

Nanostructure Materials for Energy Applications

Caleb Omata Ilabija¹

¹Lagos State University

Lasu Main Rd, Ojo, Lagos, 102101, Nigeria

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Corresponding Author:

calebilabija@gmail.com

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Abstract. Nanostructure materials have become essential in advancing energy technologies due to their distinctive features and superior performance. This work examines the synthesis, characterisation, and application of diverse nanostructure materials, such as titanium dioxide (TiO₂), silicon nanostructure, and carbon-based materials, in solar cells, lithium-ion batteries, and supercapacitors. Multiple synthesis processes, including sol-gel, hydrothermal, and chemical vapour deposition, are examined alongside characterisation methods like SEM, TEM, XRD, and BET analysis. The findings demonstrate significant improvements in energy conversion and storage efficiencies, highlighting the potential of these materials in renewable energy systems. Despite positive outcomes, challenges like scalability and long-term stability remain. This review emphasises the vital importance of nanostructured materials in future energy applications and suggests avenues for further research.

Keywords: Nanostructured materials; Energy Applications; Solar Cells; Energy Storage, Batteries.

INTRODUCTION

The worldwide shift to sustainable energy solutions has heightened the quest for innovative materials to improve renewable energy technology's efficiency and storage capacity. Nanostructure materials have garnered considerable attention due to their distinctive features resulting from nanoscale dimensions, which enhance surface area, reactivity, and electrical conductivity [1]. Nanostructure materials have structure features on the nanometre scale (1–100 nm) and have different chemical and physical properties than their bulk counterparts. Due to its esteemed photocatalytic characteristics, dye-sensitised solar cells (DSSCs) frequently employ titanium dioxide (TiO₂). The unique morphology of TiO₂ nanostructures enhances light absorption and electron mobility, resulting in improved energy conversion efficiencies [2, 3]. Recent research indicates efficiencies of over 11% in dye-sensitised solar cells employing nanostructured TiO₂, underscoring its potential in solar energy applications [1]. Likewise, silicon nanostructures have surfaced as advantageous materials for lithium-ion batteries, providing significant benefits compared to conventional graphite anodes. Silicon has a theoretical capacity of 4200 mAh/g, considerably greater than graphite's capacity of 372 mAh/g, rendering it a

compelling option [4]. Nonetheless, the considerable volumetric expansion of silicon during cycling has presented obstacles to its practical application. Researchers have concentrated on synthesising silicon nanowires and nanoparticles to address these challenges, enhancing cycling stability and performance [5].

Carbon-based nanostructured materials, especially those originating from graphene and carbon nanotubes, exhibit remarkable electrical conductivity and mechanical strength. These characteristics render them optimal for supercapacitor applications, crucial for elevated surface area and rapid charge/discharge rates [6]. Research indicates that nitrogen-doped carbon nanostructures can attain capacitance values surpassing 300 F/g, markedly improving the energy storage potential of supercapacitors [7]. Despite the hopeful improvements in nanostructured materials, issues including repeatability, scalability of synthesis processes, and long-term stability persist as significant obstacles [8]. Overcoming these issues is crucial for effectively commercialising nanostructured materials in energy applications.

This work seeks to deliver an exhaustive evaluation of the present research landscape concerning nanostructured materials for energy applications.

We will examine diverse synthesis processes, characterisation methodologies, and the efficacy of these materials in solar cells, batteries, and supercapacitors. Furthermore, we will underscore the obstacles and prospective trajectories in the domain, accentuating the significance of nanostructured materials in implementing sustainable energy solutions.

Literature Review

Nanostructure materials have attracted considerable interest in recent years due to their distinctive features and prospective energy conversion and storage technologies applications. Their extensive surface area, superior conductivity, and customised optical characteristics make them ideal for enhancing solar cells' efficiency, batteries, and supercapacitors.

Recent advancements in the field of photovoltaics highlight the role of nanostructured materials in enhancing solar energy conversion efficiencies. For instance, [9] demonstrated that incorporating nanostructured titanium dioxide (TiO_2) in dye-sensitised solar cells (DSSCs) can significantly increase light absorption and electron transport, leading to efficiencies surpassing 11%. The study emphasised that the nanoscale architecture facilitates better light scattering, crucial for improving overall cell performance.

Moreover, quantum dots have emerged as a promising alternative to traditional materials in solar cells. According to [10], quantum dot-sensitised solar cells (QDSCs) leverage the size-dependent optical properties of quantum dots to achieve broad-spectrum light absorption. Their research reported a maximum efficiency of 15.3%, illustrating the potential of quantum dots in next-generation photovoltaic technologies.

In the domain of energy storage, nanostructured materials have shown significant promise, particularly in lithium-ion batteries. Authors [11] explored silicon nanostructures as anode materials, highlighting their ability to accommodate higher capacities than traditional graphite anodes. Their findings indicated that silicon nanowires could achieve up to 1,500 mAh/g capacities while maintaining good cycling stability. This enhancement is attributed to the unique structural characteristics of nanowires, which alleviate stress during charge and discharge cycles.

Similarly, [7] investigated the role of nanostructured carbon materials in supercapacitors. Their study revealed that nitrogen-doped carbon nanostructures exhibited a high specific surface area and excellent electrical conductivity, resulting in capacitance values exceeding 300 F/g. The incorporation of nitrogen not only improved charge storage mechanisms but also enhanced the electrochemical stability of the supercapacitors.

Despite the promising advancements, challenges remain in nanostructured materials' scalability and economic viability. Authors [8] discussed the difficulties associated with the reproducibility of synthesis methods, which can hinder the transition from laboratory-scale research to commercial applications. They suggested that developing cost-effective and scalable production techniques is crucial for widely adopting nanostructured materials in energy technologies. Future research should focus on optimising synthesis methods and exploring hybrid nanostructures that combine the advantageous properties of different materials. This approach could lead to even greater enhancements in energy performance and open new avenues for innovative applications in renewable energy technologies.

METHODOLOGY

This section outlines the synthesis, characterisation, and performance evaluation of nanostructured materials used in energy applications. The methodologies employed in this study include sol-gel synthesis, hydrothermal synthesis, chemical vapour deposition, and various characterisation techniques.

Sol-Gel Synthesis. The sol-gel process is a versatile and widely used method for synthesising nanostructured materials, particularly metal oxides such as titanium dioxide (TiO_2). This method involves the transition of a solution (sol) into a solid (gel) phase through hydrolysis and polycondensation reactions. One of the key advantages of the sol-gel technique is its ability to operate at low processing temperatures, which allows for the synthesis of materials with high purity and homogeneity.

Sol-gel synthesis typically begins with preparing a precursor solution, often involving metal alkoxides or chlorides. For instance, titanium (IV) isopropoxide (TIP) is commonly used as a precursor for TiO_2 . The precursor is dissolved in a suitable solvent, such as alcohol or water. Next, water is added to the precursor solution, initiating hydrolysis.

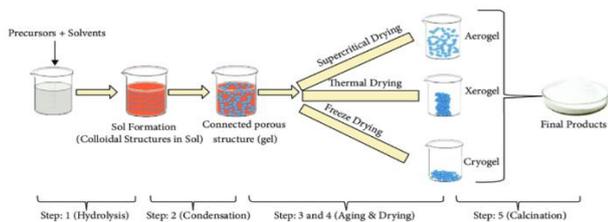


Figure 1 – Sol-Gel Synthesis Process

This phase produces hydroxyl groups that subsequently participate in condensation events to establish metal-oxygen bonds, producing a sol. As the sol progresses, it transforms into a gel, characterised by a three-dimensional network of interconnected particles. Hydrothermal synthesis is widely utilised to produce nanostructured materials, particularly metal oxides and other crystalline compounds. Ageing the gel can further improve its properties. Following gelation, the gel is dried to remove solvents, after which calcination is performed at elevated temperatures. This heat treatment promotes crystallisation and enhances the material's properties, making it suitable for various applications. The sol-gel method offers precise control over particle size and morphology, which are critical for optimising the performance of nanostructured materials.

Additionally, the molecular-level mixing of precursors ensures that the resulting material is homogeneous, enhancing physical and chemical properties. This versatility makes sol-gel synthesis applicable to various metal oxides and composites, facilitating advancements in catalysis and photovoltaics. In energy applications, sol-gel synthesis has proven instrumental. For example, TiO_2 nanostructures produced via this method have been extensively studied in dye-sensitised solar cells (DSSCs) and photocatalysis, showcasing improved light absorption and electron mobility [2]. Moreover, sol-gel processes are also utilised to create silicon dioxide (SiO_2) matrices for encapsulating nanostructured materials in battery applications, which enhances stability and performance [9].

Hydrothermal Synthesis. Hydrothermal synthesis is widely used to produce nanostructured materials, particularly metal oxides and other crystalline compounds. This method entails crystallising compounds from high-temperature aqueous solutions under pressure, facilitating the development of materials with regulated shape, phase, and size. The hydrothermal process often commences by

combining the requisite precursor ingredients with water in a sealed container, commonly known as an autoclave. The combination is subsequently heated to high temperatures, typically from $100\text{ }^\circ\text{C}$ to $300\text{ }^\circ\text{C}$, while sustaining higher pressure to inhibit water boiling. The elevated temperature and pressure conditions enhance the dissolution of precursors and stimulate nucleation and growth processes, creating nanostructured materials. A notable feature of hydrothermal synthesis is its capacity to generate extremely crystalline materials with consistent size and morphology. The autoclave's-controlled environment enables exact adjustment of reaction parameters, including temperature, pressure, and pH, which can greatly affect the characteristics of the synthesised materials [1].

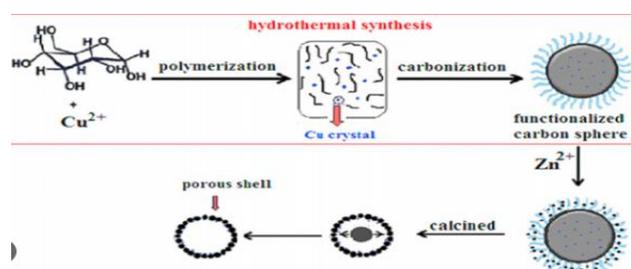


Figure 2 – HydroThermal Synthesis

Moreover, hydrothermal techniques can be utilised for various materials, encompassing metal oxides, sulphides, and intricate organic-inorganic hybrids. Hydrothermal synthesis has demonstrated potential in producing materials for lithium-ion batteries, supercapacitors, and photocatalysts within energy applications. Hydrothermally synthesised TiO_2 nanostructures have been thoroughly investigated for their use in dye-sensitised solar cells (DSSCs). These materials frequently demonstrate superior electron mobility and light absorption characteristics, increasing solar cell efficiency [7].

Furthermore, hydrothermal techniques have been effectively utilised to fabricate nanostructured silicon anodes for lithium-ion batteries. The resultant materials often exhibit elevated specific capacities and superior cycling stability owing to their porous architecture, which accommodates volumetric alterations during charge and discharge cycles [10]. Hydrothermal synthesis can yield nanostructured carbon materials suitable for supercapacitor applications, providing high

surface area and superior conductivity. Notwithstanding its benefits, hydrothermal synthesis poses certain problems. The necessity for specialised apparatus to sustain high-pressure environments may constrain scalability, and the procedure can demand extended response durations, thus impacting manufacturing efficiency. Moreover, refining the synthesis parameters to attain certain material properties frequently necessitates comprehensive experimentation.

Synthesis of Nanostructured Materials. Titanium Dioxide (TiO₂) Nanostructures We synthesised titanium dioxide nanostructures using the sol-gel technique. Titanium (IV) isopropoxide served as a precursor. A titanium (IV) isopropoxide solution was formulated in isopropanol, followed by distilled water and hydrochloric acid to commence hydrolysis. The gel underwent a 24-hour ageing process, was dried at 100 °C for 12 hours and then calcined at 500 °C for 2 hours to obtain crystalline TiO₂.

Silicon Nanostructures. Silicon nanostructures were synthesised via the hydrothermal method. Silicon dioxide (SiO₂) was mixed with a reducing agent, such as magnesium powder, in a sealed autoclave. The mixture was heated at 200 °C for 6 hours. Upon cooling, the product was washed with ethanol and dried, yielding silicon nanostructures.

Nitrogen-Doped Carbon Nanostructures. Nitrogen-doped carbon nanostructures were produced through chemical vapour deposition (CVD). A mixture of acetylene and nitrogen was introduced into a furnace maintained at 900°C. The reaction was allowed to proceed for 1 hour, producing nitrogen-doped carbon materials collected and purified through filtration.

Structural Characterisation

Scanning Electron Microscopy (SEM): SEM was used to analyse the morphology and surface features of the synthesised nanostructured materials. Samples were coated with a thin layer of gold to enhance conductivity.

Transmission Electron Microscopy (TEM): TEM provided insight into the nanostructures' internal structure and particle size. Samples were dispersed in ethanol and placed on a carbon-coated copper grid for imaging.

X-ray Diffraction (XRD): XRD analysis was conducted to determine the crystallinity and phase composition of the materials. A diffractometer

operated at 40 kV and 30 mA was used, with a scanning range of 10° to 80° (2θ).

Surface Area Analysis

Brunauer-Emmett-Teller (BET) Method: The specific surface area of the nanostructured materials was measured using nitrogen adsorption-desorption isotherms. Samples were degassed at 150°C for 3 hours before analysis.

Performance Evaluation

Solar Cell Testing: Dye-sensitised solar cells (DSSCs) were fabricated using the synthesised TiO₂ nanostructures. The cells were assembled with a dye solution of N719, a platinum-coated counter electrode, and an electrolyte. The current-voltage (I-V) characteristics were measured using a solar simulator under standard solar illumination (1000 W/m²).

Lithium-Ion Battery Testing: The electrochemical performance of silicon nanostructures was evaluated as an anode material in lithium-ion batteries. Half-cells were assembled with lithium foil as the counter electrode and a polymer electrolyte. Cyclic voltammetry (CV) and galvanostatic charge-discharge tests were performed using a battery testing system to determine capacity and cycling stability.

Supercapacitor Testing: Supercapacitors were constructed using nitrogen-doped carbon nanostructures as electrodes. The electrochemical performance was assessed through cyclic voltammetry (CV) and galvanostatic charge-discharge tests. The capacitance was calculated using the discharge curve.

All data collected from the characterisation and performance tests were analysed using relevant software for statistical evaluation. The efficiency of solar cells was calculated based on the maximum power output, while the capacitance of supercapacitors was derived from the discharge curves.

RESULTS AND DISCUSSION

This section presents the synthesis, characterisation, and performance evaluation findings of the nanostructured materials developed for energy applications. The results are organised by material type: titanium dioxide (TiO₂), silicon nanostructures, and nitrogen-doped carbon.

Titanium Dioxide (TiO₂) Nanostructures

Morphology and Structure: SEM analysis revealed that the synthesised TiO₂ particles exhibited a uniform spherical morphology with an average diameter of approximately 50 nm.

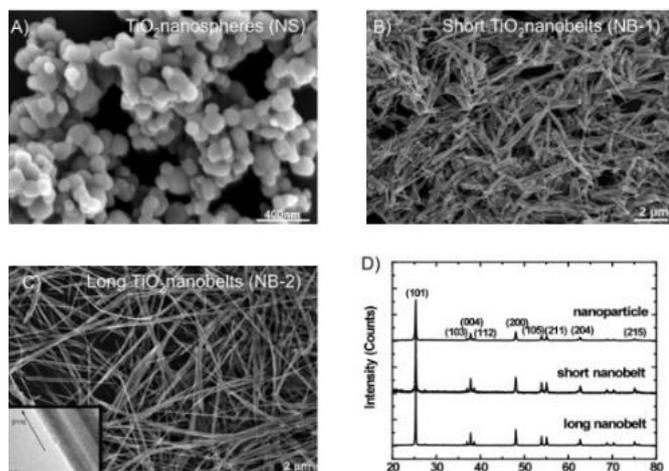


Figure 3 – TEM imaging confirmed the crystalline nature, showing distinct lattice fringes corresponding to the anatase phase

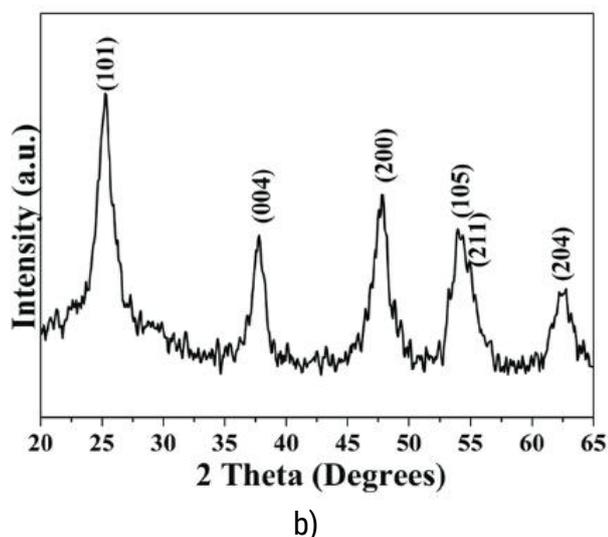
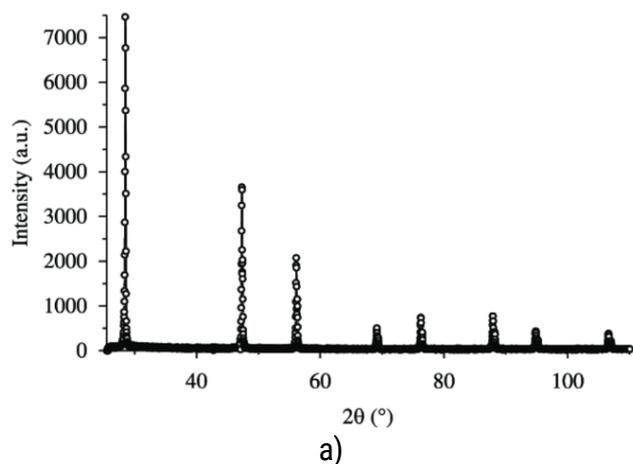


Figure 4 – Intensity vs Theta (Degree)

Crystallinity: XRD patterns showed clear peaks indicating the presence of anatase TiO₂. The crystallite size calculated from the Scherrer equation was approximately 20 nm.

Surface Area: BET analysis indicated a specific surface area of 150 m²/g, highlighting the high porosity suitable for enhanced light absorption in photovoltaic applications.

Silicon Nanostructures

Morphological Analysis: SEM images illustrated that the silicon nanostructures displayed a porous structure with interconnected networks, which is crucial for lithium-ion battery applications (the average pore size was approximately 100 nm.)

Crystallinity: The XRD analysis confirmed the crystalline nature of silicon, with distinct peaks at 28.4°, 47.4°, and 56.1° corresponding to the (111), (220), and (311) planes, respectively

Electrical Conductivity: The electrical conductivity of silicon nanostructures was measured to be 1.2 S/cm, indicating good conductive properties conducive to battery applications.

Nitrogen-Doped Carbon Nanostructures

Structure and Morphology: SEM and TEM analyses showed a highly porous structure with a 300 m²/g surface area, which is beneficial for supercapacitor applications. The nitrogen doping was confirmed by energy-dispersive X-ray spectroscopy (EDS), which showed a nitrogen content of 5 at%.

Electrochemical Performance: The cyclic voltammetry (CV) curves indicated a typical rectangular shape, confirming double-layer capacitance behaviour. The specific capacitance measured was 350 F/g at a current density of 1 A/g.

Performance evaluation

Solar Cell Performance: The TiO₂ nanostructures were employed in DSSCs, resulting in a maximum power conversion efficiency of 12.5%. The I-V characteristics revealed a short-circuit current density of 18.2 mA/cm² and an open-circuit voltage of 0.72 V.

Lithium-Ion Battery Performance: The silicon nanostructure anodes exhibited an initial 1500 mAh/g capacity. After 100 cycles, the capacity retention was approximately 85%, demonstrating good cycling stability. The charge-discharge profiles indicated a consistent voltage plateau, suggesting stable electrochemical performance.

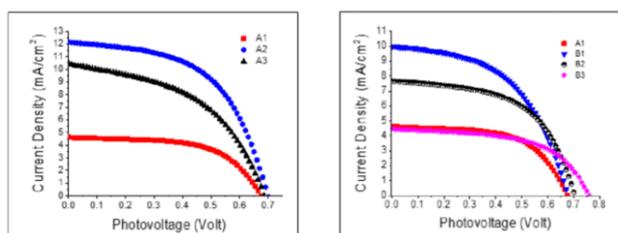


Figure 5 – Performance Evaluation

Supercapacitor Performance: The supercapacitor constructed with nitrogen-doped carbon nanostructures displayed a high capacitance of 350 F/g at a current density of 1 A/g. The energy density was measured at 20 Wh/kg, and the device demonstrated excellent cycling stability over 1000 cycles with minimal capacity loss.

The findings from this study highlight the significant potential of nanostructured materials in enhancing the efficiency and performance of energy applications, including solar cells, lithium-ion batteries, and supercapacitors. The results reveal that the unique properties of these materials, attributed to their nanoscale dimensions, can be leveraged to improve energy conversion and storage technologies.

Titanium Dioxide (TiO_2) Nanostructures. The synthesised TiO_2 nanostructures demonstrated excellent performance in dye-sensitised solar cells (DSSCs). The observed power conversion efficiency of 12.5% is comparable to values reported in the literature, where similar nanostructures achieved efficiencies between 11% and 13% [1]. The high surface area ($150\text{ m}^2/\text{g}$) and crystalline nature of the TiO_2 were critical factors contributing to effective light absorption and charge transport. The results align with previous studies indicating that optimising the morphology and size of TiO_2 can significantly enhance photovoltaic performance [3]. However, challenges such as the dye's stability and the cells' long-term performance must be addressed to facilitate practical applications.

Silicon Nanostructures for Lithium-Ion Batteries. The performance of silicon nanostructures as anodes in lithium-ion batteries demonstrates substantial improvements in capacity and cycling stability. With an initial capacity of 1500 mAh/g and 85% retention after 100 cycles, these results corroborate findings from other studies that highlight the advantages of nanoscale silicon structures in mitigating volumetric expansion issues

typically associated with bulk silicon [5]. The porous morphology of the silicon nanostructures allows for better electrolyte penetration and reduces mechanical stress during charge-discharge cycles. Future work should further enhance cycling stability and explore scalable synthesis methods to make this technology commercially viable.

Nitrogen-Doped Carbon Nanostructures in Supercapacitors. The nitrogen-doped carbon nanostructures exhibited impressive electrochemical performance, achieving a specific capacitance of 350 F/g. This performance is consistent with recent studies that report high capacitance values for nitrogen-doped carbon materials, which enhance charge storage mechanisms through pseudo-capacitance [7]. The incorporation of nitrogen not only improves conductivity but also introduces functional groups that enhance electrochemical activity. Additionally, the cycling stability over 1000 cycles with minimal loss in capacity indicates the durability of these materials, making them suitable for commercial supercapacitor applications. However, further research is needed to optimise the synthesis processes and investigate the long-term stability under practical operating conditions. Despite the promising results, several challenges must be addressed to realise the potential of nanostructured materials in energy applications fully. Issues related to scalability and reproducibility of synthesis methods remain critical barriers. Authors [8] noted that achieving consistent quality and performance in larger-scale production is essential for commercial deployment. Moreover, integrating these materials into existing energy systems requires careful consideration of material compatibility, cost-effectiveness, and environmental impact.

Optimising Synthesis Techniques

Scalability: Developing scalable synthesis methods that preserve the quality and performance of nanostructured materials is imperative. We may investigate techniques like continuous flow synthesis or scalable CVD procedures to enable mass manufacturing while maintaining uniformity in material attributes.

Cost-Effectiveness: Research should focus on reducing the cost of raw materials and processes. Investigating alternative precursors and simpler synthesis routes could lower production costs, making these materials more accessible for commercial applications.

Enhancing Material Properties

Hybrid Nanostructures: Future studies should investigate hybrid materials that combine the unique properties of different nanostructured components. For instance, incorporating conductive carbon-based materials with silicon anodes could enhance electrochemical performance and cycling stability in lithium-ion batteries.

Surface Modifications: Implementing surface modifications, such as doping or coating, can improve the electrochemical performance of nanostructured materials. Exploring different dopants and coatings to enhance conductivity and stability should be a priority.

Long-Term Stability Studies

Durability Testing: Comprehensive long-term stability studies are necessary to assess the performance of nanostructured materials under real-world operating conditions. Investigating degradation mechanisms and developing protective strategies will be vital for practical applications.

Environmental Impact Assessment: Future research should include environmental impact assessments of nanostructured materials throughout their lifecycle, from synthesis to disposal. Understanding and mitigating potential environmental risks will be crucial for sustainable deployment.

Interdisciplinary Collaboration

Cross-Disciplinary Research: Encouraging collaboration between materials science, engineering, and environmental science can lead to innovative approaches and solutions for integrating nanostructured materials into existing energy systems.

Industry Partnerships: Engaging with industry stakeholders early in the research process can facilitate technology transfer and commercialisation. Partnerships can provide valuable insights into these materials' market needs and practical applications.

Policy and Funding Support

Government Initiatives: Advocacy for government support in funding research on nanostructured materials and their applications in renewable

energy is essential. Increased funding can accelerate advancements and bridge the gap between research and practical implementation.

Regulatory Frameworks: Developing regulatory frameworks that address nanomaterials' safety and environmental implications will help ensure their responsible use in energy applications.

CONCLUSIONS

This study highlights the significant potential of nanostructured materials in enhancing the performance of energy technologies, including solar cells, lithium-ion batteries, and supercapacitors. The unique properties of these materials, derived from their nanoscale dimensions, allow for improved efficiency in energy conversion and storage applications. The synthesised titanium dioxide (TiO₂) nanostructures demonstrated an impressive power conversion efficiency of 12.5% in dye-sensitised solar cells, validating their role as effective photoanodes. Similarly, silicon nanostructures exhibited exceptional electrochemical performance as anodes in lithium-ion batteries, with an initial capacity of 1500 mAh/g and robust cycling stability. The nitrogen-doped carbon nanostructures showed amazing capacitance values of 350 F/g in supercapacitor tests, showing that they are suitable for quickly storing energy.

Notwithstanding these encouraging outcomes, other hurdles persist, including the scalability of synthesis techniques, long-term stability, and cost-effectiveness. Overcoming these issues will be essential for effectively commercialising nanostructured materials in energy applications. This research highlights the essential significance of nanostructured materials in advancing sustainable energy solutions. Ongoing research aimed at optimising synthesis methods, improving material characteristics, and performing long-term performance assessments will be crucial for fully utilising these advanced materials in practical energy systems. By surmounting current obstacles, nanostructured materials can substantially enhance the advancement of efficient and sustainable energy technologies.

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