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Review Article

Advances in Hybrid Nanocomposites for Solar Applications and Photo Catalysis: A Comprehensive Review

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Abstract - *Solar energy is a promising and sustainable alternative to meet the world's growing energy requirements. The creation of innovative materials is essential for better solar energy harvesting. Nanostructured hybrid nanocomposites are promising for next-generation solar technology, as they have multifunctional qualities and enhanced device performance, and this study provides a comprehensive analysis of recent developments in these materials for solar applications, including solar cells, photocatalysis, and photoelectrochemical cells, along with an overview of synthesis techniques and future challenges. An overview of chemical and physical synthesis techniques for nanostructured hybrid nanocomposites is summarized. The review also highlights the challenges and future directions to be taken in creating and applying hybrid nanocomposites for next-generation solar technology.*

Keywords - *Solar energy, Nanostructured hybrid nanocomposites, Multifunctional properties, Solar cells, Photoelectrochemical cells, Synthesis methods.*

1. Introduction

In recent years, the quest for renewable and sustainable energy sources has gained significant momentum due to growing concerns over climate change and the limited availability of conventional fossil fuels. Among the various alternative energy sources, solar energy stands out as a rich and abundant resource with the potential to transform the global energy system. The rapid development of solar technology aims to fully harness solar power, driven by the ongoing search for advanced materials and innovative device architectures. In this regard, nanostructured hybrid nanocomposites have been given attention as potential materials for enhancing the performance of solar systems with high efficiency, versatility, and functionality. Nanocomposites, which consist of nano-sized fillers within a matrix, offer unique properties due to their increased surface area and synergistic interactions. Their use of solar energy can greatly improve efficiency and sustainability. Hybrid nanocomposites, in particular, exhibit distinctive physicochemical properties at the nanoscale, which differ from their bulk counterparts. These materials hold great promise for advancing the capabilities of solar technologies by enhancing energy conversion and harvesting devices. This review provides recent progress in designing, making, and using nanocomposites for solar energy technologies. This review examines the nanostructured hybrid nanocomposites in next-generation solar systems, covering their development, synthesis, and potential applications in photocatalysis, energy storage, and solar cells. This review highlights the diverse applications of nanocomposites and advanced materials in solar energy technologies. Mei, Qin, and Agbolaghi [1] laid the foundation by discussing the potential of carbon-based nanocomposites in solar applications. Building on this, Collantes et al. [2] focused on developing stable perovskite nanocrystals, which play a crucial role in next-generation solar cells. Idumah [3] examined how conductive polymeric nanocomposites can enhance solar panel efficiency. Gorji and Ranjbar [4] introduced the concept of using nanofluids to enhance solar energy capture, demonstrating an innovative approach to boosting efficiency. Similarly, Irshad et al. [5] presented nanocomposites designed for solar desalination and power generation, offering a sustainable solution to energy and water resource challenges. Aslfattahi et al. [6] examined hybrid nanocomposites that improve energy efficiency in concentrated solar systems. In the context of environmental sustainability, Momina and Ahmad [7] investigated polymer nanocomposites for pollutant removal in solar energy production. Aggarwal et al. [8] reviewed strategies to enhance the efficiency of evacuated tube solar collectors, while Chandrasekaran et al. [9] explored hybrid nanomaterials for applications in solar aircraft, demonstrating the versatility of these materials. Alshuhail et al. [10] focused on improving thermal efficiency in solar systems through the use of nanofluids. Concurrently, Díez-Pascual [11] examined the broad applications of graphene-based nanocomposites in advancing solar cells and energy storage devices. Fan et al. [12] added to this by highlighting the potential of Titanium Carbide MXenes in solar technology. Expanding on these innovations, Abbas et al. [13] analyzed how nanofluids enhance photovoltaic thermal performance systems, while Kurc et al. [14] reviewed modern nanocomposites as electrode materials for energy storage, which is crucial for solar energy applications. Aljaerani et al. [15] further improved solar power technology by enhancing the properties of molten salts using nanoparticles. Focusing on the potential for solar-driven applications, Ismael [16] reviewed graphitic carbon nitride-based nanocomposites, which are promising for photocatalysis and other solar-related processes. Shen et al. [17] discussed graphene-polymer nanocomposites for energy storage, vital for integrating with solar panels, while Islam et al. [18] assessed the efficiency of hybrid nanocomposites in optimizing solar collectors. Nguyen et al. [19] addressed the pressing issue of carbon dioxide mitigation by presenting nanostructured semiconductors for CO2 conversion using solar energy. Graphene-based nanocomposites play a vital role in improving the efficiency of solar cells and energy storage devices, as highlighted by Xiang et al. [20]. In a related study, Nithiyanantham et al. [21] investigated the use of Al_2O_3 nanomaterials for thermal energy storage in concentrated solar power plants. Additionally, Wahab et al. [22] explored the potential of nanofluids to improve the performance of solar collectors and thermal storage systems. Javed, Sarfaraz, and Mahmood [23] developed a solar water purification system incorporating graphene-plasmonic nanocomposites to address water purification challenges in remote regions.

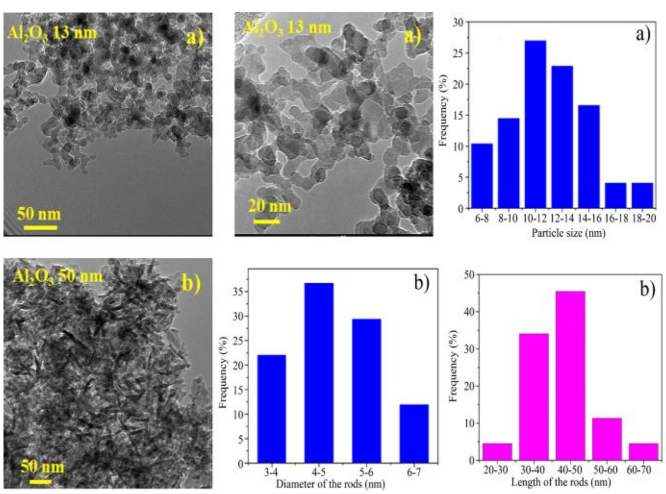

Fig. 1 TEM images of two distinct morphologies of Al_2O_3 nanomaterials, (a) Al2O3-13 nm, and (b) Al2O3-50 nm, together with the related histograms [21].

Javed, Sarfaraz, and Mahmood [23] developed a solar water purification system using graphene-plasmonic nanocomposites designed to address water purification challenges in remote areas. Luna-Sanguino et al. [24] investigated how the water matrix and oxidants affect the efficiency of pesticide removal using titania-reduced graphene oxide nanocomposites, contributing to more sustainable water treatment methods. Lonkar, Pillai, and Abdala [25] introduced a solvent-free method for synthesizing ZnO-graphene nanocomposites, which exhibit high photocatalytic activity and show promise for degrading pollutants through solar energy. Rajpurohit, Bhakar, and Nemiwal [26] focused on designing hybrid nanostructures that offer innovative solutions for both sustainable energy and environmental remediation. Muthu et al. [27] developed nanographene oxide/copper oxide nanocomposites that offer improved energy storage capabilities for solar systems, contributing to enhanced efficiency in energy storage solutions. Despite advances in solar cell technology, the efficiency and stability of these systems remain limited. Hybrid nanocomposites offer a promising solution by enhancing charge transfer, increasing surface area, and improving light absorption. However, challenges related to stability, scalability, and environmental impact need further exploration.

1.1. Novelty and Unique Contribution

The advancement of solar technologies has been extensively reviewed in the past, with precise attention on specific use in solar cells or photocatalysis. However, a comprehensive and integrated analysis of hybrid nanocomposites across multiple domains is lacking. Previous reviews have provided insights into individual applications but have not explored the comparative performance of various nanocomposites or discussed the synthesis techniques in depth. Moreover, environmental and safety considerations have often been overlooked. This review aims to bridge these gaps by offering a detailed examination of hybrid nanocomposites for solar energy use in solar cells, photocatalysis, and photoelectrochemical cells. The review provides a synthesis of the most recent developments and, introduces a comparative analysis of performance metrics, discusses environmental implications, and highlights future research directions. Furthermore, including diverse synthesis methods and their impact on nanocomposite properties offers a unique contribution to the field, making this review an essential reference for researchers and practitioners in solar technology.

2. Synthesis of Hybrid Nanocomposites

Synthesizing hybrid nanocomposites involves combining different nanomaterials to create materials with unique properties and improved functionalities. Various techniques are used, including Chemical Vapor Deposition (CVD), sol-gel synthesis, electrospinning, and chemical precipitation, each offering specific advantages and challenges based on the materials and applications. In-situ methods such as sol-gel, CVD, chemical precipitation, and hydrothermal/solvothermal synthesis involve forming or growing nanomaterials within or on the matrix. Ex-situ methods include physical mixing, electrostatic assembly, layer-by-layer deposition, and template-assisted synthesis, which involve combining pre-synthesized nanoparticles with the matrix or creating nanoscale structures (Figure 2).

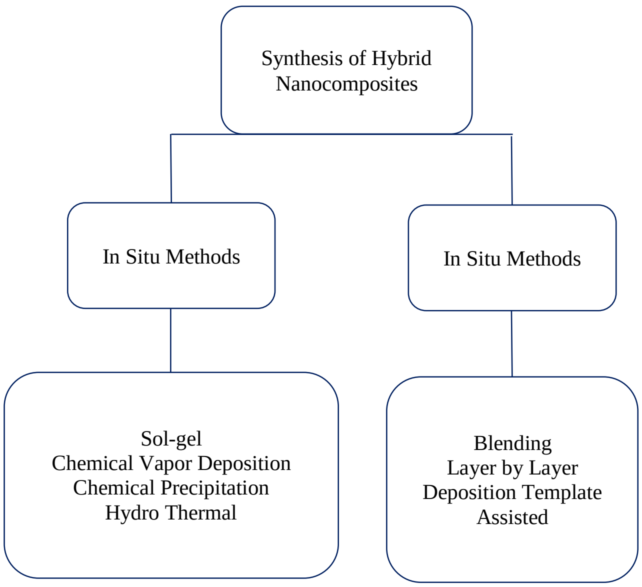

Fig. 2 In-Situ and Ex-Situ methods of nanocomposites

Nanocomposites can be synthesized through surface modification, mechanical processing, electrochemical, and template-based methods. They are classified into inorganic-inorganic (e.g., ceramic-metal and metal-metal composites) and inorganic-organic hybrids (e.g., polymer-ceramic and polymer-metal composites), each tailored to enhance specific properties for diverse applications (Figure 3).

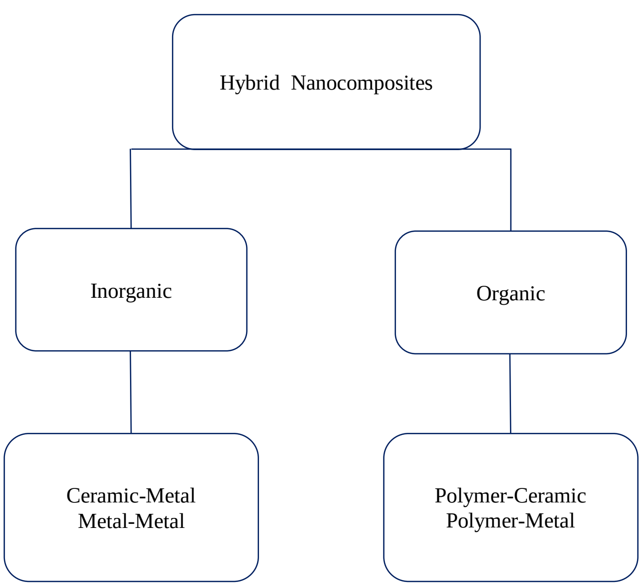

Fig. 3 Classification of hybrid nanocomposites

The classification of hybrid nanocomposites varies with research fields and applications, leading to ongoing innovations. Chu et al. [28] developed a Bi-Bi2O3/C hybrid nanocomposite with excellent photocatalytic properties for environmental and solar energy applications.

Hezam et al. [29] created a hybrid nanocomposite of $NiFe_2O_4$, MWCNTs, and ZnO with useful structural, optical, and magnetic properties for photocatalytic and magnetic applications. Behera et al. [30] reported a ZnO-Ag plasmonic nanocomposite effective in degrading industrial pollutants.

Varghese et al. [31] introduced CuS-ZnS graphene nanocomposites with notable photocatalytic capabilities for environmental and energy applications. Vignesh et al. [32] developed GNS-MnS hybrid nanocomposites for improved electrochemical energy storage. Alasti Bonab et al. developed silica aerogel/polyurethane hybrid foams, which offer potential applications in insulation and lightweight structural materials.

Giri et al. [34] synthesized a biopolymer-based hydrogel nanocomposite with promising electrochemical properties for biomedical and energy storage uses. Mariappan et al. [35] produced rGO/polypyrrole/ferrites nanocomposites with excellent electrochemical performance for supercapacitors. Qi et al. [36] fabricated SiO2-filled hybrid nanocomposites suitable for erosion-corrosion and radiation resistance in protective coatings (Figure 4). Table 1 summarizes the findings, materials and synthesizing methods of various hybrid nanocomposites.

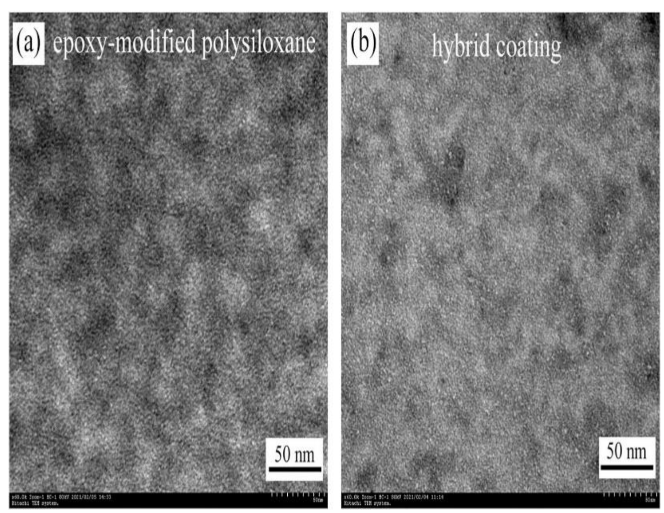

Fig. 4 TEM images of a polysiloxane treated with epoxy and a hybrid coating made of 60% SiO_2 [36]

These studies highlight the progress and potential of hybrid nanocomposites in energy storage, environmental remediation, biomedical applications, and materials science. Ongoing research continues to drive innovations and enhance material performance.

Table 1. Various methods of synthesis and review reports on hybrid nanocomposites

Authors	Materials	Synthesis Method	Outcomes
R. Shu et al. [37]	Reduced graphene oxide/zinc ferrite hybrid nanocomposite	Solvothermal route	High-performance microwave absorption
M. Shayan, B. Eghbali et al [38]	AA2024-(SiO_2np+TiO_2np) hybrid nanocomposite	Stir casting process	Improved mechanical properties
X. Huang et al. [39]	Bimetallic hybrid nanocomposite	Biological synthesis	Photocatalyst, adsorption/desorption, antimicrobial
C. V. Reddy, B. Babu, and J. Shim[40]	CdO/ZnO hybrid nanocomposite	Simple co-precipitation technique	Optical properties, photocatalytic activity
R. Ouarsal, M. Lachkar et al [41]	Hybrid phosphite nanocomposite	Solution process	Synthesis, characterization, and potential applications
J. S. Sanchez, A. Pendashteh et al. [42]	$NiMnO_3$-rGO nanocomposites	Hydrothermal rout	Electrode materials for energy storage
N. Badi, A. S. Roy et al [43]	Polyaniline/graphene oxide/sulfur nanocomposite fibers	Ice nucleation method	Cathode materials for lithium-sulfur battery
S. Dabees, A. B. Elshalakany et al [44]	High-density polyethylene-based nanocomposites	Magnetic stirring-twin screw extrusion	Enhanced surface energy, tribological, and electrical properties
J. López-Barroso et al. [45]	Hybrid carbon-epoxy nanocomposites	Report on polymeric composites of epoxy matrix reinforced with 1D and 2D nanocarbon allotropes.	Improvements in thermomechanical and electrical behavior
V. Jabbari, J. M. Veleta et al [46]	Magnetic MOF@GO and MOF@CNT hybrid nanocomposites	Green synthesis	High adsorption capacity towards organic pollutants
N. Raman, S. Sudharsan et al [47]	Inorganic-organic hybrid nanocomposites	Reports on processing techniques of inorganic-organic hybrid nanocomposites	Synthesis and structural reactivity
E. Askari et al. [48]	Bioceramic nanocomposites	In-situ synthesis	Adjustable physicochemical and biological characteristics
E. Parthiban, N. Kalaivasa et al 49]	Polyaniline/itaconic acid/Fe_3O_4 hybrid nanocomposite fibers	Polymerization reaction	Magnetic, antibacterial, and antifungal behavior
M. Isacfranklin et al. [50]	NiO-CoO hybrid nanocomposite	Hydrothermal	High-energy supercapacitor applications
Y. Wu, Y. Zang et al [51]	Conjugated microporous polymer/TiO_2 nanocomposites	In situ Sonogashira polymerization	High-performance photocatalytic antibacterial nanocomposites
F. A. Hezam, A. Rajeh et al [52]	Spinel ferrites/MWCNTs hybrid nanocomposites	Hydrothermal method	Energy storage and photocatalytic applications
A. Mushtaq et al. [53]	Magnetic hydroxyapatite nanocomposites	Review report on the development of MHAp nanocomposite	Advances from synthesis to biomedical applications
M. Zeng et al. [54]	Multicomponent multifunctional inorganic core@mesoporous silica shell nanocomposites	Scalable synthesis based on sol-gel process	Various potential applications, including drug delivery and catalysis

3. Hybrid Nanocomposites in Photocatalysis

Photocatalysis is an emerging technology with significant potential for environmental and energy applications. It is used in processes such as water purification, air cleaning, hydrogen production, and carbon dioxide reduction. Hybrid nanocomposites combine various nanomaterials and enhance photocatalysis by improving charge separation and solar energy utilization. Materials like semiconductor-metal or semiconductor-carbon combinations, along with stabilizing agents such as graphene or metal oxides, boost photocatalytic performance and stability. Prakash et al. [55] investigated noble metals-TiO2 nanocomposites, highlighting their efficiency and antibacterial properties (Figure 5). Mohammad et al. [56] reviewed how visible light-responsive nanocomposites enhance photocatalytic and photoelectrochemical performance. Kumar Maji et al. [57] demonstrated the potential of magnetic nanohybrids for effective photocatalysis and water splitting. Lonkar et al. [58] examined the solvent-free synthesis of ZnO-graphene nanocomposites exhibiting high photocatalytic activity. Khan et al.[59] investigated CdS-graphene nanocomposites for applications utilizing visible light. Gao et al. [60] studied electromagnetic induction in metal-semiconductor core-shell hybrids to improve charge separation. Table 2 summarizes the materials and synthesizing methods of various hybrid nanocomposites for the photocatalysis process.

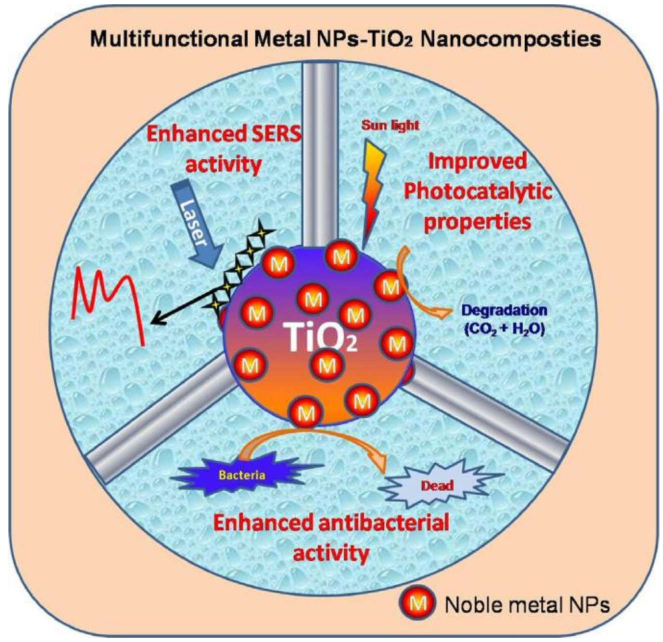

Fig. 5 TiO_2 nanocomposites multifunctional application [55]

Table 2. Materials and synthesizing methods of various hybrid nanocomposites for the photocatalysis process

Authors	Materials	Synthesis Methods	Key Findings
H. Dang et al. [61]	Au/SiC nanocomposites	Facile deposition-precipitation method	Enhanced photocatalytic and photoelectrochemical performance
Kment et al. [62]	FeO-based nanostructures	photoelectrochemical water splitting	Explored FeO-based structures for clean energy production.
M. Ismael et al. [63]	Graphitic carbon nitride (g-C_3N_4)	solar energy and remediation	Synthesis, categories, and applications of g-C_3N_4 in photocatalysis.
U. Abdullah, M. Ali et al. [64]	CdS nanostructures and hybrids	photo and electrocatalytic applications	Advancements in CdS nanostructures for photocatalysis and electrocatalysis.
S. Shabna et al. [65]	SnO_2 nanostructures	Organic pollutant degradation	SnO_2's potential for enhancing photocatalytic degradation of pollutants.
M. Mehta et al. [66]	MoS_2-TiO_2 nanocomposite	Two-step hydrothermal synthesis	Synthesized MoS_2-TiO_2 for better photocatalytic and photoelectrochemical performance.
X. A. Leontyeva et al. [67]	Semiconductor bismuth sulfide iodide	synthesis methods for photovoltaic devices	BiSI and $Bi_{13}S_{18}I_2$ for photoelectrochemical applications.
N. M. El-Shafai et al. [68]	Copper oxide	Heterojunction process	Enhanced electrochemical properties and photocurrent for photocatalytic and solar cell applications.
D. Aguilar-Ferrer et al. [69]	Polydopamine-based nanocomposites	Photocatalytic properties	Energy production with polydopamine-based composites.
A. Farhan et al. [70]	Metal ferrites-based nanocomposites	Fe_2O_3 photocatalysts and electrocatalysts	Potential for photocatalytic water treatment and electrocatalytic water splitting.
S. A. Ansari et al. [71]	Ag@m-TiO_2 nanocomposite	Fabrication and characterization by XRD and	Explored Ag@m-TiO_2 for visible light photocatalytic and photoelectrochemical

		TEM	performance.
X. Zheng et al. [72]	3D Au/ZnO hybrid inverse opal	In-situ process	Regulated charge transfer for efficient photocatalytic degradation and water splitting.
M. Batool et al. [73]	Bismuth-based heterojunction nanocomposites	Co-precipitation and hydrothermal synthesis	Bismuth-based heterojunctions for photocatalysis and heavy metal detection.
K. R. Reddy et al. [74]	Titanium dioxide (TiO_2)	Overview of TiO_2-based hybrids	TiO_2 hybrid nanostructures for enhanced photocatalysis and environmental remediation.
W. Nabgan et al. [75]	Nanostructure-based materials	Review of nanoporous materials	Design for photoelectrochemical hydrogen generation from wastewater.
S. Shafique et al. [76]	V_2O_5/rGO hybrid nanocomposites	Hydrothermal method	Improved performance for photodetector applications.
S. W. Hu et al. [77]	Graphitic carbon nitride (g-C_3N_4) with Ag doping	Thermal polymerization	Enhanced photoelectrochemical activity with g-C_3N_4 via in situ Ag doping.

The research in this table shows the wide-ranging and cross-disciplinary nature of nanocomposites, photocatalysis, and photoelectrochemical applications.

4. Hybrid Nanocomposites in Solar Cell Applications

Solar energy is of considerable interest as a clean and renewable power source. To fulfill these needs, hybrid nanocomposites are potential materials when compared to conventional solar cell materials. The investigation on the effect of hybrid nanostructured materials in various types of solar cells, such as perovskite solar cells, organic/silicon hybrid solar cells, Dye-Sensitized Solar Cells (DSSCs) and more is ongoing recent research in recent years.

Solar energy is increasingly valued as a clean and renewable power source, with hybrid nanocomposites emerging as promising materials compared to traditional solar cell materials. Recent research explores the impact of these hybrid nanostructures on various types of solar cells, including perovskite, organic/silicon hybrid, and Dye-Sensitized Solar Cells (DSSCs).

Ghosh et al. [78] examined how nanostructures affect perovskite solar cells, which are noted for their high efficiency. Liu et al. [79] studied the role of silver nanoparticles and silicon nanoholes in enhancing the efficiency of organic/silicon hybrid solar cells through localized surface plasmon resonance. Sireesha et al. [80] developed a new hybrid nanocomposite with multi-walled carbon nanotubes and Ti_2O_3 to improve DSSC efficiency (Figure 6).

Verma et al. [81] explored using ZnO nanostructures in DSSCs for better photocatalytic remediation. Khan et al. [82] reviewed graphene/inorganic nanocomposites for their potential in solar energy conversion and environmental applications. Krishnamoorthy and Prakasam [83] created a MoS2/graphene nanocomposite-based photoanode to boost DSSC performance. Gao et al. [84] used computational methods to study the effectiveness of tetraphenyl porphyrin and graphene quantum dots as sensitizers in solar cells. Sadegh et al. [85] synthesized a superparamagnetic Fe_3O_4@PANI (polyaniline) nanocomposite to enhance solar cell efficiency. El-Shafai et al. [86] improved copper oxide's electrochemical properties and photocurrent through a heterojunction process for better photocatalytic and solar cell applications.

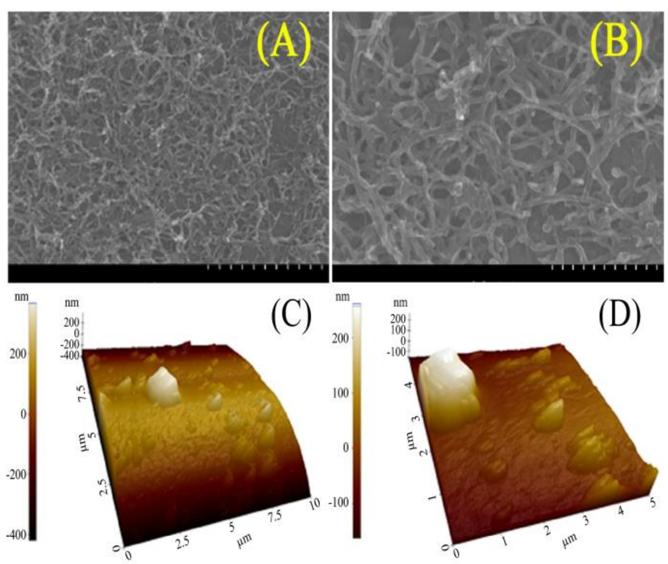

Fig. 6 - MWCNTs-PIN/Ti_2O_3 hybrid nanocomposite morphology by (A, B) field emission scanning electron microscope, and (C, D) atomic force microscopy [80]

Table 3 summarizes the materials and synthesis methods of these hybrid nanocomposites.

Table 3. Materials and synthesizing methods of various hybrid nanocomposites or solar cell applications

Authors	Materials	Synthesis Methods	Key Findings
P. S. Ramaripa et al. [87]	Phthalocyanine nanowire dye, TiO_2-MOF composite	Adsorption technology	Impact of nanowire dye on the performance of TiO_2-MOF nanocomposites
N. A. Shad et al. [88]	Bi_2WO_6/rGO nanocomposites	Facile synthesis method	Bi_2WO_6/rGO nanocomposites for enhanced photocatalytic and solar cell efficiency.
U. Ali, A. A. Qureshi et al. [89]	Ag-doped ZnO, Graphene oxide nanocomposite	Spin-coating	Improved electron extraction in perovskite solar cells
G. Sankar, P. Anbarasu et al. [90]	$CoNi_2S_4$/rGO nanocomposites	One-step hydrothermal process	Efficient Pt-free counter electrodes for dye-sensitized solar cells.
F. Babar et al. [91]	$CoNi_2S_4$/rGO nanocomposites	Review of DSSC performance	Photo anode materials for dye-sensitized solar cells.
N. M. El-Shafai et al. [92]	TiO_2-ZnO hybrid nanocomposite, Graphene oxide	Hybrid nanocomposite synthesis	Applications in solar cells, water treatment, and electrochemical properties.
A. Mezni et al. [93]	Plasmonic platinum-titania nanocomposites	Solvothermal wet chemical process	Self-cleaning applications using solar light with plasmonic nanocomposites.
R. Savari et al. [94]	Sr-doped ZnO-reduced graphene oxide nanocomposites	DSSCs using nanocomposites	Dye-sensitized solar cells with Sr-doped ZnO/rGO photo-anodes.
R. Gayathri, P. Rajeswaran et al. [95]	WO_3 nanotubes/graphene oxide hybrid structures	One-step microwave irradiation	Solar conversion efficiency in dye-sensitized solar cells.
L. Abdullatif Alshuhail, F. Shaik et al. [96]	Hybrid nanoparticles and nanofluids	Review on synthesis	Thermal efficiency enhancements in solar thermal applications.
H. Ran, J. Fan et al. [97]	Au-TiO_2 and Ag-TiO_2 plasmonic hybrid nanocomposites	Incorporation into TiO_2 composites	Dye-sensitized solar cell performance with plasmonic hybrid nanocomposites.
K. Fatima, A. H. Pandith et al. [98]	Metal Oxide@Graphene-decorated D−π1-π2 nanocomposites	Study on Sb_2O_3-decorated graphene	DFT studies for efficient light-harvesting in dye-sensitized solar cells.
B. Chen, Z. Yang et al. [99]	Metal-Organic Frameworks (MOFs) and derivatives	Review on MOFs	Advances and challenges of MOFs in solar cell applications.
N. Al Abass, T. F. Qahtan et al. [100]	ZnO/ZnSe hybrid nanostructured films	Laser-assisted synthesis	Developed films for enhanced solar-induced water splitting and decontamination.
H. Y. Abbasi, A. Habib et al. [101]	ZnO and ZnO/Graphene nanocomposites	Wet chemical route	Nanostructures for potential use in hybrid solar cells.
S. Noori, A. R. Kiasat et al. [102]	Rice husk silica-anchored cinchonine Pd nanocomposite	Eco-friendly method	Eco-friendly protocol for the Heck reaction under solar radiation.
A. Ramar, R. Saraswathi et al. [103]	TiO_2/polyisothianaphthene hybrid nanocomposite	Adsorption and blending	Efficient photoanode for dye-sensitized solar cells.
W. Mekprasart, W. Jarernboon et al. [104]	TiO_2/CuPc hybrid nanocomposites	Low-energy ball milling	Hybrid nanocomposites for dye-sensitized solar cell applications.

5. Conclusion

In conclusion, nanostructured hybrid nanocomposites represent a significant advancement in the field of solar technology, offering the potential to revolutionize energy harvesting through their multifunctional properties and superior performance. This comprehensive review underscores the importance of continued research in synthesis techniques and material optimization to address the challenges and unlock the full potential of these materials. As the demand for sustainable energy solutions intensifies, the development and application of hybrid nanocomposites will be crucial for advancing next-generation solar technologies, paving the way for more efficient and effective energy systems.

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