

Nanocomposite Thin Films for Enhanced Solar Energy Harvesting: Materials, Mechanisms, Fabrication, Characterization and Perspectives

Dr. A.Sujala Swapna Smitha*, Dr. G. Suresh Babu**

* Department of Physics, Government Degree College for Women, Srikalahasti-517644

Andhra Pradesh, India

** Department of Physics, Government Degree College, Puttur-517 583

Andhra Pradesh, India 2026

DOI: <https://doi.org/10.5281/zenodo.23402523>

Published Date: 15-October-2026

Abstract: Nanocomposite thin films provide a versatile route for improving solar-energy harvesting by combining the optical, electrical, interfacial, and mechanical properties of a host matrix with those of nanoscale functional materials. This paper presents a literature-based research framework for the design of nanocomposite thin films intended for photovoltaic and solar-thermal applications. Particular attention is given to semiconductor nanoparticles, metal oxides, carbon nanomaterials, quantum dots, conducting polymers, and hybrid organic-inorganic architectures. The mechanisms responsible for enhanced performance are discussed in terms of broadband absorption, light scattering and trapping, interfacial charge transfer, defect passivation, exciton dissociation, carrier transport, down-conversion, and surface protection. Deposition routes including spin coating, sol-gel processing, spray coating, chemical vapor deposition, physical vapor deposition, pulsed-laser techniques, and solution-based processing are compared. The paper also proposes a systematic experimental methodology in which nanoparticle loading, film thickness, annealing temperature, and interfacial structure are treated as controlled variables. Optical, structural, morphological, electrical, and photovoltaic measurements are linked through quantitative relations for absorption coefficient, optical band gap, refractive index, sheet resistance, carrier transport, and power-conversion efficiency. A materials-selection matrix and a proposed optimization strategy are presented to guide future laboratory studies. The review indicates that the most promising nanocomposite architectures are those that simultaneously improve light management and charge extraction without introducing excessive recombination, parasitic absorption, roughness, or processing complexity. The study therefore establishes a practical framework for developing low-cost, scalable, and stable nanocomposite thin films for next-generation solar-energy harvesting.

Keywords: nanocomposite thin films; solar energy harvesting; photovoltaic devices; nanoparticles; thin-film solar cells; optical absorption; charge transport; quantum dots; carbon nanomaterials; light trapping.

1. INTRODUCTION

The transition from fossil-fuel-based energy systems toward low-carbon energy generation has increased interest in materials and device architectures capable of converting solar radiation efficiently and economically. Thin-film solar technologies are especially attractive because they can reduce material consumption, enable lightweight and flexible devices, and permit deposition on a variety of substrates. However, thin active layers also impose a fundamental optical challenge: reducing absorber thickness can decrease the probability that incident photons are absorbed before they leave the device.

Nanocomposite thin films provide a means of addressing this limitation by integrating nanoscale components into a continuous host layer. The nanocomponent can be selected to modify optical absorption, refractive index, electrical conductivity, interfacial energetics, defect density, thermal response, or mechanical stability. Earlier reviews of hybrid nanocomposite photovoltaic layers have shown that organic and inorganic constituents can be combined to exploit complementary properties such as solution processability, flexibility, charge transport, and optical functionality [1]. More recent studies have expanded this concept toward carbon-based coatings, metal-oxide nanostructures, quantum dots, and multifunctional solar-energy coatings [2, 6, 7].

The scientific basis of the present study is that solar harvesting in a thin film is not controlled by a single material parameter. Rather, it is a coupled problem involving photon propagation, absorption, photogeneration, recombination, carrier transport, interfacial extraction, and environmental stability. Consequently, simply increasing the nanoparticle concentration does not necessarily improve the final device efficiency. Excessive loading may increase optical scattering but simultaneously raise surface roughness, introduce trap states, or impede charge transport.

Recent literature provides several examples of this trade-off. Carbon nanomaterials have attracted attention for thin-film photovoltaic coatings because of their electrical, optical, and interfacial properties [6]. Nanocrystals can function not only as light absorbers but also as charge-transport or interface-modification layers [5]. TiO₂-graphene quantum-dot nanocomposites have been investigated as electron-transport-layer modifiers in perovskite solar cells, demonstrating the importance of nanocomposite engineering at interfaces rather than only in the photoactive layer [8]. Similarly, nanocomposite coatings can provide simultaneous optical and environmental functions [2].

The objective of this paper is therefore to develop a coherent research framework for *nanocomposite thin films for enhanced solar energy harvesting*. The work has four specific objectives:

- (i) to classify nanocomposite materials according to their solar-energy function;
- (ii) to explain the physical mechanisms responsible for enhanced harvesting;
- (iii) to compare practical synthesis and deposition routes;
- (iv) to propose a quantitative experimental methodology for optimizing film composition and thickness.

This manuscript is deliberately structured without invented experimental results. Numerical values reported from the literature are used only where explicitly cited; the proposed experimental section defines measurements and expected trends that can be tested in a laboratory.

2. SCIENTIFIC BASIS OF NANOCOMPOSITE THIN-FILM SOLAR HARVESTING

A nanocomposite thin film may be represented as a matrix M containing one or more nanoscale phases N_i :

$$\text{Nanocomposite} = M + \sum_i \phi_i N_i \quad (1)$$

where ϕ_i denotes the volume fraction of the i th nanocomponent. The nanoscale phase may

be metallic, semiconducting, carbonaceous, polymeric, or a hybrid material. For a solar-harvesting film, the incident solar power can be expressed as

$$P_{\text{in}} = \int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda) A_{\text{cell}} d\lambda, \quad (2)$$

where E_λ is the spectral irradiance and A_{cell} is the active area. The fraction of radiation absorbed by a film of thickness d is approximately governed by the Beer–Lambert relation:

$$I(\lambda, d) = I_0(\lambda) \exp[-\alpha(\lambda)d], \quad (3)$$

where α is the absorption coefficient. Nanoparticles can increase the effective optical path length through scattering, refractive-index modification, resonant absorption, or spectral conversion.

For photovoltaic conversion, the ultimate objective is not merely high absorption. The generated carriers must be separated and collected. The useful electrical output is

$$P_{\max} = V_{\text{mpp}} I_{\text{mpp}}, \quad (4)$$

and the power-conversion efficiency is

$$\eta = \frac{V_{\text{oc}} I_{\text{sc}} FF}{P_{\text{in}}}, \quad (5)$$

where V_{oc} is open-circuit voltage, J_{sc} is short-circuit current density, FF is the fill factor, and P_{in} is the incident power density.

The central design problem is therefore to maximize photon utilization while minimizing recombination and parasitic losses.

3. CLASSES OF NANOCOMPOSITE THIN FILMS

3.1 Metal-Oxide Nanocomposites

Metal oxides such as TiO_2 , ZnO , SnO_2 , NiO , and related transition-metal oxides are widely investigated because of their tunable optical and electronic properties. Metal-oxide nanocomposite films can be used as absorber-support layers, electron-transport layers, hole-transport layers, antireflection structures, or protective coatings.

A recent review emphasizes that transition-metal oxide nanomaterials remain important for solar-cell development because their electronic structures, surface chemistry, and nanoscale morphology can be engineered for photovoltaic applications [11]. Metal-oxide nanocomposites are particularly attractive when the desired function involves electron extraction, surface passivation, or light scattering.

3.2 Carbon-Based Nanocomposites

Graphene, graphene quantum dots, carbon nanotubes, reduced graphene oxide, and related carbon nanomaterials provide high electrical conductivity, large interfacial area, and tunable optical characteristics. Their incorporation into thin films can facilitate carrier transport and modify interfaces.

A 2025 review specifically examining carbon nanomaterials in thin-film photovoltaic coatings identifies physical and chemical vapor deposition as important routes for forming carbon-containing photovoltaic layers [6]. Carbon nanostructures can therefore serve as conductive networks or interfacial modifiers, although their concentration must be controlled because excessive carbon loading can cause parasitic optical absorption.

3.3 Quantum-Dot Nanocomposites

Quantum dots provide size-dependent optical and electronic properties. Their tunable absorption and emission make them useful for spectral conversion and light harvesting. Nanocrystal-based solar-cell strategies can involve the active absorber, charge-transport layer, or interface engineering [5].

A particularly interesting route is the use of quantum dots in flexible composite films. Chalcogenide quantum-dot-containing EVA films have been investigated as flexible optical layers capable of down-conversion and thermal-management functions [10]. Such structures illustrate that a nanocomposite may improve photovoltaic output without necessarily being part of the electrical junction itself.

3.4 Polymer–Inorganic Nanocomposites

Conducting polymers offer low-temperature processability and mechanical flexibility, while inorganic nanostructures can provide higher carrier mobility, improved optical absorption, or enhanced environmental resistance. The combination is therefore attractive for flexible and lightweight solar technologies.

Hybrid nanocomposite photovoltaic films based on conducting polymers, fullerene derivatives, metal phthalocyanines, metal oxides, chalcogenides, and silicon nanostructures have been extensively reviewed [1]. The most important variables include the organic-to-inorganic ratio, particle size, morphology, solvent system, and deposition conditions.

3.5 Perovskite-Related Nanocomposites

Perovskite solar cells have rapidly advanced because of their favorable optoelectronic properties. However, defects, ion migration, moisture sensitivity, and interfacial recombination remain important challenges. Nanocomposite engineering can address these issues by modifying electron-transport layers, interfaces, or the perovskite itself.

Recent reviews discuss rapid progress in high-performance inverted perovskite solar cells and the importance of transport materials and interfaces [13]. Nanocomposite approaches have also been demonstrated using TiO₂ and graphene quantum dots in electron-transport layers [8], while carbon-nanotube-based nanocomposites have been investigated for carbon-based perovskite solar cells [9].

4. MECHANISMS OF PERFORMANCE ENHANCEMENT

4.1 Enhanced Optical Absorption

For a thin absorbing layer, the absorbed fraction can be written approximately as

$$A(\lambda) = 1 - R(\lambda) - T(\lambda), \quad (6)$$

where R and T are reflectance and transmittance. Nanoparticles can reduce reflection and increase effective absorption by altering the local electromagnetic field.

The enhancement can originate from:

- nanoscale scattering;
- localized optical resonances;
- refractive-index grading;
- increased optical path length;
- spectral down-conversion;
- broadband antireflection.

Light-trapping structures are especially useful when the absorber is thin. Silicon nanofilms, for example, have been investigated as optical structures capable of enhancing light absorption through refractive-index engineering [4].

4.2 Charge Separation and Transport

Nanoparticles can create additional interfaces where photogenerated carriers are transferred from one phase to another. If the energy levels are appropriately aligned, an electron may preferentially transfer into an electron-accepting nanophase while holes remain in the matrix.

The carrier diffusion length can be approximated as

$$L_D = \sqrt{D\tau}, \quad (7)$$

where D is the carrier diffusion coefficient and τ is the effective carrier lifetime. Nanocomposite design should therefore aim to reduce the distance that carriers travel before reaching a collecting interface while avoiding excessive recombination centers.

4.3 Defect Passivation

Defects at surfaces and grain boundaries can act as recombination centers. A suitable nanocomponent can chemically or electronically passivate these states. This is particularly relevant in perovskite and polycrystalline thin films.

4.4 Spectral Conversion

Some nanocomposites can absorb high-energy photons and re-emit at wavelengths better matched to the absorber. The process can be represented schematically as



where NC^* represents an excited nanostructure. The converted photons may then be absorbed by the photovoltaic layer.

4.5 Thermal and Environmental Protection

Nanocomposite coatings may also modify thermal emissivity, moisture resistance, UV stability, and mechanical robustness. This multifunctionality is important because a solar device must retain performance under environmental stress, not only under laboratory illumination.

5. MATERIALS SELECTION STRATEGY

The choice of nanocomponent should be guided by the intended function rather than by nanoparticle availability alone.

Table 1: Representative nanocomposite components and their potential solar-energy functions.

Nanocomponent Matrix / host		Primary function	Key concern
TiO ₂	Polymer / oxide	Electron transport, scattering, antireflection	Excessive recombination or aggregation
ZnO	Polymer / oxide	Electron extraction, optical modification	Surface defects and stability
Graphene / rGO	Polymer / oxide	Conductive network, interface engineering	Parasitic absorption, aggregation
CNTs	Polymer / carbon	Charge transport and mechanical reinforcement	Percolation threshold and dispersion
Graphene quantum dots	TiO ₂ , polymers	Charge transport, optical modification	Interface compatibility
Chalcogenide QDs	EVA / polymers	Spectral conversion and light harvesting	Stability and toxicity depending on composition
Si nanocrystals	Dielectric / semiconductor	Light trapping and spectral engineering	Surface passivation
Conducting polymers	Inorganic nanoparticles	Flexible charge transport	Environmental stability

The literature suggests that the nanoparticle size, concentration, shape, surface chemistry, and distribution can be as important as the intrinsic properties of the nanomaterial itself [1, 5].

6. THIN-FILM FABRICATION TECHNIQUES

6.1 Spin Coating

Spin coating is suitable for laboratory-scale optimization because film thickness can be controlled through solution concentration, viscosity, rotation speed, and time. It is particularly useful for polymer and hybrid nanocomposites.

6.2 Sol–Gel Processing

Sol–gel processing provides a relatively simple route to oxide nanocomposite films. Hydrolysis, condensation, precursor concentration, aging, and annealing influence the final microstructure.

6.3 Spray Coating

Spray coating offers greater potential for large-area deposition than spin coating. It is attractive for scalable coatings, although uniformity must be controlled.

6.4 Vapor-Phase Deposition

Physical and chemical vapor deposition can produce controlled and uniform nanocomposite or carbon-containing films. Recent reviews identify vapor deposition as an important route for thin-film photovoltaic surface engineering [6].

6.5 Pulsed-Laser and Related Techniques

Pulsed-laser-based approaches can provide controlled deposition of inorganic nanostructures and composite layers. They are particularly useful for research into optical and electrical properties of nanocomposite films.

7. PROPOSED EXPERIMENTAL METHODOLOGY

The following methodology is proposed as a reproducible research program for 2025-oriented laboratory investigation.

7.1 Preparation of Nanocomposite Solutions

A suitable polymer or sol–gel matrix may be selected according to the intended device architecture. Nanoparticles should first be dispersed in an appropriate solvent using controlled sonication. The concentration should be varied systematically rather than selected arbitrarily.

A representative concentration series is

$$0, 0.5, 1.0, 2.0, 3.0, 5.0 \text{ wt\%}.$$

The exact range should be adjusted according to the material system and dispersion stability.

7.2 Deposition

The films may be deposited on cleaned glass, quartz, FTO, or another device-relevant substrate. For spin coating, the experimental variables can include:

1. solution concentration;
2. spin speed;
3. spinning time;
4. substrate temperature;
5. post-deposition annealing.

The final thickness should be measured independently rather than inferred solely from deposition conditions.

7.3 Thickness Optimization

Film thickness is a critical variable because it simultaneously controls absorption and carrier-collection distance. A proposed thickness matrix is

$$d = 50, 100, 150, 200, 300, 500 \text{ nm}.$$

The optimum thickness should be identified by jointly evaluating optical absorption, sheet resistance, carrier lifetime, and device efficiency.

7.4 Structural Characterization

X-ray diffraction should be used to determine phase composition and crystallinity. The average crystallite size can be estimated from the Scherrer relation:

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (9)$$

where D is crystallite size, K is the shape factor, λ is the X-ray wavelength, β is the corrected full width at half maximum, and θ is the diffraction angle.

Scanning electron microscopy and, where available, transmission electron microscopy should be used to determine particle distribution, grain structure, porosity, and interfacial morphology.

7.5 Optical Characterization

UV-Vis spectroscopy should provide transmittance and absorbance spectra. The absorption coefficient can be estimated from

$$\alpha = \frac{2.303A}{d} \quad (10)$$

where A is absorbance and d is film thickness.

For a direct allowed transition, the optical band gap may be estimated using the Tauc relation

$$(\alpha h\nu)^2 = B(h\nu - E_g) \quad (11)$$

where B is a material-dependent constant and E_g is the optical band gap.

If an indirect transition is appropriate, the exponent should instead reflect the relevant transition mechanism. The transition type should therefore be justified rather than assumed.

7.6 Electrical Characterization

Sheet resistance can be measured using a four-point probe. If the film thickness is known, electrical conductivity may be approximated by

where R_s is sheet resistance.

$$\sigma = \frac{1}{R_s d} \quad (12)$$

Hall measurements, impedance spectroscopy, or temperature-dependent conductivity can provide additional information about carrier concentration, mobility, and transport mechanisms.

7.7 Photovoltaic Characterization

For a complete solar-cell device, current density–voltage measurements should be carried out under calibrated simulated sunlight. The principal parameters are:

$$J_{sc}, \quad V_{oc}, \quad FF, \quad \eta \quad (13)$$

The fill factor is

$$FF = \frac{V_{mpp} J_{mpp}}{V_{oc} J_{sc}} \quad (14)$$

and the conversion efficiency is

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (15)$$

External quantum efficiency measurements should additionally be used to determine whether an increase in photocurrent originates from improved spectral response.

8. OPTIMIZATION FRAMEWORK

The most useful optimization strategy is a multi-objective approach. A film that maximizes absorption but has poor conductivity should not be considered optimal.

A normalized performance index can be defined as

$$\Phi = w_A A_n + w_C \sigma_n + w_P \eta_n + w_S S_n, \quad (16)$$

where A_n , σ_n , η_n , and S_n are normalized absorption, conductivity, photovoltaic efficiency, and stability scores, respectively, and the weights satisfy

$$w_A + w_C + w_P + w_S = 1. \quad (17)$$

For a photovoltaic application, a larger weight may be assigned to η and long-term stability than to absorption alone.

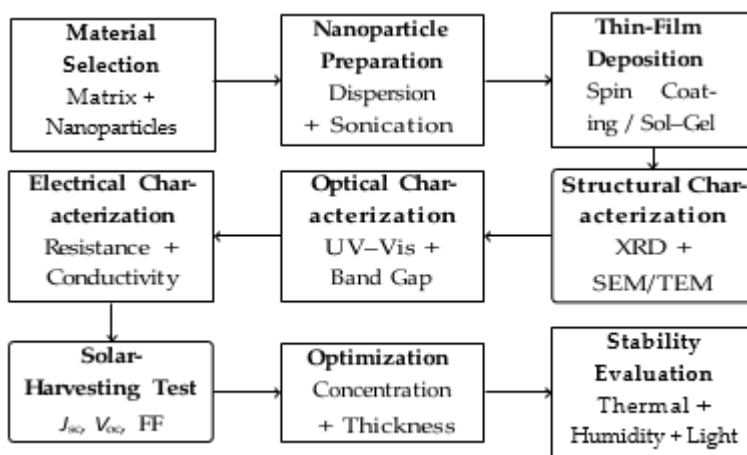


Figure 1: Proposed research workflow for the development and optimization of nanocomposite thin films for enhanced solar energy harvesting.

9. EXPECTED RELATIONSHIPS BETWEEN COMPOSITION AND PERFORMANCE

The expected behavior is generally non-monotonic. At low nanoparticle concentration, isolated nanostructures may not sufficiently alter the optical or electrical properties of the host. As concentration increases, the density of useful interfaces and scattering centers increases. Beyond an optimum, aggregation and defect formation can dominate.

A conceptual response can therefore be represented by

$$\text{Performance} \approx f(\phi, d, T_a, M), \quad (18)$$

where ϕ is nanoparticle loading, d is film thickness, T_a is annealing temperature, and M represents morphology.

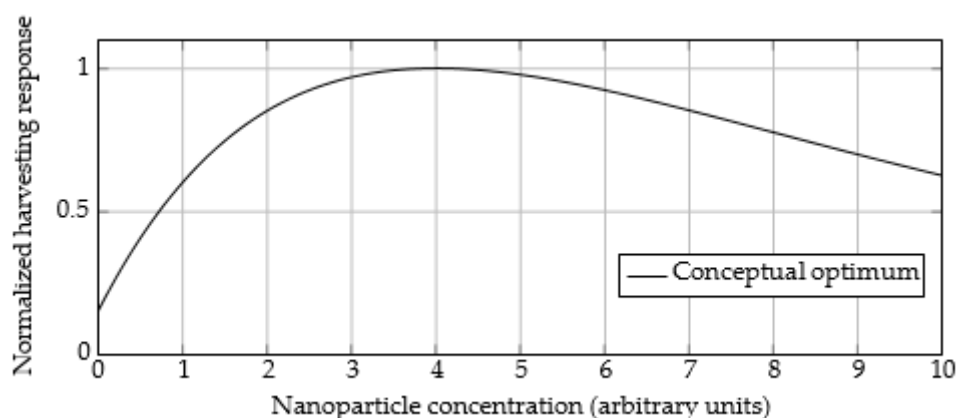


Figure 2: Conceptual illustration of an optimum nanoparticle concentration. The curve is illustrative and is not experimental data.

The optimum occurs because several competing effects act simultaneously:

1. increased optical interaction with increasing nanoparticle content;
2. improved interfacial charge transfer at moderate loading;
3. aggregation at excessive loading;
4. increased recombination through poorly passivated interfaces;
5. increased scattering or parasitic absorption that can reduce useful transmitted light.

10. DISCUSSION IN THE CONTEXT OF RECENT LITERATURE

The current research direction is moving from single-function nanoparticles toward multifunctional nanocomposite interfaces. Reviews of nanomaterials for solar-energy harvesting emphasize that 1D and 2D structures can provide tunable optical and electronic properties while offering routes toward scalable solar-energy technologies [7].

Hybrid nanocomposite photovoltaic films remain important because organic and inorganic phases can provide complementary properties [1]. More recent work extends this principle to carbon nanomaterials, where conductivity and surface interactions can improve thin-film device architectures [6].

Perovskite photovoltaics provide an especially strong demonstration of the value of interface engineering. The rapid development of inverted perovskite solar cells has been associated with improved transport materials and interface control [13]. In 2025, TiO₂-graphene quantum-dot nanocomposite electron-transport layers were reported as a route to improving perovskite-cell performance, illustrating how a nanoscale composite can be engineered specifically at a charge-selective interface [8]. Carbon-nanotube/Zn-based nanocomposite structures have likewise been explored in carbon-based perovskite solar cells [9].

Another emerging direction is the use of nanocomposite optical films outside the electrical junction. Chalcogenide quantum-dot/EVA composite films have been reported for flexible photovoltaic applications, where down-conversion and thermal effects can jointly contribute to improved solar-cell output [10]. This suggests that future solar modules may use several nanocomposite layers, each optimized for a distinct function.

Metal-oxide nanocomposite films are also promising because they can combine optical, electrical, thermal, and mechanical improvements [3]. Polymer nanocomposite coatings have been considered for solar-energy applications such as solar collectors and optical/absorbing surfaces [12].

The overall conclusion from these developments is that the phrase “enhanced solar harvesting” should be interpreted broadly. Enhancement may result from increased absorption, reduced reflection, improved carrier extraction, spectral conversion, reduced operating temperature, or improved long-term stability. The highest-performing architecture will therefore be the one that balances all of these contributions.

11. CHALLENGES

Despite substantial progress, several technical challenges remain.

11.1 Nanoparticle Aggregation

Aggregation can reduce the effective surface area and create nonuniform electrical pathways. Surface functionalization, controlled sonication, appropriate solvents, and optimized precursor chemistry are required.

11.2 Interface Defects

Every additional phase boundary can potentially introduce trap states. Nanocomposite design should therefore maximize *useful* interfaces while minimizing electronically defective ones.

11.3 Reproducibility

Nanomaterial synthesis can be sensitive to precursor purity, reaction temperature, aging time, ligand chemistry, and particle-size distribution. Standardized characterization is essential for meaningful comparison between laboratories.

11.4 Scalability

A method that works on a few square centimeters may not transfer directly to module-scale sub-strates. Spray coating, slot-die coating, printing, and vapor-phase deposition deserve increasing attention for scale-up.

11.5 Environmental and Economic Considerations

The selection of nanoparticles should include toxicity, material abundance, recyclability, and life-cycle considerations. Nanocomposites containing scarce or hazardous elements may provide excellent laboratory performance but create barriers to sustainable deployment.

11.6 Long-Term Stability

Photovoltaic materials must withstand humidity, oxygen, ultraviolet radiation, temperature cycling, and mechanical stress. Stability testing should therefore be integrated into the initial optimization rather than treated as a final step.

12. FUTURE RESEARCH DIRECTIONS

The following research directions are recommended:

- Multifunctional interfaces:** Develop nanocomposites that simultaneously improve light management, carrier extraction, and defect passivation.
- Earth-abundant materials:** Increase the use of TiO₂, ZnO, Si, carbon, copper-based chalcogenides, and other relatively abundant material systems.
- Low-temperature processing:** Develop deposition routes compatible with flexible polymer substrates.
- Printed nanocomposites:** Investigate inkjet, spray, blade, and slot-die deposition for large-area production.
- Data-driven optimization:** Combine design-of-experiments and machine learning with optical and electrical measurements to identify optimal compositions.
- In situ characterization:** Monitor morphology and optical properties during annealing and operation.
- Stability-by-design:** Treat environmental stability as a primary optimization parameter.
- Tandem architectures:** Integrate nanocomposite light-management layers with per-ovskite, organic, silicon, or other thin-film photovoltaic technologies.

13. PROPOSED RESEARCH HYPOTHESIS

The central hypothesis of this research is:

A properly engineered nanocomposite thin film with optimized nanoparticle concentration, particle size, film thickness, and interfacial chemistry can enhance solar-energy harvesting by simultaneously increasing effective optical absorption and improving photocarrier extraction, provided that aggregation and recombination are controlled.

This hypothesis can be tested experimentally by preparing a controlled concentration series and correlating structural, optical, electrical, and photovoltaic measurements.

14. PROPOSED EXPERIMENTAL MATRIX

Table 2: Suggested experimental matrix for a laboratory study.

Parameter	Suggested levels	lev-	Measurement	Purpose
Nanoparticle loading	0–5 wt%		Composition analysis	Identify optimum loading
Film thickness	50–500 nm		Profilometry / ellipsometry	Balance absorption and transport
Particle size	Multiple controlled sizes	con-	SEM/TEM	Study scattering and interfaces
Annealing temperature	Material-dependent series		XRD/UV–Vis/electrical	Optimize crystallinity
Optical absorption	300–1100 nm or broader		UV–Vis–NIR	Determine spectral harvesting
Sheet resistance	Four-point probe		Electrical test	Evaluate transport
Photoluminescence	Steady-state / time-resolved	/	PL/TRPL	Examine recombination
J–V characteristics	Standard illumination		Solar simulator	Determine PCE
Stability	Thermal/humidity/light exposure		Periodic J–V	Assess durability

15. CONCLUSION

Nanocomposite thin films represent a flexible materials platform for improving solar-energy harvesting because nanoscale components can be engineered to control optical absorption, light scattering, carrier transport, interfacial recombination, spectral conversion, and environmental protection. The literature demonstrates that successful nanocomposite architectures are not necessarily those containing the largest quantity of nanoparticles; rather, they are structures in which composition, morphology, thickness, and interfaces are optimized together.

Metal oxides, carbon nanomaterials, quantum dots, conducting polymers, silicon nanostructures, and hybrid organic–inorganic systems each provide distinct opportunities. Recent research increasingly emphasizes interface engineering and multifunctional coatings rather than simple bulk doping. This trend is particularly evident in perovskite photovoltaic devices and in optical nanocomposite layers designed for flexible or large-area solar technologies.

The proposed research methodology provides a practical pathway from material selection to device optimization. By correlating XRD, microscopy, UV–Vis spectroscopy, electrical measurements, photoluminescence, and photovoltaic characterization, it becomes possible to determine whether performance gains originate from enhanced absorption, improved carrier extraction, reduced recombination, or a combination of mechanisms.

REFERENCES

- [1] M. Kovacova, et al., “Hybrid Nanocomposite Thin Films for Photovoltaic Applications: A Review,” *Nanomaterials*, vol. 11, no. 5, 1117, 2021. doi:10.3390/nano11051117.
- [2] G. Regmi, “Unlocking Multifunctional Advantages with Nanocomposites Coatings for Solar Cells: A Comprehensive Review,” *Current Nanoscience*, vol. 27, no. 22, pp. 1946–1959, 2023. doi:10.2174/0113852728281107231212044214.

- [3] S. Chackrabarti, "Metal Oxide Nanocomposite Thin Films," in *Metal Oxide Nanocomposite Thin Films for Optoelectronic Device Applications*, Wiley, 2023. doi:10.1002/9781119865636.ch13.
- [4] "Theoretical simulation and experimental perspective of refractive index-controlled silicon nanofilms for solar cell efficiency improvement," *Solar Energy Materials and Solar Cells*, vol. 251, 112145, 2023. doi:10.1016/j.solmat.2022.112145.
- [5] B. Yang, J. Cang, Z. Li, and J. Chen, "Nanocrystals as performance-boosting materials for solar cells," *Nanoscale Advances*, vol. 6, pp. 1331–1360, 2024. doi:10.1039/D3NA01063E.
- [6] "Carbon nanomaterials in coatings: A review focusing thin film photovoltaic solar cells," *Materials Science in Semiconductor Processing*, vol. 185, 108929, 2025. doi:10.1016/j.mssp.2024.108929.
- [7] S. Aftab, S. Goud, Z. Ali, M. A. Assiri, J. H. Kim, N. Rubab, and E. Akman, "Advancements in nanomaterials for solar energy harvesting: Challenges, innovations, and future prospects," *Chemical Engineering Journal*, vol. 516, 164224, 2025. doi:10.1016/j.cej.2025.164224.
- [8] S. Sucharitakul, V. Yarangsi, S. Thanasanvorakun, T. Sintiam, S. Yarin, K. Hongsih, S. Phadungdhithidhada, and S. Choopun, "Enhanced perovskite solar cells with TiO₂-Graphene nanocomposite quantum dots in electron transport layer," *Electrochimica Acta*, vol. 521, 145901, 2025. doi:10.1016/j.electacta.2025.145901.
- [9] F. Arjmand and S. J. Fatemi, "Improved performance of carbon-based perovskite solar cells using a multi-walled carbon nanotubes/Zn(COO)₂ nanocomposite," *Scientific Reports*, vol. 15, 23488, 2025. doi:10.1038/s41598-025-08040-z.
- [10] "Enhanced photovoltaic output of flexible polyethylene vinyl acetate film hetero-genized by chalcogenide quantum dots," *Solar Energy*, vol. 301, 113945, 2025. doi:10.1016/j.solener.2025.113945.
- [11] L. V. Hublikar, S. V. Ganachari, F. A. Shilar, and N. Raghavendra, "Recent advances in transition metal oxide nanomaterials for solar cell applications: A status re-view and technology perspectives," *Materials Research Bulletin*, vol. 187, 113351, 2025. doi:10.1016/j.materresbull.2025.113351.
- [12] "Polymer nanocomposite films and coatings for solar energy applications," in *Polymer Nanocomposite Films and Coatings: Processes, Fundamental Properties and Applications*, Woodhead Publishing, pp. 371–408, 2024. doi:10.1016/B978-0-443-19139-8.00025-5.
- [13] Q. Jiang and K. Zhu, "Rapid advances enabling high-performance inverted perovskite solar cells," *Nature Reviews Materials*, vol. 9, pp. 399–419, 2024.
- [14] C. Yang, W. Hu, J. Liu, C. Han, Q. Gao, A. Mei, Y. Zhou, F. Guo, and H. Han, "Achievements, challenges, and future prospects for industrialization of perovskite solar cells," *Light: Science & Applications*, vol. 13, 227, 2024. doi:10.1038/s41377-024-01461-x.
- [15] C. Zhang and N.-G. Park, "Materials and methods for cost-effective fabrication of perovskite photovoltaic devices," *Communications Materials*, vol. 5, 194, 2024. doi:10.1038/s43246-024-00636-8.
- [16] T. Liu, M. M. S. Almutairi, J. Ma, A. Stewart, Z. Xing, M. Liu, B. Hou, and Y. Cho, "Solution-Processed Thin Film Transparent Photovoltaics: Present Challenges and Future Development," *Nano-Micro Letters*, vol. 17, 49, 2025. doi:10.1007/s40820-024-01547-6.
- [17] "Recent progress on nanocellulose-based nanocomposites for application in photovoltaic solar cells and supercapacitors," *Journal of Materials Research and Technology*, vol. 37, pp. 1682–1704, 2025. doi:10.1016/j.jmrt.2025.05.013.
- [18] "Development in PANI based solar cells: Progress on high-throughput methods, physical-chemical properties and device performance," 2025.
- [19] M.-C. Kao, K.-H. Chen, and C.-S. Hsiao, "Enhanced Photovoltaic Performance of TiO₂ Thin Films Dye-Sensitized Solar Cells by Incorporating TiO₂ Nanoparticles," *Engineering Proceedings*, vol. 108, no. 1, 21, 2025. doi:10.3390/engproc2025108021.