Recent Advancements of Emerging Nanomaterials for Energy Storage Applications

***Dipankar Gogoi, Ananta Sasmal, and T. D. Das**

Department of Basic and Applied Science, National Institute of Technology Arunachal Pradesh, Jote, India-791113

**Email: nehu.nanodg@gmail.com*

Abstract

The investigations of recent trends in developing nanomaterials designed primarily for use in energy storage. The study of nanomaterials remains increasingly important, with energy storage technologies playing a critical part in fulfilling the growing need for sustainable and environmentally friendly energy solutions. The special qualities of nanomaterials, such as their enhanced surface area, mechanical strength, and electrical conductivity, offer considerable potential for boosting the effectiveness of energy storage devices. It clarifies the many production procedures and structural features of a variety of nanomaterials, including those based on carbon, metal oxides, polymers, metal halide and sulphide, metal carbide and nitride (MXenes), and metal borides (MBenes). A study is also conducted of recent advancements in the engineering and design of nanomaterials for energy storage. The possibilities and challenges of the subject are also covered, emphasising the importance of environmental sustainability, cost-effectiveness, and scalability. This extensive assessment is a helpful resource for researchers in academics and engineers in industries working to further the development of next-generation energy storage systems.

Keywords: Nanomaterials, Energy Storage Applications, Supercapacitor, Metal oxides, Battery, Chemical Stability and Future Challenges

1. INTRODUCTION

The investigation of advanced materials has become crucial because of rising worldwide energy demand and the need to move towards sustainable energy sources (Armaroli & Balzani, 2007, Chu & Majumdar, 2022). Because of their unique characteristics at the nanoscale, nanomaterials have become ground-breaking competitors in energy storage sectors (Simon & Gogotsi ,2008, Wang & Polleux, 2007). This innovative field combines the concepts of energy storage technology with nanoscience, offering potential discoveries that could change the way power delivery and storage systems are implemented (Chhowalla & Shin, 2013, Bruce & Freunberger, 2011). The distinct properties shown by nanomaterials arise from their nanoscale size, typically ranging from 1 to 100 nanometers. This spectrum of materials has unique mechanical, optical, electrical, and thermal characteristics that set them apart from bulk materials (Xia & Xiong, 2008, Halas & Lal, 2011). By utilizing these characteristics, researchers and developers have been able to create materials with improved performance metrics, which makes them the best options for a range of energy storage uses (Wang & Yang, 2011, Zhao & Song, 2016).

The development of cutting-edge energy storage technologies is one of the main applications for nanomaterials. Since the energy density, charging rates, and overall performance of conventional energy storage devices are limited, the addition of nanomaterials has opened up new avenues for avoiding these limits (Shao & Liu,.2009). The reliability, efficiency, and environmental effect of energy storage systems could be completely transformed by the use of nanomaterials, whether they are used in lithium-ion batteries, sodium-ion batteries, supercapacitors (SPs), or other emerging technologies (Guo & Hu, 2008, Tarascon & Wan, 2001). Utilizing modern techniques including Chemical Vapor Deposition (CVD) (Li & Li, 2019), sol-gel procedures (Wang & Hsu, 2020), and atomic and molecular precision engineering (Yang & Fu, 2021), nanomaterials for energy storage are produced and manufactured. These methods enable the production of tailored nanomaterials, such as nanocomposites and nanostructured electrodes, with precisely controlled characteristics to optimise energy storage device performance (Zhao & Song, 2016). Through in-depth analysis, advanced characterisation techniques such as electron microscopy, spectroscopy, and diffraction methods allow researchers to gain a deeper understanding of and optimise the behaviour of nanomaterial formations (Li & Rivarola, 2016).

This study will carefully navigate the diverse landscape as it embarks on a comprehensive inquiry into nanomaterials for energy storage. The chapters that follow will explain the intricacies of the synthesis and characterization of various nanomaterials, as well as their applications in energy storage, ranging from SPs to lithium-ion batteries. Within these chapters lie revelations about the latest advancements, persistent challenges, and the promising future prospects within this dynamic and swiftly evolving domain. Transitioning seamlessly into the subsequent sections, the focus turns towards a detailed exploration of various classes of nanomaterials and their composites. The narrative then shifts to the presentation of diverse synthesis methods for producing these nanomaterials. This methodical approach seeks to offer a full grasp of nanomaterials by tying together all of their various aspects and opening the door to a thorough understanding of their significance in energy storage.

2. CURRENT SCENARIO OF VARIOUS NANOMATERIALS ON ENERGY STORAGE

Nanomaterials research has gained momentum due to the growing need for efficient energy storage solutions brought on by the integration of renewable energy sources, portable electronics, and electric cars. These materials have the potential to enhance the efficiency of energy storage systems such as batteries and SPs due to their unique characteristics at the nanoscale. In this article, we evaluate the state of nanomaterials in energy storage and talk about recent developments and difficulties. **Fig. 1** lists the nanomaterials that have the greatest potential to be used in energy-related applications. A number of particular nanomaterials, such as graphene, carbon nanotubes (CNTs), and carbon nanofibers, have been the subject of much research in the field of energy storage because of their high surface area, remarkable conductivity, and mechanical durability. They function as electrodes in batteries and SPs, facilitating high energy and power densities (Sun & Wang, 2017, Heiba & Shabha, 2024). Metal oxides, particularly transition metal oxides (e.g., MnO_2, Fe_2O_3) and binary metal oxides (e.g., TiO_2, ZnO); possess appealing theoretical capacities, making them suitable for batteries and SPs. Nanostructuring enhances their surface area and ion diffusion, elevating energy storage performance (Deka, 2023). Sulfide-based nanomaterials like MoS_2 and WS_2 exhibit promise due to their high specific capacities and stability, making them viable as battery electrodes for high-energy-density storage (Hannan & Khalil, 2022). Polymers such as PPy and PANI are explored for SPs, leveraging their pseudocapacitive behavior and high capacitance, with nanostructuring enhancing charge storage capacity and cycling stability (Li & Zhou, 2021). Combinations of nanomaterials, like carbon nanotubes/graphene-metal oxides, offer synergistic effects, improving conductivity, strength, and stability (Qi & Yang, 2016, Jang & Kim, 2019). These nanocomposites hold potential for next-generation energy storage technologies, addressing the demand for efficient and sustainable solutions across applications (Chen & Skordos, 2020). In summary, a growing number of businesses, such as grid storage, electric vehicles, and portable gadgets, are in need of effective energy storage. Because of this, a lot of research is being done to create better nanomaterials that are more cost-effective, scalable, and electrochemically efficient.

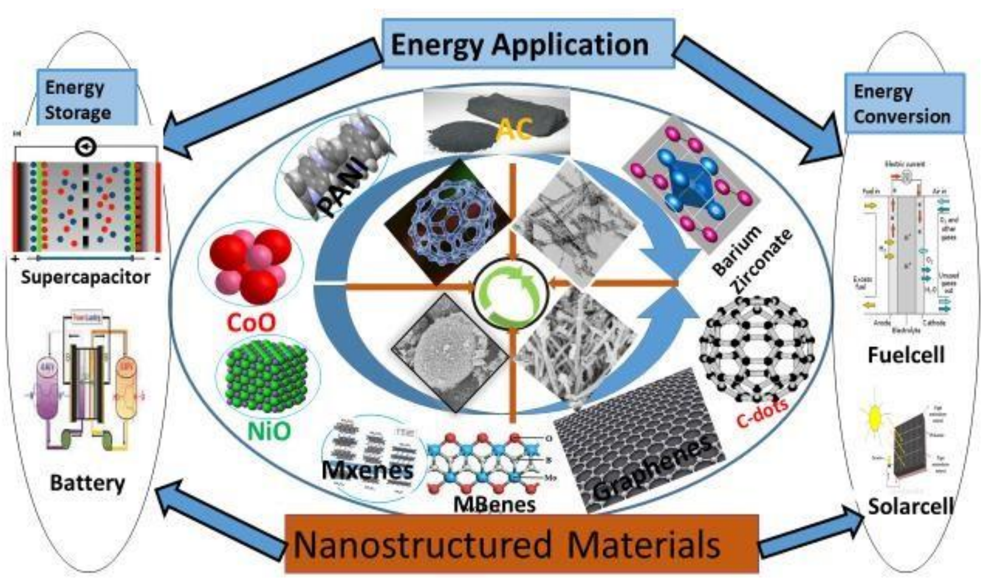

Fig.1: The several varieties of nanomaterials that hold the most potential for usage in applications pertaining to energy.

3. WORKING PRINCIPLE AND DEVICE MECHANISM

3.1. Batteries

A battery is a device that can generate a limited quantity of electrical energy when required. It does this by use of the basic building block of a battery called a cell, which is made up of three main parts: an electrolyte that sits between two terminals (an anode and a cathode) and two terminals themselves. This cell is protected by an outside shell, which is usually a box made of plastic or metal. The positive and negative terminals for external connections are identified as electrical connections coming from the anode and cathode. In order to complete the circuit, ions—charged particles—that travel across the terminals are produced when the electrolyte in the cell is activated with these terminals linked (Miao & Hynan, 2019). **Fig.2** depicts a schematic of cell of a battery. Zinc-carbon batteries are a common type of battery. These batteries use a manganese oxide-coated carbon rod for the positive terminal and a zinc alloy negative terminal with an ammonium chloride paste acting as the electrolyte. The circuit is powered by the zinc at the negative terminal of the battery, which is transformed into electrons and zinc ions when the terminals are linked. Ammonia is created at the positive terminal as a result of the reduction of manganese oxide (Miao & Hynan, 2019).

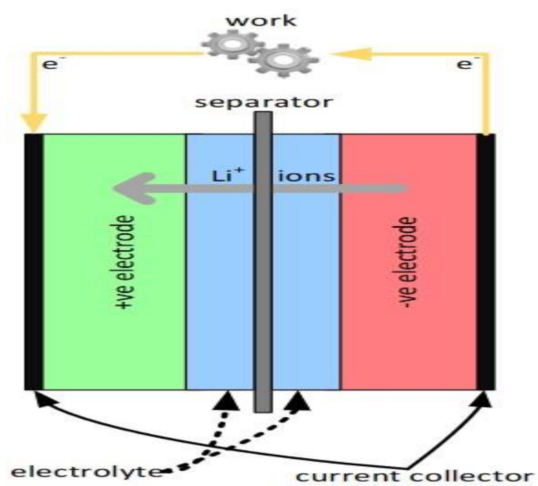

Fig.2: Schematic representation of a lithium ion battery. Adapted from ref. (Miao & Hynan, 2019)

3.2. Supercapacitors

The supercapacitors (SCs) are energy storage devices based on the idea of electrochemical energy conversion. They are sometimes referred to as electrochemical capacitors, particularly electric double-layer capacitors (EDLCs). Their low maintenance requirements, long life cycle, zero memory effect, high power density, and high specific capacitance have all drawn a lot of interest (Gupta & Singh, 2019). SCs obtain their charge through the process of electrosorption, in which surface level oxidation and reduction events take place. High specific capacitances are the outcome of this faradic process. Instead of reacting with the substance, the ions adsorbed on the electrode surface include the transfer of charge from the electrolyte to the electrode material. The chemical affinity of the electrode material with the adsorbed ions, as well as their chemical structure and pore size, determine the capacity. However, SCs are divided into two varieties based on their energy storage mechanisms: electric double-layer capacitors (EDLCs) and pseudo-capacitors. EDLCs work by electrostatically adsorbing and desorbing charges on the electrode surface, which is a rapid process that results in high power density and long cycle life. In contrast, pseudo-capacitors store energy using reversible faradic redox processes (Simon & Gogotsi, 2008). SCs, like batteries, have electrodes (cathode and anode) consisting of carbon, metal oxides, carbon nanotubes (CNTs), graphene, and other materials. The electrolyte is a critical component that controls the cell's operational voltage. It should have high conductivity, low viscosity, strong chemical stability, and be cost-effective (Liu & Yu, 2010). **Fig. 3** shows the basic mechanism of SCs.

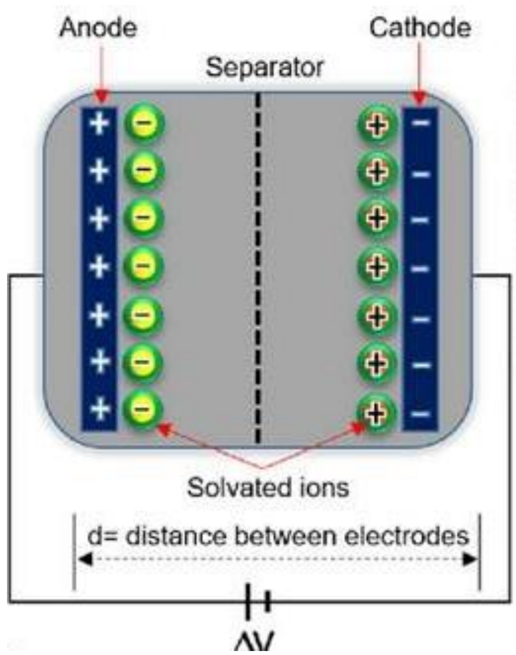

Fig. 3: shows the mechanism of SCs. Adapted from ref. (Bokhari & Siddique, 2020)

4. BASIC INTRODUCTION OF NANOMATERIALS USED FOR ENERGY STORAGE

Researchers are delving into novel nanomaterials with improved electrochemical performances for energy storage application like batteries and SPs (Yuan & Kong, 2017, Yi & Pan, 2020). This includes the production of new carbon-based nanomaterials such as carbon nanotubes, graphene, and nanofibers, as well as metal oxides, sulphides, and conducting polymers (Wei & Jia, 2017, Wen & Kang, 2019). The primary goals are to increase energy density, cycling stability, and rate capability. The study of 2D materials is becoming more popular due to its special qualities, which include high surface area, mechanical flexibility, and tunable electrical characteristics. Graphene, MXenes, MBenes, and transition metal di-chalcogenides (TMDs) are a few examples of these materials (Cai & Zhang, 2015, Shaikh & Ubale, 2022). These materials have potential for use in energy storage systems. The graphical depiction of different kinds of nanostructured materials for energy storage is presented in **Fig. 4**. In this section, we go over the many kinds of nanomaterials that might be good candidates for energy storage. **Table 1** outlines the electrochemical characteristics of various nanostructured functional materials.

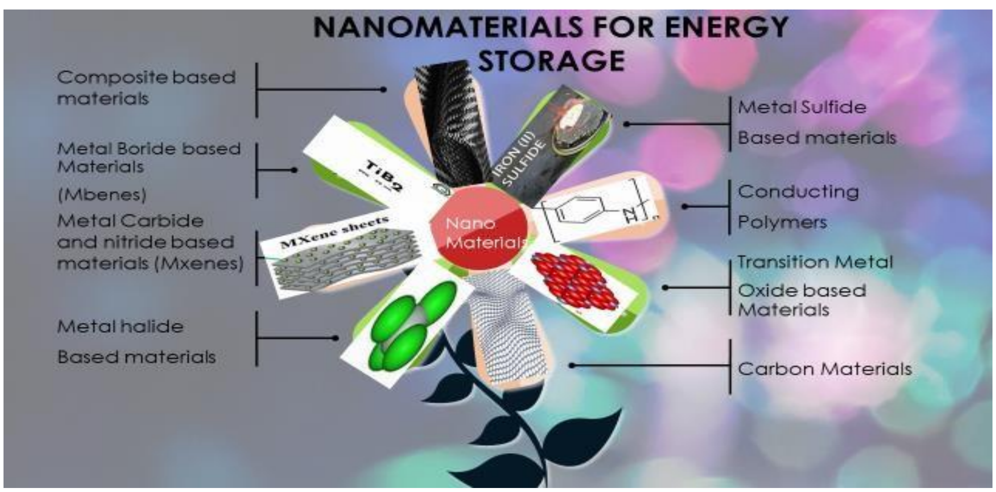

Fig. 4: The graphical representation of various nanomaterials for energy storage.

4.1. Carbon-based Nanomaterials

Carbon materials with remarkable qualities including large surface area, conductivity, and durability such as graphene, carbon nanotubes, nanofibers, activated carbon, aerogels, and carbonaceous composites are essential for energy storage (Ali & Shah, 2021, Yadav & Amini, 2020). Carbon nanofibers improve energy storage performance, whereas graphene and CNTs increase energy and power densities in batteries and SPs (Wang & Shi, 2009). Although carbon aerogels are lightweight and perfect for energy storage applications, activated carbon is preferred in SPs due to its porous structure and remarkable capacitance (Li & Dai, 2016). Composites made of carbon-based materials and other nanomaterials perform better and have better conductivity, which could lead to improvements in energy storage applications (Lv & Ma, 2020).

Table 1. Shows the electrochemical properties of various nanostructured functional materials.

Materials	Morphology	Specific Capacitance (F/g)	Energy density (Wh/Kg)	Power density (W/Kg)	References
NiO	Nanoflakes	305	5.3	225	(Sethi & Shenoy, 2021)
$NiMn_2o_4/C$	Nanosheets	789.3	36.11	1000	(Thonge & Dhas,2024)
Carbon Nano Fibers (CNF)	Nano fibers	186	25.8	500	(Karuppasamy & Lin, 2024)
TiO_2/PANI	Nanoparticles	421.66	--	--	(Naik & Kariduraganavar, 2024)
$TiN\text{-}MoS_2$	Nanosheets	535	32.62	9610	(Riaz & Cao, 2024)
$Mo_4VC_4T_x$	Nanoparticle	219	--	--	(Hussain & Rehman, 2024)
$CH_3NH_3SnCl_3$	Nanocrystal	2050	12	1020	(Tudu & Layek, 2024)
MBene-MoB	Layered structure	201.28	81.86	2500	(Wei & Kale, 2024)

4.2. Metal Oxide based Nanomaterials

Metal oxide-based materials are essential in energy storage applications because they have unique properties and can be applied to a wide range of energy storage devices (Novoselov & Mishchenko , 2016). Among commonly used metal oxide-based materials are lithium cobalt oxide ($LiCoO_2$) (Lachini & Eslami , 2024), lithium iron phosphate ($LiFePO_4$) (Maia & Gomes , 2024, nickel cobalt aluminum oxide (Zackrisson & Avellán , 2010), nickel manganese cobalt oxide (Ko & Jeong, 2023), vanadium pentoxide (V_2O_5) (González & Nacimiento, 2016), titanium dioxide (TiO_2) (sami & Etesami , 2017), and zinc oxide (ZnO) (Shaheen & Ahmad , 2020). These materials provide outstanding energy density, stability, and cycle life for a variety of applications, from portable devices to grid storage. They are utilised as cathodes or anodes in lithium-ion batteries, vanadium redox flow batteries (VRFBs), and other energy storage systems (Rajangam & Gowri ,2019). The current research aims to optimise these materials for improved performance, cost, and sustainability in order to meet the growing need for effective energy storage solutions for a wide range of applications.

4.3. Conducting Polymer Nanomaterials:

Conducting polymer-based materials have the potential for usage in energy storage applications because of their unique properties. Common ones include polyaniline (PANI) for SPs (Eftekhari & Li , 2017), polypyrrole (PPy) for flexibility (Huang & Li , 2016), PEDOT for stability (Shi & Liu , 2015), polythiophene (PTh) for ease of synthesis (Adedoja & Sadiku , 2023), and polyaniline based composites for enhanced performance (Heme & Alif , 2021). Ongoing research aims to optimize these materials for improved energy density and cycling stability, catering to various applications like portable electronics and electric vehicles.

4.4. Metal sulfide based Nanomaterials

Metal sulphides have come up as interesting possibilities for energy storage due to their large theoretical specific capacities, good electrochemical stability, and abundance of constituent elements (Rui & Tan , 2014). Among the commonly studied metal sulfides are molybdenum disulfide (MoS_2) (Paravannoor & Babu, 2019), tungsten disulfide (WS_2) (Rehman & Afzal, 2023), iron sulfides (FeS_2 and Fe_2S_3) (Manohar & Malkhandi, 2012), cobalt sulfides (CoS_2 and CoS) (Aloqayli & Ranaweera, 2017), and nickel sulfides (NiS_2 and Ni_3S_2) (Pothu & Bolagam, 2020). The potential of these materials in lithiumion batteries and SPs is being studied, providing opportunities for high-energydensity storage solutions (Aloqayli & Ranaweera, 2017). Particularly promising are iron sulphides because of their abundance and friendliness to the environment, and cobalt sulphides because of their high specific capacities and stable cycling (Ranter & Breckpot, 2010). Nickel sulphides also have the potential to improve energy density and cycling stability in energy storage systems (Sambathkumar & Kumar, 2021). In order to fully utilise metal sulphides in a variety of energy storage applications, from portable electronics to grid-scale energy storage devices, ongoing research endeavours to optimise the characteristics of these materials and investigate novel synthesis techniques.

4.5. Nanocomposites

The energy storage area is paying close attention to composite-based nanomaterials due to their unique properties and the synergistic effects of combining diverse materials. These materials' improved surface area, mechanical strength, conductivity, and electrochemical performance make them promising for a range of energy storage applications (Yang & Shen, 2015). Carbon-based composites such as graphene and carbon nanotubes, which are known for their conductivity and resilience, are employed in SPs and lithium-ion batteries (Iqbal & Khatoon, 2019). Despite problems with conductivity and stability, metal oxide composites are prized for their high theoretical capacity; overall performance is improved by combining them with conductive polymers or carbonaceous materials (Ali & Ahmad, 2023). When combined with metal oxides or carbon nanomaterials, conductive polymer composites such as polypyrrole and polyaniline, which have mechanical weaknesses but a high specific capacitance, perform better (Mohamed & Huang, 2024). Metal oxide nanoparticles atop graphene sheets, which are perfect for SP electrodes, are an example of hybrid nanostructures integrating several nanomaterials to produce synergies. Structures that embed nanowires or nanotubes in a conductive matrix are examples of nanostructured composites, which improve electrochemical characteristics by decreasing diffusion distances and increasing surface area (Jiang & Li,2012). The versatile qualities of organic-inorganic composites enable them to meet specialised energy storage requirements, such as those of SPs and lithium-ion batteries (Karthikeyan & Narenthiram, 2021). The promise of composite-based nanomaterials could be fully realised with more study, which could lead to a major change in energy storage technology.

4.6. MBenes (metal boride based materials): a new class of materials

Boron carbide (B4C) is a common designation for materials that contain a mixture of boron and carbon, often known as "boron-carbon" or "boron-carbide" compounds (Zhang & Zhou, 2022). One of the main examples of an MBene (Metal BorideGraphene) material is boron carbide. These materials usually contain carbon and boron atoms arranged in a crystalline structure (Sharma & Rangra, 2022). They have excellent mechanical properties, such as remarkable wear resistance and hardness, as well as excellent thermal stability and electrical conductivity, which makes them a good fit for energy storage applications (Khaledialidusti & Ghasemi, 2021). An instance involves blending metal borides like titanium diboride (TiB_2) (Zhang & Wang, 2022) or molybdenum boride (MoB) with graphene (Barik & Pal, 2023), resulting in composite materials that exhibit improved electrochemical performance for batteries and SPs. When compared to conventional electrode materials, these MBene composites provide improvements in charge storage capacity, faster charge/discharge rates, and improved cycling stability (Hou & Gao, 2020). Additionally, by altering their composition and structure, MBene materials can be tailored to meet specific energy storage needs, opening up opportunities for the development of effective and environmentally friendly energy storage solutions (Jin & Schwingenschlögl, 2022).Generally the uses of various metal borides can be utilized in energy sectors such as battery and supecapacitor application. So the utilization of Mbenes in various energy storage devices is shown in **Fig. 5**.

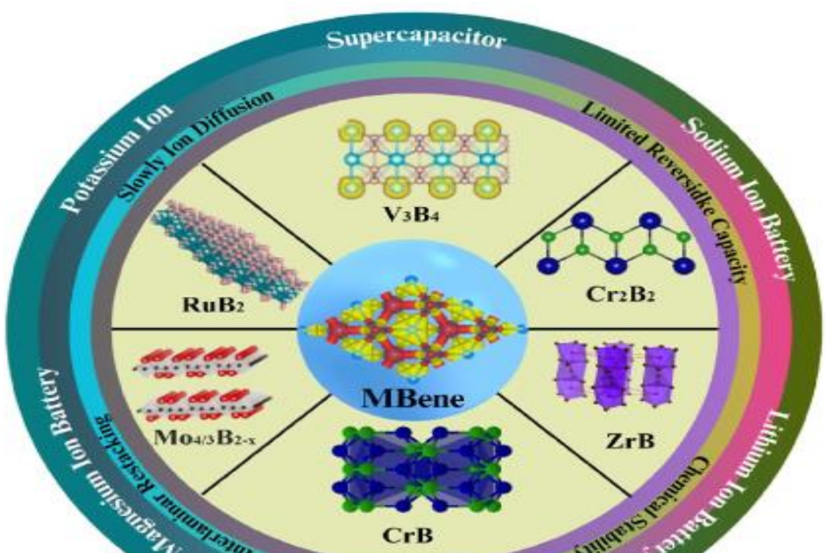

Fig. 5: Utilization of Mbenes in various energy storage devices (Javed & Zhang, 2024).

4.7. MXenes based materials

Energy storage has shown a great deal of interest in MXenes, a family of twodimensional transition metal carbides, nitrides, and carbonitrides, denoted by the formula $M_{n+1}X_nT_x$ (where M is an early transition metal, X is carbon and/or nitrogen, and Tx indicates surface functional groups like hydroxyl (-OH) or fluoride (-F)). Their large surface area, exceptional ion accommodation capacity, and excellent electrical conductivity are what make them so appealing (Mian & Qing, 2019). In SPs and batteries, for example, titanium carbide ($Ti_3C_2T_x$) is used as a highly conductive electrode material that provides quick charge storage and release (VahidMohammadi & Liang, 2021). Vanadium carbide (V_2CT_x) shows promise for pseudocapacitors and lithium-ion batteries due to its high specific capacitance and cycling stability, while molybdenum carbide (Mo_2CT_x) shows promise in lithium-ion batteries due to its high storage capacity, rate capability, and cycling stability (Niu & Zhang, 2020). MXenes offers a broad variety of energy storage materials, each designed to meet the demands of a particular technology. The goal of ongoing research is to enhance MXene uses in energy storage technology (Ge & Huo, 2019). The various techniques which is adopted to synthesize the mxene materials for the energy storage application shown in **Fig.** 6.

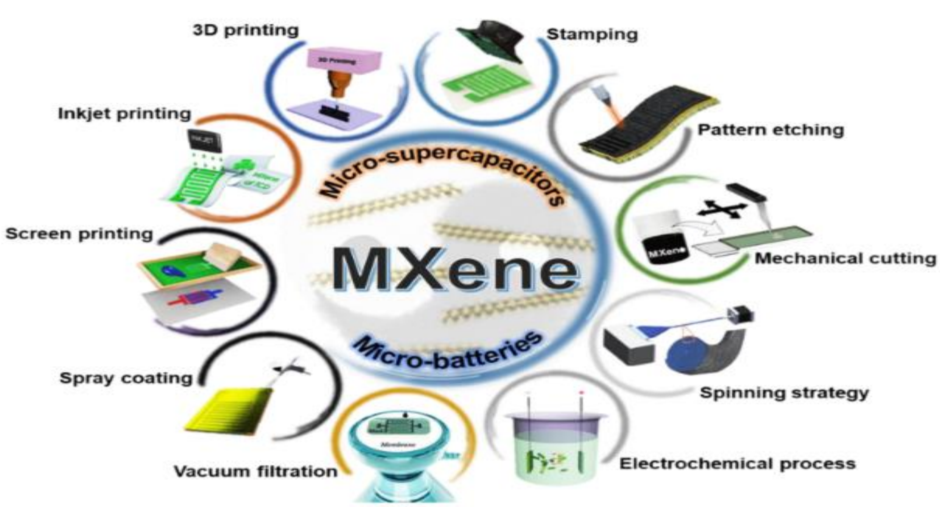

Fig. 6: shows the various methods to synthesize Mxenes for effective energy storage devices (Zhu & wang, 2022).

4.8. Metal halide based materials

Metal halide-based nanomaterials have special qualities and are versatile in electrochemical systems, which makes them promising for energy storage. These materials have good ionic conductivity and a large charge storage capacity because they are made up of metal cations and halogen anions that form nanoscale crystalline formations (Narayan & Parikh, 2021). Organometal halide perovskites, such as $MAPbI_3$, are a prominent example of perovskite-type metal halides that are well-known for their optoelectronic characteristics and appropriateness for solar cells, LEDs, and batteries (Zhang & Miao, 2020). Comparably, large surface area and electrochemical activity of metal halide nanoparticles, including copper halides (CuX), render them appropriate for use as SP and battery electrodes. Metal halide nanoparticles, which can be synthesised in a variety of ways, can be customised in size, shape, and composition to maximise their use in energy storage systems (Li & Zhou, 2021). Taking everything into account, these materials show a lot of promise for advancing energy storage technology. They offer greater efficiency, dependability, and sustainability in a range of applications, and additional study and development will be needed for further optimisation.

5. SYNTHESIS METHOD FOR THE PREPARATION OF NANOMATERIALS

Nanomaterials are appealing for a range of applications because their mechanical, chemical, and physical characteristics set them apart from bulk materials. Precise manipulation of nanomaterials' size, shape, content, and structure is necessary to accurately tailor them to particular application needs (Wang & Wang, 2024). Here, we describe the various synthesis methods used to create nanomaterials, emphasising their significance in enabling a broad range of energy storage applications. Synthesis of nanomaterials involves a number of methods, each with unique benefits and potential. In this section, we describe a number of synthesis procedures that are used to prepare nanoparticles for energy storage. **Fig.7** Illustrates the several ways that nanomaterials are prepared.

5.1. Physical method:

5.1.1. Mechanical Milling

A versatile technique for producing nanomaterials is mechanical milling, which reduces bulk materials into microscopic particles. Because of its versatility, scalability, and ability to alter the characteristics of nanomaterials for energy storage applications, it is growing in popularity (Zuo

& Zhang, 2024). Lithium-ion batteries, SPs, and hydrogen storage systems can use the nanoparticles produced by mechanically milling a variety of materials, such as metals, metal oxides, and carbon-based compounds (Babić & Prvulović, 2024). The environment, speed, and duration of milling must all be adjusted to produce the required particle characteristics. Mechanical milling produces nanomaterials with increased properties such as improved lithium-ion diffusion kinetics, higher charge storage capacities, and better hydrogen storage capacities (Rong & Mu, 2024). Mechanical milling offers accurate control over particle shape and size as well as scalable production, even in the face of difficulties like contamination concerns and parameter optimisation (Moradi & Groth, 2019). X-ray diffraction and electron microscopy are two essential characterisation techniques for evaluating the characteristics of nanomaterials. In conclusion, mechanical milling seems to have a bright future for the creation of customised nanomaterials used in high-performance energy storage devices (Pourjafarabadi & Rahighi, 2024).

5.1.2. Physical Vapor Deposition (PVD)

One versatile technique for depositing thin layers of materials onto substrates in a vacuum environment is physical vapour deposition, or PVD. This method offers fine control over film structure, content, and thickness, making it suitable for creating materials tailored for energy storage applications (Rar & Frafjod, 2004).

5.1.3. Chemical Vapor Deposition (CVD)

Chemical Vapour Deposition (CVD) is a versatile process widely used to create coatings, thin films, and nanostructures that allows for precise control over structure, morphology, and composition (Harutyunyan & Pradhan, 2002). When it comes to creating materials specifically tailored for various device components in the energy storage application space, CVD offers unique advantages. It calls for the chemical reaction of gaseous precursors to form thin films or nanostructures on a substrate surface. At high temperatures, precursor gases undergo breakdown or reactivity, resulting in the formation of solid-phase materials on the substrate (Zhang & Wang, 2020).

5.2. Chemical Methods:

5.2.1. Sol-Gel Method

An effective way to create nanomaterials specifically for energy storage is through a process called sol-gel synthesis, which is based on the reaction of precursor materials in a solution to form a sol that solidifies to form the desired material. This method allows for precise control over composition, morphology, and structure, which makes it perfect for energy storage applications such as batteries and SPs (Kumar, 2020). Examples of substances that improve performance and stability are titanium dioxide for the anodes of lithium-ion batteries and lithium cobalt oxide or lithium iron phosphate for the cathodes. Sol-gel synthesised silicabased materials can also be used as solid electrolytes or separators, increasing their mechanical strength and ion conductivity (Varshney & Siddiqui, 2020). Overall, sol-gel synthesis provides diversity in the preparation of nanomaterials for energy storage, with the possibility for further progress.

5.2.2. Hydrothermal/Solvothermal Synthesis

Nanomaterials for energy storage can be efficiently created using solvothermal and hydrothermal techniques. These methods create nanomaterials in a liquid media at high temperatures and high pressures, giving perfect control over the properties of the particles (Manikandan & Subramani, 2020). These techniques can be used to synthesise a wide range of compounds, such as carbon-based materials, metal oxides, and sulphides. Hydrothermal/solvothermal nanomaterials provide better electrochemical characteristics, like optimised ion diffusion and increased surface area (Sasmal & Nayak, 2023). Examples include TiO_2 (Choi & Jung, 2020) and MnO_2 (Yoon & Choi, 2021) for lithium-ion batteries, MoS_2 (Velický & Toth, 2017) and CoS_2 (Chen & Wei, 2020) for SPs, and graphene and carbon nanotubes for diverse energy storage applications (Niu & Zhang, 2020). Achieving the desired properties of nanomaterials requires fine-tuning synthesis parameters, such as pressure and temperature. Overall, the efficient and adaptable method of tailoring nanomaterials by hydrothermal/solvothermal synthesis propels the development of energy storage devices (Yang & Jia, 2020).

5.2.3. Electrochemical Deposition

Electrochemical deposition produces nanoparticles for energy storage by carefully depositing an electrolyte over a conductive substrate (Mohapatra & Das, 2023). Metal oxides and conductive polymers are often utilised materials specifically designed for lithiumion batteries and SPs. With the precise property customisation made possible by this approach, thin coatings with a large surface area and improved performance are produced. It is perfect for commercial energy storage applications since it is affordable and scalable (Zhang & Chen, 2020).

5.2.4. Chemical Precipitation

One popular technique for creating nanoparticles for energy storage is chemical precipitation. To create nanoscale particles, it involves carefully regulating the precipitation of soluble precursors. Many materials are created, such as metal oxides and sulphides, which have uses in SPs, lithium-ion batteries, and hydrogen storage (Iqbal & Zakar, 2020). This approach is scalable and provides fine control over particle properties. Chemical precipitation shows potential for high-performance energy storage materials, despite obstacles such as precursor selection (Weber & Osuji, 2016).

5.3. Template-Assisted Methods:

5.3.1. Hard Templating

Rigid templates, such as porous membranes or sacrificial materials, are used in hard templating, a technique for producing nanomaterials with exact size, shape, and structure, to direct the production of the nanomaterial (Zhang & Cheng, 2021). It has the potential to be used in energy storage devices like fuel cells, batteries, and SPs since it makes it possible to replicate template structures and create nanomaterials with certain morphologies. Precursor infiltration, template preparation, and template removal are the steps in the process that produce nanomaterials with improved characteristics, such as increased surface area and ion transport for lithium-ion batteries, effective charge storage for SPs, and enhanced durability and efficiency for fuel cells (Hou & Mao, 2021). Optimising template removal and guaranteeing compatibility between templates and precursor chemicals are issues associated with hard templating, despite its capacity to provide exact control over nanomaterial morphology, scalability, and reproducibility. Hard templating, however, has the potential to advance energy storage technology through customised nanomaterials (Haynes & Bougnouch, 2020).

5.3.2. Soft Templating

Soft templating enables customisable nanomaterial architectures, which are critical for energy storage. It uses self-assembling templates to create nanostructures with precise morphology and pore distribution (Poolakkandy & Menamparambath, 2020). Lithium-ion batteries, SPs, and fuel cells can be made from a variety of materials, including mesoporous carbon, metal oxides, and conducting polymers (Zhang & Cheng, 2021). Precursors and templating agents combine to generate ordered mesostructures that act as templates. The material is solidified and the template is removed in later stages. The resulting nanomaterials have improved specific capacitance, catalytic activity, and lithium ion diffusion due to their optimised characteristics (Shi & Shao, 2022). Large-scale production is made easier by soft templating, which guarantees control over pore size, surface area, and shape (Roostei & Rahimpour, 2023). For purity, template removal and synthesis parameter optimisation are essential. All things considered, soft templating is essential to the development of nanomaterials for reliable and effective energy storage systems (Kaplin & Lokteva, 2020).

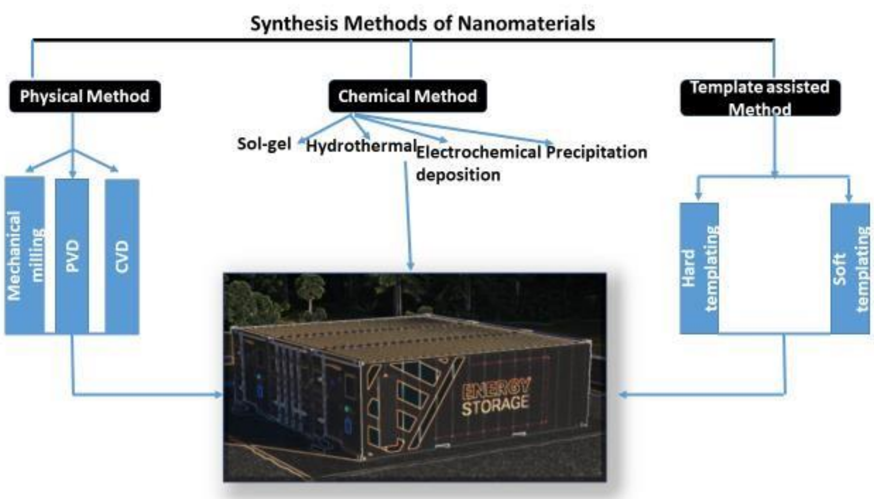

Fig. 7: shows the types of synthesis method to prepare nanomaterials for energy storage.

6. FUTURE PERSPECTIVES OF NANOMATERIALS

As the field of nanoparticle energy storage research advances, many significant opportunities begin to surface. Future advancements in the realm of nanomaterials have great potential for transformative advances. Nanomaterials offer chances to significantly enhance the performance of energy storage devices, such as batteries, SPs, and fuel cells, by accurately manipulating nanoscale structures and compositions. Higher energy densities, quicker charging rates, and longer cycle lifetimes may result from this. Additionally, nanomaterials minimise the negative environmental effects of energy storage systems by facilitating the production of more ecologically friendly technologies through the use of widely available and eco-friendly components. Furthermore, nanomaterials are essential for integrating renewable energy sources like solar and wind into the grid since they are used to create high-performance batteries and SPs that can store and provide energy on demand. Nanomaterials permit the diminution of energy storage devices, revolutionising design and functionality and opening up new possibilities in wearable electronics, portable gadgets, and implanted medical equipment. Moreover, nanomaterials aid in the creation of sophisticated energy management systems and smart grid technologies, which stabilise the grid, control peak demand, and permit dynamic energy distribution. The development of nanomaterials for energy storage requires collaborative research between disciplines like materials science, chemistry, physics, and engineering. This will spur innovation and lead to advances in the design, synthesis, characterization, and device integration of materials.

In order to achieve broad adoption, the future focus will be on increasing the manufacturing of nanomaterials and turning research findings from laboratories into marketable goods while guaranteeing affordability and resolving safety issues. To sum up, nanomaterials are the key to opening up the next wave of energy storage options. They offer performance, sustainability, and versatility never seen before, and their full potential to solve the world's energy crisis will only be realised through continued research, development, and cooperation.

7. CONCLUSION

In the energy sector, electrochemical energy storage devices are getting growing attention in the energy industry. Metal oxides, polymers, carbon-based materials, metal sulphides and hallides, metal carbide (Mxene) and metal boride (MBene)based materials, and composite mixed materials that correlate both structure and characteristics to performance are all included in the research of electrode materials. The objective is to develop high-performance electrodes with higher capacitance values and better cycle stability through ongoing efforts to discover new materials. Versatile nanomaterials are crucial for energy applications because of their exceptional properties, which include a high surface-to-volume ratio, chemical stability, efficient electron transport, and thermal conductivity. According to recent research, nanocomposites and nanohybrids can work together to produce synergistic effects that satisfy the needs of energy storage devices. Hybrid electrode materials that improve the characteristics of metal-oxide/metal nanoparticles can be made by including carbon-based nanomaterials and their derivatives. Novel materials such as core-shell nanomaterials, covalent organic frameworks, metal-organic frameworks, and metal nitrides have potential use in batteries and supercapacitors.

Author Contributions Statement

Dipankar Gogoi: Conceptualization, Investigation, Methodology, & Writing – original draft; **Ananta Sasmal:** Investigation, Writing – review & editing; and **T.D. Das:** Visualization, & Supervision.

Declarations of Ethical approval

This paper complies with all the authors' ethical responsibilities.

Data Availability Statements

Data sets generated during the current study are available from the corresponding author on reasonable request.

CONSENT FOR PUBLICATON

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CONFLICT OF INTEREST

The authors have no direct or indirect competing interests.

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