DOI: 10.5281/zenodo.17131032

CHAPTER 11

Nanomaterials for Electrochemical Energy Conversion and Storage: Synthesis, Characterization, and Applications

Tanushree Manohar Sukul

Department of Chemistry, Savitribai Phule Pune University, Ganeshkhind, Pune 411007 Maharashtra, India

Corresponding author Email: sukul.tanushree@gmail.com

Received: 05 September 2025; Accepted: 10 September 2025; Available online: 16 September 2025

Abstract: The global demand for clean and sustainable energy technologies has accelerated research into advanced materials capable of efficient electrochemical energy conversion and storage. Due to their unique physicochemical properties, high surface-to-volume ratio, tunable electronic structure, and enhanced catalytic performance, nanomaterials have gained recognition as promising candidates for future energy technologies. This chapter provides a comprehensive review of nanomaterials tailored for electrochemical applications, with emphasis on their synthesis approaches, morphological and electrochemical analysis, and functional effectiveness in wide range of energy systems. Various top-down and bottom-up synthesis methods are explored, ranging from conventional chemical techniques to green

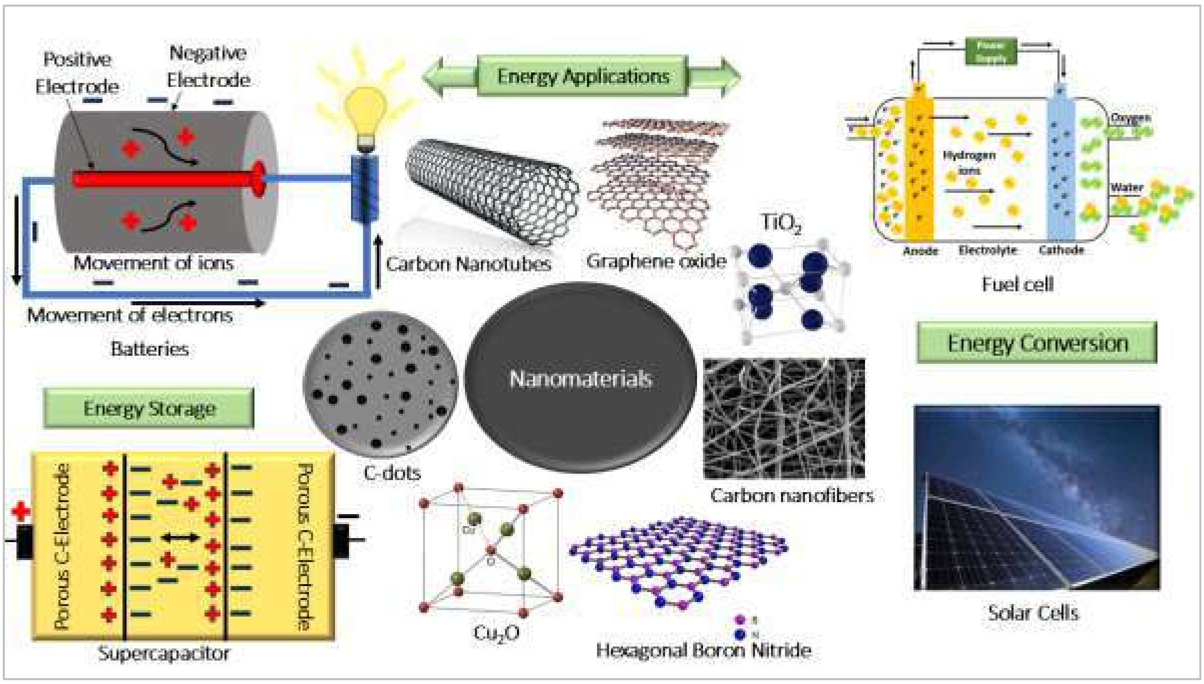
Materials Science: Advances in Synthesis, Characterization and Applications (Vol. 1) - Digambar M. Sapkal, Harshal M. Bachhav, Gaurav Mahadev Lohar, Sanjay P. Khairnar (Eds.)

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

https://doi.org/10.5281/zenodo.17131032

synthesis approaches, highlighting their advantages and limitations. Advanced characterization tools are presented for elucidating the architecture, composition, surface area, porosity, and electrochemical behaviour of nanostructures. Further chapter explores the application of nanomaterials in rechargeable batteries, supercapacitors, fuel cells, electrolyzers, and emerging CO_2 reduction technologies, underlining their role in enhancing energy efficiency, durability, and sustainability. The key challenges including large-scale production, stability, and environmental concerns are critically examined, and future research directions are outlined to guide the advancement of cost-effective and scalable nanomaterials for sustainable energy solutions.

Graphical Abstract: Engineering Nanomaterials from Synthesis and Characterization to Sustainable Energy Applications.



Keywords: Nanomaterials, Electrochemical Energy, Supercapacitors, Battery, Conversion, Storage

1. Introduction

Energy remains among the critical challenges confronting humanity in the 21st century, with global prosperity and sustainable development closely tied to the availability of clean and reliable energy sources.[1] The heavy reliance on fossil fuels has not only accelerated resource depletion but also led to serious environmental impacts such as release of greenhouse gas, atmospheric pollution, and climate disruption.[2] In 2022 alone, carbon dioxide emissions reached 36.8 gigatons, underscoring the urgent need

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

for alternative energy strategies.[3] In order to fulfil the goals set by the Paris Agreement and mitigate climate change, it is essential to minimize the reliance on conventional energy sources and advance renewable energy technologies supported by efficient energy conversion and storage systems.[4]

Electrochemical devices particularly batteries, supercapacitors, fuel cells, and electrolyzers play a pivotal role in bridging intermittent renewable energy supply with reliable and scalable storage solutions.[5] However, the performance of these systems is largely dictated by the properties of their active materials. Conventional bulk materials often exhibit limitations, including sluggish ion diffusion, low conductivity, and insufficient electrochemical stability, which restrict their performance in practical devices.[6]

Nanomaterials, by contrast, provide unique opportunities to overcome these limitations due to their tunable nanoscale properties. Their high surface area, shortened ion transport paths, and engineered electronic structures enable improved charge storage, enhanced electrocatalytic activity, and increased durability.[7] Advances in nanotechnology have enabled the design of diverse nanostructures such as nanoparticles, nanowires, nanosheets, and hierarchical frameworks that are now widely explored for energy applications.[8] Moreover, the development of innovative materials such as mxenes, metal–organic frameworks (MOFs), and covalent organic frameworks (COFs) has expanded the scope of electrochemical energy devices.[9]

In recent decade, substantial development has occurred in the synthesis, characterization, and application of nanomaterials for energy-related systems. Various strategies, including solution-based synthesis, hydrothermal methods, electrodeposition, chemical vapor deposition, and sustainable green approaches, have been developed to tailor structural and surface properties. High end characterization techniques methodologies such as electron microscopy, X-ray diffraction, spectroscopy, and electrochemical methods have offered critical perspective into the structure–property–performance relationship.[10]

This chapter aims to review the current landscape of nanostructured materials for electrochemical approaches to energy conversion and storage. It highlights their synthesis strategies, characterization tools, and application in rechargeable batteries, supercapacitors, fuel cells, electrolyzers, and CO_2 reduction. In addition to that challenges such as large-scale production, stability, and cost-effectiveness has been discussed and offers perspectives on future research directions that can accelerate the transition toward sustainable and economically viable energy solutions.

2. Nanomaterials for Electrochemical Energy Systems – Overview

Nanomaterials are generally identified as materials having at least one dimension in the nanoscale range (1–100 nm), where distinctive physicochemical attributes emerge due to size effects, surface phenomena, and quantum confinement.[11] Compared to their bulk counterparts, nanomaterials exhibit enhanced reactivity, electrical conductivity, mechanical strength, and tunable optical and catalytic properties. These features make them particularly advantageous in electrochemical energy systems, where surface reactions, ion transport, and electronic conductivity play critical roles in determining device performance.[12]

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

The incorporation of nanomaterials into electrochemical devices significantly boosts energy and power densities, improve rate capability, and extends cycle life. This is mainly accomplished through increased surface area for electrochemical reactions, shortened ion and electron diffusion pathways, and enhanced structural stability under repeated charge/discharge or catalytic cycles.[7,12]

Nanomaterials used in electrochemical energy systems can be classified based on dimensionality, composition, and functionality.[10,13]

2.1. Classification by Dimensionality

2.1.1. Zero-dimensional (0D) nanomaterials

- It includes nanoparticles, quantum dots, and nanoclusters.
- Their high surface-to-volume ratio coupled with quantum confinement effects make them excellent candidates for catalysts, active electrode materials, and additives in energy devices.
- Example includes metal nanoparticles (Au, Pt, Ag) and oxide nanoparticles (TiO_2, ZnO) used in fuel cells and photocatalytic water splitting.

2.1.2. One-dimensional (1D) nanomaterials

- It comprises nanowires, nanotubes, and nanorods.
- 1D-nanoparticles provide continuous pathways for electron transport and ion diffusion, along with superior mechanical robustness.
- Example includes Carbon nanotubes (CNTs) used as conductive networks in batteries and supercapacitors, silicon nanowires as high-performance anodes for Li-ion batteries.

2.1.3. Two-dimensional (2D) nanomaterials

- It includes graphene, mxenes, and transition metal dichalcogenides (TMDs).
- 2D-nanomaterials demonstrate high electronic conductivity, significant surface area, and tunable interlayer spacing, enabling efficient ion intercalation and charge transfer.
- Example includes graphene-based electrodes in supercapacitors, mxenes in sodium-ion and lithium-ion batteries.

2.1.4. Three-dimensional (3D) nanomaterials

- 3D-nanomaterials includes hierarchical porous structures, aerogels, and nanocomposites.
- It combines the advantages of nanoscale building blocks with interconnected macropores for electrolyte transport.

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

- Example includes 3D graphene foams and metal–organic framework (MOF)-derived carbon networks in fuel cells and CO_2 reduction studies.

2.2. Classification by Composition

Based on composition, nanomaterials are categorised into carbon-based nanomaterials (e.g. graphene, CNTs, porous carbon), metal and metal oxide-based nanomaterials (such as Pt, Au, TiO_2, MnO_2, Fe_2O_3), conductive polymers (e.g. polyaniline, polypyrrole), and hybrid materials (such as composites of carbon, polymers, and metal oxides; MOFs and COFs). Each class provides specific advantages such as carbon for conductivity and stability, oxides for redox activity, polymers for flexibility, and hybrids for synergistic effects.

2.3. Classification by Functionality in Energy Devices

Based on functionality in energy devices nanomaterials can be classified as

- Electrode materials as anodes and cathodes in batteries and supercapacitors.
- Electrocatalysts in oxygen reduction reaction (ORR), oxygen evolution reaction (OER), hydrogen evolution reaction (HER), CO_2 reduction reaction (CO_2RR).
- Electrolyte additives/separators which improves ionic conductivity and stability.
- Support frameworks which act as conductive backbones for dispersing active materials.

3. Structure–Property Relationship in Nanomaterials

The exceptional performance of nanomaterials in electrochemical energy devices arises from their structure–property relationships[14]:

- Reduced size leads to shorter ion/electron diffusion lengths.
- High porosity enhances electrolyte penetration.
- Surface functionalization improved catalytic activity and selectivity.
- Controlled morphology (0D, 1D, 2D, 3D) tailored transport properties.

Understanding and engineering these relationships is central to designing next-generation nanomaterials for high-performance, cost-effective, and durable electrochemical devices

The synthesis of nanomaterials is a critical step in tailoring their structural, electronic, and surface properties for electrochemical energy applications. Different synthesis routes can significantly influence particle size, morphology, porosity, crystallinity, and surface chemistry, which in turn dictate electrochemical behaviour. In general, nanomaterials can be prepared using top-down and bottom-up approaches, along with emerging green synthesis techniques that focus on sustainability.[15]

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic)

3.1. Top-Down Approaches

Top-down methods involve fragmenting bulk materials into nanoscale forms using physical or mechanical processes. These methods are relatively simple but might not allow accurate control over particle size and surface features.

- Mechanical milling / Ball milling reduces bulk powders to nanoparticles; widely used for oxides and carbons.
- Lithography creates nanoscale patterns for thin-film electrodes.
- Laser ablation employs high-energy lasers to fragment bulk targets into nanoparticles.
- Etching and sputtering used for fabricating nanostructured thin films and coatings.

The advantages of top-down approach are its simple, scalable and cost-effective traits whereas broad size distribution defects, and potential contamination are the underlying limitations.

3.2. Bottom-Up Approaches

Bottom-up methods build nanostructures at the atomic or molecular level, offering better control over composition, morphology, and crystallinity. These methods are widely employed in energy nanomaterials synthesis.

- Sol–gel method is used for synthesis of oxides and hybrid nanomaterials which allows uniform mixing of components at molecular level.
- Hydrothermal and solvothermal synthesis produces crystalline nanostructures (nanowires, nanorods, nanosheets) under controlled pressure and temperature.
- Co-precipitation is the low-cost method for bulk synthesis of oxide nanoparticles.
- Electrodeposition is versatile for fabricating nanostructured films, foams, and alloys (e.g., Cu, Ni, Co-based catalysts for batteries and CO_2 reduction).
- Chemical vapor deposition (CVD) and physical vapor deposition (PVD) are used for synthesis of high-quality 2D-nanomaterials like graphene and transition metal dichalcogenides (TMDs).
- Self-assembly synthesis method enables hierarchical nanostructures formation for electrodes and membranes.

Advantages of bottom-up approach includes precise control of structure and composition, ability to tailor morphology (0D, 1D, 2D, 3D) whereas high cost, complex procedure, and scalability issues are some of the limitations.

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

3.3. Green and Sustainable Synthesis Approaches

Sustainable development has driven interest in environmentally benign synthesis methods. Green synthesis reduces the exposure to toxic chemicals, reduces energy consumption, and employs renewable resources. The various methods of green synthesis of nanoparticles includes[16]:

- Biological synthesis which involves the use of plant extracts, bacteria, or fungi act as reducing and stabilizing agents for nanoparticle formation.
- Microwave-assisted preparation, a rapid energy-efficient method for producing nanostructures with controlled morphology.
- Electrochemical synthesis using eco-friendly electrolytes which enables the fabrication of cost-effective nanomaterials for energy storage and conversion.
- Use of biomass-derived precursors carbon-based nanomaterials derived from agricultural waste or biopolymers.

  The advantages of green synthesis approach include environmentally friendly, scalable, and cost effectiveness whereas limited control over morphology compared to traditional chemical methods is the limitation.

3.4. Comparative Evaluation of Synthesis Methods[17]

Method	Control	Scalability	Cost	Eco-friendliness	Examples Energy Devices
Ball milling	Low	High	Low	Moderate	Battery electrode powders
Hydrothermal	High	Moderate	Moderate	Moderate	Nanorods, nanosheets for LIBs, supercapacitors
Sol–gel	High	Moderate	Moderate	Low–Moderate	Metal oxide nanomaterials
Electrodeposition	High	High	Low	High	Porous foams, electrocatalysts
CVD/PVD	Very High	Low	High	Low	Graphene, TMDs, CNTs
Green synthesis	Moderate	High	Low	Very High	Biomass-derived carbons, bio-catalysts

3.5. Relevance to Electrochemical Energy Applications

The choice of synthesis method directly impacts the efficiency of nanomaterials in energy devices:

- Nanoporous carbons synthesized via templating show superior performance in supercapacitors.
- Electrodeposited foams and alloys enhance catalytic activity for CO_2 reduction, ORR/OER and water splitting.
- Hydrothermally prepared TMD nanosheets provide high surface area and conductivity for batteries and fuel cells.

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

- Green-synthesized nanomaterials offer cost-effective and sustainable pathways for large-scale deployment in commercial devices

4. Characterization of Nanomaterials

Effective characterization links synthesis to function by revealing crystal structure, morphology, porosity, surface chemistry, and electrochemical behaviour properties that ultimately control kinetics, stability, and device-level metrics in batteries, supercapacitors, and fuel cells. Reviews on nanostructured energy materials repeatedly emphasize that interfacial chemistry and nanoscale architecture dominate performance, making rigorous, multi-modal characterization essential.[18]

The characterization of nanomaterials is a crucial step in linking synthesis methods to functional performance in electrochemical energy devices. Structural analysis techniques such as X-ray diffraction (XRD) provide information on crystal structure, phase purity, and crystallite size, enabling the correlation between phase composition and electrochemical activity. Complementary tools such as Raman spectroscopy are widely employed to probe lattice vibrations, defect density, and bonding configurations, which are particularly important for carbon-based nanomaterials and transition metal oxides. Morphological and microstructural features are typically investigated using electron microscopy techniques. Scanning electron microscopy (SEM) offers surface topography and particle distribution, while transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) reveal lattice fringes, grain boundaries, and heterostructured interfaces at the atomic scale. These imaging methods, often coupled with selected area electron diffraction (SAED), are indispensable for visualizing the nanoscale architecture that governs electron and ion transport. In addition, atomic force microscopy (AFM) measure thickness and surface roughness of two-dimensional materials such as graphene and mxenes, parameters that strongly affect conductivity and ion accessibility.[19]

Surface area and porosity, which play a central role in electrochemical performance, are commonly analyzed using gas adsorption–desorption techniques, particularly Brunauer–Emmett–Teller (BET) surface area measurements and Barrett–Joyner–Halenda (BJH) pore size distribution analysis. High specific surface areas and hierarchical porosity have been shown to improve charge storage, enhance mass transport, and increase the number of electroactive sites. To complement these, density measurements and mercury porosimetry are sometimes used to evaluate bulk porosity and packing density of nanomaterials for electrodes. Equally important is the characterization of surface chemistry and electronic states, which can be achieved by X-ray photoelectron spectroscopy (XPS). This technique provides information about oxidation states, elemental composition, and surface functional groups, all of which determine catalytic activity, electrode stability, and interfacial compatibility with electrolytes. Additional spectroscopic methods such as Fourier transform infrared (FTIR) spectroscopy and ultraviolet–visible spectroscopy are useful for identifying chemical functionalities, organic ligands, and optical absorption properties, especially in hybrid materials, polymers, and frameworks. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) further assist in assessing composition, thermal stability, and decomposition behaviour, which are critical for processing and long-term durability.[20]

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

Electrochemical characterization techniques provide the most direct link between material properties and device performance. Cyclic voltammetry (CV) is widely used to investigate redox behaviour, reversibility, and capacitive versus diffusion-controlled contributions. Galvanostatic charge–discharge (GCD) tests provide key parameters such as specific capacity or capacitance, Coulombic efficiency, rate capability, and cycle stability, while electrochemical impedance spectroscopy (EIS) , a method to analyze charge-transfer resistance, ion diffusion, and internal resistance within electrodes. For electrocatalytic applications such as ORR, OER, HER, Tafel analysis and rotating disk electrode (RDE) studies are commonly performed for extracting kinetic parameters including Tafel slopes and electron transfer numbers. In recent years, in situ and operando characterization has gained prominence, enabling direct monitoring of phase transitions, strain evolution, and interfacial chemistry under realistic operating conditions. Techniques such as operando XRD and Raman spectroscopy can track evolution in morphology during battery cycling, while in situ TEM and XPS provide real-time insights into dendrite formation, solid–electrolyte interphase (SEI) evolution, and catalytic surface dynamics.[21]

Finally, a comprehensive evaluation of nanomaterials must also consider safety, toxicity, and sustainability. Since nanoscale particles may pose environmental and health risks, characterization approaches increasingly extend beyond physicochemical and electrochemical properties to include studies on biodegradability, recyclability, and environmental compatibility. This holistic approach ensures that nanomaterials not only deliver superior performance but also align with the principles of sustainable and responsible energy technology development.[22]

5. Nanomaterials for Electrochemical Energy Conversion and Storage Applications

Nanostructured materials have shown immense capability in advancing the efficiency of electrochemical devices by enhancing charge storage, improving catalytic efficiency, and prolonging operational stability. In rechargeable batteries, including lithium-ion, sodium-ion, and emerging multivalent systems such as zinc- and magnesium-ion batteries, nanostructured electrodes offer significant advantages over bulk materials. Reduced particle dimensions and engineered porosity shorten diffusion pathways for ions and electrons, thereby improving rate capability and cycling stability. For instance, one-dimensional nanowires and nanotubes provide continuous electron conduction paths, while two-dimensional materials such as graphene and mxenes facilitate rapid ion intercalation due to their high conductivity and tunable interlayer spacing. Hierarchical three-dimensional nanostructures further integrate these advantages by combining high surface area with efficient electrolyte transport, making them ideal for high-energy-density batteries.[23]

In supercapacitors, nanomaterials have been particularly influential in bridging the gap between high power density and moderate energy density. Carbon related nanomaterials such as graphene, carbon nanotubes, and porous carbons are employed as double-layer capacitor electrodes due to their high surface area and excellent conductivity. In contrast, pseudocapacitive materials, including transition metal oxides (e.g., MnO_2, Co_3O_4, NiO) and conducting polymers (e.g., polyaniline, polypyrrole), benefit from nanoscale engineering that enhances surface redox activity and reduces diffusion limitations. Hybrid

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

electrodes that integrate carbon supports with pseudocapacitive materials combine high power delivery with greater energy storage, offering promising pathways for next-generation energy storage systems.[24]

Nanostructured catalysts have also revolutionized the field of fuel cells by improving the kinetics of electrocatalytic reactions. In proton exchange membrane fuel cells (PEMFCs), platinum-based catalysts remain the benchmark for oxygen reduction, but high cost and poor durability limit widespread deployment. Nanostructuring has enabled significant reductions in noble-metal loading by increasing surface utilization and creating alloyed or core–shell structures with improved stability. Similarly, transition metal oxides, carbides, and nitrogen-doped carbons are being developed as cost-effective alternatives. In solid oxide fuel cells (SOFCs), nanostructured electrolytes and electrodes have lowered operating temperatures while maintaining high ionic conductivity, thereby extending device lifetime and lowering system costs.[25]

Electrolyzers for hydrogen production have benefited greatly from advances in nanoscale catalysts designed for HER and OER. Nanostructured transition metals, dichalcogenides, and layered double hydroxides have emerged as promising earth abundant metal catalysts with high catalytic activity and prolonged stability. The large surface area and tunable active sites of nanomaterials accelerate reaction kinetics and reduce overpotentials, making water splitting increasingly viable for sustainable hydrogen production. Beyond water electrolysis, nanostructured electrocatalysts are also central to the electrochemical reduction of carbon dioxide, where their morphology, surface chemistry, and electronic structure determine product selectivity toward fuels and value-added chemicals such as formate, CO, and hydrocarbons. Recent studies have shown that engineered interfaces, doped structures, and alloyed nanoparticles can significantly enhance CO_2 conversion efficiency while suppressing side reactions such as hydrogen evolution.[26,27]

Nanomaterials are also being explored in other emerging electrochemical energy technologies, including metal–air batteries, photoelectrochemical water splitting, and hybrid storage systems that integrate capacitive and battery-type mechanisms. In metal–air batteries, nanostructured bifunctional catalysts are essential for both oxygen reduction and evolution, while in photoelectrochemical devices, semiconductor nanostructures with tailored band gaps enable efficient light absorption and charge separation. Collectively, these applications highlight the transformative role of nanomaterials in advancing electrochemical energy conversion and storage. By engineering size, morphology, and composition at the nanoscale, researchers are unlocking new opportunities to overcome limitations of conventional materials and accelerate the advancement of low-cost, durable, and sustainable energy systems.[28]

6. Challenges and future Perspective

Despite the remarkable progress in nanomaterials for electrochemical energy applications, several challenges hinder their translation from laboratory-scale studies to large-scale commercialization. One of the foremost issues is the scalability and cost of synthesis. Many advanced nanostructuring techniques, such as chemical vapor deposition, template-assisted synthesis, or atomic-level doping are energy-intensive and expensive, making them impractical for mass production. Even when cost-effective routes

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

such as hydrothermal or electrodeposition methods are used, maintaining precise control over morphology, porosity, and surface chemistry on an industrial scale remains difficult. The development of sustainable, green, and scalable synthesis strategies, including the use of biomass precursors, low-temperature processes, and eco-friendly solvents, is therefore a critical research direction.

Another challenge lies in the stability and durability of nanomaterials under realistic operating conditions. Nanostructures often suffer from aggregation, coarsening, or phase transformations during long-term cycling, leading to loss of electrochemical activity. For example, transition metal nanoparticles used in electrocatalysis may undergo dissolution or surface reconstruction, while nanostructured battery electrodes frequently experience volume expansion and structural degradation. Strategies such as hybridization with carbon supports, surface coating, and defect engineering have been proposed to enhance structural integrity, but long-term stability across thousands of cycles remains a key hurdle for practical applications.

The interfacial chemistry of nanomaterials also presents challenges, particularly in systems where solid–electrolyte interphases (SEI), electrode–electrolyte interactions, or catalyst support interfaces dominate performance. Poor interfacial compatibility can lead to parasitic reactions, unstable SEI layers, or limited ion accessibility. Advanced in situ and operando characterization techniques are helping to unravel these complex processes, but a deeper mechanistic understanding is needed to design stable, high-performance interfaces. Computational modelling and machine-learning-guided materials discovery hold promise in accelerating this process by predicting optimal compositions and architectures before experimental synthesis.

Environmental and health concerns associated with nanomaterials also demand attention. The small size, high reactivity, and potential toxicity of nanoparticles raise issues regarding safe handling, recyclability, and ecological impact. To ensure sustainable deployment, life-cycle assessments and toxicity studies should accompany performance evaluation. Developing recyclable electrodes, biodegradable nanomaterials, and closed-loop manufacturing processes will be essential for aligning energy nanotechnologies with global sustainability goals.

Looking ahead, several future perspectives can guide progress in this field. First, the integration of multi-functional nanomaterials such as hybrid structures combining conductivity, catalytic activity, and mechanical stability offers a pathway to overcoming individual material limitations. Second, the exploration of emerging material classes, including mxenes, covalent organic frameworks (COFs), and defect-rich 2D heterostructures, is expected to expand the design space for next-generation devices. Third, machine learning and artificial intelligence will facilitate faster materials discovery, enabling high-throughput screening of compositions and predictive modelling of structure–property relationships. Finally, moving beyond performance metrics, research must also prioritize cost-effectiveness, environmental compatibility, and long-term reliability, ensuring that nanomaterial-based devices can be manufactured and deployed at scale for real-world energy applications.[10]

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

In summary, while nanomaterials have already demonstrated transformative potential in electrochemical energy conversion and storage, addressing scalability, durability, interfacial stability, and sustainability will determine their future success. Continued advances in synthesis, characterization, and design combined with digital tools and sustainable approaches will pave the way for commercially viable, nanostructure-enabled energy technologies that can support the global transition toward clean and sustainable energy systems.

7. Conclusion

Nanomaterials have emerged as transformative building blocks for electrochemical energy conversion and storage technologies, offering unique physicochemical properties that address the limitations of conventional bulk materials. Their high surface-to-volume ratio, tunable electronic structure, and engineered morphologies enable faster charge transport, enhanced catalytic activity, and improved durability across a wide range of devices, including batteries, supercapacitors, fuel cells, and electrolyzers. Over the past two decades, advances in synthesis techniques and characterization tools have deepened our understanding of structure–property–performance relationships, paving the way for the rational design of nanostructures tailored for specific energy applications.

Despite this progress, challenges remain in translating laboratory-scale successes into commercially viable technologies. Issues such as large-scale, cost-effective synthesis, long-term structural stability, interfacial compatibility, and environmental safety has to be systematically addressed to unlock the full capability of nanomaterials. Future research will increasingly rely on sustainable synthesis approaches, hybrid and multifunctional architectures, and digital tools such as machine learning to accelerate material discovery and optimization.

Overall, nanomaterials play a critical role in the development of next-generation energy technologies. By bridging the gap between fundamental materials science and practical energy applications, they hold the promise of enabling efficient, durable, and sustainable solutions to meet the increasing global demand for sustainable energy. The continued integration of innovative synthesis, advanced characterization, and system-level engineering will be essential to realize their role in driving the transformation toward a low-carbon and energy-secure future.

Acknowledgement

The author sincerely thanks DST-SERB for financial support. The facilities and infrastructure offered by the Department of Chemistry, Savitribai Phule Pune University, are also deeply appreciated. Special thanks are due to Prof. Santosh K. Haram for his invaluable guidance, insightful suggestions, and constant encouragement throughout the course of this work.

References

1. Kaygusuz K. Energy for sustainable development: Key issues and challenges. *Energy Sources,*

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

Part B: Economics, Planning and Policy. 2007;2(1):73-83. doi:10.1080/15567240500402560

2. Wang J, Azam W. Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers*. 2024;15(2):101757. doi:10.1016/j.gsf.2023.101757
3. Component C, Change C. *Global Warming*.
4. Robiou Du Pont Y, Jeffery ML, Gütschow J, Rogelj J, Christoff P, Meinshausen M. Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*. 2017;7(1):38-43. doi:10.1038/nclimate3186
5. Njema GG, Ouma RBO, Kibet JK. A Review on the Recent Advances in Battery Development and Energy Storage Technologies. *Journal of Renewable Energy*. 2024;2024:1-35. doi:10.1155/2024/2329261
6. Fan X, Zhong C, Liu J, et al. Opportunities of Flexible and Portable Electrochemical Devices for Energy Storage: Expanding the Spotlight onto Semi-solid/Solid Electrolytes. *Chemical Reviews*. 2022;122(23):17155-17239. doi:10.1021/acs.chemrev.2c00196
7. Guo Y, Hu J, Wan L. Nanostructured Materials for Electrochemical Energy Conversion and Storage Devices. *Advanced Materials*. 2008;20(15):2878-2887. doi:10.1002/adma.200800627
8. Zhang B, Sun J, Salahuddin U, Gao PX. Hierarchical and scalable integration of nanostructures for energy and environmental applications: A review of processing, devices, and economic analyses. *Nano Futures*. 2020;4(2):1-37. doi:10.1088/2399-1984/ab75ad
9. Chu J, Wang Y, Zhong F, et al. Metal/covalent-organic frameworks for electrochemical energy storage applications. *EcoMat*. 2021;3(5). doi:10.1002/eom2.12133
10. Maity D, Sahoo SR, Saha S. Synthesis and Characterization of Nanomaterials for Electrochemical Sensors. *ACS Symposium Series*. 2023;1437:193-222. doi:10.1021/bk-2023-1437.ch009
11. Asha AB, Narain R. *Nanomaterials Properties*. Elsevier Inc.; 2020. doi:10.1016/B978-0-12-816806-6.00015-7
12. Zhang Q, Uchaker E, Candelaria SL, Cao G. Nanomaterials for energy conversion and storage. *Chemical Society Reviews*. 2013;42(7):3127-3171. doi:10.1039/c3cs00009e
13. Dolez PI. *Nanomaterials Definitions, Classifications, and Applications*.; 2015. doi:10.1016/B978-0-444-62747-6.00001-4
14. Le T, Epa VC, Burden FR, Winkler DA. Quantitative structure-property relationship modeling of diverse materials properties. *Chemical Reviews*. 2012;112(5):2889-2919. doi:10.1021/cr200066h
15. Majumder DD, Banerjee R, Ulrichs CH, Mewis I, Goswami A. Nano-materials: Science of bottom-up and top- down. 2014;4602. doi:10.4103/02564602.10876577

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.

16. Singh NB. Green synthesis of nanomaterials. *Handbook of Microbial Nanotechnology*. Published online 2022:225-254. doi:10.1016/B978-0-12-823426-6.00007-3
17. Kolahalam LA, Kasi Viswanath I V., Diwakar BS, Govindh B, Reddy V, Murthy YLN. Review on nanomaterials: Synthesis and applications. *Materials Today: Proceedings*. 2019;18:2182-2190. doi:10.1016/j.matpr.2019.07.371
18. Ikhmayies SJ. Characterization of nanomaterials. *Jom*. 2014;66(1):28-29. doi:10.1007/s11837-013-0826-6
19. Rao CNR, Biswas K. Characterization of nanomaterials by physical methods. *Annual Review of Analytical Chemistry*. 2009;2:435-462. doi:10.1146/annurev-anchem-060908-155236
20. Lin PC, Lin S, Wang PC, Sridhar R. Techniques for physicochemical characterization of nanomaterials. *Biotechnology Advances*. 2014;32(4):711-726. doi:10.1016/j.biotechadv.2013.11.006
21. Baer DR, Engelhard MH, Johnson GE, et al. Surface characterization of nanomaterials and nanoparticles: Important needs and challenging opportunities. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*. 2013;31(5). doi:10.1116/1.4818423
22. Abdelbasir SM, McCourt KM, Lee CM, Vanegas DC. Waste-Derived Nanoparticles: Synthesis Approaches, Environmental Applications, and Sustainability Considerations. *Frontiers in Chemistry*. 2020;8(August):1-18. doi:10.3389/fchem.2020.00782
23. Balasingam SK, Sivalingam Nallathambi K, Abdul Jabbar MH, Ramadoss A, Kamaraj SK, Kundu M. Nanomaterials for Electrochemical Energy Conversion and Storage Technologies. *Journal of Nanomaterials*. 2019;2019:1-3. doi:10.1155/2019/1089842
24. Wu Y, Cao C. The way to improve the energy density of supercapacitors: Progress and perspective. *Science China Materials*. 2018;61(12):1517-1526. doi:10.1007/s40843-018-9290-y
25. Omeiza LA, Abdalla AM, Wei B, et al. Nanostructured Electrocatalysts for Advanced Applications in Fuel Cells. *Energies*. 2023;16(4). doi:10.3390/en16041876
26. Vij V, Sultan S, Harzandi AM, et al. Nickel-based electrocatalysts for energy-related applications: Oxygen reduction, oxygen evolution, and hydrogen evolution reactions. *ACS Catalysis*. 2017;7(10):7196-7225. doi:10.1021/acscatal.7b01800
27. O'Brien CP, Miao RK, Shayesteh Zeraati A, Lee G, Sargent EH, Sinton D. CO2 Electrolyzers. *Chemical Reviews*. 2024;124(7):3648-3693. doi:10.1021/acs.chemrev.3c00206
28. Nair G, Nagabhushana H, Dhoble N, Dhoble SJ. *Emerging Energy Materials*.; 2024. doi:10.1201/9781003315261

ISBN: 978-93-95369-55-8 (paperback) 978-93-95369-46-6 (electronic) | © 2025 Advent Publishing.