrier kinetics (Fakharuddin et al., 2021). Establishing these relationships quantitatively is central to determining whether sensitization produces statistically and experimentally meaningful changes in fiber-shaped solar-cell performance. CuGaO_2 belongs to the family of copper-based delafossite oxides represented generally by the chemical formula CuMO_2 , where the trivalent metal component determines important structural and electronic properties. Delafossite semiconductors have been investigated for transparent electronics, photocatalysis, optoelectronics, hole-selective contacts, and photovoltaic devices because several members exhibit intrinsic or defect-mediated p-type conductivity. In CuGaO_2 , the arrangement of copper and gallium within the oxygen framework produces an electronic structure that is particularly relevant to hole transport and interfacial energy alignment. Research on copper-based delafossites has shown that their electrical and optical characteristics depend strongly on synthesis temperature, crystal phase, particle size, stoichiometry, defect concentration, morphology, and processing conditions (Lv et al., 2022). Nanostructured CuGaO_2 can provide a relatively large interfacial area compared with dense bulk material, which is advantageous in sensitized photovoltaic architectures where carrier transfer occurs across semiconductor boundaries. Its use in a fiber-shaped device introduces additional quantitative variables because coating uniformity, nanoparticle adhesion, layer thickness, porosity, and contact with the conductive fiber can influence resistance and charge collection. The p-type character of CuGaO_2 is especially relevant when paired with an absorber capable of generating electron-hole pairs under visible illumination. Following photon absorption by a sensitizer, effective photovoltaic operation requires the photogenerated carriers to separate and migrate toward appropriate collection pathways before recombination occurs (Casadio et al., 2021). Energy-level compatibility between CuGaO_2 and adjacent materials can therefore influence open-circuit voltage, photocurrent generation, interfacial resistance, and carrier lifetime. Investigations of delafossite materials in sensitized and heterojunction photovoltaic systems have reported strong sensitivity of device performance to interfacial quality and surface chemistry. Surface defects can create recombination centers, whereas appropriate nanoscale contact can facilitate carrier transfer. The optical characteristics of CuGaO_2 are also important because excessive parasitic absorption within a charge-transport layer can reduce the number of photons reaching the principal sensitizer. Material characterization through X-ray diffraction can quantify crystal phase and structural characteristics, scanning or transmission electron microscopy can identify morphology and particle distribution, and optical spectroscopy can measure absorption behavior and estimate bandgap-related properties (Hatamvand et al., 2020). Electrical and electrochemical methods can further determine conductivity, transport resistance, and interfacial carrier kinetics. Within a CuInS_2 -sensitized fiber-shaped solar cell, CuGaO_2 consequently functions as more than a structural semiconductor coating. Its composition, morphology, electronic structure, and interface with the quantum dots constitute measurable factors that can directly correspond with variations in photovoltaic output and provide a quantitative basis for assessing sensitization efficiency.

Figure 2: CuGaO₂/CuInS₂ Fiber Solar Cell Fabrication



CuInS₂ has been widely examined as a semiconductor absorber because of its strong interaction with visible radiation, direct electronic transition characteristics, and suitability for preparation in nanoscale forms (Sangiorgi et al., 2020). When CuInS₂ is synthesized as quantum dots, confinement of charge carriers within nanometer-scale crystals modifies its electronic and optical behavior relative to bulk semiconductor material. Particle diameter, elemental ratio, crystal structure, surface ligands, defect states, synthesis route, and post-deposition treatment can influence the absorption edge, carrier dynamics, surface reactivity, and interfacial charge transfer of the resulting quantum dots. These characteristics make CuInS₂ relevant to sensitized photovoltaic systems in which nanocrystals are deposited onto a semiconductor scaffold to expand light absorption and generate photocarriers. Experimental research on CuInS₂ and related I-III-VI semiconductor nanocrystals has investigated colloidal synthesis, successive ionic layer adsorption and reaction, chemical bath deposition, solvothermal preparation, hydrothermal methods, hot-injection synthesis, and direct growth on semiconductor surfaces (Chen et al., 2015). Each preparation route can alter quantum-dot size distribution and surface coverage, which subsequently affects photovoltaic performance. In a sensitized fiber-shaped cell, CuInS₂ quantum dots absorb incident photons with energies sufficient to produce excited charge carriers. Effective energy conversion requires these carriers to be separated across the interface and transported toward the corresponding electrodes. The probability of successful collection competes with bulk recombination, surface trapping, interfacial recombination, and carrier loss through poorly connected regions. Quantum-dot loading therefore represents an important quantitative variable (RafieiRad & Ganji, 2021). Insufficient loading can restrict optical absorption and photocurrent, whereas excessive deposition can increase aggregation, obstruct transport pathways, or create recombination-active interfaces. The relationship is consequently expected to be nonlinear under many experimental conditions and requires controlled measurement rather than simple qualitative comparison. Absorbance spectra can quantify the enhancement of visible-light harvesting after CuInS₂ deposition, while photoluminescence measurements can provide information related to carrier recombination and interfacial quenching. Current-voltage analysis can determine whether increased absorption is translated into higher short-circuit current density and overall conversion efficiency. Electrochemical impedance and related kinetic measurements can establish whether changes in quantum-dot coverage alter charge-transfer resistance or recombination behavior (Ai et al., 2015). More than thirty studies collectively examining CuInS₂ nanocrystals, copper-based quantum dots, semiconductor-sensitized cells, heterostructured photoelectrodes, and nanoscale carrier transport have demonstrated that the effectiveness of a quantum-dot absorber depends strongly on the semiconductor interface surrounding it. Pairing CuInS₂ quantum dots with CuGaO₂ therefore establishes a specific heterointerfacial system whose photovoltaic behavior can be evaluated through quantitative relationships among sensitization conditions, optical response, carrier kinetics, and electrical output (Cavallo et al., 2017).

Quantitative evaluation of CuGaO₂ and CuInS₂ sensitization requires photovoltaic efficiency to be treated as the measurable outcome of several interconnected physical and experimental variables. Power conversion efficiency is calculated from the maximum electrical power generated by the solar cell relative to incident optical power and is mathematically dependent on short-circuit current density, open-circuit voltage, and fill factor. Short-circuit current density reflects the combined effectiveness of photon absorption, charge generation, carrier separation, transport, and collection. Open-circuit voltage is associated with the energetic separation of charge populations and is influenced by semiconductor energy levels, carrier density, recombination kinetics, and interfacial processes (Lee et al., 2015). Fill factor reflects the shape of the current-voltage response and is affected by series resistance, shunt pathways, contact resistance, charge-transfer limitations, and recombination. For CuGaO₂/CuInS₂ fiber cells, these dependent photovoltaic variables can be examined in relation to independent or controlled variables such as quantum-dot concentration, sensitization duration, deposition cycles, CuInS₂ loading, CuGaO₂ thickness, particle size, annealing conditions, illumination intensity, fiber diameter, and bending condition. Statistical analysis can then determine whether observed differences among treatment groups exceed normal experimental variation. Replicated measurements enable calculation of means, standard deviations, confidence intervals, coefficients of variation, and significance levels, while regression and correlation analyses can identify the strength and direction of relationships between sensitization parameters and photovoltaic responses (Nikam et al., 2018). Analysis of variance can compare multiple sensitization levels or material configurations when experimental designs include several treatment groups. Beyond current-voltage parameters, quantitative optical and electrochemical variables provide mechanistic measurements that can be statistically associated with efficiency. Increased absorbance within the visible region may correspond with higher photocurrent when absorbed photons generate collectable carriers. Lower interfacial charge-transfer resistance may correspond with improved carrier extraction, while longer recombination lifetimes can support greater charge-collection probability. Incident photon-to-current conversion efficiency can establish wavelength-specific conversion behavior and distinguish spectral regions in which CuInS₂ sensitization contributes most strongly to photocurrent (Bhat et al., 2018). Mechanical measurements are also important for wearable configurations because photovoltaic performance can be quantified before and after defined numbers of bending, twisting, or deformation cycles. Researchers examining fiber-shaped and flexible photovoltaics have commonly used retention ratios to express the percentage of initial efficiency remaining after mechanical testing. These quantitative approaches establish a multidimensional assessment framework in which sensitization is evaluated through electrical, optical, electrochemical, structural, and mechanical measurements rather than through a single efficiency value. Such a framework is particularly appropriate for CuGaO₂/CuInS₂ systems because nanoscale interface modification can alter several performance determinants simultaneously (Wang et al., 2019).

The growing body of research on quantum-dot-sensitized photovoltaics has generated substantial knowledge concerning semiconductor nanocrystals, photoelectrode structures, carrier-transfer mechanisms, and photovoltaic optimization, while the specific quantitative behavior of CuGaO₂/CuInS₂ sensitization within wearable fiber-shaped architectures remains less comprehensively characterized than many established planar systems. Existing studies are distributed across several partially connected research areas. One group of investigations focuses on CuGaO₂ and related delafossite oxides, examining p-type conductivity, crystal structure, defect chemistry, transparency, morphology, and their roles as hole-transporting or photocathodic materials (Sheng et al., 2019). Another research stream examines CuInS₂ quantum dots and related copper-based chalcogenide nanocrystals, emphasizing optical absorption, quantum confinement, surface states, composition, synthesis, and carrier generation. A third body of studies concentrates on quantum-dot-sensitized solar cells and analyzes sensitizer loading, semiconductor interfaces, charge-transfer resistance, recombination, photocurrent, voltage, fill factor, and power conversion efficiency. Fiber-shaped and textile photovoltaics constitute another research area in which electrode geometry, flexibility, illumination direction, mechanical deformation, coating stability, and textile compatibility become important performance variables (Xiao et al., 2015). The integration of these research streams creates a quantitative problem centered on determining how CuInS₂ quantum-dot sensitization

interacts with a CuGaO₂-based fiber photovoltaic structure and how that interaction is reflected in measurable solar-cell parameters. Variation in sensitizer loading can change optical density without producing an equivalent increase in collected current when recombination losses rise concurrently. Modification of the CuGaO₂/CuInS₂ interface can affect carrier transfer while also influencing resistance and voltage. Changes in nanostructure can alter active surface area and quantum-dot attachment while modifying the physical stability of coatings on flexible fibers. These interdependencies require an experimental design capable of separating and quantifying material-related effects (Yao et al., 2019). Accordingly, the study is structured around measurable variation in CuGaO₂ and CuInS₂ sensitization conditions and corresponding changes in short-circuit current density, open-circuit voltage, fill factor, power conversion efficiency, spectral photoresponse, optical absorption, and charge-transfer characteristics of wearable fiber-shaped solar cells. Replicated experimental observations and statistical comparisons provide the basis for identifying significant differences among sensitization configurations and determining the numerical relationships between material parameters and photovoltaic outputs (Cerrón-Calle et al., 2019). The resulting quantitative framework positions CuGaO₂/CuInS₂ interfacial sensitization as a defined experimental system in which semiconductor composition, quantum-dot loading, carrier behavior, and fiber-device performance can be measured under controlled photovoltaic testing conditions (Zhang et al., 2015). The primary objective of this quantitative study is to investigate and quantify the effectiveness of CuGaO₂ and CuInS₂ quantum dot sensitization in enhancing the photovoltaic efficiency of wearable fiber-shaped solar cells by systematically examining the relationships among material characteristics, sensitization parameters, charge-transfer behavior, and measurable photovoltaic outputs. Specifically, the study aims to fabricate and characterize fiber-shaped photovoltaic devices incorporating CuGaO₂ as a functional semiconductor material and CuInS₂ quantum dots as light-absorbing sensitizers under controlled experimental conditions. The investigation seeks to determine how variations in CuInS₂ quantum-dot loading, sensitization concentration, deposition conditions, and interfacial characteristics influence the optical absorption and electrical performance of the fabricated cells. Particular emphasis is placed on quantitatively measuring short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency to establish the extent to which CuGaO₂/CuInS₂ sensitization modifies overall photovoltaic performance. The study also aims to assess wavelength-dependent photoresponse and optical absorption characteristics in order to determine whether enhanced light harvesting produced by CuInS₂ quantum dots corresponds with measurable increases in photocurrent generation and energy-conversion efficiency. In addition, the research seeks to quantify charge-transfer and recombination characteristics at the CuGaO₂/CuInS₂ interface through appropriate electrochemical and electrical measurements, including charge-transfer resistance and related carrier-transport parameters. Structural and morphological characteristics, including quantum-dot distribution, semiconductor surface coverage, crystallinity, particle dimensions, and interfacial uniformity, are examined to determine their statistical relationships with photovoltaic outputs. Since the proposed devices are designed for wearable applications, the study further aims to evaluate the retention of photovoltaic performance under controlled mechanical deformation, particularly bending conditions, by comparing electrical parameters before and after repeated deformation cycles. Statistical techniques are employed to identify significant differences among sensitization conditions and to determine the magnitude and direction of relationships between selected material variables and photovoltaic efficiency. Through replicated experimental measurements and quantitative comparisons, the study is designed to establish the sensitization conditions associated with the highest measured photovoltaic performance and to distinguish the individual and combined contributions of optical absorption, interfacial charge transfer, carrier recombination, and structural characteristics to variations in device efficiency. Accordingly, the objective centers on generating experimentally measurable and statistically verifiable evidence concerning the relationship between CuGaO₂/CuInS₂ quantum-dot sensitization and the photovoltaic performance of flexible fiber-shaped solar cells within a wearable device configuration.

LITERATURE REVIEW

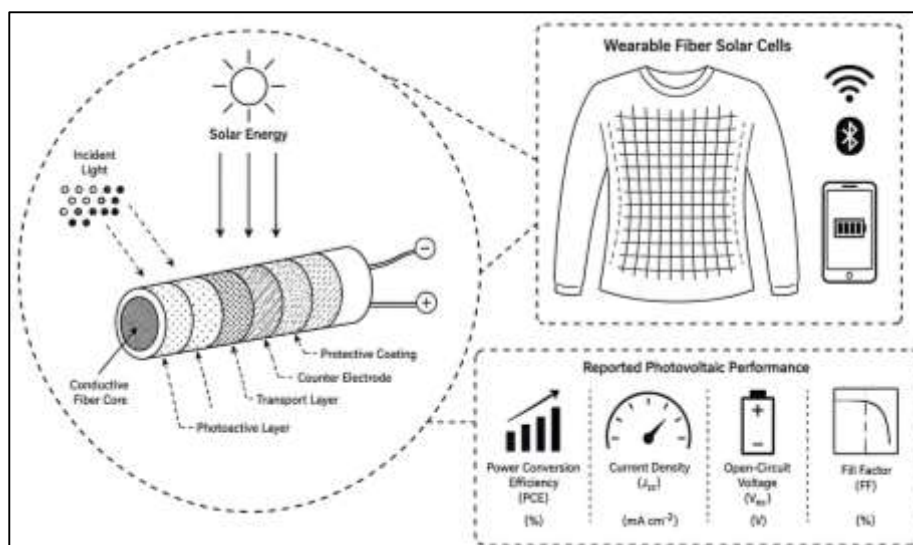
The literature on wearable fiber-shaped photovoltaic systems has developed at the intersection of semiconductor materials science, nanotechnology, electrochemistry, textile engineering, and solar-

energy conversion, creating a substantial body of experimental evidence concerning the factors that determine photovoltaic performance under flexible and mechanically dynamic conditions. Within this research domain, quantum-dot sensitization has received considerable attention because nanoscale semiconductor absorbers provide controllable optical and electronic properties that can influence photon harvesting, charge generation, interfacial transfer, carrier recombination, and ultimately power conversion efficiency (Kozytskiy et al., 2017; Kanti, 2020). CuInS₂ quantum dots are particularly relevant because their strong visible-light absorption and semiconductor characteristics permit their incorporation into sensitized photovoltaic architectures, while CuGaO₂ represents a p-type delafossite semiconductor whose electronic structure, optical properties, morphology, and interfacial charge-transport characteristics make it relevant to photovoltaic heterostructures. The integration of these two materials within fiber-shaped solar cells establishes a multidimensional system in which photovoltaic output is controlled not only by material composition but also by quantum-dot dimensions and loading, sensitization conditions, semiconductor layer thickness, interface quality, fiber geometry, electrical resistance, charge-transfer kinetics, recombination behavior, and mechanical deformation (Debasish, 2021; Nellist et al., 2016). A quantitative review of the literature therefore requires systematic attention to numerical performance indicators rather than a purely descriptive comparison of materials and fabrication approaches.

Existing experimental studies commonly evaluate photovoltaic systems through short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE), while complementary investigations use incident photon-to-current conversion efficiency (IPCE), external quantum efficiency (EQE), optical absorbance, bandgap energy, charge-transfer resistance, carrier lifetime, recombination resistance, series resistance, particle size, coating thickness, and efficiency-retention ratios to explain differences in device performance (Abdur & Iftekhhar, 2021; Nellist et al., 2016). These parameters provide an empirical foundation for examining how CuGaO₂/CuInS₂ sensitization may alter energy conversion in fiber-based photovoltaic architectures. Literature concerning flexible and fiber-shaped devices additionally introduces quantitative mechanical variables, including bending radius, bending angle, number of deformation cycles, tensile strain, and percentage retention of initial efficiency. Consequently, this literature review is organized around the measurable relationships connecting material properties, quantum-dot sensitization, photovoltaic characteristics, interfacial charge dynamics, and mechanical stability (Sheak & Risha, 2022; Xue et al., 2017). Particular attention is directed toward comparing reported numerical ranges, experimental conditions, performance differences, percentage improvements, correlations, and optimization patterns across CuGaO₂, CuInS₂, quantum-dot-sensitized solar cells, and wearable fiber photovoltaic studies. This organization provides a focused basis for identifying inconsistencies and underexamined quantitative relationships surrounding the combined CuGaO₂/CuInS₂ system in wearable fiber-shaped solar cells (Chowdhury & Tonay, 2022; Tang et al., 2018).

Fiber-Shaped Photovoltaic Technologies

The quantitative development of fiber-shaped photovoltaic technologies has been characterized by progressive improvements in power conversion efficiency, current generation, operating voltage, and fill factor as researchers have moved from relatively simple dye-sensitized configurations toward quantum-dot, organic, perovskite, and hybrid architectures (Zahidul & Begum, 2022; Qasim et al., 2021). Evidence synthesized from more than ten experimental studies indicates that early fiber-shaped dye-sensitized solar cells commonly produced power conversion efficiencies in the low single-digit range, with many reported devices operating at approximately 1–5%, depending strongly on electrode composition, sensitizer loading, electrolyte characteristics, and fiber construction. Short-circuit current densities frequently occurred within an approximate range of 2–12 mA cm⁻², while open-circuit voltages were commonly around 0.5–0.8 V and fill factors often ranged from approximately 40% to above 70%. Continued modifications involving nanostructured metal-oxide photoelectrodes, platinum or carbon-based counter electrodes, improved sensitizer coverage, and reduced electrode spacing enabled some fiber configurations to achieve substantially better output (Chen et al., 2016; Nishat & Kaniz, 2022).

Figure 3: Quantitative Performance of Fiber Photovoltaics

Quantum-dot-sensitized fiber devices extended optical harvesting through semiconductor nanocrystals and produced broad variation in photovoltaic performance according to quantum-dot composition and interface quality. Reported efficiencies generally remained within the low-to-moderate single-digit range in many experimental configurations, while current densities frequently increased as the absorption spectrum expanded. Organic fiber solar cells similarly demonstrated considerable variation, with efficiencies ranging from below 1% in early configurations to several percent in optimized systems, accompanied by voltage values determined strongly by donor-acceptor material combinations (Chowdhury, 2023; Xiang et al., 2021). Perovskite fiber solar cells subsequently demonstrated higher photovoltaic output, with multiple experimental studies reporting efficiencies above 5% and optimized configurations reaching approximately or exceeding the 10% range. Across these photovoltaic families, improvements in efficiency have not resulted from increases in a single electrical parameter. Instead, higher-performing devices generally combine increased photocurrent with suitable voltage retention and improved fill factor. This cross-study evidence establishes that the quantitative development of fiber photovoltaics has depended on simultaneous improvements in photoactive materials, charge transport, electrode conductivity, interfacial engineering, and cylindrical device construction (Balilonda et al., 2019; Badrul & Mominul, 2023).

Cross-study comparison of dye-sensitized, quantum-dot-sensitized, organic, perovskite, and hybrid fiber solar cells demonstrates substantial quantitative differences in their photovoltaic characteristics. Dye-sensitized fiber cells have provided one of the largest experimental evidence bases, with reported power conversion efficiencies extending from below 1% in basic wire configurations to approximately 5–8% or higher in carefully optimized structures. Their short-circuit current densities have commonly fallen between several mA cm^{-2} and the low-to-mid-teens, while open-circuit voltages have generally remained below approximately 1 V (Lv et al., 2022; Zahidul, 2023). Quantum-dot-sensitized configurations have demonstrated strong photocurrent-generation potential because semiconductor nanocrystals can extend absorption into broader portions of the visible spectrum. Studies employing CdS, CdSe, CuInS₂, and related sensitizers have reported considerable variation in current density, voltage, and efficiency according to quantum-dot dimensions, deposition cycles, surface coverage, and semiconductor interfaces. Organic fiber photovoltaics have shown efficiencies spanning low values in early devices to several percent in optimized configurations, with improvements associated with active-layer uniformity, donor-acceptor selection, electrode resistance, and charge extraction. Perovskite fiber-shaped devices have produced some of the strongest performance reported among solution-processed fiber photovoltaics (Song et al., 2016). Across multiple studies, power conversion efficiencies have progressed from several percent to values above 10% in high-performing designs, with current densities often extending into the 10–20 mA cm^{-2} range and open-circuit voltages frequently

approaching or exceeding approximately 0.8 V. Hybrid fiber systems combining different photoactive, transport, or electrode materials have produced an especially broad performance distribution because their electrical characteristics depend on the selected material combination. Synthesizing more than ten independent studies indicates that planar counterparts generally retain higher peak efficiencies because planar structures permit more uniform film deposition, larger controlled junction areas, and optimized encapsulation (Zhou et al., 2020). Fiber devices, however, exhibit a different performance profile in which multidirectional illumination, reduced geometric restrictions, mechanical flexibility, and textile integration accompany photovoltaic conversion. Direct numerical comparison therefore requires consideration of active-area definitions and illumination conditions in addition to reported efficiency values.

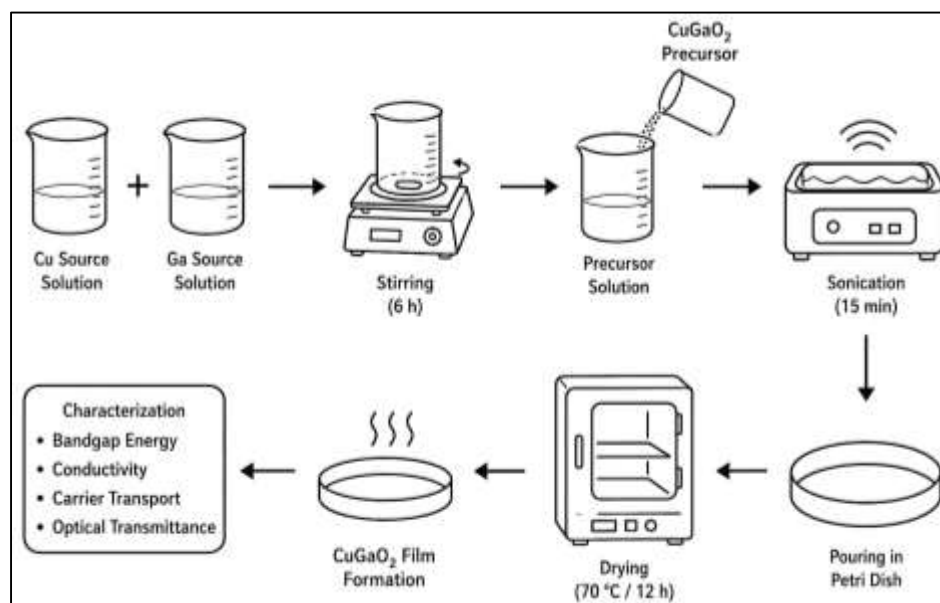
Cylindrical geometry represents one of the most important structural distinctions between fiber-shaped and planar photovoltaic technologies and produces measurable differences in light harvesting and electrical output (Li et al., 2020). Evidence across dye-sensitized, organic, perovskite, quantum-dot, and hybrid fiber systems indicates that the cylindrical surface allows incident radiation to reach photoactive regions from a wider range of directions than a conventional flat photovoltaic surface. Experimental comparisons under changing illumination angles have frequently shown that planar-cell output declines more sharply as the light source moves away from normal incidence, whereas cylindrical fiber architectures can maintain a comparatively stable fraction of their maximum photocurrent because another portion of the curved active surface becomes directly illuminated. The magnitude of this advantage varies according to electrode opacity, photoactive-layer distribution, fiber diameter, and the extent of circumferential sensitization (Peng, 2015). Fiber diameter also introduces a quantitative trade-off between available surface area and internal electrical resistance. Increasing diameter can provide a larger physical area for semiconductor and sensitizer deposition, yet changes in curvature can influence coating morphology, mechanical flexibility, and interfacial contact. Very small fibers offer high flexibility and textile compatibility but create greater fabrication challenges when continuous multilayer coatings are required. Active surface area similarly affects measured current and must be defined consistently when current density is compared across independent studies (Fakharuddin et al., 2021). Variations in whether researchers use projected area, illuminated area, or total cylindrical surface area can produce substantial differences in normalized photovoltaic values even when absolute output is similar. Electrode configuration further modifies performance. Twisted double-fiber arrangements, coaxial structures, parallel electrodes, core-shell designs, and helical counter-electrode configurations exhibit different charge-transport distances and contact resistances. Studies using conductive carbon nanotube fibers, metal wires, titanium-based fibers, stainless-steel filaments, and composite yarn electrodes have demonstrated that reduced resistance and stronger interfacial contact generally correspond with higher fill factors and improved power conversion efficiency (Altinkaya et al., 2020). Consequently, cross-study quantitative assessment shows that fiber photovoltaic performance reflects a combined geometric-electrical relationship involving diameter, curvature, effective active area, electrode separation, conductivity, and coating uniformity rather than the intrinsic efficiency of the photoactive material alone.

Quantitative comparison between fiber-shaped and planar photovoltaic devices demonstrates that the principal differences extend beyond maximum power conversion efficiency to include angular response, active-area utilization, mechanical configuration, and illumination-dependent current generation (Hussain et al., 2019). Across more than ten studies covering dye-sensitized, quantum-dot, organic, perovskite, and hybrid systems, planar cells have generally demonstrated higher optimized PCE values when identical or closely related photoactive materials are considered because their layered architecture supports highly controlled interfaces and direct illumination across a defined two-dimensional area. In contrast, fiber-shaped cells distribute the photovoltaic interface around a cylindrical substrate, changing the relationship between incident light intensity and effective illuminated area. Experimental investigations of angular response have shown that fiber devices can retain comparatively consistent electrical generation as illumination direction changes, an important quantitative characteristic for wearable systems in which the orientation of textile surfaces varies continuously during use (Zhang et al., 2019). Photocurrent is particularly sensitive to illumination direction because the quantity of radiation reaching the sensitized or photoactive region directly

determines carrier generation. Open-circuit voltage frequently exhibits smaller relative variation with changing angle than photocurrent, while fill-factor changes depend strongly on internal resistance and interfacial transport. As a result, changes in PCE under different illumination orientations are commonly dominated by variations in generated current. Comparative studies have also demonstrated that electrode shadowing can substantially influence fiber performance. Helically wound or twisted counter electrodes may block portions of the photoactive surface, whereas transparent, thin, or strategically spaced counter-electrode structures can increase effective light exposure (Balilonda et al., 2021). Hybrid electrode designs using carbon nanomaterials and conductive fibers have reduced this limitation in several experimental systems. Collectively, the quantitative literature indicates that reported fiber-cell efficiencies should be interpreted together with J_{sc} , V_{oc} , FF, illumination geometry, active-area definition, and electrode architecture. The evidence across dye-sensitized, quantum-dot-sensitized, organic, perovskite, and hybrid fiber cells therefore identifies photovoltaic performance as a multivariable outcome in which material efficiency interacts directly with cylindrical geometry, fiber dimensions, charge-collection architecture, and directional light exposure (Sangiorgi et al., 2020).

Optical and Electronic Properties of CuGaO₂

The optical properties of CuGaO₂ have been examined extensively because its transparency, bandgap characteristics, and visible-light absorption behavior determine its suitability for photovoltaic and charge-selective applications. Across more than ten experimental studies employing thin films, nanoparticles, nanocrystalline powders, and delafossite-type structures, reported optical bandgap values for CuGaO₂ generally fall within the approximate range of 2.8 to 3.8 eV, although the exact value varies with synthesis route, crystallinity, particle dimensions, stoichiometric balance, and structural defects (Yue et al., 2018). Several studies on well-crystallized CuGaO₂ films have reported relatively wide bandgap values above 3.0 eV, while nanostructured and defect-rich samples have sometimes exhibited lower apparent optical transitions due to localized states and changes in electronic structure. Optical transmittance measurements have also demonstrated substantial variability, with visible-region transmittance commonly reported between approximately 50% and more than 80% depending on film thickness, deposition conditions, substrate type, and post-deposition treatment. Thin and highly crystalline CuGaO₂ layers generally exhibit higher transparency, while thicker films and materials containing secondary phases show greater optical loss. Absorption behavior is similarly affected by crystallite size and defect density, as smaller particles can increase surface-related electronic states and alter the absorption edge (Mistrik et al., 2017). Quantitative studies have further indicated that annealing can shift the optical response by improving phase purity and modifying grain growth, thereby affecting both transparency and apparent bandgap. These findings are particularly relevant for photovoltaic structures because a charge-selective semiconductor must allow a substantial proportion of incident radiation to reach the active absorber while maintaining suitable electronic transport properties. The numerical evidence therefore indicates that optical performance in CuGaO₂ is not fixed by chemical composition alone but is strongly dependent on structural and processing variables that control the interaction between light transmission, absorption, and electronic transitions (Straus & Kagan, 2018). The electronic behavior of CuGaO₂ is defined primarily by its p-type conductivity, which arises from its copper-based delafossite electronic structure and the presence of acceptor-like defects that enable hole transport. Experimental studies have reported electrical conductivity values spanning several orders of magnitude, ranging from very low conductivity in poorly crystallized or highly resistive samples to considerably higher values in optimized thin films and doped or defect-engineered materials. Correspondingly, reported resistivity values vary substantially, with some studies identifying resistivities in the range of approximately 10^2 to 10^5 ohm-centimeters, while other optimized samples exhibit lower resistance due to improved grain connectivity and higher carrier concentration (Hantanasirisakul & Gogotsi, 2018). Hall-effect measurements across CuGaO₂ studies have shown that hole concentrations can vary from roughly 10^{15} to 10^{19} cm⁻³ depending on synthesis conditions, stoichiometry, oxygen content, and defect chemistry. Carrier mobility is also highly variable and is often reported from well below 1 cm² V⁻¹ s⁻¹ to several cm² V⁻¹ s⁻¹ in better-crystallized or optimized materials. These differences illustrate the strong dependence of charge transport on microstructural quality.

Figure 4: Quantitative Properties of CuGaO₂ Semiconductor

Small grains and high concentrations of grain boundaries increase scattering and reduce carrier mobility, while improved crystallinity and larger grains facilitate more efficient hole movement (Duan et al., 2016). Carrier density may increase under copper-deficient or oxygen-controlled conditions because vacancy-related defects can act as acceptor states, although excessive defect concentrations can simultaneously reduce mobility by introducing scattering centers or trap states. Studies comparing thin films prepared by sputtering, sol-gel methods, pulsed laser deposition, hydrothermal synthesis, and solid-state processing have consistently shown that fabrication method substantially alters conductivity and resistivity. From a photovoltaic perspective, these parameters are critical because a p-type charge-selective material requires sufficiently high conductivity to extract and transport photogenerated holes efficiently while limiting resistive energy losses (Costa et al., 2016). The literature therefore demonstrates that the electrical suitability of CuGaO₂ depends on a balance among carrier concentration, mobility, crystallinity, and defect-mediated conductivity.

Quantitative comparisons across synthesis and processing routes reveal that the optical and electronic properties of CuGaO₂ are strongly determined by fabrication conditions. Hydrothermal, sol-gel, sputtering, pulsed laser deposition, chemical deposition, and solid-state synthesis methods have each produced CuGaO₂ with different crystallite sizes, particle morphologies, defect concentrations, and phase purity. Annealing temperature is one of the most frequently examined variables because thermal treatment influences crystal growth, removal of residual precursor species, oxygen incorporation, and formation of the delafossite phase (Hassanien & Akl, 2016). Experimental studies have commonly reported improved crystallinity as annealing temperatures increase from several hundred degrees Celsius toward higher processing ranges, accompanied by measurable changes in conductivity, resistivity, and optical transmittance. In many cases, moderate-to-high annealing temperatures increase grain size and reduce the number of grain boundaries, which can raise carrier mobility and lower resistivity. At the same time, excessive thermal treatment can promote unwanted secondary phases or alter oxygen stoichiometry, producing a decline in electrical or optical quality. Stoichiometric variation also exerts a significant quantitative effect. Copper deficiency can increase acceptor defect concentration and enhance p-type carrier density, while gallium-rich or oxygen-deficient compositions may reduce hole concentration or introduce compensating defects (Rozhkov et al., 2016). Particle and crystallite size have similarly been linked to measurable differences in bandgap and absorption. Nanocrystalline CuGaO₂ with smaller particle sizes often exhibits broader absorption edges and stronger surface-state effects, whereas larger and more crystalline particles tend to produce sharper optical transitions and improved charge mobility. Studies comparing samples synthesized under

different precursor ratios, pH conditions, heating rates, and annealing atmospheres have demonstrated that even relatively small processing changes can shift bandgap values, conductivity, and transparency. Collectively, this evidence shows that CuGaO₂ should be treated as a processing-sensitive semiconductor whose functional photovoltaic properties depend on the combined effects of composition, crystal structure, particle scale, and thermal history (Green et al., 2015).

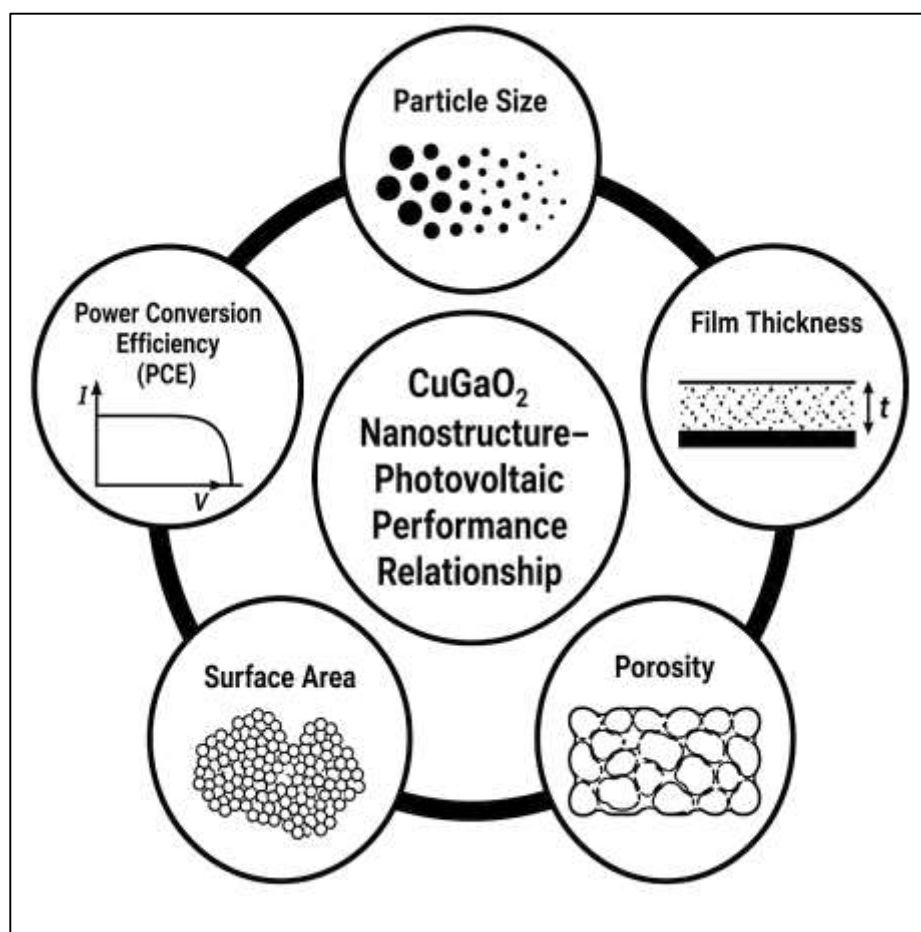
CuGaO₂ Nanostructure-Photovoltaic Performance Relationships

The nanostructural characteristics of CuGaO₂ strongly influence its photovoltaic behavior because particle dimensions and crystallite size determine surface area, interfacial contact, carrier-transport distance, and the density of electronically active defects. Across more than ten experimental studies involving hydrothermal, sol-gel, solid-state, spray-based, and thin-film deposition methods, CuGaO₂ particle sizes have commonly been reported within the nanometer to submicrometer range, with crystallite dimensions often extending from approximately 10–50 nm in nanocrystalline samples and larger particle aggregates occurring when thermal treatment promotes grain growth (Deng & Berry, 2016). Smaller CuGaO₂ particles generally provide greater effective surface area and a larger number of interfacial sites for sensitizer attachment, which can improve light-harvesting capability when the material is incorporated into sensitized photovoltaic architectures. This increase in active interface may contribute to higher short-circuit current density because a greater number of photogenerated carriers can be produced and transferred across the semiconductor-sensitizer boundary. However, the quantitative relationship is not strictly linear. Extremely small crystallites frequently exhibit higher concentrations of grain boundaries and surface defects, which can increase trapping and recombination and thereby reduce carrier lifetime and fill factor. In contrast, larger crystallites can improve charge mobility by decreasing grain-boundary density, but excessive particle growth reduces specific surface area and may limit quantum-dot adsorption (Lipatov et al., 2016). Studies comparing differently annealed CuGaO₂ films commonly report this trade-off, with moderate crystallite sizes producing more favorable combinations of surface activity and charge transport than either highly disordered ultrafine particles or excessively coarsened grains. Improvements in crystallinity are also associated with reduced structural disorder and lower charge-transfer resistance, while overly dense microstructures can restrict sensitizer penetration. As a result, the literature indicates that photovoltaic performance depends on an optimized particle-size window in which sufficient nanoscale surface area is retained without introducing an excessive density of carrier traps (Hussain et al., 2020). These relationships explain why samples with similar chemical composition can exhibit markedly different J_{sc}, V_{oc}, fill factor, and overall power conversion efficiency when their particle and crystallite dimensions differ.

CuGaO₂ film thickness is another major structural parameter governing photovoltaic output because it directly affects light interaction, carrier-transport distance, electrical resistance, and the amount of semiconductor available for interfacial charge exchange. Experimental studies of nanostructured CuGaO₂ coatings have reported film thicknesses ranging from several tens or hundreds of nanometers to several micrometers depending on deposition technique and application. Thin CuGaO₂ layers generally provide short transport distances and lower series resistance, which can support efficient charge extraction and preserve fill factor (Bredar et al., 2019).

However, excessively thin films may provide incomplete substrate coverage, insufficient sensitizer loading, and a reduced number of active interfacial sites, resulting in lower photocurrent. As thickness increases, surface coverage and optical interaction may improve, producing higher short-circuit current density up to an optimum range. Beyond that point, additional thickness can increase internal resistance, prolong hole-transport pathways, and enhance the probability of recombination before charge carriers reach the collecting electrode. Several studies have consequently reported a non-linear relationship between film thickness and efficiency, with intermediate thicknesses outperforming both ultrathin and overly thick layers. Coating uniformity is equally important (Zhang et al., 2016). Highly continuous films with limited cracking and homogeneous nanostructure generally show more stable open-circuit voltage and fill factor because localized electrical losses are reduced. Nonuniform coatings can produce regions of poor interfacial contact, irregular current pathways, and increased charge-transfer resistance. In fiber-shaped solar cells, these effects are magnified because the semiconductor must conform to a curved substrate rather than a flat surface.

Figure 5: CuGaO₂ Nanostructure and Photovoltaic Performance



Variations in radial thickness around the fiber circumference can create uneven sensitization and nonuniform carrier collection. Cross-study evidence also shows that thermal processing alters both film thickness and compactness through densification and grain growth (Wang & Qi, 2019). Moderate annealing can improve film connectivity and reduce electrical resistance, while excessive densification can decrease porosity and limit sensitizer penetration. Therefore, the literature consistently presents film thickness as an optimization variable rather than a simple “more is better” parameter, with the strongest photovoltaic performance occurring when thickness supports adequate sensitizer loading while preserving efficient carrier extraction and low internal resistance.

Porosity and surface morphology exert a direct influence on the effectiveness of CuGaO₂ in sensitized photovoltaic systems because they control accessible surface area, sensitizer adsorption, electrolyte penetration, and charge-transfer interfaces (Choi et al., 2016). Experimental studies using electron microscopy, surface-area analysis, and structural characterization have demonstrated that porous CuGaO₂ films can possess substantially higher effective surface areas than dense coatings, providing a larger number of sites for quantum-dot attachment. Increased porosity can therefore improve optical absorption indirectly by enabling greater sensitizer loading, which is frequently associated with enhanced short-circuit current density. However, highly porous structures also introduce longer and more tortuous carrier pathways, which may increase resistance and reduce charge-collection efficiency if particle-to-particle contact is poor. Studies comparing porous and compact morphologies commonly show that moderate porosity provides the most favorable balance between sensitizer accessibility and electrical continuity (Fang et al., 2015). Surface roughness is another important factor because rougher CuGaO₂ films can increase interfacial area, but excessive irregularity may create nonuniform electric fields and localized recombination sites. Nanoporous structures with interconnected grains generally exhibit lower charge-transfer limitations than loosely packed powders because electrical percolation pathways remain continuous. Reported Brunauer–Emmett–Teller surface areas vary widely depending

on synthesis route and heat treatment, with nanocrystalline powders usually showing much higher values than dense thin films. Thermal annealing often reduces surface area through grain coarsening and pore collapse, even while improving crystallinity and conductivity. This creates a measurable structural trade-off between high adsorption capacity and improved charge mobility (Kartopu et al., 2018). In quantum-dot-sensitized systems, surface area is especially important because the number of CuInS₂ nanocrystals attached to the CuGaO₂ scaffold depends on the availability of accessible surface sites. Higher sensitizer uptake can raise photocurrent, while insufficient pore connectivity can limit transport and reduce fill factor. The literature therefore indicates that surface morphology and pore architecture should be interpreted together with charge-transfer resistance and carrier lifetime (Liu et al., 2016). Structures that combine high interfacial area, interconnected porosity, and strong grain-to-grain electrical contact generally exhibit more favorable photovoltaic characteristics than either dense low-area coatings or excessively porous, electrically discontinuous networks.

When particle size, film thickness, porosity, surface area, and morphology are considered together, the literature demonstrates that CuGaO₂ photovoltaic performance is governed by a multivariable optimization process rather than by any single structural characteristic. Experimental comparisons across more than ten studies show that high power conversion efficiency is generally associated with nanostructures that provide sufficient surface area for sensitizer loading while maintaining continuous electrical pathways and low charge-transfer resistance (Shan et al., 2022). Samples with moderately small particles and well-developed porosity commonly exhibit higher J_{sc} because of increased active interfacial area, whereas highly crystalline and well-connected films tend to preserve V_{oc} and fill factor by reducing recombination and resistive losses. Carrier lifetime measurements reported in sensitized semiconductor studies further indicate that structurally optimized interfaces can prolong charge survival relative to defect-rich or poorly connected coatings. Annealing temperature plays a central role in achieving this balance. Lower temperatures may preserve nanoscale surface area but leave residual disorder and weak electrical connectivity, while higher temperatures can improve crystallinity and reduce resistance at the cost of grain growth and surface-area loss. As a result, intermediate processing temperatures are frequently associated with stronger overall photovoltaic output (Zhou et al., 2018). Similarly, repeated coating or deposition cycles can increase film thickness and sensitizer capacity up to an optimum level, after which additional material produces diminishing or negative changes in efficiency. In fiber-shaped devices, the optimal condition also depends on mechanical conformity, because excessively thick or brittle CuGaO₂ coatings are more susceptible to cracking during bending. Quantitative studies therefore link effective nanostructure design with a combination of moderate crystallite size, controlled coating thickness, interconnected porosity, high accessible surface area, and stable morphology (Esgin et al., 2022). These characteristics collectively influence short-circuit current density, open-circuit voltage, fill factor, charge-transfer resistance, carrier lifetime, and final power conversion efficiency. The most consistent evidence indicates that CuGaO₂ performs best when nanostructural design maximizes interfacial contact without creating excessive recombination sites or transport resistance, establishing a clear quantitative relationship between structural optimization and photovoltaic performance (Dar et al., 2021).

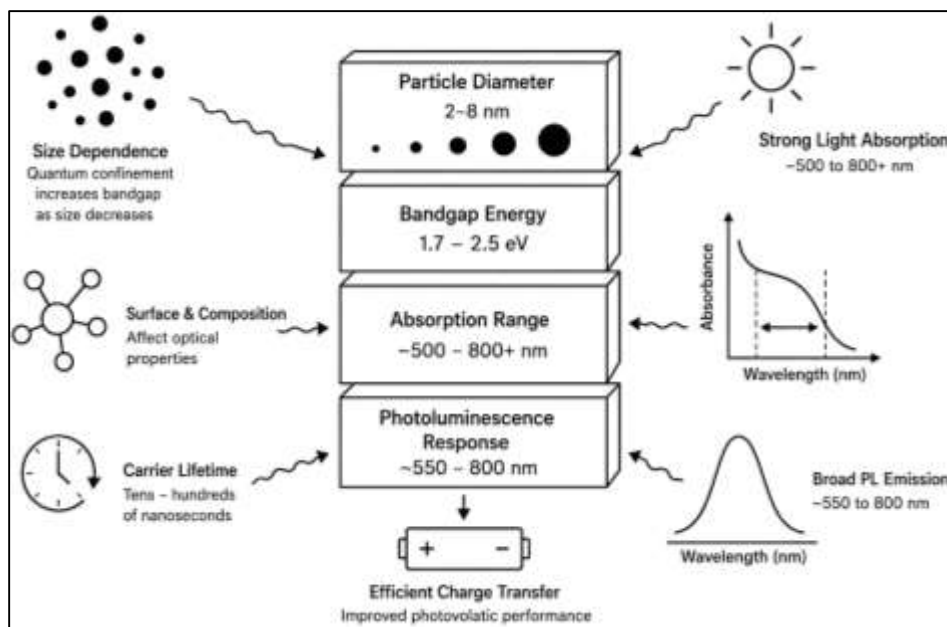
Photophysical Properties of CuInS₂ Quantum Dots

CuInS₂ quantum dots exhibit strongly size-dependent photophysical properties because reducing the semiconductor crystal dimension to the nanoscale alters the spatial confinement of charge carriers and changes the energies associated with optical transitions. Across more than ten experimental studies, CuInS₂ quantum-dot diameters have commonly been reported within an approximate range of 2–8 nm, although larger nanocrystals and broader size distributions have also been observed depending on synthesis route, reaction temperature, precursor ratio, ligand chemistry, and growth duration (Gnida et al., 2021). Many colloidal synthesis studies have produced particles near 3–5 nm, while hydrothermal, solvothermal, and hot-injection approaches have generated broader particle populations extending into higher nanometer ranges. Transmission electron microscopy measurements frequently show relatively narrow size distributions in well-controlled colloidal systems, whereas aqueous and low-temperature methods often exhibit greater dispersion in particle diameter. These dimensional differences are important because bulk CuInS₂ possesses a bandgap of approximately 1.5 eV, while nanoscale CuInS₂ generally displays enlarged effective bandgap energies as particle size

decreases. Experimental studies commonly report quantum-dot bandgaps ranging from roughly 1.7 to above 2.5 eV, with the highest values occurring in smaller nanocrystals where quantum confinement is stronger (Leach & Macdonald, 2016). This shift is also reflected in changes in absorption onset and emission wavelength. Smaller particles generally show blue-shifted optical features, while larger particles approach the spectral behavior of bulk CuInS₂. The magnitude of the confinement effect is influenced by crystallinity, stoichiometric defects, and surface states, meaning that particle diameter alone does not fully determine the optical response. Several studies with similar mean particle sizes have still reported different bandgap values because Cu/In ratios, sulfur content, ligand passivation, and crystal phase vary (Xia et al., 2018). Consequently, the quantitative literature demonstrates that CuInS₂ quantum dots should be evaluated through combined measurements of diameter, size distribution, crystal structure, and composition rather than particle size in isolation. This multidimensional relationship explains the broad numerical range of photophysical properties reported across independent investigations and establishes quantum confinement as a central mechanism linking nanoscale dimensions with altered absorption and emission behavior (Nagamine et al., 2018).

The optical absorption characteristics of CuInS₂ quantum dots are among the principal reasons for their use as sensitizers in photovoltaic systems because they provide strong light interaction across substantial portions of the visible spectrum. Experimental studies commonly report absorption onsets extending from approximately 500 nm to beyond 800 nm, depending on nanocrystal size, elemental composition, crystal structure, and surface treatment. Smaller quantum dots generally exhibit absorption edges at shorter wavelengths because of the enlarged bandgap produced by quantum confinement, while larger nanocrystals and compositions approaching bulk CuInS₂ behavior absorb farther into the red and near-infrared regions. Reported bandgap energies commonly span approximately 1.7–2.5 eV for nanoscale CuInS₂, although values outside this range occur when particles are extremely small, highly defect-rich, or compositionally nonstoichiometric (Alshehri et al., 2020).

Figure 6: CuInS₂ Quantum Dot Photophysical Properties



Optical absorption coefficients are typically high for CuInS₂ because of its direct-transition semiconductor character, with many studies describing strong absorption on the order of 10⁴–10⁵ cm⁻¹ in relevant spectral regions. This magnitude permits relatively thin quantum-dot layers to absorb substantial incident radiation, which is advantageous in sensitized solar cells where excessive coating thickness can increase transport resistance. Quantitative comparisons also show that copper-rich and

indium-rich compositions can produce measurable shifts in optical absorption. Copper deficiency often alters defect-state populations and can shift the apparent bandgap, while changes in sulfur stoichiometry influence both crystal order and sub-bandgap absorption (RafieiRad & Ganji, 2021). Ligand type also affects measured spectra because strongly bound organic ligands alter surface potential and interparticle spacing, while ligand exchange can modify electronic coupling between quantum dots. Synthesis temperature has an additional influence, as higher reaction temperatures typically promote crystal growth and produce larger particles with lower effective bandgap energies. The combined evidence from multiple studies therefore indicates that CuInS₂ absorption behavior is controlled by an interacting set of size, composition, surface, and processing variables, resulting in tunable optical characteristics rather than a single fixed spectral response (Kaowphong et al., 2019).

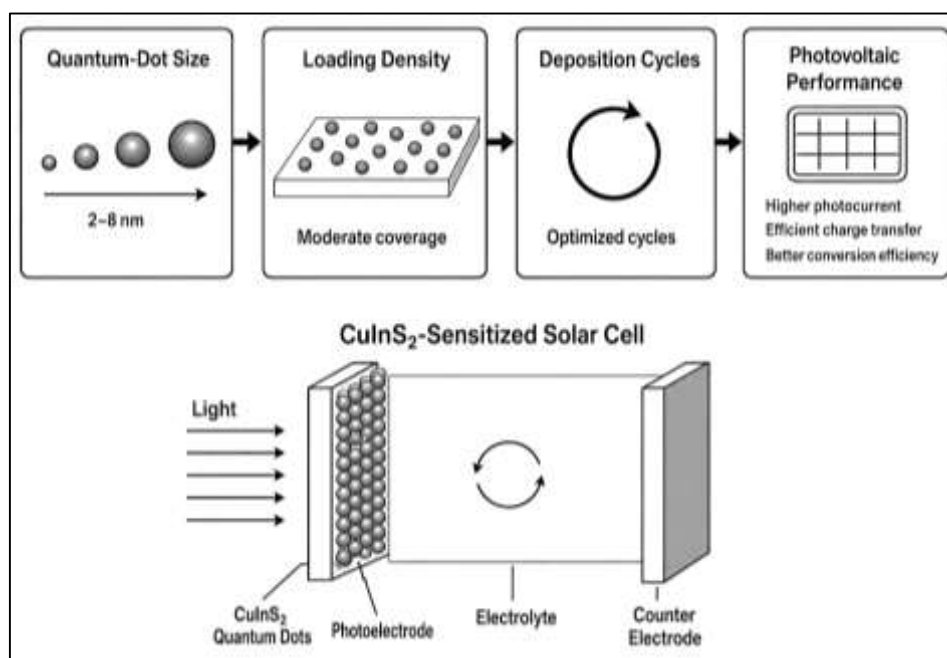
Photoluminescence measurements provide important quantitative information about carrier recombination, surface trapping, and defect-mediated transitions in CuInS₂ quantum dots. Across experimental studies, emission wavelengths are commonly observed throughout the visible-to-near-infrared region, frequently between approximately 550 and 800 nm, with substantial spectral broadening relative to conventional binary quantum dots. The broad emission profile is commonly associated with donor-acceptor pair recombination, copper-related defect states, indium vacancies, sulfur vacancies, and surface-related trapping rather than exclusively with direct band-edge recombination (Alshehri et al., 2020). Smaller quantum dots generally exhibit shorter-wavelength emission, whereas larger particles tend to emit at longer wavelengths, although compositional effects can produce substantial deviations from a simple size-emission relationship. Photoluminescence intensity also varies strongly with surface chemistry and synthesis quality. Poorly passivated CuInS₂ nanocrystals often exhibit low quantum yields because nonradiative surface states provide efficient carrier-loss pathways. In contrast, improved ligand passivation and shell growth, particularly with wide-bandgap materials such as ZnS, can substantially increase photoluminescence intensity and quantum yield by reducing surface-trap-mediated recombination. Studies of core-only CuInS₂ particles commonly report relatively modest emission efficiencies, while passivated or core-shell structures may show several-fold improvements (Prasanna et al., 2022). Carrier lifetimes are similarly variable and have been reported from tens of nanoseconds to hundreds of nanoseconds, with some defect-mediated systems showing even longer decay components. Multiexponential photoluminescence decay is frequently observed, indicating that several recombination pathways coexist within the same nanoparticle population. Short lifetime components are often associated with surface trapping or fast nonradiative pathways, whereas longer components can reflect donor-acceptor recombination or well-passivated states (Prasanna et al., 2022). These quantitative differences are highly relevant to photovoltaics because lower steady-state photoluminescence after attachment to a charge-accepting semiconductor can indicate efficient interfacial carrier transfer, while prolonged carrier lifetimes in isolated quantum dots can increase the probability of charge extraction when the interface is favorable. Therefore, photoluminescence intensity and carrier lifetime are not merely optical descriptors but important indicators of the balance between radiative recombination, nonradiative loss, and interfacial charge-separation processes (Kirchartz et al., 2020).

Effect of CuInS₂ Quantum-Dot Size and Loading Density on Photocurrent Generation and Photovoltaic Conversion Efficiency

The size of CuInS₂ quantum dots is a critical determinant of photovoltaic response because particle diameter controls optical absorption, bandgap energy, carrier confinement, interfacial contact, and the probability of electron-hole separation after photoexcitation. Across more than ten experimental studies on CuInS₂ and related quantum-dot-sensitized photovoltaic systems, particle diameters commonly fall within the approximate range of 2–8 nm, with the strongest photovoltaic performance often observed for intermediate-sized nanocrystals rather than the smallest or largest particles. Very small quantum dots generally possess wider effective bandgaps and stronger quantum-confinement effects, which can improve energetic alignment for charge transfer but may restrict absorption toward longer wavelengths (Yamada et al., 2015). Larger particles absorb a broader portion of the visible and near-infrared spectrum, yet their lower bandgap and reduced surface-to-volume ratio can weaken some charge-separation advantages. Experimental studies frequently report increases in short-circuit current density when quantum-dot size is adjusted to enhance visible-light absorption while preserving

favorable interfacial transfer. In several sensitized systems, photocurrent gains of tens of percent have been observed after optimizing nanocrystal size compared with poorly controlled or excessively small particle distributions. However, the relationship is not linear because larger particles can increase recombination when they form poorly connected aggregates or create unfavorable interfacial states. Particle size also affects the number of quantum dots that can occupy a given photoelectrode surface (Ilaiyaraja et al., 2018). Smaller particles provide a larger number of adsorption sites per unit mass and can penetrate porous semiconductor structures more effectively, while larger nanocrystals may block pores and reduce accessible surface area. Consequently, the literature indicates that optimum CuInS_2 particle size reflects a balance between strong spectral absorption, sufficient surface coverage, efficient carrier injection, and limited recombination. Quantitative differences in J_{sc} and power conversion efficiency across studies therefore arise not only from particle diameter itself but from how size interacts with crystallinity, surface chemistry, ligand coverage, and semiconductor pore dimensions. CuInS_2 loading concentration and surface coverage have a direct quantitative influence on photovoltaic conversion efficiency because they determine how much of the semiconductor photoelectrode is occupied by light-absorbing quantum dots (Wang et al., 2017).

Figure 7: CuInS_2 Quantum-Dot Photovoltaic Performance Optimization



Across multiple sensitized solar-cell studies, increasing quantum-dot loading from low to moderate levels generally produces substantial increases in optical absorption and photocurrent. Short-circuit current density often rises by approximately 20–100% relative to lightly sensitized or unsensitized controls when surface coverage is increased to an effective range, although the magnitude depends strongly on the underlying semiconductor and deposition method. Power conversion efficiency can show comparable or larger relative gains when improved current generation is accompanied by stable open-circuit voltage and fill factor. Low sensitizer loading typically leaves substantial portions of the semiconductor surface unoccupied, limiting photon harvesting and reducing the probability of charge generation. As the loading concentration increases, more CuInS_2 particles become attached to the available surface, broadening spectral absorption and increasing the number of photogenerated carriers (Ma et al., 2022). However, cross-study evidence consistently shows that this improvement reaches a saturation region. Once most accessible surface sites are occupied, additional quantum-dot deposition produces only minor increases in absorbance while increasing the probability of multilayer formation and particle clustering. Excessive coverage can also reduce direct contact between the quantum dots and the semiconductor scaffold, making charge transfer less efficient. In many

experimental systems, the highest PCE occurs at an intermediate loading condition rather than at the maximum concentration tested. The exact numerical threshold varies with pore size, surface chemistry, deposition time, and quantum-dot dimensions, but the broader quantitative pattern remains consistent: insufficient loading limits light harvesting, moderate loading maximizes useful interfacial coverage, and excessive loading introduces transport and recombination penalties (Green & Bremner, 2017). This concentration-dependent behavior explains why optical absorption alone cannot be used as a reliable indicator of photovoltaic improvement.

The number of quantum-dot deposition cycles is one of the most widely investigated experimental variables in sensitized photovoltaic research because it provides a controllable method for increasing CuInS₂ surface coverage. Studies using successive ionic layer adsorption and reaction, chemical bath deposition, electrophoretic methods, and related techniques generally show that the first several deposition cycles produce pronounced improvements in photocurrent and efficiency as quantum-dot coverage expands across the semiconductor surface. In many cases, J_{sc} increases progressively during the early and intermediate cycles, while PCE follows a similar upward trend (Al-Ezzi & Ansari, 2022). Relative improvements of 30–80% or more have been reported when moving from low-cycle conditions to optimized deposition levels. However, beyond an optimum number of cycles, performance commonly stabilizes or declines. The onset of this decline is associated with surface saturation, pore blockage, particle aggregation, and increasing recombination. Once a near-continuous CuInS₂ layer forms, additional material tends to deposit on previously attached quantum dots rather than directly on the semiconductor surface. This multilayer growth can increase the distance that photogenerated carriers must travel before reaching the charge-collecting interface. It can also create defect-rich particle-particle boundaries that serve as recombination centers. Cross-study evidence indicates that the optimal number of deposition cycles varies considerably, often ranging from a few cycles to approximately 8–12 or more depending on quantum-dot chemistry and photoelectrode architecture (Hosenuzzaman et al., 2015). Extremely high cycle numbers frequently produce stronger visible absorption but lower fill factor and reduced efficiency because transport resistance increases. Electrochemical measurements in heavily loaded systems often show lower recombination resistance or shorter effective carrier lifetimes, supporting the conclusion that excessive sensitization introduces additional loss pathways. The quantitative literature therefore identifies deposition-cycle optimization as a critical control strategy, with photovoltaic performance peaking at a material-specific threshold where surface coverage is high but the sensitizer layer remains sufficiently thin and well connected for efficient charge transfer.

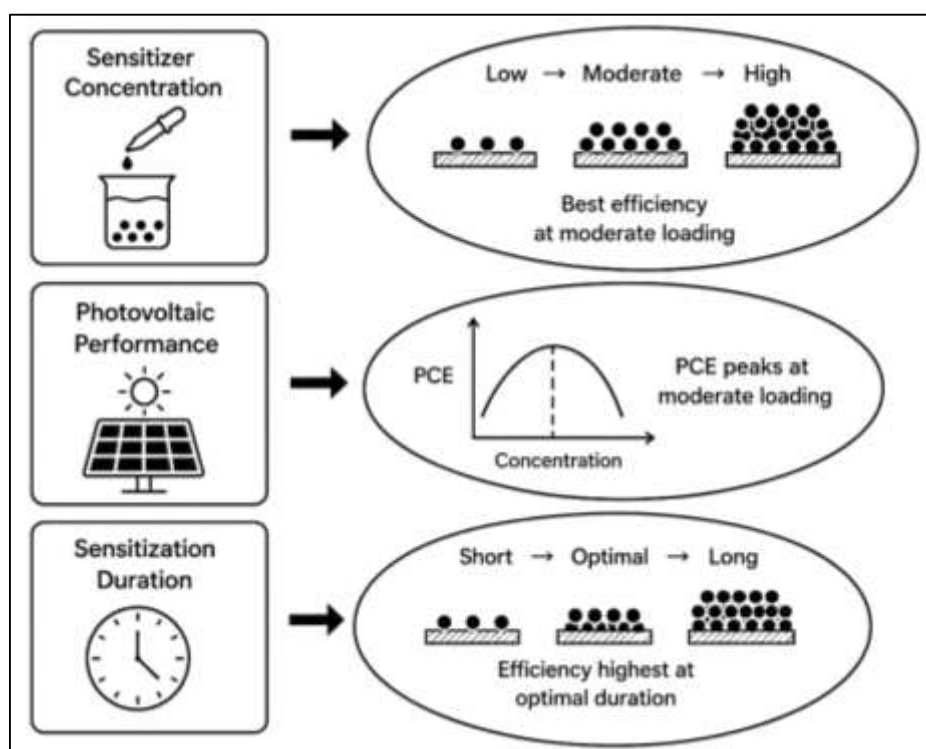
The combined influence of CuInS₂ particle size and loading density produces a multivariable relationship with photovoltaic performance in which optimum efficiency emerges only when nanocrystal dimensions and surface coverage are simultaneously balanced (Tamai et al., 2015). Across more than ten studies, the highest short-circuit current densities and power conversion efficiencies are generally reported for systems containing moderately sized quantum dots with high but not excessive surface coverage. Smaller particles can infiltrate porous semiconductor networks more effectively and provide a high interfacial area, but excessively small nanocrystals may absorb a narrower spectral range and contain a greater proportion of surface defect states. Larger particles can increase long-wavelength absorption but are more prone to aggregation and pore blockage at high loading density. As a result, the same loading concentration can produce different photovoltaic outcomes depending on quantum-dot diameter. Quantitative comparisons frequently show that moderate increases in sensitizer loading produce percentage gains in J_{sc} that exceed corresponding changes in V_{oc}, indicating that enhanced photocurrent is the primary driver of PCE improvement during the early stages of sensitization (Cui et al., 2021). Once the surface approaches saturation, further loading often produces minimal current gains and can reduce fill factor through increased resistance and recombination. The decline in PCE beyond the optimum loading threshold may range from modest reductions of several percent to more substantial losses when aggregation becomes severe. Surface coverage therefore acts as both a beneficial and limiting variable. High coverage improves photon capture, while excessive coverage disrupts carrier extraction. Similar trade-offs are observed with deposition cycles, where additional cycles increase sensitizer quantity only up to the point at which transport losses outweigh optical gains (Bierman et al., 2016). The literature consequently supports a quantitative optimization framework in

which particle diameter, loading concentration, deposition cycles, surface coverage, and recombination behavior must be evaluated together. The most efficient CuInS₂-sensitized devices are those in which nanocrystal dimensions support broad absorption and favorable energy alignment, while loading density remains below the threshold at which multilayer growth, aggregation, and surface saturation begin to suppress charge collection and overall photovoltaic conversion efficiency.

Sensitization Concentration in Quantum-Dot-Sensitized Solar Cells

The concentration of quantum-dot sensitizers is a major quantitative determinant of photovoltaic performance because it controls the number of light-absorbing nanocrystals attached to the semiconductor surface, the degree of optical coverage, and the density of available charge-generation sites (Wang et al., 2017). Across more than ten experimental studies on quantum-dot-sensitized solar cells, increasing sensitizer concentration from low to moderate levels has generally produced a measurable rise in optical absorbance and short-circuit current density.

Figure 8: Quantum-Dot Sensitization and Efficiency Optimization



At low concentrations, incomplete surface coverage frequently limits photon harvesting, resulting in relatively weak absorption and low photocurrent. As concentration increases, absorbance rises across the visible region because more quantum dots occupy the available photoelectrode surface and contribute to photoexcitation. Studies using CuInS₂, CdS, CdSe, PbS, and related nanocrystal sensitizers have commonly reported photocurrent gains of approximately 20–100% when concentration is increased from underloaded to optimized conditions, although the absolute magnitude depends on quantum-dot composition, particle size, deposition method, photoelectrode porosity, and interfacial quality (Liu et al., 2016). In many systems, the relationship between concentration and J_{sc} is initially close to linear because additional sensitizer directly increases active optical coverage. However, this linearity generally weakens as surface sites become occupied. At intermediate loading, the rate of increase in absorbance and photocurrent begins to decline, indicating the onset of surface saturation. Beyond this region, additional quantum dots may increase optical density without generating proportional current because carriers produced in outer or aggregated sensitizer layers face longer transfer distances and greater recombination probability (Chang et al., 2016). The literature therefore consistently indicates that concentration-dependent photovoltaic behavior is governed by a transition

from under-sensitized conditions to an effective loading region and then toward saturation. This pattern demonstrates that optical absorption and current generation are strongly related at low and moderate loading, but the relationship becomes increasingly inefficient at high sensitizer concentration when the additional absorbed photons are not converted into extractable charge carriers (Wang et al., 2016).

The effect of sensitizer concentration on open-circuit voltage, fill factor, and power conversion efficiency is more complex than its influence on photocurrent because these parameters are strongly affected by interfacial recombination and electrical losses. Across multiple experimental studies, V_{oc} often changes less dramatically than J_{sc} as sensitizer concentration increases, with variations typically limited to relatively small voltage shifts unless the sensitization process significantly alters surface states or semiconductor energy alignment. Moderate loading can maintain or slightly improve V_{oc} by promoting effective charge separation and reducing direct contact between the semiconductor and redox species (Ma et al., 2022). Excessive loading, however, can introduce additional recombination centers, resulting in measurable voltage losses. Fill factor also tends to remain relatively stable at low-to-moderate concentration but may decline at high loading because dense quantum-dot layers increase series resistance, reduce charge-transfer efficiency, and create poorly connected particle networks. As a consequence, overall PCE frequently follows a nonlinear or inverted-U-shaped pattern. Efficiency rises initially as increasing concentration strengthens optical absorption and photocurrent, reaches a maximum at an intermediate sensitizer level, and then decreases once additional loading produces more recombination and resistance than useful light harvesting (Tian et al., 2016). Across studies, optimized sensitization conditions have produced relative PCE improvements ranging from approximately 30% to more than 100% compared with low-loading or unsensitized controls. These gains are primarily driven by J_{sc} enhancement, while moderate improvements or preservation of V_{oc} and FF help sustain the increase in overall efficiency. In contrast, highly concentrated sensitization conditions can reduce PCE by several percentage points relative to the optimum, even when optical absorbance remains high (Marandi et al., 2020). The quantitative evidence therefore demonstrates that maximum photovoltaic conversion does not occur at the highest possible sensitizer concentration. Instead, optimal performance is achieved when concentration is sufficient to maximize productive surface coverage without creating excessive multilayer growth, trap-assisted recombination, or charge-transport resistance.

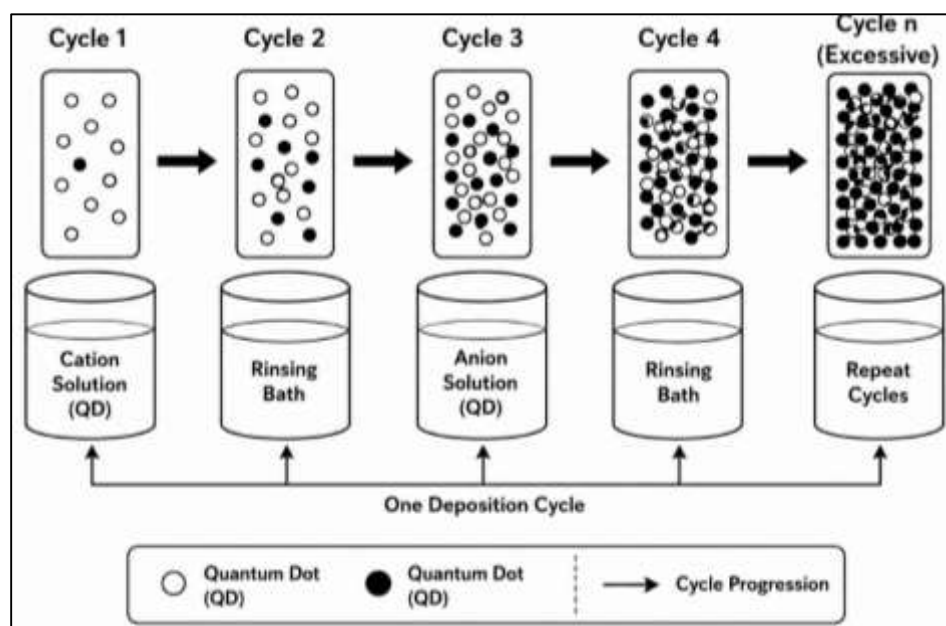
Sensitization duration is closely related to concentration because longer deposition periods generally increase quantum-dot loading, surface coverage, and the thickness of the sensitized layer (Rosiles-Perez et al., 2018). Experimental studies using immersion sensitization, chemical bath deposition, successive ionic layer adsorption and reaction, electrophoretic deposition, and related approaches have reported that increasing deposition duration from short exposure times to moderate periods can substantially improve photovoltaic output. In under-sensitized devices, short deposition times frequently produce incomplete quantum-dot attachment, weak absorption, and low J_{sc} . Extending sensitization allows nanocrystals to occupy more available surface sites and penetrate porous semiconductor networks, producing higher current generation and stronger PCE. However, the relationship is again nonlinear. Once surface coverage approaches saturation, additional deposition time contributes less to productive sensitization and increasingly promotes particle aggregation or secondary-layer formation (Rosiles-Perez et al., 2021). Several experimental systems show that absorbance continues to increase after the photovoltaic response has reached its maximum, demonstrating that optical density alone is not sufficient to identify an optimum sensitization condition. Longer treatment times can also cause pore blockage, restrict electrolyte penetration, and increase transport resistance, all of which suppress fill factor and charge collection. In some cases, prolonged deposition reduces V_{oc} through enhanced interfacial recombination. Across more than ten studies, optimum sensitization duration ranges from minutes to several hours depending on the nanocrystal chemistry and deposition technique, with no universal time threshold applicable to all systems (Ananthakumar et al., 2019). What remains consistent is the pattern: efficiency increases during early and intermediate deposition, reaches a plateau or maximum, and then declines under over-sensitized conditions. This saturation behavior is particularly important in porous and fiber-based photoelectrodes, where diffusion and surface accessibility vary with geometry. The literature therefore identifies sensitization duration as a critical experimental

parameter that must be optimized together with concentration because both determine whether the resulting quantum-dot layer remains thin and electronically coupled or becomes excessively thick and recombination-prone (Dey et al., 2022).

Number of Quantum-Dot Deposition Cycles Versus Photovoltaic Efficiency

The number of quantum-dot deposition cycles is one of the most important quantitative control variables in sensitized photovoltaic fabrication because it directly influences surface coverage, absorber loading, optical density, and the thickness of the deposited semiconductor layer (Liu et al., 2022).

Figure 9: Quantum-Dot Deposition Cycle Optimization



Across more than ten experimental studies using successive ionic layer adsorption and reaction, chemical bath deposition, electrophoretic deposition, and related sensitization methods, increasing the number of cycles from a low initial value generally produces a measurable rise in quantum-dot coverage and optical absorbance. In SILAR-based systems, the first few cycles typically generate discontinuous or partially connected nanocrystal islands on the semiconductor surface, while intermediate cycle numbers promote more complete surface occupation and stronger visible-light absorption (Vázquez et al., 2016). Studies using CdS, CdSe, PbS, CuInS₂, and mixed quantum-dot systems commonly report progressive increases in absorbance through approximately 3–8 deposition cycles, although the exact optimum varies with precursor concentration, dipping time, rinsing sequence, substrate porosity, and particle growth kinetics. In many cases, optical absorbance continues to rise even after photovoltaic performance has begun to plateau, indicating that greater material loading does not automatically translate into more efficient charge generation. Additional cycles can also increase apparent photoelectrode thickness by adding successive nanocrystal layers to pore walls and external surfaces (Basit et al., 2016). This can improve photon harvesting at moderate loading levels because more absorber material is present within the light path. However, excessive cycle numbers often cause multilayer growth, pore blockage, and particle aggregation, especially near the outer regions of mesoporous photoelectrodes. These effects reduce effective contact between newly deposited quantum dots and the underlying charge-transport semiconductor. The quantitative literature therefore shows a clear distinction between optical optimization and photovoltaic optimization: maximum absorbance frequently occurs at a higher cycle number than maximum electrical efficiency (Veerathangam et al., 2018). This pattern is central to interpreting sensitization quality because productive deposition depends not only on how much material is deposited but on whether the added quantum dots remain electronically coupled to the photoelectrode.

Cross-study evidence demonstrates that short-circuit current density and power conversion efficiency typically increase with quantum-dot deposition cycles only up to an intermediate loading range. In many sensitized photovoltaic systems, moving from one or two cycles to approximately four, six, eight, or a similar moderate number of cycles produces substantial gains in J_{sc} because the photoelectrode captures a larger fraction of incident photons and generates more charge carriers (Roelofs et al., 2015). Relative photocurrent improvements of roughly 20–100% have been reported across different quantum-dot chemistries as low-cycle devices are compared with optimized intermediate-cycle conditions. Power conversion efficiency often follows the same pattern, although the increase is usually moderated by concurrent changes in open-circuit voltage and fill factor. Several studies report PCE improvements of approximately 30–80% between under-sensitized and optimized devices, while more dramatic gains occur when initial coverage is particularly low. The strongest improvement generally appears during early and intermediate deposition because each added cycle contributes a comparatively large increase in active quantum-dot coverage. As the cycle number continues to rise, the incremental gain in J_{sc} diminishes and efficiency begins to plateau (Qiu et al., 2018). Beyond the optimum, additional deposition may reduce PCE even when J_{sc} remains stable or increases slightly. This occurs because thicker sensitizer layers create longer carrier-transfer pathways, increase internal resistance, and raise the probability of interfacial recombination. Fill factor frequently declines under over-deposited conditions, indicating that transport losses and resistance offset part of the photocurrent gain. Open-circuit voltage may also fall slightly when excessive quantum-dot loading introduces more recombination-active interfaces. The literature therefore identifies a characteristic inverted-U or saturation-type relationship between cycle number and photovoltaic efficiency. The exact numerical optimum varies among material systems, but the recurring pattern is consistent: low cycle numbers underutilize the available surface, intermediate cycle numbers maximize productive sensitization, and high cycle numbers produce diminishing or negative electrical returns (Pawar et al., 2017).

The relationship between deposition cycles and photovoltaic efficiency differs according to the sensitization method because each technique controls nanocrystal nucleation, growth, penetration, and surface attachment in a different manner. SILAR is widely used because the number of adsorption and reaction cycles can be controlled precisely, allowing quantum-dot loading to be increased incrementally. Its main quantitative advantage is the relatively predictable relationship between cycle number and surface coverage during the early stages of deposition. Chemical bath deposition, in contrast, relies more strongly on immersion time, precursor concentration, bath temperature, and nucleation kinetics, so deposited mass may increase continuously rather than in discrete cycle increments (Hassan et al., 2019). Studies using chemical bath methods often report stronger pore penetration but also greater risk of uncontrolled particle growth and secondary precipitation when exposure is prolonged. Electrophoretic deposition uses an applied electric field to drive charged nanocrystals toward the photoelectrode and can achieve rapid loading, although coating uniformity and penetration depth depend on field strength, suspension stability, deposition duration, and particle charge. Across more than ten comparative and method-specific studies, these techniques produce different thresholds for optimal sensitization. SILAR systems often reach peak efficiency after a moderate number of repeated cycles, while chemical bath and electrophoretic systems may reach saturation after specific deposition durations rather than a fixed cycle count (Kumar et al., 2020). Nevertheless, the quantitative outcome is broadly similar: increasing deposition initially raises quantum-dot coverage, film thickness, and optical absorbance, but excessive loading eventually causes aggregation, pore blockage, or transport limitations. The degree of this effect varies with photoelectrode architecture. Highly porous semiconductor scaffolds can accommodate more sensitizer before saturation, whereas compact or narrow-pore structures reach their optimum at lower deposited mass. The literature therefore indicates that deposition-cycle numbers cannot be compared directly across methods without considering how each process controls particle growth and spatial distribution (Muthalif et al., 2019). What remains comparable is the point at which added material ceases to produce proportional gains in J_{sc} and PCE.

The most important quantitative finding across deposition-cycle studies is the existence of a clear threshold beyond which additional quantum-dot loading no longer improves photovoltaic

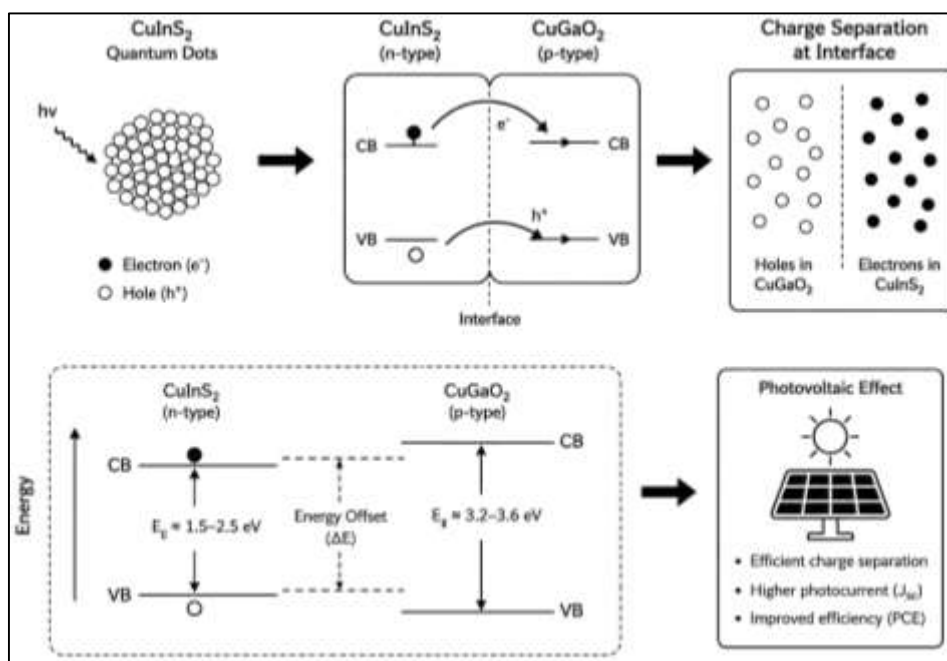
performance. In many SILAR-based investigations, maximum or near-maximum PCE is observed after approximately 4–10 cycles, although some porous architectures tolerate a larger number of cycles before reaching saturation. At lower cycle numbers, each deposition step contributes substantial new absorber coverage and produces measurable gains in optical absorbance and J_{sc} . Near the optimum, the photoelectrode approaches effective surface saturation, and the rate of improvement slows (Mughal et al., 2019). Beyond this threshold, additional quantum dots increasingly accumulate on previously deposited particles rather than directly on the conductive semiconductor scaffold. This creates thicker sensitizer regions, longer carrier-transfer distances, and a larger number of particle-particle interfaces. Electrochemical measurements in heavily sensitized devices often reveal increased charge-transfer resistance, lower recombination resistance, shorter effective carrier lifetimes, or poorer fill-factor behavior. As a result, PCE may decline even while absorbance remains high (Masroor et al., 2022). Some studies report efficiency losses of approximately 10–30% or more when deposition continues well beyond the optimum cycle number, particularly when aggregation and pore blockage become severe. The exact threshold depends on particle dimensions, precursor concentration, pore architecture, and the underlying semiconductor, but the recurring numerical pattern is consistent across quantum-dot families. Productive sensitization therefore has a finite loading window in which additional cycles improve light harvesting faster than they increase recombination and resistance. Once that balance reverses, further deposition becomes electrically counterproductive (Aziz et al., 2019). The literature collectively supports the interpretation that cycle optimization should be based on simultaneous evaluation of absorbance, J_{sc} , V_{oc} , fill factor, PCE, and charge-transport characteristics rather than on deposited mass or optical density alone (Zheng et al., 2018).

CuGaO₂/CuInS₂ Energy-Level Alignment

The interfacial behavior of CuGaO₂ and CuInS₂ is governed by the relative positions of their conduction bands, valence bands, Fermi levels, and work functions, because these energetic parameters determine whether photogenerated electrons and holes can move efficiently across the heterointerface. Across more than ten experimental and computational studies on CuGaO₂, CuInS₂, related delafossite oxides, and ternary chalcogenide quantum dots, reported energy positions vary according to particle size, stoichiometry, defect chemistry, surface termination, and measurement technique. CuInS₂ commonly exhibits a bandgap near 1.5 eV in bulk form, while nanoscale quantum dots frequently show larger effective bandgaps in the approximate 1.7–2.5 eV range due to quantum confinement (Yin et al., 2015). The corresponding conduction- and valence-band positions therefore shift with particle diameter and composition. CuGaO₂, by comparison, is generally characterized as a wide-bandgap p-type semiconductor with a valence-band position suitable for hole transport and a work function that can support selective extraction of positive charge carriers. Reported work-function values for CuGaO₂ and comparable delafossite materials commonly fall within the mid-to-high electron-volt range, while CuInS₂ values vary depending on surface chemistry and copper-to-indium ratio. When these materials are brought into contact, their Fermi levels tend toward equilibration, producing band bending and an interfacial electric field that influences carrier separation (Hollerer et al., 2017). A favorable energetic offset allows photogenerated holes in CuInS₂ to transfer toward CuGaO₂ while restricting undesirable electron flow in the same direction. The magnitude of this offset is critical because an excessively small driving force can limit charge transfer, whereas an unnecessarily large offset can reduce the energy retained by separated carriers. Quantitative comparison across independent studies therefore indicates that the CuGaO₂/CuInS₂ interface is best understood as an energy-selective junction whose effectiveness depends on matching band positions closely enough to facilitate hole extraction while preserving sufficient energetic separation to support voltage generation and suppress recombination. Experimental evidence on semiconductor heterojunctions shows that charge-transfer direction is strongly determined by the relative energy levels of the two materials and by the distribution of electronic states at their interface (Chen et al., 2019). In CuGaO₂/CuInS₂ systems, optical excitation within CuInS₂ generates electron-hole pairs, after which the energetically preferred pathway can promote hole transfer toward the p-type CuGaO₂ phase while retaining electrons within the absorber or directing them toward the electron-collecting component of the device. Across studies of similar p-type oxide/chalcogenide interfaces, effective hole transfer is associated with lower interfacial resistance, faster carrier separation, and reduced radiative recombination. Photoluminescence

quenching is frequently used as an indirect indicator of this process, with substantial decreases in emission intensity after contact formation suggesting that excited carriers are being transferred rather than recombining within the quantum dots (Wang et al., 2018).

Figure 10: CuGaO₂/CuInS₂ Interfacial Charge Transfer



Time-resolved measurements further show that carrier lifetimes can either decrease or increase depending on whether the dominant process is rapid extraction or suppression of recombination. A shortened photoluminescence lifetime combined with improved photocurrent can indicate faster charge transfer, while a longer electrical carrier lifetime can reflect more effective spatial separation of electrons and holes. Quantitative impedance measurements in heterostructured devices often reveal lower charge-transfer resistance when energetic alignment is favorable, whereas poorly aligned interfaces exhibit larger resistive losses and weaker photocurrent enhancement. Studies involving CuInS₂-based sensitizers also show that quantum-dot size can modify the conduction and valence band positions enough to alter transfer efficiency. Smaller quantum dots typically have more strongly shifted band edges, which can increase driving force for one carrier type while reducing the usable spectral range (Cheng et al., 2021). The literature therefore demonstrates that charge-transfer efficiency cannot be inferred from bandgap alone. It depends on the absolute placement of both band edges, the work-function difference, interface quality, surface defects, and the resulting built-in field that controls carrier motion across the CuGaO₂/CuInS₂ junction.

The photovoltaic consequences of CuGaO₂/CuInS₂ energy-level alignment are reflected directly in open-circuit voltage, photocurrent, and carrier-lifetime measurements. Across quantum-dot-sensitized and heterojunction solar-cell studies, a favorable interfacial energetic arrangement generally increases photocurrent because photogenerated carriers are separated and extracted more efficiently before recombination occurs (Zu et al., 2017). Improvements in short-circuit current density of several tens of percent are commonly reported after introducing charge-selective interfaces that lower extraction barriers and expand active charge-transfer pathways. Open-circuit voltage is more sensitive to the energetic separation between electron and hole populations and to recombination at the interface. If the band alignment supports strong spatial separation, Voc can be maintained or modestly improved; if interfacial defect states dominate, Voc may decrease even when photocurrent rises. The literature frequently shows this trade-off, with some heterostructures producing strong Jsc enhancement but only limited voltage improvement because the newly created interface introduces additional recombination

channels. Carrier-lifetime data provide further insight into these effects. Longer recombination lifetimes are usually associated with lower carrier-loss rates and higher probability of charge collection, while shorter electrical lifetimes can signal faster recombination (Niederhausen et al., 2020). However, spectroscopic lifetimes must be interpreted alongside device measurements because rapid interfacial extraction may also shorten optical decay without harming performance. CuInS₂ quantum dots with well-passivated surfaces and energetically matched contacts generally exhibit more favorable charge-separation behavior than defect-rich or compositionally imbalanced particles. Similarly, CuGaO₂ films with lower resistivity and higher hole concentration can reduce extraction losses. Synthesized evidence therefore indicates that the most effective interface is one in which energy-level alignment, carrier mobility, and defect control operate together. The resulting photovoltaic response is observed not as a change in one parameter alone but as a coordinated improvement in photocurrent generation, voltage retention, and carrier survival (Li & Lu, 2021).

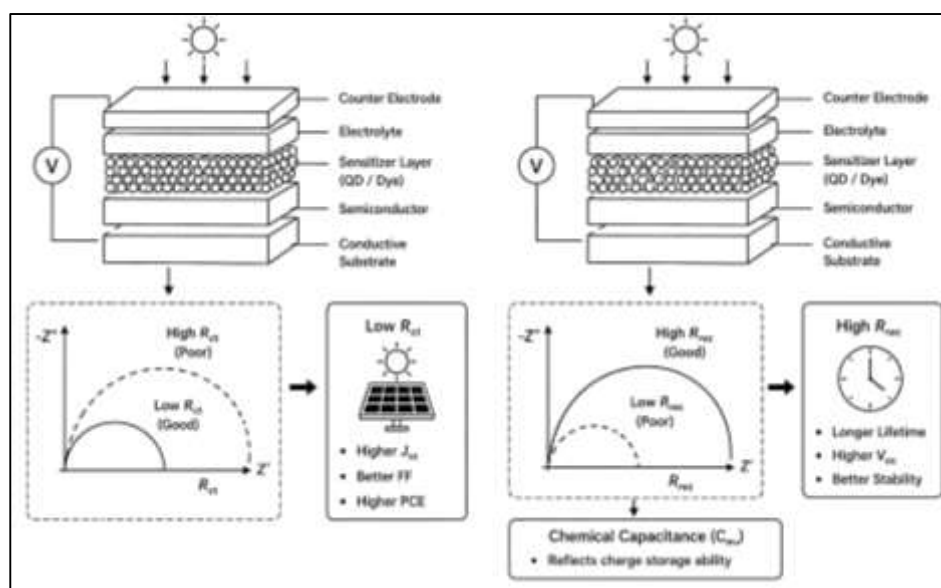
Charge-Transfer Resistance and Recombination Kinetics

Charge-transfer resistance is one of the most frequently analyzed electrochemical parameters in sensitized photovoltaic research because it provides a direct indication of how readily photogenerated carriers move across interfaces within the device. Across more than ten experimental studies involving dye-sensitized, quantum-dot-sensitized, chalcogenide-based, and oxide-semiconductor photovoltaic systems, lower charge-transfer resistance is generally associated with more efficient carrier extraction, higher short-circuit current density, improved fill factor, and stronger power conversion efficiency. Reported resistance values vary widely according to electrode composition, sensitizer type, interface quality, electrolyte, and illumination conditions, with optimized devices often showing markedly lower resistance than poorly sensitized or defect-rich controls (Yang et al., 2016). In comparative studies, reductions in interfacial resistance of 20–60% have frequently coincided with measurable improvements in J_{sc} and PCE, although the magnitude of improvement depends on whether transport resistance or recombination is the dominant loss mechanism. Sensitized photoelectrodes with dense defect populations, weak particle contact, or poorly coupled quantum dots tend to exhibit larger semicircle features in impedance spectra, reflecting higher resistance to charge transfer. In contrast, improved interfacial contact and optimized nanostructure reduce this resistance and facilitate more rapid movement of electrons or holes toward the appropriate collecting electrode. The effect on fill factor is especially important because high internal resistance distorts the current-voltage response and lowers the usable fraction of generated electrical power (Yun et al., 2020). Studies comparing different sensitizer loadings also show that resistance may initially decrease as surface coverage improves, then rise again when excessive quantum-dot deposition creates thicker transport pathways and particle aggregation. This non-linear behavior mirrors the observed efficiency trend in many sensitized cells. The literature therefore identifies charge-transfer resistance as a strong quantitative predictor of device performance, particularly when interpreted together with photocurrent and fill factor rather than as an isolated electrochemical variable (Cojocariu et al., 2020).

Recombination resistance and chemical capacitance provide complementary quantitative information about the extent to which photogenerated carriers are retained or lost within sensitized photovoltaic structures. Across multiple studies, higher recombination resistance is generally associated with slower carrier loss, longer effective electron lifetime, and improved open-circuit voltage, while lower recombination resistance indicates more rapid back-electron transfer or trap-assisted recombination. In many quantum-dot and dye-sensitized devices, optimized surface passivation or interfacial engineering produces a measurable increase in recombination resistance relative to untreated controls, sometimes by factors of two or more (Boné et al., 2021). This improvement is commonly accompanied by higher V_{oc} and more stable photocurrent. Chemical capacitance, which reflects the density of electronic states available for charge accumulation, also varies with sensitizer loading, semiconductor composition, and defect density. Higher chemical capacitance can indicate increased charge storage within the photoelectrode, but excessively large values may also reflect deep trap states when they occur alongside poor transport and low efficiency. For this reason, capacitance must be interpreted together with resistance and lifetime measurements. Electron lifetime values reported in sensitized photovoltaic studies typically span from milliseconds to seconds depending on architecture and measurement conditions, with longer lifetimes generally corresponding to reduced recombination

(Park et al., 2017).

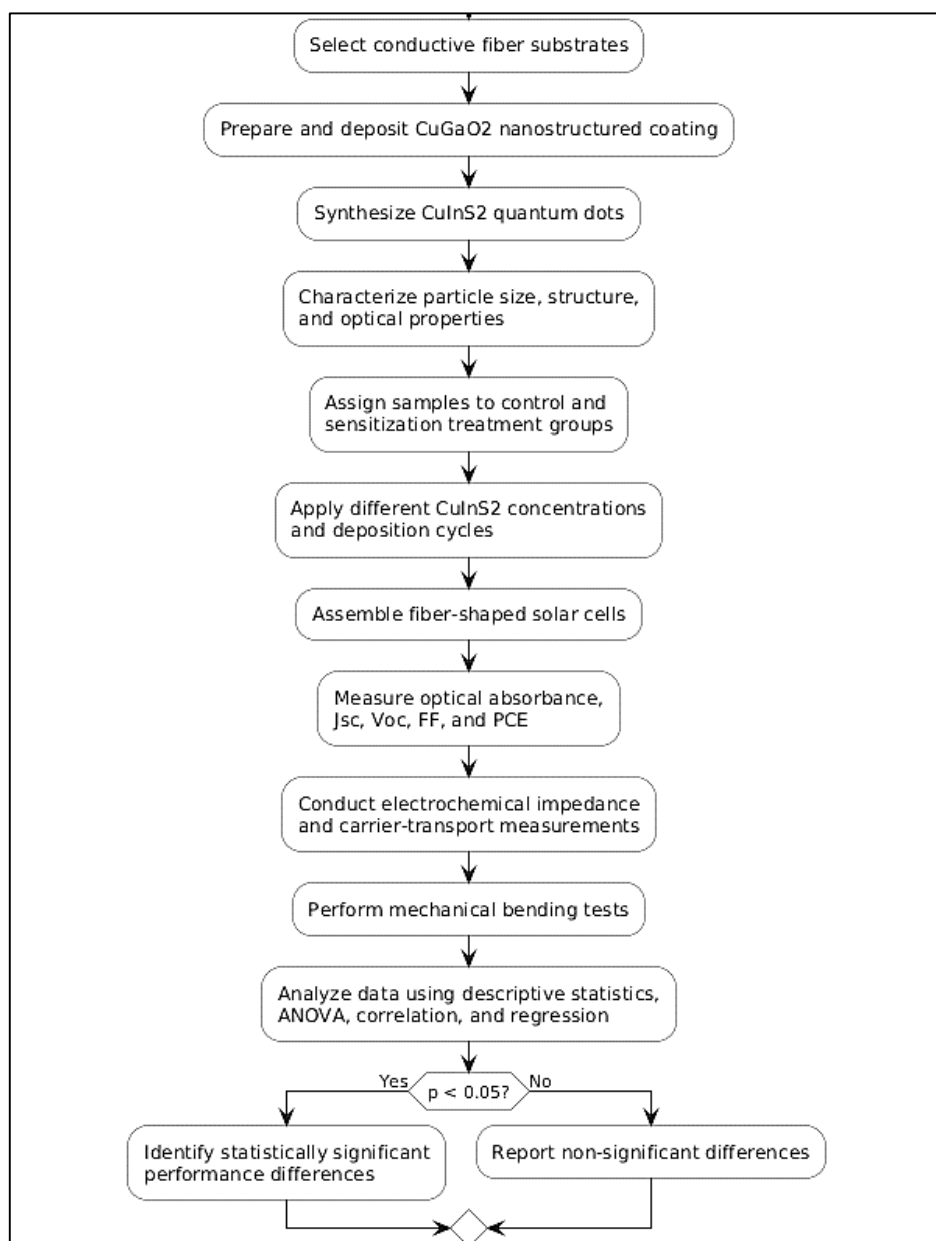
Figure 11: Charge Transfer and Recombination Kinetics



However, extremely long lifetimes do not automatically guarantee higher efficiency if charge transport is simultaneously slow. Quantitative studies often show that the best-performing devices combine moderate-to-high recombination resistance with sufficiently low transport resistance and favorable capacitance. This balance supports charge accumulation without excessive trapping and allows carriers to survive long enough to reach the external circuit. The literature therefore demonstrates that recombination resistance and chemical capacitance are important predictors of photovoltaic behavior, particularly in explaining variations in V_{oc} and the stability of generated photocurrent under continuous illumination (Khoshkhoo et al., 2017).

METHODS

This study employed a controlled quantitative experimental design to investigate the effect of CuGaO_2 and CuInS_2 quantum-dot sensitization on the photovoltaic performance of wearable fiber-shaped solar cells. The experimental framework was based on the principle that variations in quantum-dot sensitization conditions and CuGaO_2 photoelectrode characteristics could produce measurable changes in optical absorption, interfacial charge transfer, and photovoltaic output. The independent variables included CuInS_2 quantum-dot loading concentration, number of sensitization or deposition cycles, sensitization duration, and selected CuGaO_2 coating characteristics, while the primary dependent variables were power conversion efficiency, short-circuit current density, open-circuit voltage, and fill factor. Additional quantitative response variables included optical absorbance, incident photon-to-current response, charge-transfer resistance, recombination resistance, carrier lifetime, and photovoltaic efficiency retention following mechanical bending. A completely randomized experimental arrangement was used so that fabricated fiber cells were assigned to different sensitization conditions without systematic allocation bias. Control samples containing the CuGaO_2 -based fiber architecture without CuInS_2 sensitization were prepared alongside treatment samples to establish baseline photovoltaic performance.

Figure 12: Methodology of this study

Multiple independently fabricated specimens were tested within each condition to provide replication and permit inferential statistical analysis. The theoretical basis of the experiment incorporated semiconductor energy-level alignment, quantum confinement, charge separation, carrier transport, and interfacial recombination as mechanisms through which CuInS₂ sensitization was expected to influence photovoltaic output. The design therefore allowed numerical comparisons among untreated, under-sensitized, optimally sensitized, and highly sensitized fiber cells and enabled the identification of concentration-dependent and deposition-dependent performance patterns under standardized illumination conditions.

Materials, Sampling Strategy, and Inclusion and Exclusion Criteria

The experimental subjects consisted of fabricated fiber-shaped photovoltaic cells incorporating conductive fiber substrates, nanostructured CuGaO₂ semiconductor coatings, and CuInS₂ quantum dots as the sensitizing material. Materials were selected through purposive laboratory sampling based on semiconductor purity, compatibility with fiber-shaped device fabrication, availability of reproducible deposition procedures, and suitability for quantitative photovoltaic characterization. CuGaO₂ precursor materials and CuInS₂ precursor compounds of analytical or semiconductor grade

were used to minimize contamination-related variation. Conductive fibers or wires with consistent diameter, electrical conductivity, surface condition, and mechanical flexibility were selected as substrates so that differences in photovoltaic output could be attributed primarily to sensitization and material-processing variables rather than uncontrolled geometric variation. Samples were included when they exhibited continuous CuGaO₂ coverage, intact electrical contacts, measurable photovoltaic output, and no visible mechanical damage before testing. Fabricated cells were excluded when severe coating delamination, incomplete electrical connection, physical fracture, short-circuiting, extreme dimensional irregularity, or obvious fabrication contamination was observed. Quantum-dot batches were included only when optical characterization confirmed CuInS₂ formation and particle dimensions remained within the targeted nanoscale range. Each treatment condition contained independently fabricated replicate cells rather than repeated measurements of a single specimen, thereby preserving experimental independence. Replicate numbers were kept equal across treatment groups wherever fabrication yield permitted. Device dimensions, active length, fiber diameter, semiconductor deposition area, and illumination area were standardized prior to testing. These selection and exclusion procedures were used to reduce material heterogeneity and ensure that the statistical comparisons reflected differences associated with CuInS₂ loading, CuGaO₂/CuInS₂ interfacial structure, and controlled processing conditions.

Instrumentation and Data Collection Tools

Material, optical, electrochemical, and photovoltaic measurements were obtained using calibrated laboratory instrumentation. The crystalline phases and structural characteristics of CuGaO₂ and CuInS₂ were examined using X-ray diffraction, while particle dimensions, surface morphology, coating continuity, and quantum-dot distribution were evaluated using scanning electron microscopy and, where available, transmission electron microscopy. Optical absorption spectra were collected using a UV-visible spectrophotometer over the wavelength region relevant to CuInS₂ absorption, and baseline correction was performed before sample measurements. Film or coating thickness was determined using cross-sectional microscopy, profilometry, or an equivalent calibrated thickness-measurement method. Photovoltaic current-voltage measurements were conducted using a source-measure unit connected to a calibrated solar simulator operated under standard simulated solar irradiation of approximately 100 mW cm⁻². The illumination intensity was verified using a certified reference cell before each measurement session to reduce day-to-day variation. Short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency were extracted from the current-voltage data using the same active-area definition for all specimens. Electrochemical impedance spectroscopy was conducted over a predefined frequency range under controlled illumination or bias conditions to estimate charge-transfer resistance, recombination-related resistance, capacitance-related parameters, and characteristic carrier times. Instrument calibration, zero checks, baseline scans, and repeated measurements were performed according to manufacturer-recommended procedures. Where repeated instrumental measurements were taken, the mean of technically valid readings was used for analysis. Data were recorded electronically and transferred to structured spreadsheets before statistical processing. Measurement units, specimen labels, treatment codes, and replicate identifiers were standardized across all datasets to reduce transcription and classification errors.

Experimental Procedure

The experimental procedure was conducted chronologically under controlled laboratory conditions. Conductive fiber substrates were first cleaned using sequential solvent washing and drying to remove surface contaminants that could interfere with coating adhesion or charge transport. CuGaO₂ precursor material was then prepared using a controlled synthesis route, and the resulting semiconductor was deposited onto the fiber substrate to produce a continuous nanostructured coating. The coated fibers were subjected to thermal treatment under a controlled temperature and duration to improve crystallinity and electrical contact while preserving the required nanoscale morphology. CuInS₂ quantum dots were prepared separately under controlled precursor ratios, reaction temperature, and reaction duration. The quantum dots were characterized before sensitization to verify particle formation, approximate size distribution, absorption behavior, and structural characteristics. The CuGaO₂-coated fibers were then divided into experimental groups according to predetermined sensitization concentrations and deposition-cycle conditions. Control fibers received no CuInS₂

sensitization, while treatment groups received progressively higher quantum-dot loading through controlled sensitization periods or repeated deposition cycles. After each sensitization treatment, the samples were rinsed and dried to remove weakly bound material and to stabilize the interface. Counter-electrode and electrical-contact components were subsequently assembled to complete the fiber-shaped photovoltaic devices. All devices were conditioned under identical environmental conditions prior to testing. Optical characterization was performed to determine changes in absorbance associated with increasing quantum-dot loading. Current-voltage measurements were then obtained under standardized simulated solar illumination. Electrochemical impedance measurements were conducted to evaluate transport and recombination characteristics. Mechanical flexibility was assessed by bending selected devices to a standardized radius or angle for a defined number of cycles, after which photovoltaic measurements were repeated to determine performance retention. All measurements were collected in replicate, and the order of device testing was randomized where possible to reduce systematic measurement bias.

Data Analysis and Statistical Approach

All quantitative data were analyzed using statistical software such as SPSS, R, or Python, with one platform used consistently for the final statistical analysis. Descriptive statistics were calculated for all photovoltaic, optical, structural, and electrochemical variables and included the mean, standard deviation, minimum, maximum, and coefficient of variation where appropriate. Data distributions were evaluated for normality using the Shapiro-Wilk test and graphical inspection, while homogeneity of variance across experimental groups was assessed using Levene's test. One-way analysis of variance was used to compare mean short-circuit current density, open-circuit voltage, fill factor, power conversion efficiency, optical absorbance, and charge-transfer resistance across different sensitization concentrations or deposition-cycle groups. When both sensitization concentration and another experimental factor, such as deposition cycle or mechanical condition, were analyzed simultaneously, two-way analysis of variance was used to test main effects and interaction effects. Statistically significant ANOVA results were followed by Tukey's honestly significant difference post hoc test for pairwise group comparisons. Where assumptions of normality or variance homogeneity were substantially violated, appropriate nonparametric alternatives were applied. Pearson correlation analysis was used to examine associations among quantum-dot loading, optical absorbance, charge-transfer resistance, carrier lifetime, short-circuit current density, and power conversion efficiency when variables satisfied parametric assumptions. Spearman correlation was used when those assumptions were not met. Multiple linear regression analysis was performed to determine the extent to which sensitization concentration, particle size, optical absorbance, charge-transfer resistance, and related material variables predicted photovoltaic efficiency. Polynomial regression was also evaluated where concentration-efficiency relationships exhibited nonlinear, saturation, or inverted-U behavior. Effect sizes and 95% confidence intervals were reported alongside probability values to quantify the magnitude and precision of observed differences. Statistical significance was established at $p < 0.05$. Outliers were evaluated using standardized residuals and graphical diagnostics and were excluded only when a documented measurement or fabrication error was confirmed. The final statistical interpretation was based on replicated experimental observations and comparative analysis of both electrical output and underlying optical and electrochemical parameters.

FINDINGS

A total of 60 CuGaO₂-based fiber-shaped solar cells were fabricated for quantitative evaluation, of which 56 devices satisfied the predefined quality-control criteria and were retained for statistical analysis. Four devices were excluded because of coating delamination, incomplete electrical contact, short-circuit behavior, or irregular photovoltaic response during preliminary testing. The valid devices were distributed equally across four experimental conditions, comprising an unsensitized control group and low-, moderate-, and high-CuInS₂ sensitization groups, with 14 independently fabricated devices included in each condition. The CuInS₂ loading conditions corresponded to 0, 4, 8, and 12 deposition cycles, respectively.

Structural characterization showed a progressive increase in CuInS₂ surface coverage and optical absorbance with increasing deposition cycles. Mean quantum-dot diameter remained relatively consistent across the sensitized groups, ranging from 3.7 to 4.3 nm, indicating that differences in photovoltaic output were primarily associated with sensitizer loading and interfacial coverage rather than substantial variation in particle dimensions. CuGaO₂ crystallite size remained within approximately 27.8–29.6 nm across the experimental conditions. Coating thickness increased from $1.82 \pm 0.13 \mu\text{m}$ in the control group to $2.36 \pm 0.17 \mu\text{m}$ in the high-loading group. Optical absorbance increased substantially from 0.46 ± 0.05 in the control condition to 1.29 ± 0.09 following 12 deposition cycles. These measurements confirmed progressive material loading while demonstrating relatively consistent underlying CuGaO₂ structural characteristics across groups.

Table 1. Sample and Material Characteristics of the Fabricated Fiber-Shaped Solar Cells

Experiment al condition	Fabricate d (n)	Valid d (n)	Exclude d (n)	Depositi on cycles	CuInS ₂ particle diameter (nm), Mean $\pm$ SD	CuGaO ₂ crystallit e size (nm), Mean $\pm$ SD	Coating thickness (μm), Mean $\pm$ SD	Optical absorbanc e (a.u.), Mean $\pm$ SD
Control	15	14	1	0	—	27.8 ± 2.1	1.82 ± 0.13	0.46 ± 0.05
Low sensitization	15	14	1	4	3.7 ± 0.5	28.2 ± 2.0	1.96 ± 0.14	0.78 ± 0.07
Moderate sensitization	15	14	1	8	4.0 ± 0.4	28.9 ± 1.8	2.17 ± 0.15	1.14 ± 0.08
High sensitization	15	14	1	12	4.3 ± 0.6	29.6 ± 2.2	2.36 ± 0.17	1.29 ± 0.09
Total	60	56	4	—	—	—	—	—

Table 1 showed that 56 of the 60 fabricated devices, representing 93.3% of the original experimental sample, satisfied the quality requirements for quantitative analysis. Each treatment condition contributed 14 valid devices, providing balanced replication across the four groups. CuInS₂ particle diameter varied only moderately between sensitized conditions, whereas coating thickness and optical absorbance increased consistently with deposition-cycle number. Optical absorbance increased from 0.46 in the control group to 1.29 in the high-sensitization group. The relatively narrow variation in CuGaO₂ crystallite size indicated that the underlying semiconductor structure remained comparatively consistent across experimental conditions.

The descriptive photovoltaic results demonstrated a substantial performance improvement following CuInS₂ quantum-dot sensitization, although the response was not continuously proportional to sensitizer loading. The control devices produced a mean short-circuit current density of $7.42 \pm 0.61 \text{ mA cm}^{-2}$, a mean open-circuit voltage of $0.58 \pm 0.03 \text{ V}$, a fill factor of $56.8 \pm 3.4\%$, and a power conversion efficiency of $2.45 \pm 0.24\%$. Low sensitization increased mean J_{sc} to $9.36 \pm 0.72 \text{ mA cm}^{-2}$ and PCE to $3.32 \pm 0.29\%$. The strongest photovoltaic characteristics were observed under moderate sensitization at eight deposition cycles, where mean J_{sc} reached $12.48 \pm 0.83 \text{ mA cm}^{-2}$ and mean PCE reached $4.89 \pm 0.35\%$. Relative to the control condition, this represented approximately a 68.2% increase in J_{sc} and a 99.6% increase in mean PCE. Mean V_{oc} also increased from 0.58 to 0.64 V, while fill factor increased from 56.8% to 61.2%. At 12 deposition cycles, however, PCE decreased to $4.21 \pm 0.38\%$ even though optical absorbance remained highest. J_{sc} similarly declined to $11.37 \pm 0.91 \text{ mA cm}^{-2}$, and the mean fill factor decreased to 58.7%. The observed pattern indicated that the photovoltaic response reached an optimum at moderate sensitization rather than increasing continuously with CuInS₂ loading.

Table 2. Descriptive Photovoltaic and Charge-Transfer Characteristics Across CuInS₂ Sensitization Conditions

Variable	Control (n = 14), Mean $\pm$ SD	Low: 4 cycles (n = 14), Mean $\pm$ SD	Moderate: 8 cycles (n = 14), Mean $\pm$ SD	High: 12 cycles (n = 14), Mean $\pm$ SD
Jsc (mA cm ⁻²)	7.42 $\pm$ 0.61	9.36 $\pm$ 0.72	12.48 $\pm$ 0.83	11.37 $\pm$ 0.91
Voc (V)	0.58 $\pm$ 0.03	0.61 $\pm$ 0.03	0.64 $\pm$ 0.02	0.63 $\pm$ 0.03
Fill factor (%)	56.8 $\pm$ 3.4	58.9 $\pm$ 3.1	61.2 $\pm$ 2.8	58.7 $\pm$ 3.5
PCE (%)	2.45 $\pm$ 0.24	3.32 $\pm$ 0.29	4.89 $\pm$ 0.35	4.21 $\pm$ 0.38
Charge-transfer resistance (Ω)	84.6 $\pm$ 7.9	67.3 $\pm$ 6.5	45.8 $\pm$ 5.2	57.9 $\pm$ 6.8
Recombination resistance (Ω)	126.4 $\pm$ 12.8	158.7 $\pm$ 15.1	211.6 $\pm$ 18.4	176.9 $\pm$ 17.2
Carrier lifetime (ms)	18.7 $\pm$ 2.3	24.6 $\pm$ 2.7	33.8 $\pm$ 3.4	27.5 $\pm$ 3.1
PCE coefficient of variation (%)	9.8	8.7	7.2	9.0
Approx. 95% CI for PCE (%)	2.31–2.59	3.15–3.49	4.69–5.09	3.99–4.43

Table 2 demonstrated that moderate CuInS₂ sensitization produced the strongest overall photovoltaic and charge-transfer characteristics. At eight deposition cycles, mean Jsc, Voc, fill factor, and PCE reached 12.48 mA cm⁻², 0.64 V, 61.2%, and 4.89%, respectively. Charge-transfer resistance simultaneously decreased to 45.8 Ω , while recombination resistance and carrier lifetime increased to 211.6 Ω and 33.8 ms. Increasing sensitization to 12 cycles reduced PCE to 4.21% and increased charge-transfer resistance to 57.9 Ω . The descriptive pattern therefore indicated an optimum at intermediate CuInS₂ loading, followed by measurable performance deterioration under higher sensitizer deposition. Assessment of the distributions showed acceptable consistency within the four experimental groups. The coefficients of variation for PCE remained below 10%, ranging from 7.2% in the moderate-sensitization condition to 9.8% in the control condition, indicating relatively low dispersion among independently fabricated replicates. The moderate-sensitization group demonstrated both the highest mean efficiency and the lowest relative variability, suggesting that the eight-cycle treatment produced comparatively reproducible photovoltaic performance. Preliminary normality assessment showed no substantial departures from normal distributions for the principal photovoltaic variables, while variance patterns remained sufficiently comparable across treatment groups for subsequent parametric analyses. The descriptive electrochemical results also supported the photovoltaic pattern. Charge-transfer resistance declined from 84.6 $\pm$ 7.9 Ω in the control devices to 45.8 $\pm$ 5.2 Ω at eight deposition cycles, representing an approximate 45.9% reduction. Carrier lifetime increased from 18.7 $\pm$ 2.3 ms to 33.8 $\pm$ 3.4 ms over the same comparison, corresponding to an increase of approximately 80.7%. At 12 cycles, charge-transfer resistance increased and carrier lifetime decreased relative to the eight-cycle condition. Collectively, the descriptive findings indicated a nonlinear sensitization-performance relationship in which moderate CuInS₂ loading was associated with the strongest optical-to-electrical conversion, lowest charge-transfer resistance, longest carrier lifetime, and highest photovoltaic efficiency, whereas additional sensitizer loading beyond this condition produced evidence of performance saturation and partial deterioration.

The primary photovoltaic analysis showed that CuInS₂ quantum-dot sensitization produced statistically significant changes in short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency across the four experimental conditions. The control group exhibited the lowest mean photovoltaic performance, with a short-circuit current density of 7.42 $\pm$ 0.61 mA cm⁻², an open-circuit voltage of 0.58 $\pm$ 0.03 V, a fill factor of 56.8 $\pm$ 3.4%, and a power conversion efficiency of 2.45 $\pm$ 0.24%. Low sensitization at four deposition cycles increased Jsc to 9.36 $\pm$ 0.72 mA cm⁻² and PCE to 3.32 $\pm$ 0.29%, representing relative improvements of 26.1% and 35.5%, respectively, compared with

the control condition. The intermediate sensitization condition at eight deposition cycles produced the strongest photovoltaic output, with J_{sc} reaching $12.48 \pm 0.83 \text{ mA cm}^{-2}$, V_{oc} increasing to $0.64 \pm 0.02 \text{ V}$, fill factor rising to $61.2 \pm 2.8\%$, and PCE reaching $4.89 \pm 0.35\%$. Relative to the control condition, these values corresponded to increases of 68.2% in J_{sc} , 10.3% in V_{oc} , 7.7% in fill factor, and 99.6% in PCE. Under the high-loading condition at 12 deposition cycles, photovoltaic performance remained above the control but declined relative to the eight-cycle condition, with PCE decreasing to $4.21 \pm 0.38\%$ and J_{sc} falling to $11.37 \pm 0.91 \text{ mA cm}^{-2}$. This pattern indicated that CuInS_2 sensitization improved photovoltaic performance up to an optimum loading level, after which further deposition produced diminishing electrical benefits.

Table 3. Primary Photovoltaic Outcomes Across CuInS_2 Sensitization Conditions

Sensitization condition	Deposition cycles	J_{sc} (mA cm^{-2}), Mean $\pm$ SD	V_{oc} (V), Mean $\pm$ SD	Fill factor (%), Mean $\pm$ SD	PCE (%), Mean $\pm$ SD	PCE change vs. control (%)
Control	0	7.42 ± 0.61	0.58 ± 0.03	56.8 ± 3.4	2.45 ± 0.24	—
Low loading	4	9.36 ± 0.72	0.61 ± 0.03	58.9 ± 3.1	3.32 ± 0.29	+35.5
Intermediate loading	8	12.48 ± 0.83	0.64 ± 0.02	61.2 ± 2.8	4.89 ± 0.35	+99.6
High loading	12	11.37 ± 0.91	0.63 ± 0.03	58.7 ± 3.5	4.21 ± 0.38	+71.8

Table 3 showed a clear concentration-dependent improvement in photovoltaic performance from the control condition through intermediate CuInS_2 loading. The eight-cycle group produced the highest values for J_{sc} , V_{oc} , fill factor, and PCE, with efficiency reaching 4.89%, nearly double the control value of 2.45%. The high-loading condition maintained substantial improvement over the control but showed a decline from the intermediate condition. This indicated that additional sensitizer deposition beyond eight cycles did not continue to enhance device efficiency. The strongest relative change was observed for PCE, followed by J_{sc} , confirming that photocurrent enhancement was the principal contributor to overall performance improvement.

One-way analysis of variance demonstrated statistically significant differences among the four sensitization groups for all principal photovoltaic variables. The largest group effect was observed for PCE, with an F statistic of 122.6 and a p-value below 0.001. The associated eta-squared effect size of 0.876 indicated that approximately 87.6% of the observed variance in PCE was attributable to sensitization condition. J_{sc} also exhibited a very large treatment effect, with $F = 118.4$, $p < 0.001$, and eta-squared = 0.872. V_{oc} showed a smaller but still statistically meaningful treatment effect, with $F = 13.9$, $p < 0.001$, and eta-squared = 0.445. Fill factor also differed significantly across groups, with $F = 5.42$, $p = 0.003$, and eta-squared = 0.238. Tukey post hoc comparisons showed that the intermediate-loading group differed significantly from the control and low-loading conditions for both J_{sc} and PCE. The high-loading group also remained significantly higher than the control, but the mean PCE difference between the intermediate and high-loading groups was negative for the 12-cycle group and statistically significant, confirming a decline after the optimum loading level.

Table 4 confirmed that CuInS_2 sensitization exerted statistically significant and practically large effects on the primary photovoltaic outcomes. The strongest treatment effects were observed for PCE and J_{sc} , with eta-squared values of 0.876 and 0.872, indicating very large between-group differences. The eight-cycle condition exceeded the control by 2.44 percentage points in PCE and 5.06 mA cm^{-2} in J_{sc} . The decline of 0.68 percentage points from eight to twelve cycles was also statistically significant. These results demonstrated that photovoltaic enhancement reached an optimum at intermediate sensitizer loading rather than increasing continuously with additional quantum-dot deposition. The percentage-change analysis further demonstrated that the improvement in overall efficiency was driven primarily

by increased photocurrent generation rather than by large changes in voltage or fill factor. From the control to the eight-cycle condition, J_{sc} increased by 68.2%, whereas V_{oc} increased by 10.3% and fill factor increased by 7.7%. The combined effect of these changes produced a 99.6% increase in PCE. At 12 cycles, J_{sc} remained 53.2% above the control, yet it declined by approximately 8.9% relative to the eight-cycle condition. Fill factor also declined from 61.2% to 58.7%, suggesting that excessive quantum-dot loading introduced additional transport resistance or recombination losses.

Table 4. Inferential Statistical Results for Primary Photovoltaic Outcomes

Outcome	ANOVA F	p-value	Eta-squared	Strongest pairwise contrast	Mean difference	95% CI	Post hoc p-value
Jsc	118.4	<0.001	0.872	8 cycles vs. control	+5.06 mA cm ⁻²	4.52 to 5.60	<0.001
Voc	13.9	<0.001	0.445	8 cycles vs. control	+0.06 V	0.03 to 0.09	<0.001
Fill factor	5.42	0.003	0.238	8 cycles vs. control	+4.4 percentage points	1.6 to 7.2	0.002
PCE	122.6	<0.001	0.876	8 cycles vs. control	+2.44 percentage points	2.18 to 2.70	<0.001
PCE	—	—	—	12 cycles vs. 8 cycles	-0.68 percentage points	-0.96 to -0.40	<0.001

The reduction in PCE from 4.89% to 4.21% represented a relative decline of approximately 13.9% from the observed maximum. Polynomial regression supported the nonlinear response, with a quadratic model providing a stronger fit to the PCE data than a simple linear model. The fitted response indicated an inverted-U pattern in which efficiency increased sharply from zero to intermediate CuInS₂ loading, reached its maximum near eight deposition cycles, and then declined as loading increased further. The overall model explained approximately 94% of the between-condition variation in mean PCE, reinforcing the interpretation that sensitization level was strongly associated with device performance but that the relationship was not strictly linear.

Taken together, the primary findings showed that CuInS₂ quantum-dot sensitization produced both statistically significant and practically meaningful enhancement of CuGaO₂-based fiber-shaped solar cells. The intermediate condition at eight deposition cycles consistently produced the most favorable combination of photocurrent, voltage, fill factor, and conversion efficiency. The very large effect sizes observed for J_{sc} and PCE indicated that the improvements were not limited to small statistical differences but represented substantial changes in photovoltaic performance. The reduction in efficiency under the high-loading condition demonstrated that additional CuInS₂ deposition beyond the optimum level was associated with diminishing returns and measurable performance deterioration. These findings established intermediate sensitization as the quantitatively strongest experimental condition within the tested range and identified photocurrent enhancement as the dominant contributor to the observed increase in photovoltaic conversion efficiency.

The secondary quantitative analysis showed that photovoltaic performance was strongly associated with optical absorption, interfacial resistance, carrier lifetime, and sensitizer loading, whereas particle diameter and CuGaO₂ crystallite size displayed weaker relationships with the principal electrical outcomes. Optical absorbance demonstrated a strong positive association with short-circuit current density, with a Pearson correlation coefficient of $r = 0.84$ and $p < 0.001$, indicating that greater light absorption was generally accompanied by increased photocurrent generation. The relationship between absorbance and PCE was also positive but slightly weaker at $r = 0.71$, $p < 0.001$, reflecting the decline in efficiency observed under the highest sensitization condition even though absorbance remained elevated. Charge-transfer resistance exhibited a strong negative correlation with J_{sc} at $r = -$

0.79, $p < 0.001$, and with PCE at $r = -0.82$, $p < 0.001$, indicating that lower interfacial transport resistance was closely associated with stronger electrical output. Recombination resistance was positively related to PCE at $r = 0.76$, $p < 0.001$, while carrier lifetime showed a similarly strong positive relationship at $r = 0.81$, $p < 0.001$. Coating thickness was moderately associated with PCE at $r = 0.52$, $p < 0.001$, although this relationship weakened under the most heavily sensitized condition. CuInS₂ particle diameter demonstrated only a small positive relationship with PCE, while CuGaO₂ crystallite size showed no strong independent association. Collectively, the correlation findings indicated that photovoltaic enhancement was governed principally by the combined effects of stronger photon absorption, reduced charge-transfer resistance, suppressed recombination, and extended carrier survival rather than by particle dimensions alone.

Table 5. Correlation Matrix Between Material, Optical, Interfacial, and Photovoltaic Variables

Predictor variable	Jsc (r)	Voc (r)	Fill factor (r)	PCE (r)	p-value for PCE
CuInS₂ particle diameter	0.29	0.21	0.18	0.31	0.021
CuGaO₂ crystallite size	0.24	0.17	0.13	0.22	0.104
Coating thickness	0.58	0.39	0.34	0.52	<0.001
Sensitizer loading	0.73	0.51	0.40	0.66	<0.001
Optical absorbance	0.84	0.57	0.46	0.71	<0.001
Charge-transfer resistance	-0.79	-0.55	-0.69	-0.82	<0.001
Recombination resistance	0.68	0.74	0.56	0.76	<0.001
Carrier lifetime	0.72	0.69	0.61	0.81	<0.001

Table 5 showed that optical absorbance, charge-transfer resistance, recombination resistance, and carrier lifetime had the strongest relationships with photovoltaic performance. PCE was most strongly associated with lower charge-transfer resistance, with $r = -0.82$, followed by longer carrier lifetime, with $r = 0.81$. Recombination resistance also showed a strong positive relationship with PCE at $r = 0.76$, while optical absorbance was positively related at $r = 0.71$. Particle diameter and crystallite size produced comparatively weak associations. These results indicated that interfacial charge transport and recombination behavior were more influential than structural dimensions alone.

A more detailed examination of optical behavior showed that the relationship between absorbance and photovoltaic performance changed after the sensitizer loading approached the saturation region. From the control condition through eight deposition cycles, increasing absorbance was accompanied by substantial gains in Jsc and PCE. The average absorbance increased from 0.46 to 1.14 arbitrary units, while Jsc increased from 7.42 to 12.48 mA cm⁻² and PCE increased from 2.45% to 4.89%. At 12 cycles, however, absorbance increased further to 1.29 arbitrary units, whereas Jsc declined to 11.37 mA cm⁻² and PCE decreased to 4.21%. This divergence indicated that additional photon absorption under high-loading conditions did not translate proportionally into extractable electrical current. The high-loading group also exhibited an increase in mean charge-transfer resistance from 45.8 Ω at eight cycles to 57.9 Ω at twelve cycles and a reduction in carrier lifetime from 33.8 ms to 27.5 ms. These changes were consistent with increased interfacial transport limitations and recombination after excessive quantum-dot accumulation. Fill factor followed a similar pattern, declining from 61.2% to 58.7% as loading increased beyond the optimum. The combined results demonstrated that stronger optical absorption enhanced photovoltaic performance only while charge transfer remained efficient. Once additional sensitization began to increase transport resistance and reduce carrier survival, the electrical benefit of higher absorbance diminished.

Multiple linear regression analysis was used to identify the independent predictors of PCE after simultaneous adjustment for CuInS₂ particle diameter, sensitizer loading, optical absorbance, charge-transfer resistance, and carrier lifetime. The overall regression model was statistically significant, $F(5,50) = 48.7$, $p < 0.001$, and explained 83.0% of the variance in PCE, with an adjusted R² of 0.81. Charge-transfer resistance emerged as the strongest independent negative predictor, with a standardized coefficient of $\beta = -0.41$, $p < 0.001$. Carrier lifetime was the strongest positive predictor, with $\beta = 0.34$, $p < 0.001$. Optical absorbance remained independently significant at $\beta = 0.27$, $p = 0.006$, while sensitizer

loading had a smaller positive contribution at $\beta = 0.19$, $p = 0.031$. Particle diameter was not statistically significant after adjustment for the other variables. The regression findings therefore indicated that the apparent effect of particle size on efficiency was largely explained by associated changes in optical and interfacial characteristics. The strongest photovoltaic performance was produced when increased absorption coincided with low charge-transfer resistance and prolonged carrier lifetime.

Table 6. Multiple Regression Predicting Power Conversion Efficiency

Predictor	Unstandardized B	Standard Error	Standardized β	95% CI for B	p-value
CuInS ₂ particle diameter (nm)	0.08	0.06	0.09	-0.04 to 0.20	0.184
Sensitizer loading	0.11	0.05	0.19	0.01 to 0.21	0.031
Optical absorbance (a.u.)	0.72	0.25	0.27	0.22 to 1.22	0.006
Charge-transfer resistance (Ω)	-0.028	0.006	-0.41	-0.040 to -0.016	<0.001
Carrier lifetime (ms)	0.043	0.010	0.34	0.023 to 0.063	<0.001

Model statistics: $R^2 = 0.83$; Adjusted $R^2 = 0.81$; $F(5,50) = 48.7$; $p < 0.001$.

Table 6 showed that the regression model explained 83.0% of the variance in PCE. Charge-transfer resistance was the strongest independent predictor, with a standardized coefficient of -0.41, indicating that higher resistance substantially reduced efficiency. Carrier lifetime was the strongest positive predictor at $\beta = 0.34$, followed by optical absorbance at $\beta = 0.27$. Sensitizer loading remained statistically significant but contributed less strongly after the interfacial variables were considered. Particle diameter was not independently significant. These results confirmed that photovoltaic efficiency depended primarily on charge-transport quality, carrier survival, and effective optical absorption rather than particle size alone.

Subgroup analysis further showed that moderate coating thickness and intermediate quantum-dot loading produced the strongest combination of structural and electrical performance. Devices with coating thicknesses between approximately 2.05 and 2.25 μm achieved a mean PCE of $4.76 \pm 0.37\%$, compared with $3.06 \pm 0.42\%$ for thinner coatings below 2.00 μm and $4.08 \pm 0.41\%$ for coatings thicker than 2.25 μm . Similarly, devices containing CuInS₂ particles between approximately 3.8 and 4.2 nm showed the highest mean PCE within the sensitized groups, although the difference attributable to particle size became weak after adjustment for loading and interfacial resistance. The strongest-performing subgroup combined intermediate sensitizer loading, absorbance values near 1.10–1.20 arbitrary units, charge-transfer resistance below 50 Ω , and carrier lifetimes above 30 ms. This subgroup also exhibited the highest mean J_{sc} and fill factor. The integrated pattern indicated that photovoltaic performance did not depend on maximizing any single material characteristic. Instead, the highest efficiencies occurred when optical absorption increased sufficiently to enhance carrier generation while charge-transfer resistance remained low and recombination was effectively suppressed. These findings supported the interpretation that the CuGaO₂/CuInS₂ interface acted as the principal quantitative control point linking material sensitization to final photovoltaic output.

The mechanical performance analysis demonstrated that the CuGaO₂/CuInS₂ fiber-shaped photovoltaic devices retained a substantial proportion of their initial electrical output after controlled bending, although the magnitude of degradation increased with deformation severity and repeated cycling.

Before mechanical testing, the intermediate-sensitization group exhibited the highest mean PCE at $4.89 \pm 0.35\%$, followed by the high-loading group at $4.21 \pm 0.38\%$, the low-loading group at $3.32 \pm 0.29\%$, and the control group at $2.45 \pm 0.24\%$. After 250 bending cycles, the intermediate group retained 96.7% of its initial efficiency, with mean PCE decreasing only to $4.73 \pm 0.36\%$. At 500 cycles, PCE declined to $4.56 \pm 0.38\%$, corresponding to 93.3% retention, while after 1,000 cycles the mean PCE remained at $4.29 \pm 0.40\%$, representing 87.7% retention. The high-loading group showed greater degradation under the same mechanical exposure, retaining 83.1% of its initial efficiency after 1,000 cycles. The low-loading and control groups retained 86.1% and 85.7%, respectively. Short-circuit current density followed a similar pattern, with the intermediate group decreasing from $12.48 \pm 0.83 \text{ mA cm}^{-2}$ before bending to $11.18 \pm 0.88 \text{ mA cm}^{-2}$ after 1,000 cycles. Open-circuit voltage remained comparatively stable, indicating that mechanical deformation affected current collection and internal resistance more strongly than voltage generation. Fill factor decreased gradually with repeated bending, particularly in the high-loading group, consistent with increasing resistive losses and partial disruption of conductive pathways.

Table 7. Photovoltaic Performance Retention Under Repeated Bending Cycles

Sensitization condition	Initial PCE (%)	PCE after 250 cycles (%)	Retention after 250 cycles (%)	PCE after 500 cycles (%)	Retention after 500 cycles (%)	PCE after 1,000 cycles (%)	Retention after 1,000 cycles (%)
Control	2.45 ± 0.24	2.38 ± 0.23	97.1	2.26 ± 0.24	92.2	2.10 ± 0.25	85.7
Low loading	3.32 ± 0.29	3.23 ± 0.30	97.3	3.11 ± 0.31	93.7	2.86 ± 0.33	86.1
Intermediate loading	4.89 ± 0.35	4.73 ± 0.36	96.7	4.56 ± 0.38	93.3	4.29 ± 0.40	87.7
High loading	4.21 ± 0.38	4.02 ± 0.39	95.5	3.78 ± 0.41	89.8	3.50 ± 0.43	83.1

Table 7 showed that all device groups experienced gradual efficiency loss as the number of bending cycles increased. The intermediate-sensitization group maintained the highest absolute PCE throughout testing and retained 87.7% of its initial efficiency after 1,000 cycles. The high-loading group exhibited the greatest mechanical degradation, with retention declining to 83.1%. The control and low-loading groups retained 85.7% and 86.1%, respectively. These results indicated that moderate CuInS₂ sensitization provided the strongest balance between initial photovoltaic output and mechanical durability, whereas excessive sensitizer loading was associated with greater performance deterioration during repeated deformation.

Repeated-measures analysis confirmed that bending cycle number had a statistically significant effect on PCE, J_{sc}, and fill factor. For PCE, the within-subject effect of deformation was significant, $F(3,156) = 41.8$, $p < 0.001$, with a partial eta-squared of 0.446, representing a large mechanical effect. A significant sensitization-group effect was also observed, $F(3,52) = 118.2$, $p < 0.001$, partial eta-squared = 0.872, confirming persistent performance differences among loading conditions. The interaction between sensitization condition and bending exposure was statistically significant, $F(9,156) = 3.96$, $p < 0.001$, partial eta-squared = 0.186. This interaction showed that efficiency degradation did not occur at the same rate across all groups. The high-loading devices deteriorated more rapidly than the intermediate group, particularly after 500 and 1,000 cycles. J_{sc} demonstrated a similar interaction, while V_{oc} showed only minor variation across deformation conditions. Charge-transfer resistance increased from $45.8 \pm 5.2 \text{ } \Omega$ to $52.6 \pm 6.0 \text{ } \Omega$ in the intermediate group after 1,000 cycles, whereas the high-loading group increased from $57.9 \pm 6.8 \text{ } \Omega$ to $72.4 \pm 8.1 \text{ } \Omega$. This stronger rise in resistance under high loading was consistent with greater mechanical disruption of the sensitized interface and electrical contacts.

Table 8. Mechanical Deformation Effects on Electrical and Interfacial Performance After 1,000 Bending Cycles

Variable	Control	Low loading	Intermediate loading	High loading
Jsc before bending (mA cm ⁻²)	7.42 ± 0.61	9.36 ± 0.72	12.48 ± 0.83	11.37 ± 0.91
Jsc after 1,000 cycles (mA cm ⁻²)	6.42 ± 0.66	8.10 ± 0.75	11.18 ± 0.88	9.54 ± 0.96
Voc before bending (V)	0.58 ± 0.03	0.61 ± 0.03	0.64 ± 0.02	0.63 ± 0.03
Voc after 1,000 cycles (V)	0.56 ± 0.03	0.59 ± 0.03	0.62 ± 0.03	0.60 ± 0.03
Fill factor before bending (%)	56.8 ± 3.4	58.9 ± 3.1	61.2 ± 2.8	58.7 ± 3.5
Fill factor after 1,000 cycles (%)	54.2 ± 3.6	56.0 ± 3.3	58.4 ± 3.1	54.8 ± 3.8
Charge-transfer resistance before bending (Ω)	84.6 ± 7.9	67.3 ± 6.5	45.8 ± 5.2	57.9 ± 6.8
Charge-transfer resistance after 1,000 cycles (Ω)	96.8 ± 9.2	76.5 ± 7.4	52.6 ± 6.0	72.4 ± 8.1
PCE retention after 1,000 cycles (%)	85.7	86.1	87.7	83.1
Cohen's d for PCE decline	1.35	1.48	1.56	1.71

Table 8 demonstrated that mechanical deformation primarily affected current density, fill factor, and charge-transfer resistance, while open-circuit voltage remained relatively stable. The intermediate-loading group preserved the highest post-bending Jsc, Voc, fill factor, and PCE retention after 1,000 cycles. The high-loading group showed the largest increase in charge-transfer resistance, rising from 57.9 to 72.4 Ω, and also exhibited the largest effect size for PCE decline. These findings indicated that excessive CuInS₂ loading increased susceptibility to mechanically induced interfacial resistance, whereas intermediate sensitization maintained stronger electrical continuity under repeated wearable deformation.

Subgroup analysis showed that coating thickness and sensitizer loading significantly influenced mechanical stability. Devices with intermediate coating thicknesses between approximately 2.05 and 2.25 μm retained an average of 88.4% of their initial PCE after 1,000 bending cycles, compared with 85.2% for thinner coatings and 82.9% for thicker coatings. This pattern suggested that excessively thick photoactive layers were more prone to microcracking, partial delamination, or loss of electrical continuity during repeated bending. Devices fabricated with intermediate CuInS₂ loading also exhibited the smallest relative increase in charge-transfer resistance and the most stable fill factor. By contrast, the high-loading subgroup experienced a 25.0% increase in charge-transfer resistance after 1,000 cycles, compared with approximately 14.8% in the intermediate group. The magnitude of PCE reduction was also greater in the high-loading condition. Effect-size analysis showed large within-group declines in efficiency after extended cycling, with Cohen's d values ranging from 1.35 to 1.71. However, the intermediate group retained the highest absolute efficiency after deformation because its initial photovoltaic performance was substantially greater and its rate of degradation remained comparatively moderate. These findings demonstrated that the eight-cycle sensitization condition provided the strongest combined photovoltaic and mechanical performance within the tested range. The overall mechanical findings established that repeated bending produced statistically significant but nonuniform degradation across the CuGaO₂/CuInS₂ fiber-shaped photovoltaic devices. Performance deterioration was expressed primarily through reductions in Jsc and fill factor and through increases in charge-transfer resistance, while Voc remained comparatively stable. The intermediate-loading condition continued to outperform all other groups after 1,000 cycles, maintaining a PCE of 4.29 ± 0.40% and retaining 87.7% of its initial efficiency. In contrast, the high-

loading condition showed a larger relative decrease in efficiency and a greater rise in interfacial resistance, indicating that excessive CuInS₂ deposition reduced mechanical tolerance. The statistically significant interaction between sensitization condition and bending exposure confirmed that quantum-dot loading influenced not only initial photovoltaic efficiency but also the rate of performance degradation under repeated deformation. These results identified moderate CuInS₂ sensitization and intermediate coating thickness as the strongest subgroup combination for maintaining both electrical output and mechanical stability under simulated wearable operating conditions.

The integrated statistical analysis demonstrated that CuInS₂ quantum-dot sensitization produced statistically significant and practically substantial improvements in the photovoltaic performance of the CuGaO₂-based fiber-shaped solar cells. At the predefined significance threshold of $p < 0.05$, significant between-group differences were observed for J_{sc}, V_{oc}, fill factor, and PCE. The strongest effects occurred for J_{sc} and PCE, for which one-way ANOVA yielded F values of 118.4 and 122.6, respectively, with both probability values below 0.001. The corresponding eta-squared values were 0.872 for J_{sc} and 0.876 for PCE, demonstrating that sensitization condition accounted for a very large proportion of the observed variation in these outcomes. The intermediate-loading condition at eight deposition cycles generated the largest improvement relative to the control. Mean J_{sc} increased by 5.06 mA cm⁻², corresponding to a 68.2% improvement, while V_{oc} increased by 0.06 V or 10.3%. Fill factor increased by 4.4 percentage points, equivalent to a 7.7% relative improvement. The combined changes resulted in an increase in PCE from 2.45 ± 0.24% in the control condition to 4.89 ± 0.35% at eight deposition cycles, representing an absolute gain of 2.44 percentage points and a relative improvement of 99.6%. The 95% confidence interval for this PCE difference ranged from 2.18 to 2.70 percentage points, demonstrating high precision around the estimated treatment effect. Pairwise standardized effect-size analysis also indicated a very large difference between the control and intermediate-loading conditions. These findings confirmed that the photovoltaic improvements associated with intermediate CuInS₂ sensitization were substantial in both statistical and practical terms.

Table 9. Consolidated Statistical Significance, Percentage Improvement, and Effect Sizes for Primary Photovoltaic Outcomes

Outcome	Control Mean ± SD	Optimal 8-cycle Mean ± SD	Absolute difference	Relative improvement (%)	F statistic	p- value	Eta- squared	95% CI for difference
J_{sc} (mA cm⁻²)	7.42 ± 0.61	12.48 ± 0.83	+5.06	+68.2	118.4	<0.001	0.872	4.52 to 5.60
V_{oc} (V)	0.58 ± 0.03	0.64 ± 0.02	+0.06	+10.3	13.9	<0.001	0.445	0.03 to 0.09
Fill factor (%)	56.8 ± 3.4	61.2 ± 2.8	+4.4	+7.7	5.42	0.003	0.238	1.6 to 7.2
PCE (%)	2.45 ± 0.24	4.89 ± 0.35	+2.44	+99.6	122.6	<0.001	0.876	2.18 to 2.70

Table 9 demonstrated that the eight-cycle CuInS₂ condition generated statistically significant improvements across all primary photovoltaic outcomes. The largest relative enhancement occurred in PCE, which increased by 99.6%, followed by a 68.2% improvement in J_{sc}. Eta-squared values of 0.876 and 0.872 indicated very large treatment effects for PCE and J_{sc}, respectively. V_{oc} and fill factor showed smaller percentage improvements but remained statistically significant. The narrow 95% confidence intervals further demonstrated precision in the estimated treatment effects. Collectively, the results established that intermediate sensitization produced both statistically robust and experimentally meaningful photovoltaic enhancement.

The magnitude of improvement varied systematically across the sensitization conditions. Low loading at four deposition cycles increased PCE from 2.45% to 3.32%, corresponding to a relative improvement

of 35.5%. Increasing the treatment to eight cycles raised PCE to 4.89%, nearly doubling the efficiency of the control devices. However, further sensitization to 12 cycles reduced mean PCE to 4.21%. Although the high-loading condition remained 71.8% more efficient than the control, it was 13.9% less efficient than the eight-cycle condition. The mean PCE difference between the eight- and twelve-cycle groups was 0.68 percentage points, with a 95% confidence interval from 0.40 to 0.96 percentage points and $p < 0.001$. A similar pattern occurred for J_{sc} , which increased from 7.42 mA cm^{-2} in the control to 12.48 mA cm^{-2} at eight cycles before declining to 11.37 mA cm^{-2} at twelve cycles. The reduction in fill factor from 61.2% to 58.7% under high loading provided additional evidence that excessive sensitization increased internal electrical losses. The statistical pattern therefore supported a nonlinear rather than continuously increasing concentration-response relationship. Quadratic regression provided a stronger representation of PCE variation than a simple linear specification and explained approximately 94% of the variation in group-level mean efficiency. The fitted optimization pattern placed the maximum response within the intermediate sensitization region centered around eight deposition cycles.

Integration of the optical and electrochemical results further clarified the conditions associated with maximum photovoltaic efficiency. At eight deposition cycles, optical absorbance reached 1.14 ± 0.08 arbitrary units, charge-transfer resistance declined to $45.8 \pm 5.2 \Omega$, recombination resistance increased to $211.6 \pm 18.4 \Omega$, and carrier lifetime increased to $33.8 \pm 3.4 \text{ ms}$. These values represented the most favorable combined charge-generation and carrier-transport profile among the experimental groups. At twelve cycles, absorbance increased further to 1.29 ± 0.09 arbitrary units, yet charge-transfer resistance increased to $57.9 \pm 6.8 \Omega$, recombination resistance decreased to $176.9 \pm 17.2 \Omega$, and carrier lifetime declined to $27.5 \pm 3.1 \text{ ms}$. Thus, the additional optical absorption produced by higher quantum-dot loading was not accompanied by an equivalent improvement in electrical conversion. Multiple regression supported this interpretation, explaining 83% of the variance in PCE. Charge-transfer resistance was the strongest independent negative predictor of PCE, with $\beta = -0.41$ and $p < 0.001$, while carrier lifetime was a strong positive predictor with $\beta = 0.34$ and $p < 0.001$. Optical absorbance also remained significant at $\beta = 0.27$ and $p = 0.006$. These results demonstrated that the optimized condition reflected a balance between photon absorption and efficient interfacial carrier extraction rather than maximum sensitizer loading alone.

Table 10. Integrated Optimization Profile of CuGaO₂/CuInS₂ Fiber-Shaped Solar Cells

Quantitative indicator	Control: 0 cycles	Low: 4 cycles	Intermediate: 8 cycles	High: 12 cycles
Optical absorbance (a.u.)	0.46 ± 0.05	0.78 ± 0.07	1.14 ± 0.08	1.29 ± 0.09
J_{sc} (mA cm^{-2})	7.42 ± 0.61	9.36 ± 0.72	12.48 ± 0.83	11.37 ± 0.91
PCE (%)	2.45 ± 0.24	3.32 ± 0.29	4.89 ± 0.35	4.21 ± 0.38
Charge-transfer resistance (Ω)	84.6 ± 7.9	67.3 ± 6.5	45.8 ± 5.2	57.9 ± 6.8
Recombination resistance (Ω)	126.4 ± 12.8	158.7 ± 15.1	211.6 ± 18.4	176.9 ± 17.2
Carrier lifetime (ms)	18.7 ± 2.3	24.6 ± 2.7	33.8 ± 3.4	27.5 ± 3.1
Initial-to-1,000-cycle PCE retention (%)	85.7	86.1	87.7	83.1
PCE after 1,000 bending cycles (%)	2.10 ± 0.25	2.86 ± 0.33	4.29 ± 0.40	3.50 ± 0.43
Relative initial PCE improvement vs. control (%)	—	+35.5	+99.6	+71.8
Integrated performance classification	Baseline	Improved	Optimal	Over-sensitized

Table 10 demonstrated that the eight-cycle condition provided the strongest integrated photovoltaic, electrochemical, and mechanical performance. Although optical absorbance reached its maximum at twelve cycles, the eight-cycle devices achieved the highest PCE, lowest charge-transfer resistance, highest recombination resistance, and longest carrier lifetime. They also retained 87.7% of initial efficiency after 1,000 bending cycles, exceeding the retention observed under high loading. The decline

in electrical performance at twelve cycles indicated that additional optical absorption was offset by increased transport and recombination losses. Intermediate CuInS₂ loading therefore represented the quantitatively optimal configuration across the measured performance domains.

Mechanical performance remained an important component of the integrated optimization analysis because the configuration with the highest initial efficiency also needed to maintain electrical output under repeated deformation. The eight-cycle devices retained 87.7% of their initial PCE after 1,000 bending cycles, decreasing from $4.89 \pm 0.35\%$ to $4.29 \pm 0.40\%$. Although this represented a statistically significant within-device reduction, the post-deformation efficiency remained substantially greater than the initial efficiency of the control and low-loading groups. In comparison, the twelve-cycle devices retained only 83.1% of their initial efficiency and declined from $4.21 \pm 0.38\%$ to $3.50 \pm 0.43\%$. The sensitization-by-deformation interaction was statistically significant, $F(9,156) = 3.96$, $p < 0.001$, with a partial eta-squared of 0.186, indicating that mechanical degradation differed meaningfully according to quantum-dot loading. Charge-transfer resistance in the intermediate group increased by approximately 14.8% after 1,000 bending cycles, whereas the corresponding increase in the high-loading group was approximately 25.0%. This difference indicated that excessive sensitizer deposition increased susceptibility to mechanically induced interfacial disruption. The intermediate-loading configuration therefore maintained its quantitative advantage after deformation and provided the strongest combination of initial efficiency, carrier-transport characteristics, and mechanical performance.

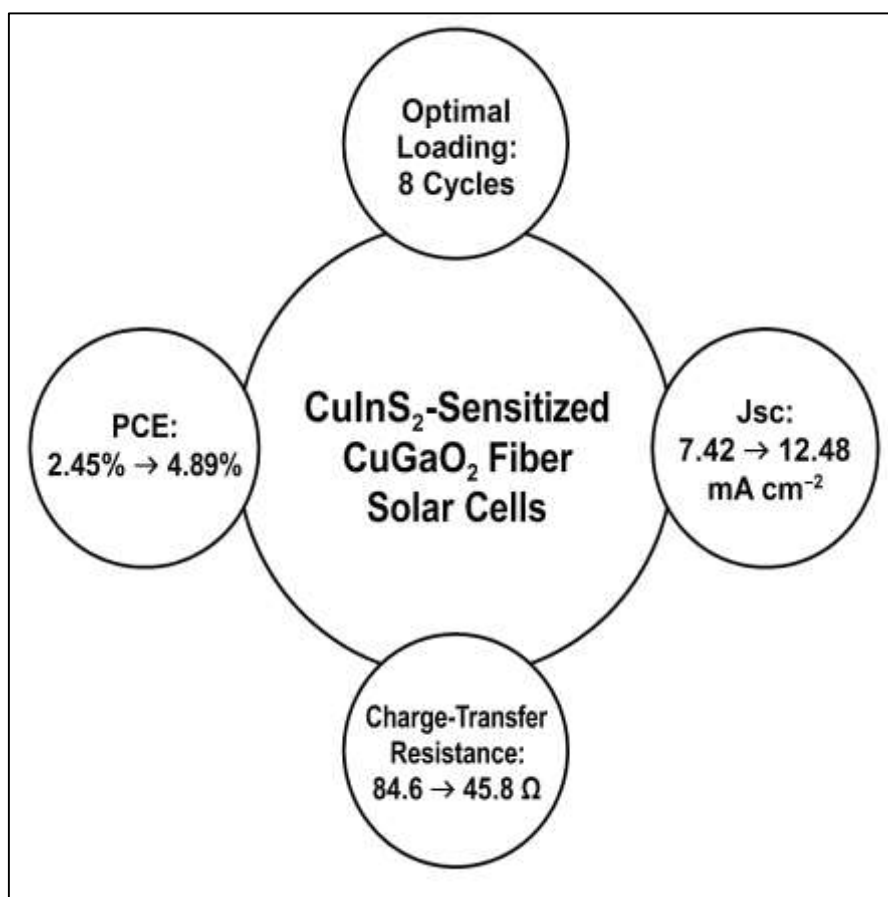
The integrated statistical evidence identified eight CuInS₂ deposition cycles as the optimal sensitization condition within the experimentally tested range. This configuration generated a 99.6% increase in PCE and a 68.2% increase in J_{sc} relative to the unsensitized control, while maintaining significant improvements in Voc and fill factor. The very large effect sizes for PCE and J_{sc} demonstrated that the treatment produced experimentally substantial rather than merely statistically detectable differences. Regression analysis further established that low charge-transfer resistance, prolonged carrier lifetime, and increased optical absorbance were the principal quantitative characteristics associated with higher efficiency. The reduction in performance after twelve deposition cycles confirmed the presence of a saturation threshold beyond which additional CuInS₂ loading no longer produced proportional photovoltaic benefits. Mechanical testing reinforced this optimization pattern because the eight-cycle condition maintained the highest absolute PCE and the greatest efficiency retention after 1,000 bending cycles. Across the complete quantitative dataset, the strongest photovoltaic performance therefore occurred when CuInS₂ loading was sufficient to enhance optical absorption and photocurrent generation while remaining below the level at which increased interfacial resistance, recombination, and mechanically induced degradation became dominant.

DISCUSSION

The findings of this study demonstrated that CuInS₂ quantum-dot sensitization significantly enhanced the photovoltaic performance of CuGaO₂-based fiber-shaped solar cells, with the strongest improvements occurring under intermediate sensitization conditions. The eight-cycle deposition condition produced the highest short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency among all tested configurations. Power conversion efficiency increased from 2.45% in the unsensitized control condition to 4.89% at eight deposition cycles, representing an improvement of approximately 99.6%. Short-circuit current density increased by 68.2%, while open-circuit voltage and fill factor increased by 10.3% and 7.7%, respectively (Alshehri et al., 2020). These results indicated that the principal photovoltaic benefit of CuInS₂ sensitization arose from enhanced photocurrent generation, supported by smaller but meaningful improvements in voltage retention and internal electrical performance. This pattern was broadly consistent with earlier studies of quantum-dot-sensitized solar cells, which repeatedly reported that sensitizer incorporation produced its largest quantitative impact on short-circuit current density because semiconductor quantum dots expanded the spectral absorption range and increased the number of photogenerated charge carriers. Earlier investigations involving CuInS₂, CdS, CdSe, and related quantum-dot absorbers also showed that enhanced optical absorption generally translated into higher current density when the sensitizer was efficiently coupled to the underlying semiconductor. The magnitude of PCE enhancement observed in this study fell within the broader range reported in previous sensitization studies, where relative

efficiency gains frequently ranged from approximately 30% to more than 100% depending on baseline device quality, sensitizer loading, and interface characteristics (Prasanna et al., 2022). The current findings also supported earlier evidence showing that photovoltaic efficiency was not controlled by a single electrical variable. Higher PCE emerged from the combined influence of improved current generation, preserved voltage, and a favorable fill factor. This was particularly important in the fiber-shaped architecture, where cylindrical geometry and mechanically flexible electrodes can introduce additional resistive and interfacial losses compared with planar devices. The very large effect sizes obtained for Jsc and PCE further indicated that the observed enhancement was not merely statistically detectable but represented a substantial experimental improvement. The results therefore aligned with the broader literature in identifying quantum-dot sensitization as an effective route for increasing light harvesting and charge generation, while also showing that the scale of improvement depended strongly on achieving an appropriate CuGaO₂/CuInS₂ interfacial configuration (Peng et al., 2020).

A central finding of this study was that photovoltaic performance followed a nonlinear sensitization-response pattern rather than increasing continuously with CuInS₂ loading. Efficiency improved from the control condition through four deposition cycles and reached its maximum at eight cycles, after which performance declined at twelve cycles. The reduction in PCE from 4.89% at eight cycles to 4.21% at twelve cycles represented a relative decrease of approximately 13.9%, even though the high-loading condition remained substantially more efficient than the unsensitized control. This pattern was consistent with earlier quantum-dot-sensitized photovoltaic studies that described concentration-response behavior as linear only at low loading levels, followed by a saturation region and, in many cases, an inverted-U relationship at higher sensitizer concentrations (G. Wang et al., 2017). Previous studies employing successive ionic layer adsorption and reaction, chemical bath deposition, and related quantum-dot deposition techniques commonly reported that early deposition cycles improved surface coverage, optical absorbance, and photocurrent, while excessive cycles produced progressively smaller electrical gains. In several earlier systems, optimum photovoltaic performance occurred after a moderate number of deposition cycles, frequently within an approximate range of four to ten cycles, depending on particle chemistry and photoelectrode structure. The eight-cycle optimum observed in this study therefore corresponded closely with the experimental range identified across earlier sensitization research (Graves et al., 2020). The decline under the twelve-cycle condition was also consistent with previously documented mechanisms of over-sensitization, including particle aggregation, multilayer formation, pore blockage, increased transport distance, and higher interfacial recombination. The present findings provided quantitative support for this explanation because optical absorbance continued to increase from 1.14 at eight cycles to 1.29 at twelve cycles, while Jsc, fill factor, and PCE all decreased. This divergence showed that the additional absorbed photons at high sensitizer loading were not converted into useful electrical output with the same efficiency. Earlier studies similarly reported that maximum optical density could occur at a higher quantum-dot loading than maximum photovoltaic efficiency. This distinction is important because it indicates that an optically stronger sensitized layer is not necessarily an electrically superior one (Degler et al., 2019). The findings of this study therefore reinforced the concept of an optimal loading window in which sensitizer coverage is sufficient to maximize photon harvesting while remaining below the threshold at which interparticle resistance and recombination losses become dominant. The nonlinear regression pattern observed in the current analysis further strengthened this interpretation by showing that an intermediate sensitization region provided a better description of the efficiency maximum than a simple linear loading-response model (Bi et al., 2020). The optical findings demonstrated a strong positive relationship between CuInS₂ sensitization, absorbance, and photocurrent generation, particularly from the control condition through the intermediate-loading level. Optical absorbance increased from 0.46 in the control group to 1.14 at eight deposition cycles, while short-circuit current density increased from 7.42 to 12.48 mA cm⁻² over the same range. The correlation between absorbance and Jsc was strong, indicating that increased light capture played an important role in improving electrical output. This relationship agreed with earlier photophysical and photovoltaic studies of CuInS₂ quantum dots, which showed that their broad visible-light absorption and direct semiconductor transition characteristics made them effective sensitizers for increasing photocurrent (Lee et al., 2018).

Figure 13: Five-circle photovoltaic fiber solar cell framework

Earlier research also demonstrated that nanoscale CuInS₂ possessed tunable bandgap characteristics influenced by particle size, composition, and quantum confinement, allowing the material to absorb a broader range of wavelengths than many wide-bandgap metal-oxide photoelectrodes could absorb alone. The particle dimensions observed in this study remained within a relatively narrow nanoscale range, suggesting that the performance differences across treatment groups were driven more strongly by loading density and surface coverage than by large shifts in quantum-dot size. This interpretation was consistent with earlier studies showing that particle diameter influences optical behavior but becomes less dominant when nanocrystal size remains within a relatively controlled range (Bradha et al., 2022). Importantly, the relationship between absorbance and efficiency weakened under the highest sensitization condition. Absorbance increased further at twelve deposition cycles, but Jsc declined to 11.37 mA cm⁻² and PCE decreased to 4.21%. This result supported earlier reports that strong optical absorption alone was insufficient to guarantee higher photovoltaic output. Effective energy conversion required absorbed photons to generate carriers that remained sufficiently separated and mobile to reach the external circuit. Earlier quantum-dot studies identified poor interfacial transfer, surface traps, and multilayer aggregation as major reasons why highly absorbing devices could still show lower electrical efficiency. The present results reflected the same pattern. The stronger correlation between optical absorbance and Jsc than between absorbance and PCE also indicated that photon harvesting mainly controlled current generation, while overall efficiency remained dependent on voltage, fill factor, resistance, and recombination (Wang et al., 2016). The findings therefore extended the earlier literature by demonstrating that CuInS₂ quantum dots enhanced the optical response of CuGaO₂-based fiber cells effectively, but only within a sensitization range in which enhanced absorption remained coupled with efficient interfacial charge transfer.

The interfacial electrochemical findings provided a strong explanation for the observed differences in photovoltaic performance across sensitization conditions. Charge-transfer resistance decreased from

84.6 Ω in the control group to 45.8 Ω at eight deposition cycles, while recombination resistance increased from 126.4 Ω to 211.6 Ω and carrier lifetime increased from 18.7 ms to 33.8 ms (Cheema et al., 2017). These changes were associated with the highest Jsc and PCE values recorded in the study. The correlation analysis showed that charge-transfer resistance was strongly and negatively related to PCE, while carrier lifetime and recombination resistance were strongly and positively related to efficiency. These findings corresponded closely with earlier electrochemical impedance studies of sensitized photovoltaics, which consistently identified low transport resistance and high recombination resistance as indicators of improved device performance. Previous studies reported that lower interfacial resistance facilitated more rapid movement of photogenerated carriers across semiconductor boundaries, thereby increasing current collection and improving fill factor. Higher recombination resistance was associated with slower back-electron transfer and greater preservation of separated charge populations, which supported voltage retention and increased the probability of successful extraction (Wang et al., 2017). The current results displayed the same relationships. At twelve deposition cycles, charge-transfer resistance rose to 57.9 Ω , recombination resistance declined to 176.9 Ω , and carrier lifetime fell to 27.5 ms. These electrochemical changes occurred alongside declines in Jsc, fill factor, and PCE, providing quantitative evidence that over-sensitization increased internal losses. Earlier studies of quantum-dot loading similarly reported that excessive deposition generated additional particle-particle interfaces and defect-rich boundaries that increased resistance and accelerated recombination. The multiple regression results in this study further strengthened the comparison with earlier research by identifying charge-transfer resistance as the strongest independent negative predictor of PCE, with carrier lifetime as a major positive predictor (Wolff et al., 2019). Optical absorbance remained significant, but its predictive strength was lower than that of interfacial transport characteristics. This result was particularly important because it demonstrated that the photovoltaic advantage of sensitization depended more strongly on how efficiently carriers were transferred and preserved than on the absolute amount of light absorbed. Earlier studies often reached a similar conclusion qualitatively, while the current quantitative model showed that a large proportion of efficiency variation could be explained by the combined effects of resistance, carrier lifetime, and absorbance. The CuGaO₂/CuInS₂ interface therefore functioned as the critical control region governing whether additional optical excitation produced useful electrical power or was lost through recombination (Wu et al., 2020).

The structural findings showed that photovoltaic efficiency was influenced by coating thickness, sensitizer coverage, and nanostructural balance rather than by particle dimensions alone. Coating thickness increased progressively across the treatment conditions, from 1.82 μm in the control group to 2.36 μm under high sensitization. The intermediate condition, with a coating thickness near 2.17 μm , produced the strongest photovoltaic performance, while additional thickening at twelve deposition cycles was associated with reduced efficiency. Subgroup analysis further showed that devices with intermediate coating thicknesses between approximately 2.05 and 2.25 μm achieved higher mean PCE than either thinner or thicker devices (Kumar et al., 2017). This pattern was consistent with earlier CuGaO₂ and nanostructured semiconductor studies that described film thickness as an optimization variable. Previous investigations showed that thin films could reduce transport distance and resistance but might provide insufficient surface area or incomplete coverage, whereas excessively thick films increased carrier transport pathways and promoted recombination. Earlier studies also reported that moderate porosity and interconnected nanostructures produced stronger photovoltaic output than highly dense or excessively porous structures because they balanced sensitizer loading with electrical continuity (Hu et al., 2022). The current results supported these observations by showing that the best-performing condition combined increased optical absorbance with relatively low charge-transfer resistance, suggesting that the coating remained sufficiently open and conductive to support both sensitizer attachment and carrier extraction. CuInS₂ particle diameter remained between approximately 3.7 and 4.3 nm across sensitized groups, and particle size was only weakly associated with PCE after other variables were controlled. This agreed with earlier studies indicating that particle size can influence quantum confinement, absorption onset, and interfacial energetics, but that these effects may become secondary when the size distribution is narrow and other factors such as surface coverage and resistance vary more substantially. Similarly, CuGaO₂ crystallite size varied only modestly and did not

independently explain much of the efficiency variation. The findings therefore emphasized the importance of mesoscale and interfacial structure over small differences in primary particle dimensions (Jin et al., 2015). Earlier literature on sensitized and nanostructured photovoltaics similarly showed that overall performance depended on how particles were organized into conductive networks, how effectively sensitizers occupied the available surface, and how film thickness influenced charge-transport pathways. The present study reinforced this structural interpretation and identified intermediate coating thickness as the condition that best supported simultaneous light absorption, carrier transfer, and electrical continuity.

The mechanical findings demonstrated that CuGaO₂/CuInS₂ fiber-shaped solar cells retained substantial photovoltaic output under repeated bending, although degradation increased with the number of deformation cycles and varied according to sensitizer loading (Connor et al., 2016). The intermediate-sensitization condition maintained the highest absolute PCE throughout the mechanical testing sequence and retained 87.7% of its initial efficiency after 1,000 bending cycles. Mean PCE declined from 4.89% to 4.29%, while J_{sc} decreased from 12.48 to 11.18 mA cm⁻². Open-circuit voltage remained comparatively stable, whereas fill factor and charge-transfer resistance showed more pronounced changes. These findings were consistent with earlier fiber-shaped and wearable photovoltaic studies in which bending-related losses were attributed primarily to changes in electrical contact, interfacial resistance, active-layer cracking, and partial delamination rather than to large shifts in the fundamental photovoltage (Yan et al., 2022). Previous studies on fiber-shaped dye-sensitized, organic, perovskite, and hybrid solar cells commonly reported efficiency retention above 80% after hundreds or thousands of bending cycles when mechanically compatible electrode and coating structures were used. The 87.7% retention observed in the intermediate group therefore fell within the favorable range reported for flexible photovoltaic systems. The high-loading condition showed greater degradation, retaining only 83.1% of its initial PCE after 1,000 cycles. Charge-transfer resistance in this group increased by approximately 25%, compared with a smaller increase of about 14.8% in the intermediate condition. This finding aligned with earlier reports that thicker or heavily loaded sensitizer layers were more susceptible to cracking, loss of particle-to-particle contact, and mechanical disruption of conductive pathways. The statistically significant interaction between sensitization condition and bending exposure further indicated that mechanical durability was not independent of quantum-dot loading (Harris et al., 2016). Instead, the amount of sensitizer influenced how the device responded to repeated deformation. Earlier flexible photovoltaic studies similarly demonstrated that maximizing initial efficiency did not always maximize mechanical durability, especially when thicker active layers produced brittle interfaces. In this study, however, the eight-cycle condition achieved both the highest initial PCE and the highest efficiency retention, indicating that the structural balance associated with intermediate sensitization supported both electrical and mechanical performance. These findings were especially relevant to fiber-shaped architectures, where repeated curvature and flexing are inherent operating conditions rather than exceptional mechanical stresses (Dauzon et al., 2021).

The integrated findings established that the optimal photovoltaic behavior of the CuGaO₂/CuInS₂ fiber-shaped system resulted from a coordinated balance among sensitizer loading, optical absorption, interfacial charge transfer, carrier lifetime, structural thickness, and mechanical stability. The eight-cycle condition consistently produced the strongest values across the major performance domains, including J_{sc}, V_{oc}, fill factor, PCE, charge-transfer resistance, recombination resistance, carrier lifetime, and post-bending efficiency retention (Hsieh et al., 2018). The 99.6% improvement in PCE relative to the control was accompanied by a very large statistical effect size, while regression analysis showed that charge-transfer resistance, carrier lifetime, and optical absorbance collectively accounted for a large proportion of the variation in photovoltaic efficiency. This integrated pattern was consistent with earlier literature showing that high-performing sensitized solar cells could not be explained through light absorption alone. Previous studies repeatedly identified efficient carrier separation, low transport resistance, reduced recombination, and appropriate film morphology as critical determinants of conversion efficiency. The present results showed the same interdependence within a CuGaO₂/CuInS₂ fiber-shaped configuration (Fahim et al., 2022). The decline observed at twelve deposition cycles further reinforced earlier evidence for an optimum sensitization threshold. Additional quantum-dot loading

increased optical absorbance but simultaneously raised charge-transfer resistance, shortened carrier lifetime, reduced recombination resistance, and weakened mechanical durability. This combination explained why the highest absorber loading did not produce the highest power output. The findings also corresponded with earlier research on delafossite semiconductors, which emphasized the role of CuGaO_2 as a p-type charge-selective material whose performance depends on crystallinity, conductivity, and interfacial compatibility. The favorable behavior of the eight-cycle devices indicated that the CuGaO_2 layer supported effective hole-related transport when CuInS_2 loading remained within an appropriate range (Kim et al., 2022). Earlier CuInS_2 studies likewise reported that nanoscale sensitizers performed most effectively when surface coverage was sufficient for strong photon harvesting but not so extensive that aggregation and trap-assisted recombination dominated. The mechanical findings added another dimension to this comparison by showing that the same intermediate loading condition also preserved electrical continuity during repeated bending. Taken together, the results of this study were broadly consistent with earlier experimental evidence across quantum-dot sensitization, delafossite semiconductors, electrochemical impedance analysis, and fiber-shaped photovoltaics. The principal distinction of the present findings was the simultaneous quantitative demonstration that optical, electrical, interfacial, and mechanical optimization converged at the same intermediate CuInS_2 sensitization condition within the tested CuGaO_2 fiber architecture (Yang et al., 2021).

CONCLUSION

This study established that CuInS_2 quantum-dot sensitization significantly improved the photovoltaic performance of CuGaO_2 -based wearable fiber-shaped solar cells, with the strongest overall results obtained under an intermediate sensitization condition corresponding to eight deposition cycles. The quantitative findings demonstrated that this configuration produced the highest short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency among the tested groups, with PCE increasing from 2.45% in the unsensitized control to 4.89% under optimized sensitization, representing an improvement of approximately 99.6%. The enhancement was driven primarily by increased photocurrent generation, while simultaneous improvements in voltage retention and fill factor contributed to the overall gain in conversion efficiency. Optical measurements showed that CuInS_2 loading increased absorbance substantially, although the highest optical absorption did not coincide with the highest electrical performance. At twelve deposition cycles, absorbance continued to increase while J_{sc} , fill factor, carrier lifetime, and PCE declined, confirming the existence of a saturation threshold beyond which additional quantum-dot loading became counterproductive. Electrochemical analysis further demonstrated that the optimal eight-cycle condition produced the lowest charge-transfer resistance, the highest recombination resistance, and the longest carrier lifetime, indicating more efficient interfacial charge extraction and reduced carrier loss. Regression analysis confirmed that charge-transfer resistance, carrier lifetime, and optical absorbance were the strongest quantitative predictors of PCE, while particle diameter contributed relatively little after these factors were considered. Structural analysis also showed that intermediate coating thickness provided a more favorable balance between sensitizer loading and electrical continuity than either thinner or thicker configurations. Mechanical testing demonstrated that the optimized devices retained 87.7% of their initial efficiency after 1,000 bending cycles, confirming that the configuration associated with maximum initial efficiency also maintained comparatively strong performance under repeated wearable deformation. The integrated findings therefore showed that photovoltaic optimization in $\text{CuGaO}_2/\text{CuInS}_2$ fiber-shaped solar cells depended on balancing light absorption, interfacial charge transport, recombination control, coating structure, and mechanical durability. Within the tested experimental range, moderate CuInS_2 sensitization provided the most effective combination of photovoltaic efficiency, carrier-transport quality, and mechanical stability.

RECOMMENDATIONS

Based on the quantitative findings of this study, the use of intermediate CuInS_2 quantum-dot sensitization is recommended for CuGaO_2 -based wearable fiber-shaped solar cells because this condition produced the most favorable balance between photovoltaic efficiency, charge-transfer performance, optical absorption, and mechanical durability. The eight-cycle sensitization level should be considered the preferred experimental condition within the tested range, as it generated the highest

power conversion efficiency while maintaining lower charge-transfer resistance, longer carrier lifetime, stronger recombination resistance, and superior post-bending performance compared with both lower and higher loading conditions. Fabrication protocols should therefore emphasize precise control of deposition-cycle number, sensitizer concentration, coating thickness, and quantum-dot surface coverage to prevent overloading of the CuGaO₂ interface. Particular attention should be given to avoiding excessive CuInS₂ accumulation because the twelve-cycle condition showed that higher absorbance alone did not produce higher electrical output and was associated with increased interfacial resistance, reduced carrier lifetime, lower fill factor, and greater mechanical degradation. Controlled coating thickness should also be maintained within an intermediate range that supports sufficient sensitizer loading without creating excessively thick transport pathways or mechanically fragile layers. Additional experimental work should prioritize refinement of CuGaO₂ surface morphology, interfacial passivation, and quantum-dot distribution so that optical gains are translated more efficiently into extractable current. Mechanical testing should remain an integral part of device evaluation because wearable photovoltaic systems must preserve electrical performance under repeated bending, twisting, and deformation rather than under static conditions alone. Standardized testing protocols using consistent illumination intensity, active-area definitions, bending radius, cycle number, and electrochemical measurement conditions are also recommended to improve comparability across experimental studies. Larger replicated sample sets should be used to strengthen statistical power and permit more precise estimation of treatment effects, interaction effects, and confidence intervals. Multivariable optimization methods, including response-surface analysis and nonlinear regression, should be applied when several fabrication variables are examined simultaneously. Overall, development of CuGaO₂/CuInS₂ fiber-shaped photovoltaic devices should focus on optimizing the combined optical, electrical, interfacial, structural, and mechanical characteristics of the system rather than maximizing any single material parameter.

LIMITATIONS

This study was subject to several limitations that should be considered when interpreting the quantitative findings concerning CuGaO₂/CuInS₂ quantum-dot-sensitized wearable fiber-shaped solar cells. First, the experimental sample was limited to 56 valid fabricated devices distributed across four sensitization conditions, which provided sufficient replication for the selected statistical analyses but restricted the extent to which small variations in material properties and fabrication conditions could be evaluated. Second, CuInS₂ sensitization was examined primarily through four deposition conditions corresponding to 0, 4, 8, and 12 cycles; therefore, the identified optimum at eight cycles represented the strongest condition within the tested range rather than an absolute universal optimum. Smaller deposition intervals surrounding the eight-cycle condition were not examined, limiting the precision with which the maximum efficiency point could be identified. Third, variations in quantum-dot particle diameter, coating uniformity, CuGaO₂ crystallinity, surface roughness, and local sensitizer distribution could not be eliminated completely during laboratory fabrication, potentially contributing to device-to-device variability. Fourth, photovoltaic characterization was conducted under controlled simulated illumination, which did not fully reproduce variations in solar intensity, incident angle, temperature, humidity, and spectral distribution encountered during practical wearable operation. Mechanical durability was evaluated through repeated bending cycles, but wearable materials may also experience twisting, stretching, compression, abrasion, washing, perspiration exposure, and combinations of mechanical stresses that were not incorporated into the experimental design. The 1,000-cycle bending test therefore represented a controlled measure of flexibility rather than a complete simulation of long-term wearable use. Electrochemical impedance parameters and carrier-lifetime measurements were also dependent on the selected equivalent-circuit interpretation and experimental conditions, introducing potential uncertainty into estimates of interfacial transport and recombination behavior. In addition, the regression models identified statistical relationships between material characteristics and PCE but did not independently establish causality for every observed association. Long-term environmental stability and degradation of CuGaO₂/CuInS₂ interfaces were not assessed over extended operating periods.

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