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Research Article

QUANTUM DOT-EMBEDDED POLYMER FILMS FOR FLEXIBLE PHOTONIC DEVICES: FABRICATION AND CHARACTERIZATION

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Abstract

The demand for flexible and wearable electronics has driven research into new materials for photonic devices that can conform to non-planar surfaces. Quantum dots (QDs) are ideal candidates due to their size-tunable emission and high quantum yields, but their integration into durable, flexible platforms remains a key challenge. This study aimed to develop and characterize highly luminescent and mechanically flexible quantum dot-embedded polymer films as a robust platform for next-generation photonic applications. We fabricated composite films by embedding cadmium selenide/zinc sulfide (CdSe/ZnS) core-shell QDs into a polydimethylsiloxane (PDMS) polymer matrix via solution casting. The structural, optical, and mechanical properties were systematically investigated using transmission electron microscopy (TEM), UV-Vis absorption, photoluminescence (PL) spectroscopy, and cyclic bending tests. The results showed that TEM analysis confirmed a uniform dispersion of QDs within the PDMS matrix without aggregation. The composite films exhibited intense, stable photoluminescence, retaining the characteristic sharp emission of the colloidal QDs. Crucially, the films demonstrated exceptional mechanical flexibility, maintaining over 95% of their initial PL intensity after 1,000 bending cycles to a 5 mm radius. The optical properties remained stable under various strain conditions, proving the effective protection afforded by the polymer matrix. This work successfully demonstrates a scalable method for producing high-quality, flexible photonic materials.

Keywords: Flexible Photonics, Polymer Composites, Wearable Devices.

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INTRODUCTION

The paradigm of personal electronics is undergoing a fundamental transformation, shifting from rigid, planar devices to soft, flexible, and wearable systems (Liu dkk., 2022; Wahab dkk., 2024). This evolution is driven by a growing demand for technologies that can seamlessly integrate with the human body and the surrounding environment, enabling applications such as real-time health monitoring, soft robotics, electronic skin, and immersive augmented reality displays. The development of these next-generation systems is critically dependent on the invention of new classes of electronic and photonic materials that are not only high-performing but also inherently flexible, stretchable, and durable.

Quantum dots (QDs) have emerged as a premier class of materials for advanced photonic applications due to their extraordinary and precisely controllable optical properties. These semiconductor nanocrystals exhibit quantum confinement effects, which allow their light emission color to be precisely tuned across the entire visible spectrum simply by changing their size (K. Li dkk., 2022; Maraveas dkk., 2022). This size-tunable emission, combined with their sharp, narrow emission peaks, high photoluminescence quantum yields, and broad absorption spectra, makes them superior to traditional organic dyes or phosphors for applications requiring high color purity and efficiency, such as in next-generation displays and lighting.

The integration of these high-performance nanocrystals into functional devices necessitates a suitable host matrix that can both protect the QDs and provide the desired mechanical properties (Gao dkk., 2022; L. Li dkk., 2023). Flexible, transparent polymers, such as polydimethylsiloxane (PDMS), have been identified as ideal candidates for this purpose. Their optical transparency, chemical inertness, and excellent mechanical flexibility make them a perfect platform for creating composite materials that combine the superior optical properties of QDs with the robust, deformable nature of a polymer, paving the way for the fabrication of truly flexible photonic devices.

A primary challenge in creating high-performance QD-polymer composites lies in achieving a uniform, non-aggregated dispersion of the nanocrystals within the polymer matrix. Quantum dots possess a very high surface-area-to-volume ratio, which makes them prone to aggregation due to strong van der Waals forces (Van Den Berg dkk., 2022; Y. Wang dkk., 2022). This aggregation can severely degrade the composite's optical performance by causing photoluminescence quenching, where the close proximity of QDs leads to non-radiative energy transfer, effectively dimming their light emission and reducing the overall efficiency of the device.

Another significant problem is the preservation of the QDs' optical integrity and stability under mechanical stress (Chen dkk., 2022; Van Den Berg dkk., 2022). For a flexible photonic device to be practical, it must be able to withstand repeated bending, stretching, and twisting without a significant loss of performance. The interface between the inorganic QD and the organic polymer matrix is a critical region where stress concentration can occur. Poor interfacial compatibility can lead to the formation of micro-cracks or delamination during mechanical deformation, exposing the QDs to oxygen and moisture, which can degrade their emissive properties over time.

The specific technological problem this research addresses is the lack of a scalable and reliable fabrication method that can simultaneously ensure uniform QD dispersion and create a robust matrix that effectively passivates and protects the QDs from both mechanical and environmental degradation (Song dkk., 2022; Van Den Berg dkk., 2022). A successful method

must prevent aggregation during the composite curing process and result in a final film where the optical performance is maintained, not compromised, by the polymer host. The challenge is to develop a material system where the photonic and mechanical properties are synergistically combined, not mutually exclusive.

The principal objective of this study is to fabricate and comprehensively characterize a highly luminescent and mechanically robust composite material by embedding core-shell quantum dots into a flexible polymer matrix. The overarching goal is to develop a foundational platform material suitable for a wide range of flexible photonic devices and to establish a clear understanding of the relationships between its fabrication process, its structure, and its ultimate opto-mechanical performance.

To achieve this primary objective, a series of specific sub-objectives have been defined. The first is to develop and optimize a solution-casting fabrication protocol that promotes the uniform dispersion of cadmium selenide/zinc sulfide (CdSe/ZnS) core-shell QDs within a polydimethylsiloxane (PDMS) matrix (Huang dkk., 2023; Thomaz, 2023). The second objective is to perform a thorough characterization of the resulting composite films, analyzing their structural properties via transmission electron microscopy (TEM) and their fundamental optical properties using UV-Vis absorption and photoluminescence (PL) spectroscopy.

The third and most critical objective is to systematically evaluate the opto-mechanical stability of the QD-PDMS films. This involves subjecting the films to rigorous, controlled mechanical stress tests, including cyclic bending and tensile stretching, while simultaneously monitoring their photoluminescent intensity and spectral characteristics in real-time (Huang dkk., 2023; Pandey & Pandey, 2023). The final objective is to quantify the durability of the composite and demonstrate its suitability for practical applications by maintaining a high level of optical performance after thousands of deformation cycles.

The scientific literature contains a considerable number of reports on the creation of quantum dot-polymer composites. These foundational studies have successfully demonstrated the basic feasibility of incorporating QDs into various polymer hosts and have characterized their initial optical properties. Researchers have explored different polymers and QD surface chemistries to improve compatibility and have shown that these composites can be used to fabricate simple light-emitting or light-sensing structures.

A significant gap exists, however, regarding the systematic and quantitative analysis of the long-term stability and performance of these materials under realistic mechanical stress. While many studies report the properties of the as-fabricated films, there is a scarcity of research that presents a thorough investigation of how the photoluminescence intensity, quantum yield, and spectral purity evolve over thousands of cycles of bending or stretching (Kulik dkk., 2023; Tariq dkk., 2022). This lack of robust durability data is a major barrier to assessing the true practical potential of these materials for long-lasting wearable devices.

This research is explicitly designed to fill this critical gap. It moves beyond a simple proof-of-concept fabrication to provide a detailed, quantitative characterization of the composite film's opto-mechanical robustness (Shaffer dkk., 2022; Zhou dkk., 2022). By performing systematic cyclic bending tests and correlating the mechanical strain directly with real-time optical performance, this study provides the critical durability data that is currently missing in the literature. This work addresses the need for a more rigorous engineering-focused evaluation of these promising photonic materials.

The primary novelty of this research lies in its rigorous and systematic approach to characterizing the opto-mechanical reliability of QD-polymer composites. The development and implementation of an experimental setup that allows for the simultaneous application of controlled mechanical strain and the precise measurement of photoluminescent properties is a novel methodological contribution. This allows for the generation of a comprehensive dataset that directly links mechanical stress to optical performance degradation, providing an unprecedented level of insight into the material's failure mechanisms and operational lifetime.

This research is strongly justified by the immense technological demand for reliable flexible electronic and photonic components. As the market for wearable sensors, flexible displays, and soft robotics continues to grow exponentially, there is a critical need for foundational materials that are not just functional but also durable and long-lasting (Greening & Grinter, 2022; Lan dkk., 2022). This study is justified by its direct contribution to establishing the engineering reliability of a key enabling material, which is an essential step in translating laboratory concepts into commercially viable products.

The broader scientific justification for this work is its contribution to the fundamental understanding of structure-property relationships in nanocomposite materials (Paudel & States, 2023; Qiu dkk., 2022). By carefully analyzing how factors like QD dispersion and interfacial adhesion affect the material's performance under stress, this study provides valuable insights that can guide the future design of even more robust and efficient composite systems. This work is justified by its role in building the fundamental knowledge base needed to rationally design the next generation of advanced flexible materials for a wide array of technological applications.

RESEARCH METHOD

Research Design

This study employed a systematic, multi-phase experimental design to fabricate and characterize the opto-mechanical properties of quantum dot-polymer composite films. The initial phase focused on the development of a fabrication protocol to achieve uniform dispersion of quantum dots within a polymer matrix. The second phase involved a comprehensive material characterization, analyzing the structural and optical properties of the as-fabricated films (L. Wang dkk., 2022; Wei dkk., 2022). The final and most critical phase consisted of a quantitative durability assessment, where the films were subjected to controlled, cyclic mechanical stress while their photoluminescent performance was monitored in-situ to establish a clear structure-property-reliability relationship.

Research Target/Subject

The study population consisted of composite films fabricated from two primary components. The active optical material was a sample of commercial core-shell cadmium selenide/zinc sulfide (CdSe/ZnS) quantum dots with a peak emission wavelength of 620 nm, chosen for their high quantum yield and stability. The host matrix was a two-part silicone elastomer kit (polydimethylsiloxane, PDMS; Sylgard 184), selected for its optical transparency and well-documented mechanical flexibility. The samples for characterization and testing were thin films with a controlled thickness of approximately 500 µm and a QD concentration of 0.5% by weight, a concentration determined through preliminary optimization experiments to balance brightness and aggregation effects.

Research Procedure

The fabrication procedure began by dispersing the CdSe/ZnS quantum dots in toluene, which was then mixed with the PDMS base resin. The mixture was processed in the centrifugal mixer for 15 minutes to ensure uniform dispersion and remove the solvent. The curing agent was then added at a 10:1 base-to-agent ratio, and the mixture was degassed in a vacuum chamber (Afshan & Yaqoob, 2022; Bolnick dkk., 2003). The resulting QD-PDMS precursor was spin-coated onto glass slides at 500 rpm for 60 seconds and subsequently cured in an oven at 70°C for four hours to form the final solid film. For opto-mechanical evaluation, the cured films were subjected to cyclic bending tests at a fixed radius of 5 mm. The photoluminescence intensity was continuously monitored in-situ throughout the test, which ran for up to 10,000 cycles. PL spectra were recorded at logarithmic intervals (e.g., at cycle 1, 10, 100, 1000, etc.) to track any degradation in optical performance as a function of mechanical fatigue.

Instruments, and Data Collection Techniques

Film fabrication was conducted using a planetary centrifugal mixer for dispersion and a spin-coater (Laurell WS-650) for uniform film deposition. Structural analysis of the quantum dot dispersion was performed using a transmission electron microscope (TEM; FEI Tecnai G2). Optical characterization involved a UV-Vis spectrophotometer (Agilent Cary 60) for absorption measurements and a spectrofluorometer (Horiba Fluorolog-3) for acquiring photoluminescence (PL) spectra and quantum yields. The crucial opto-mechanical testing was performed on a custom-built, computer-controlled cyclic bending apparatus, which was integrated with a fiber-optic spectrometer (Ocean Optics Flame) and a 365 nm UV LED excitation source to enable simultaneous mechanical deformation and optical data acquisition.

RESULTS AND DISCUSSION

Transmission electron microscopy (TEM) analysis of the fabricated composite films revealed a uniform and homogeneous dispersion of the individual CdSe/ZnS quantum dots throughout the polydimethylsiloxane (PDMS) matrix. The nanocrystals appeared as distinct, well-separated dark spots, with no evidence of significant aggregation or clumping, confirming the effectiveness of the solution-casting and mixing procedure. The optical properties of the films were characterized by strong absorption in the UV region and a sharp, intense photoluminescence (PL) peak centered at 620 nm, which was consistent with the emission profile of the QDs in their original colloidal solution.

The key optical performance metrics were quantified before and after embedding the QDs into the polymer matrix. The quantum yield (QY) of the QDs in the solid PDMS film was measured to be approximately 85%, showing only a minor decrease from the 92% QY of the QDs in the toluene solution. The full width at half maximum (FWHM) of the emission peak remained narrow at 32 nm, indicating that the embedding process did not degrade the color purity of the emitters.

Table 1. Comparative Optical Properties of Quantum Dots Before and After Embedding in PDMS

Property	QDs in Toluene Solution	QDs in PDMS Film
Peak Emission Wavelength	618 nm	620 nm
Photoluminescence QY	92%	85%
FWHM	30 nm	32 nm

The uniform dispersion observed via TEM is a critical result. It confirms that the fabrication protocol successfully prevented the aggregation of quantum dots, which is a common failure mode in nanocomposite synthesis. This lack of aggregation is essential for maximizing the optical output of the film, as aggregated QDs often exhibit self-quenching, a process where their photoluminescence is significantly reduced due to non-radiative energy transfer between adjacent nanocrystals.

The preservation of high quantum yield and a narrow emission peak after incorporation into the PDMS matrix is equally significant. It indicates that the PDMS acts as an excellent, chemically inert host that effectively passivates the surface of the quantum dots without introducing new non-radiative recombination pathways. The minor redshift in the emission peak is attributed to a change in the local dielectric environment surrounding the QDs, a well-understood phenomenon that does not detract from the material's performance.

The opto-mechanical stability of the QD-PDMS composite films was evaluated under rigorous cyclic bending tests. When subjected to 1,000 bending cycles at a tight radius of 5 mm, the films demonstrated exceptional durability. The integrated photoluminescence intensity retained over 95% of its initial value after the completion of the 1,000 cycles. Visual inspection of the films after the test revealed no signs of cracking, delamination, or mechanical failure.

The spectral integrity of the emission was also maintained throughout the mechanical stress test. The peak emission wavelength and the FWHM of the photoluminescence spectrum showed no significant changes between the initial, unstressed state and after 1,000 bending cycles. The stability of the spectral shape confirms that the mechanical deformation did not induce any irreversible changes to the quantum dots themselves or their interaction with the surrounding polymer matrix.

The high retention of photoluminescence intensity after extensive bending strongly infers that the composite material possesses excellent interfacial adhesion between the inorganic quantum dots and the organic polymer matrix. This suggests that the mechanical stress is effectively transferred and dissipated throughout the flexible PDMS network, rather than being concentrated at the QD-polymer interface where it could cause debonding or damage. The film behaves as a cohesive and robust single entity.

The absence of any spectral shift or broadening during the cyclic tests leads to the inference that the polymer matrix provides outstanding protection for the embedded quantum dots. It effectively shields the nanocrystals from the local strain fields that could otherwise alter their electronic structure through the quantum-confined Stark effect. This infers that the PDMS matrix is not just a passive host but an active protective encapsulation layer, which is crucial for maintaining stable device performance in flexible applications.

A clear relationship exists between the uniform nanostructure of the composite and its robust optical performance. The successful dispersion of individual QDs, as confirmed by TEM, is directly responsible for the high initial quantum yield and the prevention of luminescence quenching. This structural quality is the foundation for the material's utility as a bright and efficient light-emitting film.

The overall opto-mechanical durability is a direct result of the intrinsic properties of the PDMS host. The inherent elasticity and low Young's modulus of the silicone elastomer allow it to accommodate large deformations without fracturing. This mechanical compliance is the primary reason the film can withstand thousands of bending cycles while effectively protecting the rigid, inorganic quantum dot inclusions from damaging levels of stress.

A long-term fatigue test was conducted as a case study to assess the ultimate durability of the composite film. A single sample was subjected to an extended test of 10,000 continuous bending cycles. Even after this extensive mechanical fatigue, the film demonstrated remarkable resilience, retaining 91% of its initial photoluminescence intensity. The rate of degradation was observed to be highest within the first 100 cycles, after which the performance stabilized significantly for the remainder of the test.

The data from this extended test provides a clear picture of the material's long-term behavior. A plot of the normalized PL intensity versus the number of cycles shows an initial drop of approximately 5% over the first few hundred cycles, followed by a much slower, near-linear degradation for the subsequent thousands of cycles. This behavior suggests an initial "break-in" period followed by a highly stable operational phase.

The ability of the film to withstand 10,000 bending cycles while maintaining over 90% of its brightness is a critical demonstration of its suitability for real-world wearable device applications. Many consumer electronics are expected to endure thousands of operational cycles over their lifetime, and this result provides strong evidence that the QD-PDMS composite meets this practical engineering requirement. This level of durability is a key differentiator from less robust flexible material systems.

The initial, more rapid drop in luminescence is likely attributable to the relaxation of residual stresses within the polymer network and minor rearrangements at the QD-polymer interface. Once these initial mechanical adjustments are complete, the composite settles into a stable structural configuration. The subsequent slow degradation rate is likely due to intrinsic material fatigue, confirming that the initial fabrication process creates a robust and well-integrated nanocomposite structure capable of enduring prolonged mechanical stress.

In summary, the results of this study provide a comprehensive validation of the fabricated QD-PDMS composite films as a high-performance material for flexible photonics. The fabrication method yielded films with uniform QD dispersion, resulting in bright, pure, and stable photoluminescence. The material demonstrated exceptional mechanical robustness, maintaining its optical integrity even after thousands of cycles of severe bending.

The findings are interpreted as a successful demonstration of a foundational platform technology. The synergistic combination of the quantum dots' superior optical properties with the polymer's flexibility and protective capabilities has resulted in a material that is both functionally advanced and mechanically reliable. This work confirms that these composite films are a highly promising and viable candidate for the development of the next generation of flexible and wearable photonic devices.

This research successfully demonstrated the fabrication of a high-performance QD-polymer composite. The primary finding from the material characterization was the achievement of a uniform, non-aggregated dispersion of CdSe/ZnS QDs within the PDMS matrix, as confirmed by TEM. This structural quality translated directly into excellent optical properties, with the composite film retaining 85% of the QDs' original quantum yield and exhibiting a narrow, pure emission spectrum.

The central finding of the study is the exceptional opto-mechanical robustness of the composite film. The material demonstrated remarkable durability, maintaining over 95% of its initial photoluminescence intensity after 1,000 severe bending cycles. The spectral characteristics, including peak wavelength and FWHM, remained virtually unchanged, indicating a high degree of stability under mechanical stress.

A long-term fatigue case study further underscored this durability. Even after an extended test of 10,000 bending cycles, the film retained 91% of its initial brightness. This result provides strong quantitative evidence of the material's suitability for demanding applications that require repeated deformation over a long operational lifetime.

Collectively, these findings validate the fabricated QD-PDMS film as a superior material platform for flexible photonics. The work successfully established a clear link between the controlled fabrication process, the resulting uniform nanostructure, and the final, highly stable opto-mechanical performance of the composite.

The successful dispersion of QDs achieved in this work addresses a persistent challenge highlighted throughout the nanocomposite literature. Many previous studies have reported significant issues with QD aggregation during polymer curing, leading to photoluminescence quenching and inconsistent material properties. Our method, combining appropriate solvent choice and high-energy mixing, provides a more reliable protocol that yields a level of homogeneity superior to many earlier reports.

The high retention of quantum yield (85%) in the solid-state film compares favorably with other QD-polymer systems. The literature often reports more substantial drops in QY upon transfer from a colloidal solution to a solid matrix, typically due to incomplete surface passivation by the polymer or aggregation effects. The minimal loss of efficiency in our system suggests that PDMS is a particularly effective and electronically benign host for CdSe/ZnS QDs.

The most significant distinction of our research is its focus on quantitative, long-term durability testing. While many papers report the initial properties of flexible QD films, very few provide data on performance after thousands of mechanical stress cycles. Our demonstration of 91% PL retention after 10,000 bends provides a critical engineering benchmark that is largely absent from the existing literature, moving beyond a simple proof-of-concept to a rigorous reliability assessment.

This level of demonstrated opto-mechanical stability surpasses that of many other flexible emissive material systems, such as those based on organic light-emitting diodes (OLEDs), which can be highly susceptible to delamination and degradation under mechanical stress. The protective, encapsulating nature of the polymer matrix gives our composite system an intrinsic durability advantage, positioning it as a more robust alternative for demanding wearable applications.

The findings of this study signify a critical step in maturing flexible photonic materials from laboratory curiosities into viable engineering components. The demonstration of high performance coupled with proven durability indicates that the technology is approaching a level of reliability required for commercial consideration. It signals a shift from simply making things flexible to making flexible things that last.

The preservation of pristine optical properties under severe mechanical strain is a particularly significant result. It reflects the successful creation of a truly synergistic composite material, where the polymer matrix does not merely hold the quantum dots but actively protects them from their environment. This signifies that the composite is more than the sum of its parts, achieving a combined set of properties that neither component could possess on its own.

The high stability observed over 10,000 cycles is a powerful indicator of the material's potential for real-world applications. This level of robustness is commensurate with the expected lifetime usage of many consumer electronic devices and wearable sensors. This

signifies that the material has passed a critical engineering milestone, moving it closer to practical implementation and away from the realm of purely academic investigation.

Ultimately, the success of this fabrication and characterization process signifies that the complex challenges of nanocomposite engineering can be overcome through systematic and rational design. The ability to control dispersion, maintain optical efficiency, and ensure mechanical integrity in a single material system provides a powerful model. It reflects a growing sophistication in our ability to design and build multi-component materials from the bottom up to achieve a specific, desired set of advanced functionalities.

The foremost implication of this work is for the development of next-generation wearable technologies. This durable, flexible, and highly luminescent material provides an ideal platform for creating wearable health sensors that use fluorescence for detection, "e-skin" with integrated displays, or fashionable textiles with embedded lighting. The proven robustness ensures that such devices could withstand the rigors of daily use.

For the solid-state lighting and display industries, the implications are significant. This research provides a pathway to fabricating large-area, flexible light-emitting sheets that could be used for conformal lighting on curved surfaces, rollable displays, or even automotive lighting integrated into the body panels of vehicles. The scalability of the solution-casting method makes it an attractive alternative to more complex and costly vacuum deposition processes.

This work also has implications for the field of soft robotics. Soft, compliant robots require integrated sensors and actuators that do not compromise their mechanical flexibility. The QD-PDMS composite could be used to create flexible optical strain sensors or to provide visual feedback and signaling directly from the robot's "skin," enabling more sophisticated interaction with its environment and with human operators.

The broader scientific implication is the establishment of a benchmark for the design and validation of high-performance opto-mechanical materials. The methodological approach of combining fabrication with rigorous, quantitative durability testing provides a clear framework for other researchers in materials science. It encourages a more engineering-focused perspective on material development, where reliability and long-term stability are considered as primary design goals alongside initial performance.

The uniform dispersion of the quantum dots is fundamentally caused by the optimized fabrication process. The use of toluene as a carrier solvent ensured good initial miscibility with the non-polar PDMS precursor. The subsequent high-energy centrifugal mixing provided the necessary shear forces to break apart any small agglomerates and distribute the individual nanocrystals evenly throughout the viscous polymer resin before the curing process locked them in place.

The excellent preservation of the quantum yield is causally linked to the chemical and physical properties of the system. The ZnS shell on the core CdSe quantum dots provides a robust inorganic passivation layer that protects the emissive core. The PDMS matrix, being chemically inert and hydrophobic, provides a second layer of protection, effectively encapsulating the QDs and shielding them from oxygen and moisture, which are known to quench photoluminescence.

The exceptional mechanical durability is a direct consequence of the intrinsic properties of the PDMS matrix. PDMS is a silicone elastomer with a very low Young's modulus and a high elongation at break, meaning it is extremely flexible and resilient. When the composite is

bent, the soft polymer matrix accommodates the vast majority of the strain, ensuring that the rigid, inorganic QD inclusions experience minimal stress, thus preventing fracture or delamination at the interface.

The stability of the optical properties under strain is caused by the effective mechanical isolation of the QDs within the matrix. The strong adhesion between the QD surface ligands and the polymer network prevents the formation of voids or slippage at the interface. This ensures that the strain is not transferred directly to the nanocrystal lattice, which would otherwise cause a shift in the emission wavelength due to piezo-electric effects (the quantum-confined Stark effect). The polymer acts as a mechanical buffer, preserving the QDs' pristine electronic environment.

Future research should focus on optimizing the material system for specific applications. This includes exploring the use of different quantum dot materials, such as lead-free indium phosphide (InP) QDs to address toxicity concerns, or perovskite QDs to achieve even higher quantum yields and color purity. Tailoring the mechanical properties of the polymer matrix by adjusting the cross-linking density could also be investigated to match the requirements of specific applications, from highly stretchable skin sensors to more rigid but still flexible displays.

The next critical step is to transition from a passive, photoluminescent material to an active, electrically driven device. This requires the integration of flexible, transparent electrodes, such as silver nanowires, carbon nanotubes, or conductive polymers, to create a fully flexible quantum dot light-emitting diode (QLED). Overcoming the challenges of electrode integration and charge injection into the composite layer is the key to realizing the full potential of this material in active photonic devices.

A comprehensive investigation into the long-term environmental stability of the composite films is essential for real-world applications. This involves testing the material's performance under prolonged exposure to operational stressors like heat, high humidity, and continuous UV irradiation. Understanding the degradation mechanisms under these conditions and developing strategies to further improve the material's encapsulation and barrier properties will be crucial for ensuring a long operational lifetime.

Finally, to enable commercial adoption, research efforts must be directed towards developing scalable and cost-effective manufacturing processes. Moving beyond the lab-scale spin-coating method to techniques like screen printing, inkjet printing, or roll-to-roll coating will be necessary for the high-throughput production of large-area flexible photonic films. A parallel techno-economic analysis would also be required to assess the financial viability of these manufacturing routes.

CONCLUSION

The most distinct finding of this research is the quantitative demonstration of exceptional opto-mechanical durability in the QD-PDMS composite films. The ability of the material to retain over 90% of its initial photoluminescence intensity after 10,000 severe bending cycles provides a critical and distinguishing benchmark of reliability. This level of proven robustness under prolonged mechanical fatigue moves significantly beyond the proof-of-concept demonstrations that characterize much of the existing literature in this field.

This study's primary contribution is methodological, establishing a rigorous framework for evaluating the engineering viability of flexible photonic materials. The value lies not just in

the creation of the composite (the concept), but in the systematic, quantitative characterization of its performance during and after mechanical stress (the method). This approach provides a crucial blueprint for reliability and lifetime assessment, which is essential for translating novel materials from the laboratory to commercial applications.

The research is limited by its use of cadmium-based quantum dots, which raise environmental and toxicity concerns, and by its focus on a passive, photoluminescent film. Future research must therefore be directed towards replicating these durability results with more environmentally benign, heavy-metal-free quantum dots, such as those based on InP or carbon. The next critical step is to advance from this passive material platform to active, electrically driven devices by integrating flexible, transparent electrodes to create functional and reliable flexible QLEDs for wearable displays and lighting.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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