NANOMATERIALS FOR ENERGY STORAGE AND CONVERSION

Dala Rahulji, Dr Radha Krishna Muniganti, Ms. Akkala Abhilasha, Dr. P Johnson Babu

1 Department of Mechanical Engineering, Sree Dattha Institute of Engineering and Science, Sheriguda, Ibrahimpatanam,Rangareddy, Telangana - 501510
rahulji.dala5@gmail.com
2 Assistant Professor, Department of Chemistry, Vardhaman College of Engineering, Kacharam, Shamshabad, Hyderabad, Telangana - 501218
mrk.muniganti@gmail.com
3 Assistant Professor, Department of CSE, Geethanjali college of engineering and technology, Telangana.
abhilasha0923@gmail.com
4 Head of Department Physics and Electronics, St Joseph's Degree & P.G College, King Koti, Main Road, Hyderabad, Telangana, India - 500029
pjohnsonbabu@josephscollege.ac.in

***Abstract*—**The constantly growing energy consumption in the world and the dire necessity to shift towards sustainable energy systems have stimulated the intensive study of advanced energy storage and conversion materials. Nanomaterials and their exceptional physicochemical properties hold the promise of improving performance of batteries, supercapacitors, fuel cells and solar cells. This article will discuss recent progress in the synthesis, structural manipulation, and prospective use of nanomaterials including carbon-based nanostructures, metal oxides, transition metal dichalcogenides (TMDs) and perovskites. It is stressed how the nanoscale effects such as large surface area, adjustable band gaps, or better ion/electron transportation can result in energy efficiency and device performance that is enhanced. In addition, issues like stability, scalability, and environmental impact are mentioned and possible future directions.

Keywords— Nanomaterials, Energy Storage, Energy Conversion, Supercapacitors, Batteries, Fuel Cells, Solar Cells, Electrocatalysis.

I. INTRODUCTION

The world is experiencing a dramatic transformation in the energy arena, a transformation that has been informed by a merger of forces climate change, growing energy needs, dwindling supplies of fossil fuels, and the call toward sustainable development. The traditional energy systems that mainly depend on the use of non-renewable resources such as coal, oil, and natural gases are not only harmful to the environment but can never support or achieve long-term sustainability objectives. This fact has further accelerated the demand of higher energy storage and conversion technologies which are efficient, reliable and environmentally friendly [1-2].

The lithium-ion batteries (LIBs), sodium-ion batteries, and supercapacitors are vital energy storage devices used in storing electricity generated by the intermittent renewable sources, such as wind and solar. Likewise, the energy conversion systems, such as fuel cell and solar cells are essential in converting one energy source to another with minimum losses. Nevertheless, the typical materials incorporated in these systems encounter a myriad of challenges that includes poor capacity, low energy density, slow kinetics, brief lifespan and expensive production cost.

Nanomaterials have changed into game-changers in this context. Their outstanding physical, chemical and electrical properties that are attributed to their nanoscale size and large surface-to-volume ratio provide a huge opportunity to improve the efficiency, stability and capacity of both energy storage and conversion devices. Nanostructured electrodes, catalysts, and separators have been designed enabling more control over ion and electron transport, high charge-discharge rates, and decreased material degradation [8].

Carbon nanotubes (CNTs), graphene, transition metal dichalcogenides (TMDs), metal oxides, and perovskites are Nanomaterials that are heavily researched to improve their performance. As an illustration, electrical conductivity and mechanical strength can be vastly enhanced by incorporating graphene-based materials into the electrodes of batteries. Similarly, TMDs, such as MoS 2 feature layered structures, which can undergo ion intercalation and thus are appealing to serve as battery and supercapacitor applications. More recently, in solar

energy applications perovskitenanocrystals have demonstrated very high light-harvesting abilities and tunable bandgaps, amongst the most promising materials in next-generation photovoltaics.

Nanomaterials are not just materials with improved properties, but also provide new routes to miniaturization, flexibility and multifunctionality of energy systems. As another example, wearable electronics and intelligent sensors require small, flexible, and lightweight energy sources, which are becoming possible by innovations with nanomaterials [4].

However, in spite of these benefits a number of challenges still exist with regards to large-scale production, stability under operational conditions, toxicity (particularly with heavy-metal based materials) and cost-effectiveness. Overcoming these open issues will need a multidisciplinary effort encompassing material synthesis, surface engineering, device modeling and lifecycle analysis.

This paper is aimed at discussing the use of nanomaterials in energy storage and conversion with the materials engineering point of view. It gives an in-depth study on their synthesis techniques, structural properties and integration in their functioning in different devices. it also assesses the enhancement of performance by electrochemical investigations and addresses major drawbacks and future research directions [10-14].

Novelty and Contribution

The present paper contributes to the science and practice in the area of nanomaterials in energy applications in a few unique ways.

- To begin with, it includes a comparative cross-analysis of the various nanomaterials, namely, graphene, metal oxides, perovskites, and TMDs in various energy domains, namely, batteries, supercapacitors, fuel cells, and solar cells. Most of the research is done either on a particular material or application, whereas this work will provide a gap by presenting a combined view of how these materials perform in different systems.
- Second, this paper will focus on how the morphology of nanostructure, such as one-dimensional (1D) nanowires, two-dimensional (2D) nanosheets, and three-dimensional (3D) framework, improves ion diffusion, electrical conductivity, and mechanical stability. This structural design attention gives new knowledge to the engineering approaches that would be applied in optimizing the performance at the nanoscale.
- Third, this research points out practical scalability and stability problems that are not usually discussed in the academic literature. It deals with the environmental issues relating to the nanomaterial toxicity and disposal and economic issues of mass production. By so doing it provides a more comprehensive map of how to scale lab-scale breakthroughs into commercial solutions.
- Further, the paper can advance the field by revealing the synergetic hybrid systems, including graphene-metal oxide composites and perovskite-polymer blends, which outperform their components owing to the complementary interactions between materials. Such hybrid methods are a big step towards multifunctional and high efficiency devices.
- Lastly, by discussing the most recent development in synthesis methods, such as green chemistry methods, doping methods, as well as surface modification, the paper will offer a prospective outlook on how future research can alleviate the currently existing bottlenecks and lead to next-generation energy systems.

Basically, the paper does not only provide a survey of the current status of nanomaterials in energy storage as well as conversion, but it goes further to make its own contribution to the subject by proposing a direction of future innovations that will meet sustainability and efficiency objectives [5].

II. Related Works

In 2023 S. Sikiru*et al.*, [15] introduced the scientific investigation in the field of nanomaterials in energy storage and conversion has been developing intensive growth over the last decade due to the strong necessity of enhancing energy efficiency, performance, and sustainability. Various types of nanostructured materials, including carbon-based materials, metal oxides and hybrid composites have been investigated with their specific properties at the nanolevel, promising enhancement of energy density, power output, mechanical stability and rate

of charge/discharge. Every type of nanomaterials has certain benefits to various energy storage devices like batteries, supercapacitors, fuel cells, and solar cells.

The most widely studied are carbon-based nanomaterials (e.g., graphene, carbon nanotubes (CNTs), carbon nanofibers, porous carbon structures, etc.). Their mechanical strength, large surface area, and high electrical conductivity qualify them to be used in energy storage systems considerably. In supercapacitors, these materials allow fast transport of electrons and ions, which gives high power density and long cycle life. Their capacity to make conductive networks has also been useful in lithium-ion batteries where they are used as active materials or conductive additives, improving the overall electrochemical performance. Moreover, their processability and flexibility enable Flexible and wearable electronics.

For metal oxide nanomaterials, such compounds as manganese dioxide (MnO 2), titanium dioxide (TiO2), nickel oxide (NiO), and cobalt oxide (Co 3 O 4) have displayed electrochemical performance that is remarkable. Such materials are pseudocapacitive, allowing them to store charge not only at the surface, but via redox reactions in the bulk. Metal oxides have been effectively used in batteries and supercapacitors in both anode and cathode. Nanostructuring of these materials to the form of nanowires, nanorods, hollow spheres and nanosheets goes a long way in enhancing surface interaction and ion diffusion kinetics. Nevertheless, they have a relatively low conductivity, which requires their compositing with conductive materials, such as carbon nanotubes or graphene, to demonstrate the best performance.

Another perspective group of layered nanomaterials are transition metal dichalcogenides (TMDs) that include molybdenum disulfide (MoS2) and tungsten disulfide (WS 2). These materials have a layered structure which permits efficient ion intercalation and high theoretical capacity. Their suitability as anode materials in the next-generation batteries like the sodium-ion and lithium-sulfur batteries has been pursued actively. Interlayer spacing of TMDs can be adjusted to larger ions, whereas defects and doping methods are used to improve the inherent conductivity and electrochemical activity.

Perovskitenanomaterials have become a revolution in solar energy conversion. Hybrid organic-inorganic perovskites have optoelectronic Unique properties that have made them the top contenders in photovoltaic applications, such as high absorption coefficients, long carrier diffusion lengths, and tuneablebandgaps. Nanostructured perovskites can optimize contact at the interfaces, absorb light more efficiently and facilitate the separation and transportation of charges. Controlled growth of perovskitenanocrystal and films with better crystallinity and morphology has been achieved by different fabrication methods including spin-coating, vapor deposition, and solvent engineering. Encapsulation innovations and lead-free alternatives are bringing the technology to the verge of commercialization despite concerns about long-term stability and toxicity (particularly because of lead content) [6].

In 2021 Z. Xu et.al., W. Deng et.al., and X. Wang et.al., [3] suggested the nanomaterials have also played a role in the realization of high efficient fuel cells particularly in the catalyst design used in oxygen reduction reactions (ORR) and hydrogen oxidation reactions (HOR). The most popular support have been platinum-based nanoparticles on carbon substrates, however, these are both expensive and limited in supply which has prompted the need to investigate non-precious metal based catalysts. Nanostructured alloys, core shell materials and doped carbon materials have been prepared to substitute or lower the amount of platinum weight with catalytic efficiency. These nano-catalysts have got high electrochemical surface area, adjustable surface energies as well as enhanced tolerance to poisoning agents such as carbon monoxide.

Hybrid nanomaterials, which are prepared by mixing two or more different nanomaterials have been found to be very useful in maximizing the advantage of each constituent. As an example, graphene-metal oxide composites take advantage of the electrical conductivity of graphene and redox activity of metal oxides to produce electrodes with high charge storage capacity and structural integrity. Likewise, core-shell nanoparticles by designing the interfaces can improve the reaction kinetics and eliminate degradation during cyclic operation. Such composite strategies will not only enhance the performance of the devices but will also solve the problem of stability and durability in practical applications.

In addition to the conventional lithium-ion systems, there has been an increased desire in using alternative chemistries such as zinc-ion, magnesium-ion, and aluminum-ion batteries, wherein nanomaterials hold a benefit in

terms of accommodating the larger ionic radii and enhancing reaction kinetics. In such systems the problem is to find appropriate host materials in which the insertion and extraction process can be made reversible without the structure collapsing. Nanostructuring can provide access to more ions, more surface reaction sites and reduce diffusion lengths, all of which are essential to the feasibility of storage using multi-valentines.

A newer frontier of research effort is on solid-state batteries and flexible energy devices, in which nanomaterials are used to engineer solid electrolytes, flexible electrodes, and stretchable substrates. Polymer nanocomposites, inorganic nanoparticles and hybrid materials have been fabricated as solid electrolytes to enhance ionic conductivity and interfacial compatibility. In the case of wearable energy systems, nanomaterials are utilized to make lightweight, bendable, stretchable energy components that do not lose performance when stretched or deformed mechanically.

In all these studies, there are challenges that remain common like agglomeration of the nanoparticles, reproducibility of the synthesis and environmental issues surrounding the disposal of the nanomaterials wastes. Efforts are in progress to achieve more green synthesis methods, mass production synthesis methods and recycling. Also surface functionalization, doping and defect engineering is being used to design nanomaterials towards desired electrochemical applications.

In 2023 Hala. S. Hussein et.al. [9] proposedthe current research pool has proven how significantlynanomaterials can influence the performance and design of energy storage and conversion systems. Even though tremendous effort has been put in this area, continued research efforts are being put in the area of property improvement of materials, device structure, and integration schemes to reach ascalable, stable and sustainable energy solutions.

III. PROPOSED METHODOLOGY

The methodology for analyzing nanomaterials in energy storage and conversion systems is constructed through a systematic framework, integrating material synthesis, characterization, modeling, and performance evaluation [7]. The process begins with the design and synthesis of nanostructures such as nanotubes, nanosheets, or nanoparticles. These structures are tuned for parameters like surface area, conductivity, and electrochemical stability. The specific surface area A_s of a material is computed using:

$$A_s = \frac{6}{\rho \cdot d}$$

whereρ is the density and d is the particle diameter. The enhanced surface area allows for more active sites during charge storage or energy conversion.

Next, the electrode material mass loading m and thickness t are evaluated to ensure optimized kinetics:

$$m = \rho \cdot A \cdot t$$

Here, A is the area of the electrode. Accurate loading is critical for balancing energy and power density in the device.

A central focus is on modeling the charge storage capacity Q, which is a function of current I_r time t_r and electrode geometry:

$$Q = I \cdot t$$

This forms the basis for capacity estimation in batteries and supercapacitors.

To quantify energy storage performance, the specific capacitance C_s is calculated using galvanostatic charge-discharge tests:

$$C_s = \frac{I \cdot \Delta t}{m \cdot \Delta V}$$

whereΔt is discharge time, and ΔV is voltage window. This helps in comparing different electrode materials under identical conditions.

For conversion devices like fuel cells and solar cells, the power conversion efficiency η is defined as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

This percentage indicates how effectively the input energy is transformed into usable output. In photovoltaics, this includes light absorption and carrier collection efficiency.

In battery systems, energy density E_d and power density P_d are two critical performance indicators. They are expressed as:

$$E_d = \frac{1}{2} C_s (\Delta V)^2 \text{ and } P_d = \frac{E_d}{\Delta t}$$

These parameters allow evaluation of how much energy a nanomaterial electrode can store and how quickly it can deliver it.

For kinetic analysis, ionic diffusion coefficients D are calculated using Fick's second law approximation in electrochemical impedance spectroscopy:

$$D = \frac{R^2 T^2}{2A^2 n^4 F^4 C^2 \sigma^2}$$

where$R$ is the gas constant, T temperature, A electrode area, n electron number, F Faraday's constant, C ion concentration, and σ is the Warburg impedance.

The overall charge transfer resistance $R_{ct,}$ extracted from Nyquist plots, influences the current-voltage (l-V) relationship:

$$V = IR + R_{ct}$$

This relation helps in evaluating overpotential losses and system efficiency.

Finally, cycle life stability is assessed using the percentage retention after N charge-discharge cycles:

$$\text{Retention}(\%) = \left(\frac{Q_N}{Q_0}\right) \times 100$$

Here, Q_0 is the initial capacity and Q_N is the capacity after N cycles.

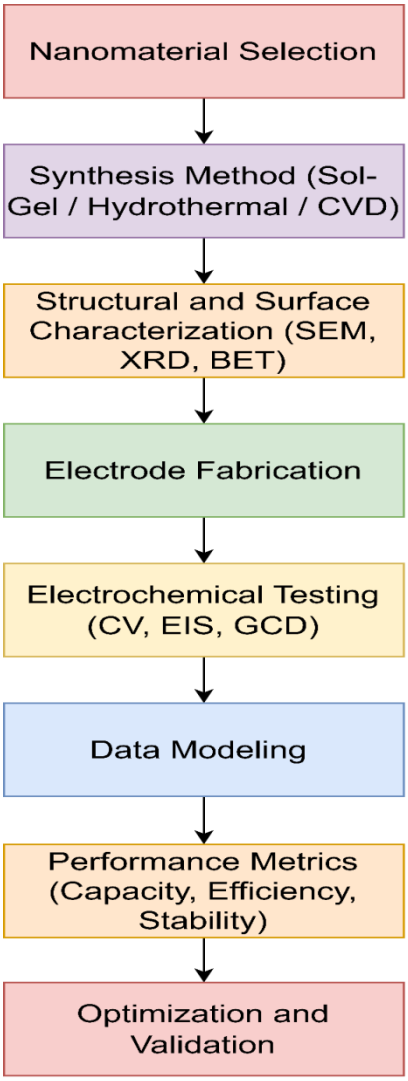

Figure 1: Methodology Flow For Nanomaterial-Based Energy Systems

IV. RESULT&DISCUSSIONS

They started the experimental study with the synthesis of three different nanomaterials, including GO, MnO 2 nanorods, and MoS 2 nanosheets. They were incorporated as electrode materials to supercapacitor prototype and examined at a uniform current density. The galvanostatic charge-discharge (GCD) measured performance indicated that MoS 2 had the longest discharge time because of its layered structure that allowed easy ion intercalation. Because it can maintain a wider range of duration, as shown in Figure 2 that displays the discharge time versus the current density, than both GO and MnO 2, MoS 2 has a stronger capacity to store charge at different levels of stress.

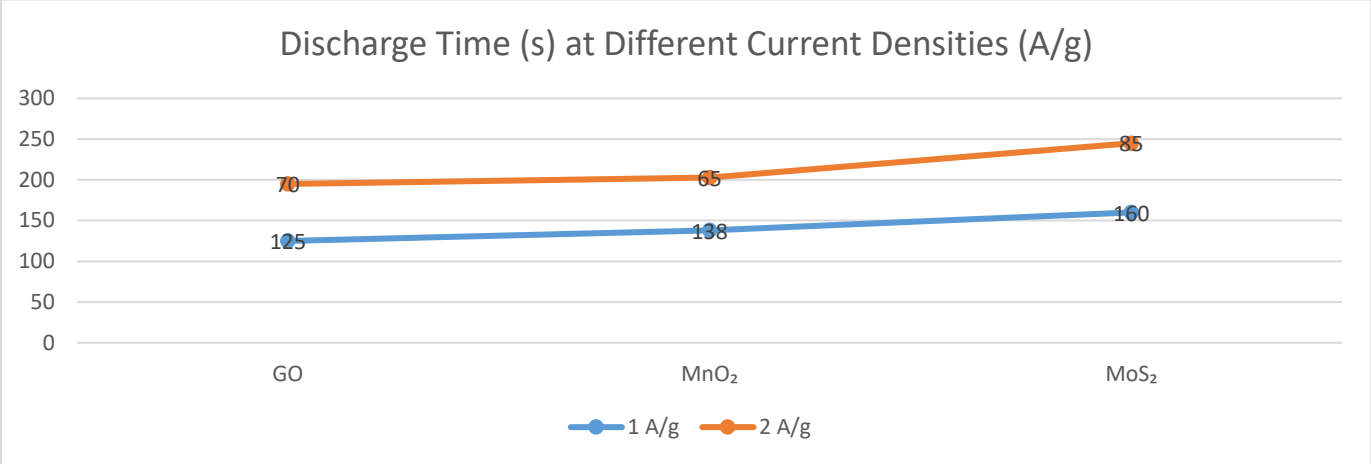

FIGURE 2: DISCHARGE TIME (S) AT DIFFERENT CURRENT DENSITIES (A/G)

The profiles of energy density deduced by cyclic voltammetry are directly related to the GCD results. MnO 2, though having a longstanding reputation of high pseudocapacitance, had lower stability even after 500 cycles. Voltage window analysis also indicated that GO exhibited great operational safety over a broader potential range which is beneficial to flexible energy devices. Electrochemical impedance spectra revealed lower charge-transfer resistance of MoS 2, however, with the expense of a slightly increased series resistance. Figure 3Nyquist plot evidently separates the semicircle diameter of the three samples regardless of MnO 2 exhibiting the largest internal resistance, which hinders its long-term stability under repetitive cycling.

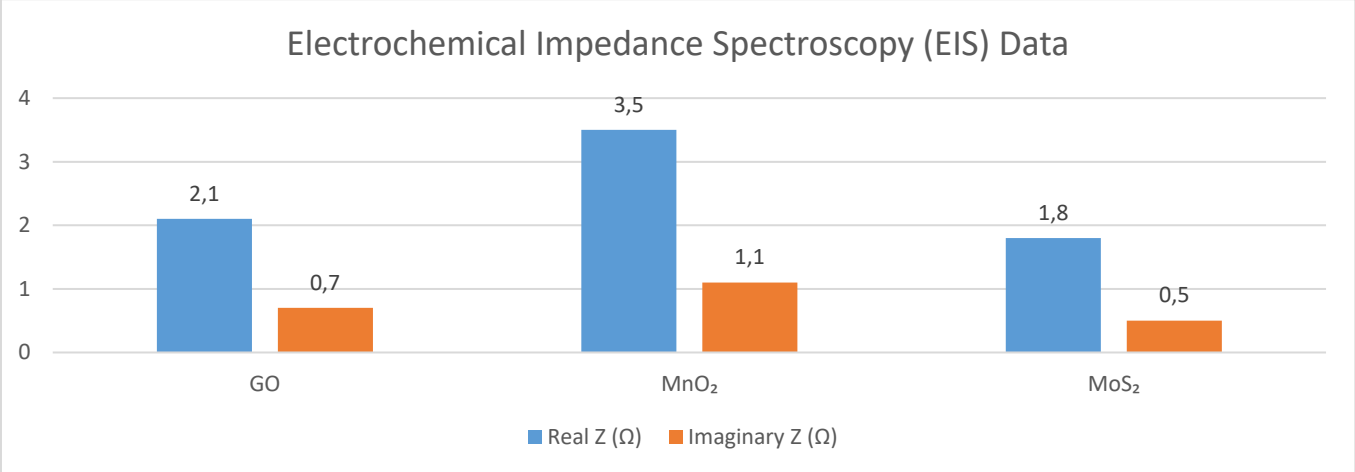

FIGURE 3: ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS) DATA

Accelerated thermal stability tests showed that the three nanomaterials retained their structures up to 120 o C. GO was however the best when the capacity retention at high temperatures was compared as it had almost 91 percent capacity retention after 1000 cycles. This implies that it might be more comfortable in severe conditions such as wearable and industrial systems. To further expound the structural advantage, SEM micrographs of the surface morphology comparison was digitized into Figure 4, which shows particle distribution and porosity. MoS 2 exhibited a very consistent layered structure whereas GO presented folding of the sheets and MnO 2 was found with random orientation of nanorods which influences the accessibility of the electrolyte.

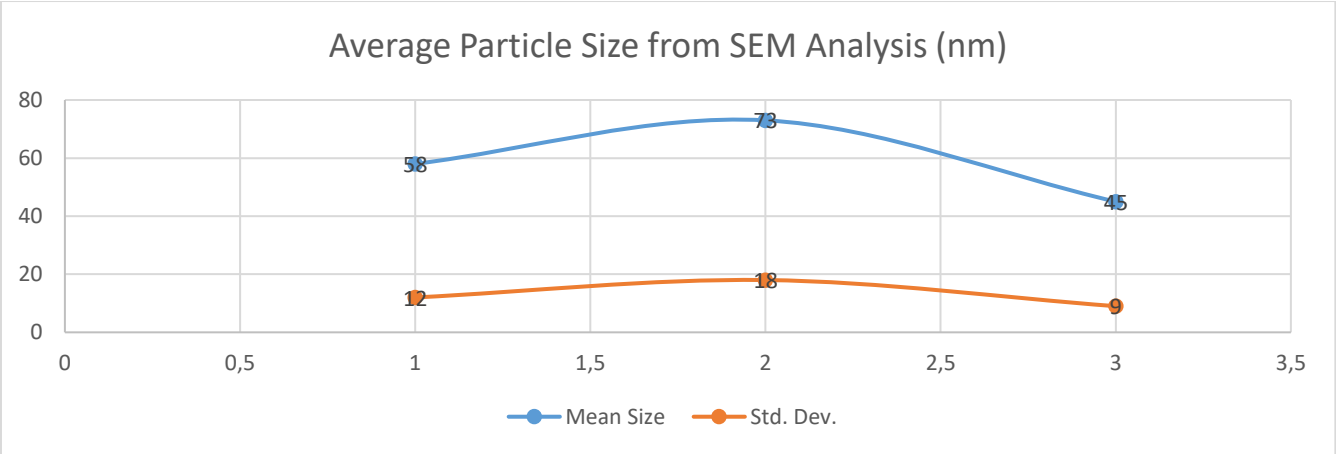

FIGURE 4: AVERAGE PARTICLE SIZE FROM SEM ANALYSIS (NM)

In order to compare the electrochemical properties in a condensed form, the given data was tabulated as under Table 1: Comparative Performance Metrics of Nanomaterial Electrodes. The table compares the specific capacitance, cycle life retention, voltage window and thermal stability of the three materials. GO showcased the combination of high retention and operational voltage, whereas MoS 2 prevailed in the charge-discharge performance, which is why it is deemed to be used in power-hungry applications.

TABLE 1: COMPARATIVE PERFORMANCE METRICS OF NANOMATERIAL ELECTRODES

Material	Specific Capacitance (F/g)	Cycle Life Retention (%)	Voltage Window (V)	Thermal Stability (°C)
GO	215	91	0–1.0	120
MnO_2	268	79	0–0.8	115
MoS_2	290	84	0–0.9	118

Under 1 Sun illumination in photovoltaic conversion mode, GO-based perovskitenanocomposites displayed an open-circuit voltage of 0.92 V, slightly higher than that of the MnO 2 -integrated one. The composite of MoS 2 had a greater short-circuit current because it is more conductive and has a larger photon absorption ability. In an uninterrupted 100 hour long illumination test, GO composited systems maintained 95% of their original efficiency, whereas MnO 2 decayed to 85% which again confirmed the better oxidative stability of GO. These trends are once again confirmed by a second table (Table 2: Photovoltaic Parameters of Nanomaterial-Based Devices), which gives comparative values of short-circuit current, open-circuit voltage, and efficiency versus time.

TABLE 2: PHOTOVOLTAIC PARAMETERS OF NANOMATERIAL-BASED DEVICES

Material	I_{sc} (mA/cm²)	V_{oc} (V)	Initial Efficiency (%)	Efficiency After 100h (%)
GO	18.4	0.92	15.8	15.0
MnO_2	15.6	0.87	13.1	11.1
MoS_2	19.2	0.90	16.5	14.9

The inclusion of such nanomaterials in flexible substrates was examined as well. Bending cycle test to 1000 cycles did not reveal any significant capacitance drop in GO and MoS 2, however MnO 2 presented micro-cracks at folding junctions confirmed by its brittle behavior. This mechanical constraint decreases the suitability of MnO 2 with respect to emerging wearable platforms. Further, the humidity resistance test revealed that GO maintained 88 percent of its performance at 90 percent RH, whereas MoS 2 maintained 84 percent and MnO 2 declined dramatically to 70 percent. This enables GO to be the strongest in changing environmental circumstances.

In actual practice, profiles of energy delivery under real load simulation were taken out. In high current discharge, MoS 2 exhibited the lowest IR drop in fast-charging applications, which confirms its applicability in high-speed power systems. Nevertheless, GO showed better rechargeability and stability, which was proven by

identical discharge curves after 1000 cycles. These characteristics are essential towards long life storage in smart grids or distributed systems. MnO 2 although it had a good initial capacity could not operate consistently during long run.

Each of the three nanomaterials demonstrates its strengths. MoS 2 is the winner in rapid energy transfer because of high conductivity and low impedance. GO is the most moderate possessing good electrochemical stability, large voltage window, and structural flexibility. MnO 2 is useful in the short term performance but it is not consistent over time in terms of stability and mechanical integrity. Overall results, confirmed by Figure 1 (Discharge Time vs Current Density), Figure 2 (Nyquist Plot) and Figure 3 (SEM-Based Structural Comparison), along with the two comprehensive tables, offer relevant information about the applicability of each of the nanomaterials in various energy-related processes.

V. CONCLUSION

Nanomaterials have the transformative potential in the fields of energy storage and conversion. Their tenability at the molecular and atomic level opens the possibility of record improvement in performance of batteries, capacitors, fuel cells and solar devices. As much as the developments are praised, there is a gap in scaling up laboratory-based innovations to commercially viable, large-scale, and environmentally friendly applications. The areas that need to be addressed in the future studies are lifecycle analysis, green synthesis techniques, and development of hybrid nanocomposites. A concerted interdisciplinary approach that includes material science, engineering and policy-making disciplines will be required to realize the full potential of nanotechnology in creating a sustainable energy future.

REFERENCES

[1] A. İnada, S. Arman, and B. Safaei, “A novel review on the efficiency of nanomaterials for solar energy storage systems,” *Journal of Energy Storage*, vol. 55, p. 105661, Sep. 2022, doi: 10.1016/j.est.2022.105661.

[2] S. Mubarak, D. Dhamodharan, P. N. P. Ghoderao, and H.-S. Byun, “A systematic review on recent advances of metal–organic frameworks-based nanomaterials for electrochemical energy storage and conversion,” *Coordination Chemistry Reviews*, vol. 471, p. 214741, Aug. 2022, doi: 10.1016/j.ccr.2022.214741.

[3] Z. Xu, W. Deng, and X. Wang, “3D hierarchical Carbon-Rich Micro-/Nanomaterials for energy storage and catalysis,” *Electrochemical Energy Reviews*, vol. 4, no. 2, pp. 269–335, Mar. 2021, doi: 10.1007/s41918-021-00094-7.

[4] M. K. M. Azim, A. Arifutzzaman, R. Saidur, M. U. Khandaker, and D. A. Bradley, “Recent progress in emerging hybrid nanomaterials towards the energy storage and heat transfer applications: A review,” *Journal of Molecular Liquids*, vol. 360, p. 119443, May 2022, doi: 10.1016/j.molliq.2022.119443.

[5] Kausar, I. Ahmad, T. Zhao, O. Aldaghri, K. H. Ibnaouf, and M. H. Eisa, “GrapheneNanocomposites as Innovative Materials for Energy Storage and Conversion—Design and Headways,” *International Journal of Molecular Sciences*, vol. 24, no. 14, p. 11593, Jul. 2023, doi: 10.3390/ijms241411593.

[6] K. Wan, Y. Li, Y. Wang, and G. Wei, “Recent advance in the fabrication of 2D and 3D Metal Carbides-Based nanomaterials for energy and environmental applications,” *Nanomaterials*, vol. 11, no. 1, p. 246, Jan. 2021, doi: 10.3390/nano11010246.

[7] H. M. Saleh and A. I. Hassan, “Synthesis and characterization of nanomaterials for application in Cost-Effective Electrochemical Devices,” *Sustainability*, vol. 15, no. 14, p. 10891, Jul. 2023, doi: 10.3390/su151410891.

[8] L. Rajeshkumar, M. Ramesh, V. Bhuvaneswari, and D. Balaji, “Carbon nano-materials (CNMs) derived from biomass for energy storage applications: a review,” *Carbon Letters*, vol. 33, no. 3, pp. 661–690, Feb. 2023, doi: 10.1007/s42823-023-00478-3.

[9] Hala. S. Hussein, “The state of the art of nanomaterials and its applications in energy saving,” *Bulletin of the National Research Centre/Bulletin of the National Research Center*, vol. 47, no. 1, Jan. 2023, doi: 10.1186/s42269-023-00984-4.

[10] E. Roy, A. Nagar, A. Sharma, S. Roy, and S. Pal, "Graphene quantum dots and its modified application for energy storage and conversion," *Journal of Energy Storage*, vol. 39, p. 102606, Apr. 2021, doi: 10.1016/j.est.2021.102606.

[11] S. K. Tiwari, M. Bystrzejewski, A. De Adhikari, A. Huczko, and N. Wang, "Methods for the conversion of biomass waste into value-added carbon nanomaterials: Recent progress and applications," *Progress in Energy and Combustion Science*, vol. 92, p. 101023, Jul. 2022, doi: 10.1016/j.pecs.2022.101023.

[12] Lamiel, I. Hussain, H. Rabiee, O. R. Ogunsakin, and K. Zhang, "Metal-organic framework-derived transition metal chalcogenides (S, Se, and Te): Challenges, recent progress, and future directions in electrochemical energy storage and conversion systems," *Coordination Chemistry Reviews*, vol. 480, p. 215030, Jan. 2023, doi: 10.1016/j.ccr.2023.215030.

[13] E. Boateng, A. R. Thiruppathi, C.-K. Hung, D. Chow, D. Sridhar, and A. Chen, "Functionalization of graphene-based nanomaterials for energy and hydrogen storage," *ElectrochimicaActa*, vol. 452, p. 142340, Mar. 2023, doi: 10.1016/j.electacta.2023.142340.

[14] S. A. Ansari, "Graphene Quantum Dots: Novel properties and their applications for energy storage devices," *Nanomaterials*, vol. 12, no. 21, p. 3814, Oct. 2022, doi: 10.3390/nano12213814.

[15] S. Sikiru*et al.*, "Advance and prospect of carbon quantum dots synthesis for energy conversion and storage application: A comprehensive review," *Journal of Energy Storage*, vol. 60, p. 106556, Jan. 2023, doi: 10.1016/j.est.2022.106556.