Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

# Recent Advancements on Supercapacitor Electrode Materials and It's Applications

**[1]Akash Indoria, [2] Rajesh Sahu#**

[1] Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jagatpura, Jaipur, India

akashindoria001@gmail.com, rajeshsahuphysics@gmail.com

Abstract- Supercapacitors, have attracted a great deal of research attention. Because of their impressive energy storage abilities, high power density, and long lifespan compared to regular capacitors and batteries. This review discusses the progress in supercapacitor technology, focusing on important areas like material improvements, manufacturing methods, energy storage processes, and challenges in increasing production. We also look at important discussions about energy density limits, the environmental impact of materials, and how they fit into renewable energy systems. By exploring the field in depth, we highlight the current research gaps: the need for more durable electrode materials, production methods that can be scaled up, and wider applications in future energy systems.

Keywords- supercapacitor, power density, renewable, energy density, electrode materials

## I. INTRODUCTION

Supercapacitors, often referred to as electrochemical capacitors, have garnered growing interest for their potential to connect traditional capacitors and batteries through high energy density coupled with quick charge-discharge cycling and a long lifespan [1]. One area of major emphasis in their development has been on electrode materials, since they strongly determine overall device performance [2]. This literature review examines recent breakthroughs in supercapacitor electrode materials, identifies current themes of interest, debates, and research gaps, and offers a comprehensive summary of recent advancements within this domain. Major breakthroughs are examined within sections dedicated to organic substances, metals oxide, conductive plastics, and novel composite structures and hybrid systems. This literature review examines recent breakthroughs in supercapacitor electrode materials, identifies current themes of interest, debates, and research gaps, and provides an overview of the state-of-the-art research in this field. Key advancements are reviewed under the categories of conducting polymers, metal oxides, carbon-based materials, and emerging composites and hybrids.

This review paper presents a detailed overview of the latest progress on supercapacitor technology, and, in particular emphasis, on the novel materials, novel fabrication methods and recent developments in design and performance tailoring. Recent advances in electrode materials, including activated carbon, graphene, carbon nanotube and metal oxide composite are elaborated in detail, particularly focusing their effect on the overall performance of supercapacitors. The contribution to the performance of different electrolyte systems - aqueous, organic and ionic liquid based - is also discussed, in particular, their involvement in device efficiency, stability and electrochemical characteristics is focused on. Further, we discuss the challenges that the supercapacitor community is undertaking in balancing energy and power densities, increasing the scalability, decreasing the environmental footprint, and decreasing the cost [3]. In addition, this review describes the future trends of

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

supercapacitor research, including technological developments and potential applications in diversified fields such as in renewable energy systems, electric vehicles, power backup systems, portable electronics, and so forth [4]. Combination of supercapacitors with other energy storage systems, including batteries and fuel cells is also discussed as a novel direction in order to design hybrid energy storage systems that can satisfy the changing energy demand of contemporary society. In this review, we intend to present an in-depth knowledge of the current state-of-the-art advances in the area of supercapacitor development, discussing the challenges, the potential, and the future prospects in this relevant technology as a solution to energy storage.

## II. SUPERCAPACITOR CONSTRUCTION AND WORKING

Regular capacitors store energy by moving electrons between two parts. Supercapacitors made from carbon have a larger surface area and use a method called the electric double layer to store charges. For supercapacitors made with metal oxides or polymers, another method called pseudo-capacitance is more important [3]. Even though both supercapacitors and regular capacitors use the same formulas for capacitance, supercapacitors can store more energy because they have thinner insulators and larger electrode surfaces this allows them to provide greater power compare to batteries and hold more energy than standard capacitors [5]. A supercapacitor (SC) uses a material that does not conduct electricity to separate two carbon electrodes. This material helps keep the charges apart and also affects how well the SC works. In a supercapacitor, charges do not move; instead, they are stored using electrical forces. When a voltage is applied, it creates an electric field in the liquid inside, causing it to become polarized. This diffuses ions to porous electrodes with the opposite charge across the dielectric. Thereby, the creation of the electric double layer at every electrode distance between the electrodes will get reduced and the surface area of electrode gets increased. It relies upon active materials used in electrolytes and active surface area of an electrode and the percentage usage rate of micro-holes available on a porous electrode [6]. Making models of supercapacitors To understand how supercapacitors work, many models have been suggested [7]. Quantitative modelling is helpful in the determination of performance characteristics, which aids the reduction of time and the cost of fabrication as well as physical experimentation [8]. The physical characteristics of SC cannot be entirely and precisely described by a single model; therefore, Several different models have been proposed to explain the behaviour of supercapacitors (SCs). In recent years, accurately characterizing SCs has become increasingly important due to their growing relevance in energy-storage applications. Electrical modelling helps explain how supercapacitors respond to changes in voltage, temperature, and operating frequency. Some of the commonly used modelling approaches include: Models based on electrical double-layer phenomena, Models represented through equivalent electrical circuits, Data-driven or intelligent computational models, Models that consider the behaviour of porous electrode structures [1, 2, 9].

## III. TYPE OF SUPERCAPACITORS AND PRINCIPLES BEHIND STORAGE

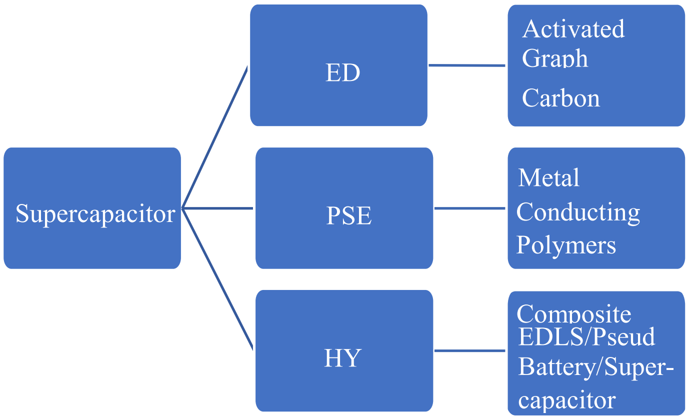


Fig. 1 Type of supercapacitor

Supercapacitors can be categorized broadly based on their energy storage mechanism and electrode material structure.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Though all supercapacitors have the common characteristic of delivering high power and fast charge–discharge, their performance properties are very much dependent on whether the storage is electrostatic only, Faradaic redox reactions only, or both mechanisms combined. On this basis, supercapacitors are classified into electric double-layer capacitors (EDLCs), pseudo capacitors, and hybrid supercapacitors [10-15].

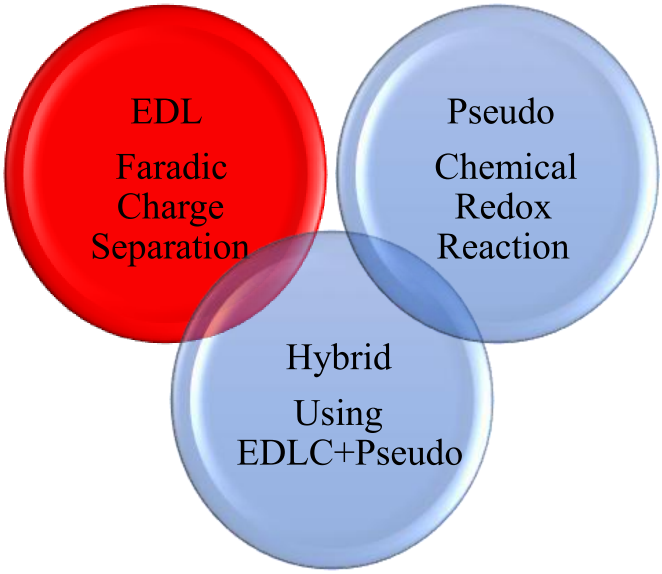


Fig. 2 Method used in charge storage

Currently, different kinds of capacitors are on the market for energy. Storage catalogued according to the dielectric employed (i.e., based on the specific dielectric employed or based on) [16-20]. Every capacitor has distinct characteristics and applications, ranging from standard capacitors used in small electronic trimming tasks to supercapacitors employed in high-voltage power factor correction [20]. In recent decades, research on supercapacitors has surged to address the growing need for applications requiring higher specific energy, improved cycle life, and enhanced reliability [21]. In recent decades, research on supercapacitors has surged to address the growing need for applications requiring higher specific energy, improved cycle life, and enhanced reliability. Supercapacitors share a similar structure with batteries. Supercapacitors are made up of two electrodes, which are kept apart by a separator and placed in an electrolyte. They store energy by charging and discharging at the spot where the electrodes meet the electrolyte. Even though they work like regular capacitors, supercapacitors are better for quickly storing and releasing energy. They have electrodes with a much larger effective surface area, which allows them to hold more charge than standard capacitors. While regular capacitors usually store energy in microfarads to millifarads, supercapacitors manage to keep low equivalent series resistance and perform well [22].

•EDL capacitance resulting from Coulombian charging at the electrode-electrolyte interface.

• Pseudocapacitance arises from surface-level redox reactions that occur at specific potentials. While both mechanisms work together to define the energy-storage behaviour of hybrid supercapacitors, they are explained separately here for clarity and ease of understanding [23].

1) *Energy Storage Mechanism in Electric Double-Layer Capacitors (EDLCs)*

EDLC works on a concept similar to that of a standard capacitor, yet the way it stores charge differs significantly. In a conventional capacitor, the amount of charge that can be stored is restricted by the physical separation between the two plates. Supercapacitors, however, can hold far more energy because the Electric Double Layer (EDL) mechanism enables them to utilize electrodes with exceptionally large surface areas. Like traditional capacitors, they are also capable of rapid charging and discharging. An EDLC stores energy by trapping ions from the electrolyte onto the active material of the electrodes. This process creates an electric double layer where charge separation takes place because of the reaction between the electrode and the electrolyte. Essentially, the charge is stored right in this layer where the two meet. In an EDLC, energy is held through the reversible attraction of these ions to the stable material in

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

the electrodes, with the charge stored directly y in this unique layer formed by their interaction [23].

Importantly, the electrode material in an EDLC does not undergo charge-transfer reactions at the interface; instead, the capacitance results purely from electrostatic effects. The charging process involves several steps, including surface dissociation, ion adsorption from the electrolyte, and interactions associated with defects in the electrode's crystal lattice. To maintain electroneutrality, any charge produced at the electrode surface is balanced by oppositely charged ions in the surrounding electrolyte. The primary factor determining the capacitance of an EDLC is the thickness of the electric double layer formed at the electrode–electrolyte interface.

Capacitance measured by the equation

$$C=A\,Є0\,/D$$

In this context, C stands for capacitance measured in farads, A indicates the surface area, ε represents the permittivity of free space, and d is the effective width of the electric double layer, also called the Debye length. The energy held in a stable EDLC relies entirely on electrostatic forces, mainly the pull between ions at the interface of the electrode and electrolyte. An EDLC is fairly straightforward in design. It includes two electrodes immersed in an electrolyte, separated by a porous insulating layer. Over time, various materials for EDLC electrodes have been created, each bringing distinct features that play a big role in how well the device works. Choosing the right electrode material is key because the way charge is stored in the double layer depends on the surface; hence, the properties of the surface can greatly impact the overall capacitance. Carbon-based materials are widely used in EDLCs due to their exceptionally high surface area. Carbon continues to be the most researched EDLC material because it is inexpensive, readily available, and can be engineered into various forms such as nanotubes, fibers, and foams. Converting carbon into active forms, such as activated carbon enhances its porosity and improves its interaction with the electrolyte. It is important to recognize that ion movement inside narrow pores differ from their behavior in bulk electrolyte. The pore size has a major effect on ion transport within the device. Although smaller pores provide better access for the electrolyte, they do not significantly improve double-layer capacitance [26]. Therefore, matching the pore size to the electrolyte is essential for optimal performance.

Carbon nanotubes (CNTs) offer additional opportunities for supercapacitor development because their unique structure can deliver higher capacitance values [27]. In addition to carbon materials, metal oxides are also being explored as promising electrode candidates. These materials can provide high capacitance and low resistance, contributing to more efficient EDLC operation. Among the various metal oxides, ruthenium oxide is particularly well-studied, especially in military-related applications [28].

2).*Psedocapacitors*

In comparison with EDLC, capacitance due to Faradaic redox reactions, that is accompanied by the rise of energy, is exhibited by the pseudo capacitors in pseudo-electrode. Pseudo capacitance is purely electrochemical in origin and is therefore no electrostatic to account for charge-transfer with finite amounts of active material, pseudo capacitor is equivalent to charge-transfer redox reaction in the storage and it is very close to a traditional electrode-based supercapacitor. To an electrochemical battery in a certain way) [29]. The pseudo capacitor in combination duplex is a supercapacitor. The ward pseudo capacitance in electrochemistry refers to an electrochemical capacitive material with linear dependence of amount of charge stored on the area of the potential window Charge storage starts from various reactions. In a pseudo capacitor, the capacitance depends on how much charge moves across electrode surface, which is where faradaic charge storage happens. The charge transfer across the double layer is also part of this process, changing with the amount of charge and the potential involved. These pseudo electrodes are mainly made from metal oxides, metal-doped carbon for conductivity, and polymers that contain carbon. The pseudo capacitance (C) is

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

defined as the derivative of the charge acceptance ($\Delta q$ ) with respect to the changing potential ($\Delta V$ )

$$C=d(\Delta V)/d(\Delta q)$$

Pseudocapacitors differ from EDLCs by incorporating rapid, reversible chemical (Faradaic) reactions on their electrode surfaces for enhanced charge storage, unlike EDLCs. Purely electrostatic mechanism These reactions are caused by energy changes [31]. When a voltage is applied to pseudo capacitor electrodes, it creates a current from the reactions of materials like. Electrons are attracted to certain ions which helps in storing charge. In contrast, EDL relies on charge build-up without these reactions. Both mechanisms are present in electrochemical capacitor, but depending on materials used, one will contribute more to the overall capacity than the other. Metal oxides and some polymers are known to show pseudo capacitance, which is usually greater than EDL, but the materials can have poor electrical performance, leading to less stability and lower power [32].

The pseudo capacitance involves charge transfer during chemical reactions, similar to how batteries work. In a pseudo capacitor, the electrodes are connected to metal current collectors and submerged in an electrolyte, separated by a membrane. The charge stored in a pseudo capacitor is directly linked to the voltage applied, showing a clear relationship [33]. Pseudo capacitance relies on both electrostatic charge storage and chemical reactions, which allows for more energy storage compared to regular capacitors. When voltage is applied, ions in the electrolyte travel to the surface of the electrode, forming a charged region. This quick movement contributes to the power of the pseudo capacitor [34]. What makes pseudo capacitors different from regular capacitors is that they also store energy through chemical reactions. When voltage is applied, electrons flow into the electrode from an external source, while ions from the electrolyte either enter or leave the electrode. This back-and-forth movement of ions increases the stored charge and overall energy capacity. These chemical reactions involve both electron transfer and ion insertion [35]. This electrocatalytic mechanism enables the pseudo capacitors to provide the considerably higher voltage capacity than those of the conventional capacitors, since they store the energy both electrostatically and through electrode surface redox reactions [36]. To facilitate these faradaic processes, pseudo capacitors typically use advanced electrode materials, such as transition metal oxides [37]. These materials are suitable for reversible redox reactions, as they undergo rapid, effective oxidation state transfer with minimal degradation. When the electrons of the external circuit are transferred to the electrode materials, these materials are oxidized and are capable of adsorbing cations from the electrolyte [38]. When the voltage is reversed, the material undergoes reduction, releasing the cations back into the electrolyte. Involving in this way Faraday's law charge storage is a new kind of energy storage layer, which brings an extra amount of energy storage capacity and hence substantially enhances the energy density of the pseudo capacitor. The synergism between the electrostatic storage by the double layer and the faradaic storage arising from the redox reaction makes pseudo capacitors an advantage over the conventional capacitors [30]. Although the electrostatic mechanism allows fast charge/discharge cycles, which is suitable for high-power use, the faradaic mechanism allows to store more charge, which leads to higher energy density. This is why, pseudo capacitors are ideally suited to be used in situations requiring both a high energy storage capacity and the high discharge rate [39]. Such examples include energy storage systems (e.g., used for grid stabilisation or regenerative braking), hybrid vehicles and high-performance electronic devices [40]. Additionally, the energy and power performance of pseudo capacitors is able to be carefully optimized according to electrode material, electrolyte type, and operating conditions. Through the choice of materials with suitable conductivity, ion storage capacity, and cyclic stability, the balance between energy density, power density, and cycle life is provided in pseudo capacitors [41]. This wide applicability enables their usage in many applications that require high capacitance and rapid response time, and they can be seen as a promising alternative to batteries and conventional capacitors for some applications of energy storage [42].

3) *Hybrid Supercapacitors*

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Electrostatic charge storage (on account of the EDLC mechanism) and faradaic charge storage (on account of the pseudocapacitive mechanism) [43]. By bringing these features together, hybrid supercapacitors pr ovide a great balance of energy density and powerdensity. This combination makes them appealing fo r quickly supplying energy and storing it efficiently [44].

In hybrid energy storage devices, the dissipated energy is associated with the electrostatic interaction at the junction between the electrolyte and the electrode. At the interface an imbalanced bilayer develops like the electrolyte ions are pushed to the electrode surface through the applied potential. Nore, in this interaction, chemical reaction is not taking place but it is mechanical and that is why, the speed is very high and the resultant high-power density of the body is achieved [45]. The number of charges which can actually be stored in such a way is restricted due to the surface area of the electrode and the properties of the electrolyte. Highly surface-active materials (e.g., activated carbon) are commonly employed in EDLCs in order to maximize the achievable energy storage capacity [46]. However, electron transfer reactions of the electrode material to electrolyte which is filled in the unit of pseudo capacitor allow it to achieve faradaic storage. This kind of effect is typically observed in transition metal oxides or conductive polymers. When these materials are subjected to an applied potential, reversible redox reactions take place involving the adsorption of ionic components of the electrolyte on the electrode surface involved in charge transfer. This type of faradaic reaction results in such good charge capacity as compared to the electrostatic one in EDLCs (respectively) that leads to the higher energy density of the device [47]. Pseudocapacitive properties are, as a whole, related to a poorer power density at the cost of a better energy density due to a slow faradaic kinetics associated with the change in preference to the purely electrostatic transformation. Rate-charge/discharge cycles are determined from EDLC, while for long-term use, pseudo capacitor offers a higher energy storage. Practically, hybrid supercapacitors are designed and built with the aim to design the electrode materials, the electrolyte composition and the cell structure to maximize their combination of power and energy densities [48]. They are typically used in applications like, electric vehicle, renewable energy system and portable electronics, which require so much energy density and rapid charging. Due to the superposition of this mechanism, hybrid supercapacitors offer increased performance compared to traditional supercapacitor and battery-type devices in certain situations, holding a significant potential for the fast rate charge-discharge phenomenon and energy storage device with high efficiency [49].

## III. FACTORS FOR SUPERCAPACITORS MATERIALS

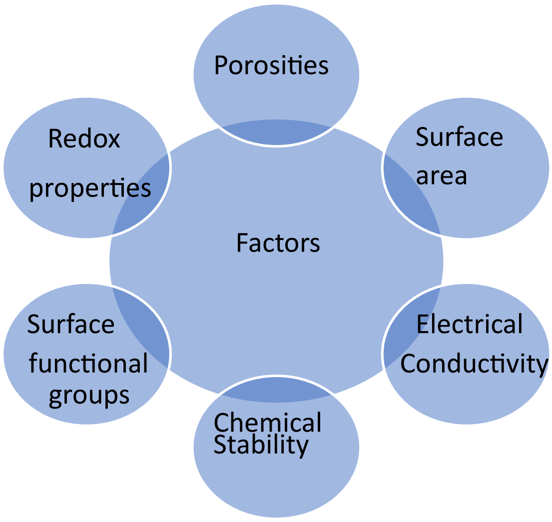


Fig. 3 Factors for supercapacitor materials

Factors should be thoroughly evaluated, as they have direct effects on the performance, stability, and real-world applicability of the device. The electrical conductivity of the material is one of the most critical parameters, as effective electron transport reduces the internal resistance and improves charge–discharge efficiency. Carbon-based materials like graphene and carbon nanotubes are commonly researched due to their high conductivity [50]. Another basic factor is the specific surface area because increased accessible surface area

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

is conducive to greater active sites for ion adsorption of electric double-layer capacitors (EDLCs). Moreover, pore size distribution is a critical factor where micropores Favor charge storage, mesopores facilitate ion transport, and hierarchical porous networks provide an optimal combination of energy and power density of equal significance is the structural and electrochemical stability of electrode material, enabling long-term endurance upon cycling between charge and discharge [51-52]. Pseudocapacitive oxides like $MnO_2$ and conductive polymers like polyaniline have pseudo capacitance that can store much higher specific capacitance via fast redox reactions, even though their cycle stability is usually in need of optimization. In addition to the above considerations, for real-world applications ion accessibility and wettability of the surface are also important since hydrophilic groups enhance penetration of electrolyte into pores, thus allowing higher utilization of active material [53]. The operating voltage window of the electrode material also determines the achievable energy density since the stored energy is Varies as the square of the voltage [54].

Aside from electrochemical characteristics, factors like mechanical stability, cost-effectiveness, scalability, and ecological sustainability are very important considerations for widespread implementation of supercapacitors [55]. Materials need to be mechanically stable to sustain volume variations during cycling while being both environmentally friendly and economically sustainable. Biomass-derived carbons and transition-metal-based oxides offer a good compromise between performance, cost, and sustainability, while noble metal oxides with their superior properties are constrained by their costliness and low availability. In all, the best electrode material for supercapacitors would need to combine high conductivity, high surface area with hierarchical porosity, good electrochemical and mechanical stability, wide voltage tolerance, and low environmental impact to achieve both good power density and long working life [56].

## IV. MATERIAL FOR SUPERCAPACITOR

1) *Activated Carbon and Derivatives*

Activated carbon and its derivatives continue to be among the most researched materials Because of their high surface area, they are ideal for supercapacitor applications also chemical stability, and cost-effectiveness. Efforts are increasingly directed toward optimizing pore size distributions to improve ion accessibility and enhance capacitance values [57]. For example, research has shown that hierarchical porosity achieved through template-assisted synthesis enhances energy density [58]. Despite advances, limitations related to low energy storage capacity under high power densities persist. Carbon-based materials have the subsequent Benefits: (1) plenty available, (2) very low cost, (3) easy to make, (4) safe to use, (5) good surface area, (6) accurate strength, (7) good electricity flow, (8) high chemical stability, and (9) wide temperature range [59]. Nanostructure size significantly influences the properties of the carbon materials. The chapter defines carbon materials as 0-dimensional, 1-dimensional, 2-dimensional, and 3-dimensional structures (respectively) [9].

A. *Zero-Dimensional Carbon Material*

Zero-dimensional (0D) carbon materials like graphene quantum dots (GQDs) and carbon dots (CDs) are attracting unprecedented interest for their potential application in supercapacitors for their unique properties to further improve the energy storage devices [60]. These materials are referred to as "zero-dimensional" since they are designed at the nanoscale with dimensions in all three directions. This special shape results in an incredibly large surface upon volume ratio and, consequently, these types of materials are the best choices for energy storage devices [61]. Due to the 0D carbon material's small size, not only does it provide more charge storage surface area, but also helps charge/discharge cycles to be faster, leads to a high-power density in supercapacitors [62].

The charge storage in 0D carbon materials mainly consists of electrostatic accumulation of ions at electrode-electrolyte interface, forming double layer that is the principle of the electric double-layer (EDLC) capacitance. Fast energy release and short charging times, typical of high-power

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

supercapacitors, are facilitated by this electrostatic interaction. Besides EDLC, 0D carbon materials are further functionalized with different chemical groups or doped with other elements, it leaves a possibility to pseudo capacitance [63]. Pseudo capacitance is a process that arises from reversible and rapid redox (electron transfer) reactions at the electrode surface and therefore greatly increases the amount of stored energy in the supercapacitor [62]. By allowing a harmonious combination of both EDLC and pseudocapacitive behaviours in these materials, the large power density, and more energy density can be reached and this is one of the significant challenges in supercapacitor development [12].

B. *One-Dimensional Carbon Material*

1D carbon materials, also carbon nanotubes (CNTs) and carbon nanofibers (CNFs), are extremely promising for supercapacitor applications owing to their structure allowing a perfect balance between high surface area, good electrical conductivity, and structural stability. Materials characterized by length diameter such as cylinders or fibers, with diameter comparable to surface area providing space for charge accumulation, etc. [64]. The high surface area of 1D carbon materials plays a key role in performance improvements to capacitance in supercapacitors, as it provides a greater amount of contact sites (for ions of the electrolyte) where ions from the electrolyte can sit when a voltage is applied hence providing more energy storage [65].

For example, carbon nanotubes (CNTs) are most widely studied 1D carbon materials for supercapacitor applications. The hollow, tubular geometry and the high aspect ratio of them are conducive to deliver high electrical conductivity, thereby speeding up the electron transfer between the electrodes during charge and discharge cycles for the enhancement of power density of the supercapacitor. CNTs also have the advantage of mechanical strength and flexibility for flexible and lightweight energy storage applications [66]. CNTs can be further functionalized or incorporated in composite materials combined with another active species, such as metal oxides (e.g., $RuO_2$) or conducting polymers, to add pseudocapacitive effect. This pairing enables increased energy density via fast, reversible redox reactions and the electrostatic charge storage mediated by electric double layer capacitance (EDLC) mechanism.1D carbon material is a further example of carbon nanofibers (CNFs), commonly employed as electrode material in a supercapacitor. Similar to CNTs, CNFs are highly sulphated with a large surface area and good electrical conductivity, but are more readily produced on an industrial scale than are CNTs [67]. CNFs, in addition, provide improved mechanical resistance and modulus, thus, they are useful in any type of supercapacitor architectures, even for ones in flexible and wearable electronics applications [68]. Both CNTs and CNFs can be grafted onto a hybrid supercapacitors or composites with another material to enhance their electrochemical properties. Nevertheless, several challenges still exist, for example, how to provide quality of consistency in long term and how to increase cycling stability. Despite these challenges, 1D carbon materials like CNTs and CNFs continue to hold great promise for enhancing the performance of supercapacitors, offering both high energy and power densities for use in electric vehicles, portable electronics, and other advanced energy storage systems [69]. Results of CNFs derived from biomass show high capacitance and a good stability for use in supercapacitors [13].

C. *Two-Dimensional Carbon Material*

2D carbon materials, graphene and reduced graphene oxide (rGO), are suggested as the optimal electrode materials for supercapacitors on account of their outstanding applied structural property and excellent electrochemical property [70]. These materials consist of one or only a few layers of (disordered) carbon atoms crystallizing into a 2D honeycomb lattice with a large surface area for charge storage. High surface area, along with good electrical conductivity of 2D carbon materials, enables it to conduct efficient charge and discharge processes leading to high power density in supercapacitors [71]. For graphene its nearly-ideal conductivity and high surface area allow it to charge by the electric double layer capacitance (EDLC) mechanism, where accumulation of ions of the electrolyte occurs on the electrode surface when a voltage

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

is applied. This process is very rapid and reversible, and thus graphene-based supercapacitors are all the more able to afford immediate energy fulcrum [72]. In addition, the 2D carbon materials have a great degree of fault tolerance and can be easily functionalized or conjugated with other materials to improve their performance. For instance, partially reduced graphene oxide (rGO), synthesized by partial reduction of graphene oxide, retains most of the benefits of graphene but provides new avenues for pseudocapacitance. Using metal oxides, conductive polymers or other materials to functionalize rGO, further redox reactions will take place at the electrode surface which will increase the storage capacity of energy, and at the same time, the energy storage capacity of supercapacitor will be also improved [14].

D. *Three-Dimensional Carbon Material*

Three-dimensional (3D) carbon materials, such as carbon aerogels, graphene foams, and carbon nanostructure frameworks, are emerging as advanced candidates for supercapacitors due to their unique structural advantages and superior electrochemical performance [73]. These materials have a porous, interconnected and highly open network architecture not only with the effect of enhancing the surface area, but also with the effect of facilitating the ion and electron transport path. By their three-dimensional architecture, these materials provide more homogeneous distribution of the electrolyte ions on the electrode surface that enables ideally high charge storage capacity, and high rate of charge/discharge cycles that, on the one hand, lead to high energy and power densities [74]. For instance, carbon aerogels, containing porous and lightweight nature, can store charge through the electric doubly-layer capacitance (EDLC) mechanism by creating a barrier for ionic movement from the electrolyte to electrode surface akin to other carbon based materials [75]. Apart from EDLC, the 3D carbon architecture allows to introduce pseudocapacitive materials, including metal oxides or conductive polymers, by which rapid and reversible redox reactions can be achieved to further build energy density of the supercapacitor [76]. Graphene foams, as another category of 3D carbon materials, have a very porous morphology with exceptional mechanical strength, large electrical conductivity and large still surface area for ion storage, thus suitable for supercapacitor applications [15].

E. *Porous Carbon for Supercapacitors*

Porous carbon materials are used in supercapacitors due to their large electrochemical properties, high surface area, and structural stability. Porous carbon materials include activated carbon, carbon nanotubes, and graphene, which offer advantages for energy storage applications [77]. The high surface area of porous carbon materials provides many available sites for ion adsorption, which increases the charge storage capacity and improves the energy density of supercapacitors. The porosity is very important, because the ions can move and store in the electrode material efficiently. This means, that the charge and discharge rates can be fast [78]. This is the reason for the high-power density of supercapacitors. Another advantage of porous carbon materials is that they have good cycle stability. This means that they are suitable for long-term, repeated use in energy storage devices [79]. Activated carbon is one of the most popular porous carbon materials because it is low-cost, eco-friendly, and easily available. One of the drawbacks of porous carbon is its low conductivity, but this can be overcome by blending it with conductive materials such as graphene or carbon nanotubes [80]. Porous carbon materials are an essential and key element in supercapacitor construction, providing an excellent combination of high surface area, stability, and fast charge/discharge characteristics, which makes them a must-have material for energy storage applications [81].

F. *N-Doped Carbon Materials for Supercapacitors*

Nitrogen-doped carbon (N-doped carbon) has attracted much attention as an electrochemically active carbon material in supercapacitors because of its enhanced electrochemical properties [82]. The addition of nitrogen to carbon improves the material's electrical conductivity, pseudo capacitance, and ion adsorption, leading to better overall performance in energy storage devices. Nitrogen doping introduces functional groups into the carbon lattice, thereby increasing surface wettability

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

and electrochemical activity of the material. Those functional groups improve the interaction in the electrode material and the electrolyte Also increase capacitance and energy density compared to undoped carbon materials. The presence of nitrogen also stabilizes electrode material and improves cycle stability and longevity [83]. The large power density and fast charge/discharge rates of N-doped carbon materials are also accompanied by the fact that they are relatively inexpensive and environmentally friendly [84]. This makes them good for big scale energy storage applications like electric vehicles and grid storage systems. To sum up, the nitrogen-doped carbon materials are an effective and recommended material for supercapacitors with enhanced conductivity, higher capacitance and better cycle stability, which make them an attractive candidate for next-generation supercapacitor technologies [85].

2) *Graphene and its Derivatives*

Graphene and its Derivatives graphene oxide (rGO), which shows high capacitance at low production cost. Hybrid methods that doped graphene with pseudocapacitive materials also possess potential for enhancement of specific capacitance and the energy density [16]. Nonetheless, there are problems including aggregation and high material cost that need to be further studied [17]. Graphene and its derivatives are most promising materials for supercapacitors because of its large electrical conductivity and high surface area and mechanical properties. Graphene is a two-dimensional honey comb lattice, with which carbon atoms are arranged in one layer, and due to its peculiar properties, it can be used in energy storage like super capacitors [86]. Due to its large surface area, graphene offers a greater number of sites where the ions from electrolyte can deposit, which is critical for charge storage. In supercapacitors, graphene mainly operates through the electric double-layer capacitance (EDLC) mechanism, where the energy is stored electrostatically by the accumulation of ions at the electrode-electrolyte interface [87]. Through this mechanism, graphene-based supercapacitors can provide good power density and Quick charge/discharge cycles [88].

One of the important derivatives of graphene is reduced graphene oxide (rGO), produced by chemical reduction of graphene oxide (GO) [89]. GO possesses the oxygen-containing functional groups (e.g., hydroxyl, epoxide, carboxyl) which increases hydrophilicity and processibility of the GO, but decreases the conductivity. By depleting GO, rGO restores most of the high conductivity and mechanical characteristics of graphene with retained functionality of some of the functional moieties that can promote pseudocapacitive performance. Their existence permits rGO to carry out rapid, reversibly redox reactions at the electrode surface, which results in an increased energy density as compared to pure EDLC-based devices [90]. Electrodes of supercapacitor can be categorized into 0D, 1D and 2D as well as 3D structure. Noise (0D) contains graphene dots and powders; noise (1D) contains fibers and yarns. 2D structures include graphene films and composites; 3D are foams and sponges. Graphite supercapacitors use varied forms of graphite or graphite derivatives for improvement of energy-storage devices. The shape and structure of graphite in these supercapacitors play a central role to calculating the energy density, power density, and hence total efficiency [91]. The performance parameters can be drastically different depending on the dimensionality of the graphite material applied (1D, 2D, or 3D). Below are the different types of graphite-based supercapacitors:

A. *1D Graphite-Based Supercapacitors (Carbon Nanotubes and Fibers)*

Graphite-based materials like carbon nanotubes (CNTs) and carbon nanofibers (CNFs) are now being used in supercapacitors. This is because they conduct electricity well, have a large surface area, and boast great mechanical strength These materials are essentially long, cylindrical (CNTs) or fibrous (CNFs) structures with a high aspect ratio [92].

a. Carbon Nanotubes (CNTs):- CNTs exhibit excellent mechanical robustness, electrical conductivity, and surface area, and thus, for supercapacitors. Their good conductivity allows fast charge/discharge cycles which lead to high power density. In supercapacitors, charge is stored by CNTs through

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

the electric double-layer capacitance (EDLC) model [93]. With large surface area and therefore a large number of sites for ions to adsorb, their capacitance is further enhanced. Moreover, CNTs can be functionalized with other materials such as metal oxides or conductive polymers, providing pseudo capacitance, ultimately yielding higher energy density [55].

b. Carbon Nanofibers (CNFs):- CNFs have a structure very similar to CNTs but are generally lower cost and easier to fabricate in high numbers [94]. CNFs have good conductivity and can afford a large surface area, which makes them usable in energy storing applications. Similarly to CNTs, CNFs spontaneously accumulate charge electrostatically by EDLC and can be further improved with pseudocapacitive materials for efficiency [95].

B *2D Graphite-Based Supercapacitors (Graphene and Graphene Oxide)*

2D graphite-based materials are widely employed in supercapacitors because of their very high surface area and good electrical conductivity [96]. Because of the two-dimensional structure of the graphene, the accessibility of the surface for the generation of electrolyte ion is easily achieved, and therefore it is super-efficient for charge storage.

1) Graphene

Graphene a single layer of carbon atoms that form a flat, honeycomb shape. It is one of the best materials for supercapacitors because it has more surface area and conducts electricity very well. It mainly stores energy using a method called electric double-layer capacitance. Due to the extensive surface area graphene offers a greater charge storage capacity which makes it suitable for high-power applications. In addition, graphene can be hybridized with other materials (e.g., metal oxides or conductive polymers) to form hybrid supercapacitors that can take advantage of pseudo capacitance and, hence, lead to enhanced energy density [97]. Graphene oxide is a precursor material with oxygenated functional groups (hydroxyl, carboxyl, etc. that increase its water solubility and processability. GO can be chemically depolymerized to afford reduced graphene oxide (rGO) which restored many of the conductive and structural features of graphene, whilst preserving certain functional units that enable pseudocapacitive functions. Such graphene derivatives are commonly employed in hybrid materials, in which the graphene portion contributes a high conductivity and surface area while the pseudocapacitive component contributes to an improved energy density [80].

C. *3D Graphite-Based Supercapacitors (Graphene Foam and Graphene Aerogels)*

3D graphite-based materials are characterized by a porous, interconnected structure, which in turn enhances superior supercapacitors through improved ionic diffusion and access to the electrode surface. Also, the 3d structure of architecture all contributed toward increasing mechanical stability of the material and enabling its efficient ability of ion and electron transport, leading to the enhancement of the overall supercapacitor performance. Graphene Foam: Graphene foam is a 3D, porous structure of graphene that features both the characteristics of graphene and the advantage of 3D structure [98]. The porous nature of graphene foam allows for greater electrolyte penetration and ion diffusion, which enhances the capacitance and performance of supercapacitors. This 3D structure improves both the energy and power density by providing more surface area for charge accumulation while allowing faster ion movement for quicker charge/discharge cycles [99]. Graphene foam can also be modified or combined with other materials to additionally enhance its electrochemical performance.

a. *Graphene Aerogels*

Graphene aerogels are ultra-flexible, ultra porous, three-dimensional porous materials composed of graphene sheets. They are very low in density and have large surface areas, which is why they are suitable for energy storage devices [100]. Graphene aerogels combine the high conductivity of graphene with a highly interconnected porous structure, facilitating better ion transport and providing a large surface area for charge storage [101]. These materials also very stable, that stabilizes the supercapacitors performance of cycling. Interconnected pores of 3D graphene architectures support ion transport.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Microporous graphene foams through template-directed assembly techniques Electrochemical performance of manganese oxide ($MnO_2$) based hybrid electrodes in 3D graphene frameworks are markedly improved. Graphene aerogels and hydrogels exhibit good strength-weight ratio and electrical conductivity. Nanocomposite electrodes with polymers enhance capacitance and energy density. [17,102]

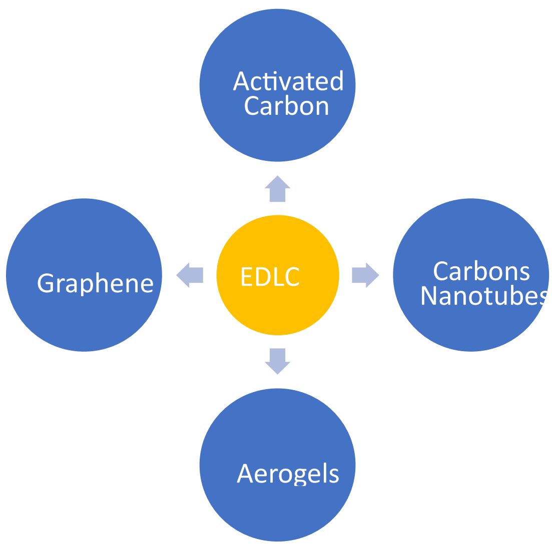


Fig. 4 Materials follow edlc type mechanism

3) *Metal Oxides*

Transition metal oxides show pseudo capacitance where charge storage is mediated via rapid redox reactions reversible on the surface of the electrodes. This greatly enhances the energy density of supercapacitors when compared with conventional EDLCs based on electrostatically accumulated charge [103]. The good pseudo capacitance is attributable to the multiple oxidation states of the transition metal, which causes higher charge storage capability in electrochemical cycling [104].Transition metal group is composed of many elements, including manganese (Mn), nickel (Ni), cobalt (Co), iron (Fe) and so on, mixed oxides exhibiting various electrochemical properties [105]. Each one of these metal oxides has a distinct combination of properties, including high surface area, conductivity and stability, which allows optimized tailoring of its properties for particular applications. Specifically, hybridization of these materials with other conductive materials can further enhance their performance [106]. Transition metal oxides, particularly those in combination with carbon materials, have been shown to provide improved power and energy densities, high-rate capability, and long cycle stability [107]. Through the synergy between the metal oxide component and carbon component, the disadvantages of both components are alleviated to result in superior overall performance in supercapacitors [108].

A. *Classical Transition Metal Oxides*

Metal oxides, such as $MnO_2$, $RuO_2$, are well-known pseudocapacitive materials due to their inherent redox activity [54]. $RuO_2$ still shows the highest capacitance among all metal oxides but its high cost and instability in aqueous electrolytes make it less commercially viable. Scientists have been trying to synthesize low-cost alternatives, such as $MnO_2$ nanotubes to achieve similar performance [38].

## V. COMMON TRANSITION METAL OXIDE MATERIALS FOR SUPERCAPACITORS

1) *Manganese Oxide ($MnO_2$)*

Manganese oxide (Mn oxide) is an attractive supercapacitor material because of its very high pseudo capacitance, which enhances energy storage. Manganese oxide, such as MnO2 (manganese dioxide), has excellent electrochemical properties like good capacitance and energy density, which makes it an attractive alternative to carbon-based materials for supercapacitors [109]. Mn oxide materials can store Faradaic charge through reversible redox reactions, which gives them high energy density and long cycle life [110]. It's affordable and good for the environment, which makes it a great choice for big projects. It's affordable and good for the environment, which makes it a great choice for big projects. Low conductivity is a limitation [111]. Mn oxide can be combined with conductive

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

materials, like carbon, graphene, to enhance performance [112-113].

*2) Cobalt Oxide*

Cobalt oxide, or Co oxide, has been considered as a promising material for supercapacitors because of its excellent electrochemical properties, especially its extremely high pseudo capacitance [114]. Cobalt oxide, especially $Co_3O_4$ (cobalt (III) oxide) and CoO (cobalt (II) oxide), shows strong Faradaic charge storage through reversible redox reactions, which greatly enhances the energy density and capacitance compared to conventional carbon-based materials. Cobalt oxide materials have very high specific capacitance and good stability [115]. This makes them suitable for high performance supercapacitors. They can achieve high power density and good cycle life at the same time. This is important for long term energy storage applications. Cobalt oxide is also relatively cheap and environmentally abundant. This further enhances its potential as an alternative material [116]. However, a major drawback of pure cobalt oxide is its poor electrical conductivity. The low conductivity of cobalt oxide can be overcome by doping it with conductive materials, such as carbon-based materials, graphene, or conductive polymers. The performance of the cobalt oxide is enhanced [117]. To conclude, cobalt oxide has been demonstrated to be a promising supercapacitor material with large pseudo capacitance, good energy density, and high stability. With further improvements in conductivity and optimization, cobalt oxide could become a prominent material for next-generation energy storage technologies Nickel Oxide (NiO) [118].

3) Nickel oxide

Ni oxide is an attractive supercapacitor material because of its pseudocapacitive behaviour, which contributes to high energy density and capacitance [119]. In particular, Ni oxide, in the NiO (nickel (II) oxide) state, stores energy via Faradaic redox reactions, enhancing the performance of supercapacitors compared to purely electrical double-layer capacitors. Ni oxide has good specific capacitance value, great cycle stability, and high-rate capability. These properties make it suitable for energy storage devices that require high power and long-term reliability [120]. Ni oxide is relatively inexpensive and environmentally abundant, increasing its appeal for large-scale applications [121]. However, as with other metal oxides, low electrical conductivity limits the performance of Ni oxide. This limitation can be overcome by co-doping Ni oxide with conductive materials like carbon-based materials to improve electron transport and enhance its electrochemical performance [122]. Conclusion Nickel oxide is a promising material for supercapacitors with its high pseudo capacitance, good energy storage properties, and excellent stability. Improvements in conductivity will lead to further applications in next-generation supercapacitor technologies [123].

4) Fe Oxide as Supercapacitor Material

Iron oxide (Fe oxide) materials are attracting interest as potential candidates for supercapacitors due of their abundance, low cost and environmental friendliness. In addition, Fe oxide materials such as $Fe_3O_4$ (magnetite) and $Fe_2O_3$ (hematite) may provide electrochemical properties that are particularly suitable for energy storage devices [124]. In particular, Fe oxide materials typically exhibit a pseudo capacitance in which Faradaic reactions are responsible for charge storage, alongside the edlc that is typical of carbon-based supercapacitors [125]. This pseudo capacitance allows supercapacitors to have an increased energy density, making Fe oxide materials attractive for applications with both high energy and power densities [126]. The low electrical conductivity of iron oxide materials may limit their performance, but by combining Fe oxide with conductive materials like carbon or conducting polymers, charge transfer can be enhanced and the overall efficiency of the supercapacitor can be improved [127]. In summary, Fe oxide-based materials provide an attractive and sustainable alternative for supercapacitors, with the addition of conductive additives allowing for enhanced energy storage and performance, which increases their applicability for next-generation supercapacitor technologies [128].

5) Vanadium Oxide

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Vanadium oxide is a promising TMO material for supercapacitors, owing to the presence of a high energy density and fabulous electrochemical stability. A reversible redox process occurs and results in the pseudo capacitance observed in these materials [129]. Nevertheless, owing to its limited conductivity, it cannot be used as it is and thus, vanadium oxide is commonly used with conducting supports or other materials, in order to effectively enhance its overall electrochemical response [130-131].

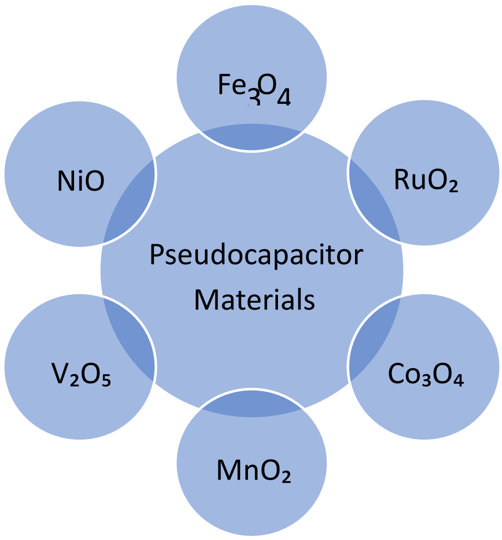


Fig. 5 Metal oxide with pseudocapacitor type mechanism

## VI. ADVANTAGES OF TRANSITION METAL OXIDES

I. High Pseudo capacitance- Transition metal oxides show pseudo capacitance, i.e., charge storage species arise from rapid, reversible redox processes at the electrode surface. This offers a significantly higher energy density for supercapacitors compared with standard EDLCs depends on electrostatic charge accumulation alone. The good pseudo capacitance is attributed to the multiple oxidation states of the transition metal, which allow to store more charges in the electrochemical cycles [132].

II. Wide Variety of Materials- Transition metal group includes a wide variety of elements including manganese (Mn), nickel (Ni), cobalt (Co), iron (Fe) and so on, the oxides of which have different electrochemical properties. These metal oxides each provide a distinctive set of properties including high surface area, conductivity, and stability which allow for targeted improvement for particular applications [133]. Moreover, by hybridizing these materials with other conducting materials, like carbon materials, performance can be further optimized.

III. Cost-Effectiveness: In contrast to other high-performance materials [e.g., platinum or ruthenium containing compounds], because TMOs (e.g., manganese and iron oxide) are abundant, low-cost, and eco-friendly [8]. This is why they are more desirable for big-scale applications which are driven by cost and scalability.

IV. Enhanced Electrochemical Performance: Transition metal oxides, especially with carbon material, has been reported to deliver high power and energy densities, large capability, and long cycle stability. Synergistic effect between the metal oxide and the carbon moiety enables overcoming of the drawback of each one of them, and the resultant increased performance of the whole system can be highlighted in supercapacitors Ternary and Mixed Metal Oxides [134].

Recent works have been reported on ternary and mixed oxides where synergetic effects contribute toward both electrical conductivity and redox activity. Materials, in this case, exhibited higher capacitance values with superior cycling stabilities, but their synthesizing methods need further advancement to be scalable along with uniform phase control [135].

IV. Conducting Polymers- The conducting polymers polypyrrole (PPy), polyaniline (PANI) and PEDOT are

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

characterized by tunable conductivity, lightweight material, and high pseudo capacitance [136]. Remedies that have been proposed recently include the blending of conducting polymers with carbon materials or metal oxides to make it more stable and more energetic in terms of retaining energy [137].

V. Emerging Composites and Hybrids- The last few years have witnessed exceptional progress in composite and hybrid materials that combine the complementary features of metal oxides, carbon materials and conducting polymers. A recent example is graphene-metal oxide hybrids, such as graphene/$MnO_2$ hybrids, which have shown remarkably high specific capacities and extraordinary cycle life, with optimal conductivity and high redox activity [138]. Carbon nanotube/PANI composites also show improved mechanical stability and capacitance retention after long-term cycling [139].

VI. D and Nanostructured Materials - A rapidly developing area of research is that of 2D materials, such as MXenes and nanostructured frameworks [140]. MXenes are very conductive, have tunable surface terminations, and show excellent capacitance retention; however, the susceptibility to oxidation has restricted their use [139]. Other areas of research include metal-organic frameworks (MOFs) as templates for the synthesis of hierarchical electrode materials with optimized porosity and energy density [141].

## VII. ELECTROLYTES FOR SUPERCAPACITORS

Electrolytes are an important ingredient in supercapacitors which has a significant effect on the performance, efficiency, power density energy density and operational life of supercapacitors. Supercapacitors, which are designed to store and deliver electrical energy through electrochemical processes, rely on electrolytes to facilitate ion movement between electrodes during charge and discharge cycles [142]. The electrolyte plays key role in formation of electric double layer at electrode-electrolyte interface in EDLCs or for faradaic reaction in pseudo capacitors [143]. Since it has a direct effect on the behaviour of the device, selection of an appropriate electrolyte is critical for achieving the best overall performance of supercapacitors [144].

EDLCs store energy exclusively through electrostatic interactions between ions and electrodes, while pseudo capacitors store energy by the electrostatic and faradic factors. Such discrepancies affect choice of electrolytes which, in addition to being facilitating to ionic transport, should also accommodate to redox reactions in pseudo capacitors [145].

I. Aqueous Electrolytes- Aqueous electrolytes with sulfuric acid and potassium hydroxide offer high conductivity, but with a low voltage window therefore, a significant research effort lately has concentrated on improving aqueous electrolyte stability while trying to increase the voltage windows and enhancing energy density [146]. Aqueous electrolytes, containing dissolved salts in the water phase, are the most widely exploited electrolytes in supercapacitors owing to their ability to provide high ionic conductivity, be cost effective, and be environmentally benign. Typical salts for aqueous electrolytes are sulfuric acid potassium hydroxide, and sodium sulfate. These electrolytes provide several benefits:

A. High Ionic Conductivity- Water-based electrolytes have high ionic conductivity because of the high salt dissociation of salt in water. The ionic conductivity contributes to an increased rate of ion diffusion during charge and discharge cycles, and as a result, a higher power density and overall supercapacitor performance is achieved [147].

B. Environmental Safety and Low Cost- Water is an innocuous, highly available, and low-cost solvent so that aqueous electrolytes are appealing from both an environmental and economic perspective. Therefore, aqueous supercapacitors are appropriate for needs that call for, low cost and eco-friendly solutions [148]. Established and Reliable: Aqueous electrolytes are well-known and highly-used, providing consistent and reproducible operation for many applications [149].

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

II. Organic Electrolytes- Organic electrolytes have been found interesting because of their larger window of voltage. This has led to greater energy density. The drawbacks are lower conductivity as compared to aqueous electrolytes. Recent research is in this direction, focusing on high conductivity without sacrificing stability [150]. Organic electrolytes are typically composed of a salt dissolved in an organic solvent like acetonitrile (ACN), propylene carbonate (PC), or ethylene carbonate (EC). These electrolytes offer several significant advantages over aqueous electrolytes:

A. Wider Electrochemical Stability Window- Organic electrolytes can tolerate a wider voltage window than aqueous electrolytes. This higher voltage window enables organic electrolyte-based supercapacitors to achieve higher energy densities, the amount of energy stored depends on the square of the operating voltage. Due to higher energy density, organic electrolytes are desirable in more energy-demanding applications [151].

B. Higher Energy Density- Because of the larger voltage window, supercapacitors with organic electrolytes achieve higher energy densities than those with aqueous-based supercapacitors. This makes them ideal for use in devices in situations where storing more energy is really important, like in electric vehicles (EVs) and systems that store renewable energy [152].

C. Better Thermal Stability and Safety- Organic solvents typically have higher thermal stability than aqueous solvent and thus organic electrolytes can be stabilized over a wider temperature range. They further include more robust and less susceptible to the loss of properties at elevated temperatures, which can be beneficial for demanding applications [153].

III. Ionic Liquids- Ionic liquids have wide windows that hold promise for supercapacitor applications [154]. Such electrolytes exhibit excellent thermal stability and high conductivity. Innovations are recently taking the form of environmentally friendly ionic liquids, aimed at improving supercapacitor performance [155]. Salt(s) in a liquid form at room temperature (i.e., molten or liquid) due to their large size and skewed geometry of their ions are known as ionic liquids (ILs). These electrolytes attract for the development of supercapacitors because of their special properties:

Wide Electrochemical Stability Window: Ionic liquids, with an incredibly large electrochemical stability window in comparison with aqueous and organic electrolytes, are presented. Due to this high stability, supercapacitors can be designed to operate at very high energy densities, and ionic liquid electrolytes are perfectly suitable for high-performance applications having both high power and energy density [156].

A. Excellent Ionic Conductivity- Ionic liquids possess high ionic conductivity and low viscosity, which enable effective ion transport throughout the electrolyte and also fast charges/discharges. This property improves the power density of the supercapacitor there by, it suits the high-power output applications [157].
B. Non-Volatility and Thermal Stability- Ionic liquids are non-volatile, thus less hazardous compared to organic electrolytes which are prone-to-evaporation or degradation due to their organic composition. Their stability across a big temperature range makes them useful for use in extreme conditions, where other electrolytes might fail [158].
C. Chemical and Electrochemical Stability- Ionic liquids are highly resistant to electrochemical degradation, thus leading to increased cycle life and stability in supercapacitors [159-160].

TABLE I Materials vs capacitance

| S.no. | Electrode Material | Capacitance | Ref. |
|---|---|---|---|
| 1. | Biomass-derived carbon electrodes | 226.7 F/g | [161] |
| 2. | Activated Carbon Electrodes with Improved Sorption Capacity | 257 F $g^{-1}$ | [162] |
| 3. | Activated Carbon | 138.12 F $g^{-1}$ | [163] |

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

| | | | |
|---|---|---|---|
| 4. | Pecan Shell-Derived Activated Carbon | 269 F $g^{-1}$ | [164] |
| 5. | Biomass Derived 3D Hierarchical Porous Activated Carbon | 501 F $g^{-1}$ | [165] |
| 6. | Graphite Paper Electrode | 219 F $g^{-1}$ | [166] |
| 7. | α- $MnO_2$ nanorods | 643.5 F $g^{-1}$ | [167] |
| 8. | $Cr_2V_4O_{13}$ Nanoparticles | 171 F/g | [168] |
| 9. | graphene/manganese oxide | 225 F $g^{-1}$ | [169] |
| 10. | $MnO_2$/Graphene Flower-like | 500 F $g^{-1}$ | [170] |
| 11. | CoFe2O4@Co3O4 | 373.5 F $g^{-1}$ | [171] |
| 12. | carbon-coated iron oxide (ISCC-$Fe_3O_4$) | 170.6 F/g | [172] |
| 13. | Manganese nickel oxide integrated imidazole functionalized multiwalled carbon nanotubes | 2147 F/g | [173] |
| 14. | MXene/$MnCo_2O_4$ | 668 F $g^{-1}$ | [174] |
| 15. | manganese oxide/biomass porous carbon composite | 482 F $g^{-1}$ | [175] |
| 16. | Copper chromite/graphene oxide nanocomposite | 370 F $g^{-1}$ | [176] |
| 17. | $Co_{0.85}Se$ Microspherelike Architectures | 719 C $g^{-1}$ | [177] |
| 19. | $Bi_2S_3$ nanosheet/$ZnCo_2O_4$ | 3032.8 F/g | [178] |
| 20. | $DyCoO_3$@rGO nanocomposite | 1418 F/g | [179] |

## VIII. APPLICATIONS OF SUPERCAPACITORS

Supercapacitors are advanced energy-storage devices that retain energy through electrostatic mechanisms rather than through chemical reactions, as seen in conventional batteries. They can deliver very high power over short time periods, making them particularly suitable for systems that require rapid charging and discharging along with long service lifetimes. Their distinctive combination of high-power density, quick response, and exceptional cycle durability allows them to be used across a wide range of industries. Below is a more detailed overview of some of the key applications of supercapacitors in various fields.

I. Energy Storage and Power Backup Systems- Supercapacitors are being more and more employed in energy storage systems because of their high energy storage and release rate. They are of particular utility in power supply or power supply demand scenarios that necessitate backup power or power supply while the main power supply is interrupted [180].

A. Uninterruptible Power Supplies (UPS) - In this supercapacitor provide a temporary power source to critical systems, such as computers, data centres, medical equipment, and telecommunication networks, when the main power supply is interrupted. Supercapacitors can provide a high-power pulse at the onset of operation to support the continuous function of systems until a generator or battery come on line. Because of the long cycle life and their ability to serve in harsh temperatures, supercapacitors are used in UPS systems and therefore are ensured reliability and cost-effectiveness by reducing dependence on traditional batteries, which have short-life cycles [181].

B. Grid Energy Storage and Power Conditioning- Supercapacitors are used in smart grids and grid energy storage applications to smooth out the intermittent power supply from renewable energy sources like wind and solar energy. These sources tend to have dips and supercapacitors can assist the grid by delivering power instantaneously to handle peaks in demand or lack of supply. The supercapacitors' high charging and discharging speed enables them to function as high-response and quick energy storage system, so they can help maintain stability of grid by making up for the energy loss due to the randomness of generating power. Capacitors are also used for power conditioning, enhancing power quality by filtering

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

voltage transients, attenuating transients, and providing power to the grid without interruptions [182].

II. Electric Vehicles (EVs) - Supercapacitors are being more and more used in transportation applications. These vehicles take advantage of the high-power pulses capability of supercapacitors in acceleration and braking, and use it to increase the overall efficiency and performance [183].

A. Regenerative Braking Systems- The use of supercapacitors for regenerative braking systems is one area of its potential application to electric and hybrid vehicles. Once a vehicle decelerates the kinetic energy is normally transformed into heat and dissipated. Nevertheless, in case of regenerative braking, such kinetic energy is gathered and stored by supercapacitors and can be recycled during the acceleration. Supercapacitors are ideal for this application because they can quickly absorb large amounts of energy during braking and discharge that energy efficiently during acceleration. Not only does this lead to an energy efficiency gain of the vehicle as a whole, but also leads to a decrease in the usage of the vehicle's principal battery [184].

B. Power Assistance for Acceleration- In addition to regenerative braking, supercapacitors provide instantaneous power boosts during acceleration. The supercapacitor can quickly release the stored energy to compensate the battery power when it is needed for a short burst of power, e.g., highway merge, overtake. This not only lowers the stress on the battery but also increases the battery's lifetime duration. Supercapacitors are highly desired in this aspect, owing to the capability to release energy significantly more rapidly than conventional batteries, which is crucially needed for high-power demand scenarios.

III. Consumer Electronics- Supercapacitors are also making significant strides in the consumer electronics industry, where they are used to extend battery life, enhance device performance, and provide more efficient power management [3].

A. Smartphones, Tablets, and Wearables- In smartphones, tablets, and wearable devices (such as smartwatches and fitness trackers), supercapacitors are used to augment the performance of lithium-ion batteries. They offer rapid power when needed only for a relatively short but intense energy requirement, e.g., high-end gaming, video streaming or fast charging. Supercapacitors play a vital role to guarantee the availability of the power for the device that could support the peak demand without overcharging the battery and consequently improve the performance of battery and the device. Further, due to the high cycle life of supercapacitors, they can be used for a much longer period compared to traditional batteries, which tend to decrease in efficacy over time due to repeated charge and discharge.

B. Laptops and Portable Electronics- In laptops and other portable electronics, supercapacitors can be used to supply energy during sudden power surges or periods of heavy processor load. This helps prevent system failures due to power fluctuations and ensures smoother operation during demanding tasks like video editing, gaming, or 3D rendering. Supercapacitors can also support fast charging and therefore be used to quickly bring the user back to using the device [185].

IV. Pulse Power Applications- Supercapacitors are the best option for applications where pulse power or the ability to provide large amounts of energy in bursts is needed. Due to their capacity to concomitantly store and release energy within fractions of a second, they are ideal for systems requiring rapid power bursts [186].

V. Military Applications- In military platforms, e.g., railguns or directed energy weapons, supercapacitors offer the necessary pulse power to produce the high energy discharges required for projectiles or other energy-dependant tasks. These devices demand extremely high-power-density, transient, rates of delivery, below which supercapacitors come through delivering rapid discharge rates which are unattainable in common batteries or other energy storage devices [187].

VI. Medical Devices- Supercapacitors are used in medical applications, but especially in defibrillators. All of these

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

devices need high voltage and fast discharge to deliver life-saving electrical shocks to the heart. Supercapacitors are able to discharge energy much faster than conventional batteries, thus they are suitable for those applications [188].

VII. Regenerative Energy Systems- Supercapacitors have important applications in regenerative energy systems, a system that captures and stores gratuitously produced excess energy during defined steps and uses it later. These applications are particularly beneficial in systems where energy recovery is important [185].

VIII. Wind and Solar Energy Systems- Supercapacitors are employed for smoothing out the output of wind turbines and solar panels which generate variable amounts of power because of weather variations. In wind farms, supercapacitors can store surpluses that are available during high wind speeds and release energy during low demand or low wind speeds. Similarly, in solar energy systems, supercapacitors can store energy during the day when sunlight is abundant and provide power at night or during periods of low sunlight [189].

IX. Regenerative Braking in Trains and Buses- Supercapacitors are employed in high-speed rail lines and electric buses to absorb and store braking energy. As the car decelerates, the converted energy transforms into electrical energy, and is accumulated into supercapacitors that may be subsequently used to support acceleration or power auxiliary systems. This energy recovery from braking contributes to fuel savings and, on a system level, to system efficiency [190].

X. Telecommunications and Data Centres- In telecommunications as well as data centres, supercapacitors play a role for different applications, such as backup power and power conditioning for smooth operation of the key systems.

A. Telecom Network Backup- Reliable power needs to be available for continuous operation, especially for emergency communication, in telecommunications' networks. Supercapacitors can deliver "on the fly" reserve power during brief outages, providing the system operation during restoration of main power sources or operation by backup generators [191].

B. Data Centre Power Conditioning- In data centres, supercapacitors are used to smooth voltage fluctuations and provide instantaneous power during voltage dips or surges. They ensure that sensitive computing equipment remains powered during temporary interruptions in the main electrical supply, thereby preventing data loss, hardware damage, or downtime [192].

XI. Automated and Robotic Systems- Supercapacitors are becoming more and more popular tools for applications in automated systems and robotics, where a high-power density and a fast discharge capability are indispensable for effective operation [193].

Industrial Robots- In the field of industrial robotics supercapacitors supply fast surges of energy for situations in which acceleration or deceleration is needed. In particular, robotic arms to pick and place items on assembly lines for instance, may require fast energy supply to be able to complete tasks efficiently. Supercapacitors are used in robots to perform those tasks with high throughput and reliability while minimizing energy loss [194]. Autonomous Vehicles (AGVs) In automated guided vehicles (AGVs) in warehouses, factories, and distribution centres, supercapacitors supply the required power for overcoming obstacles, transporting loads, or accelerating rapidly. These vehicles are based upon very fast energy pulses at their locomotion and supercapacitors are suitable for such applications because of high rate of charge/discharge [195].

XII. Aerospace and Space Exploration- In aerospace and space exploration systems, supercapacitors have important functions in energy storage and release for specific purposes, in which energy efficiency, space saving, and fast response are critical [196]. Satellite Systems In satellites, supercapacitors can store energy for communication systems, onboard experiments, and propulsion systems. They are employed to deliver short bursts of power as needed, and to guarantee that their critical functions are performed to the best of their ability even during low power time periods [197].

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Spacecraft Systems- Supercapacitors are applicable for spacecraft applications to supply high-power bursts to spacecraft systems, e.g., to launch propulsion or science instruments. These applications benefit from the lightweight and reliable nature of supercapacitors, as well as their ability to deliver high power quickly without compromising their long lifespan.

XIII. Consumer Electronics: Supercapacitors are utilized in devices such as mobile phones and laptops to facilitate rapid charging and prolonged battery life [198]. The supercapacitor-battery integration is one of the critical research areas that aim to improve the overall performance of portable electronics [199].

## IX. CONCLUSION

Supercapacitors are an exciting new class of energy storage devices that offer significant advantages over conventional energy storage devices such as batteries. They are particularly suited for applications that require rapid charge and discharge cycles. The fact that supercapacitors can deliver extremely fast charge and discharge cycles makes them particularly good for applications that require short bursts of power. Unlike batteries, supercapacitors have a very high-power density so they can charge and discharge much faster and still have a long cycle life [200]. This makes them ideal for use in devices where frequent cycling is required. One of the biggest benefits of supercapacitors is that they can perform consistently over a very high number of charge and discharge cycles without much degradation, unlike batteries which tend to lose capacity over time [201]. This longevity, coupled with the fact that they have a lower environmental impact since they require less materials to build, makes supercapacitors a more sustainable energy storage solution in the long run. However, supercapacitors generally have a low energy density than batteries, which means that they cannot store as much energy for long periods of use. This limitation has limited their use to applications that require short bursts of energy rather than a continuous supply of energy [202]. This limitation has led to supercapacitors being used in applications that need fast bursts of energy rather than continuous energy supply. As a result, supercapacitors are often used in combination with batteries, where they provide fast energy bursts while the battery provides long-term energy storage. Research continues to focus on increasing energy density, improving material efficiency, and lowering costs. Advances in materials such as graphene and carbon nanotubes could have a major impact on supercapacitor performance. With these advancements moving forward, supercapacitors are expected to be important for future energy storage systems. They will offer options for various uses, such as electric vehicles, everyday gadgets, and large energy storage for renewable power sources. In conclusion, supercapacitors are not an alternative to batteries in all applications, but they continue to play a vital role in the wider energy storage ecosystem. Their combination of fast power delivery, long cycle life and sustainability makes them an indispensable technology, particularly for applications where high-power density and very fast energy transfer are key [203]. With continued advancements, supercapacitors are poised to make important contributions to the future of energy storage and the transition to cleaner, more efficient energy systems [204].

## REFERENCES

[1] M. Yaseen *et al.*, "A Review of Supercapacitors: Materials Design, Modification, and Applications," *Energies*, vol. 14, no. 22, p. 7779, Nov. 2021, doi: 10.3390/en14227779.

[2] S. Karthikeyan, B. Narenthiran, A. Sivanantham, L. D. Bhatlu, and T. Maridurai, "Supercapacitor: Evolution and review," *Materials Today: Proceedings*, vol. 46, pp. 3984–3988, 2021, doi: 10.1016/j.matpr.2021.02.526.

[3] A. Schneuwly and R. Gallay, "Properties and applications of supercapacitors From the state-of-the-art to future trends," 2000.

[4] G. Gautham Prasad, N. Shetty, S. Thakur, Rakshitha, and K. B. Bommegowda, "Supercapacitor technology and its applications: a review," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 561, no. 1, p. 012105, Oct. 2019, doi: 10.1088/1757-899X/561/1/012105.

[5] M. S. Halper, "Supercapacitors: A Brief Overview," 2006.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

[6] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[7] H. Gualous, H. Louahlia, and R. Gallay, "Supercapacitor Characterization and Thermal Modelling With Reversible and Irreversible Heat Effect," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3402–3409, Nov. 2011, doi: 10.1109/TPEL.2011.2145422.

[8] F. Rafik, H. Gualous, R. Gallay, A. Crausaz, and A. Berthon, "Frequency, thermal and voltage supercapacitor characterization and modeling," *Journal of Power Sources*, vol. 165, no. 2, pp. 928–934, Mar. 2007, doi: 10.1016/j.jpowsour.2006.12.021.

[9] C. Liu, F. Li, L. Ma, and H. Cheng, "Advanced Materials for Energy Storage," *Advanced Materials*, vol. 22, no. 8, Feb. 2010, doi: 10.1002/adma.200903328.

[10] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[11] S. Sharma and P. Chand, "Supercapacitor and electrochemical techniques: A brief review," *Results in Chemistry*, vol. 5, p. 100885, Jan. 2023, doi: 10.1016/j.rechem.2023.100885.

[12] S. Z. Hussain, M. Ihrar, S. B. Hussain, W. C. Oh, and K. Ullah, "A review on graphene-based transition metal oxide composites and its application towards supercapacitor electrodes," *SN Appl. Sci.*, vol. 2, no. 4, p. 764, Apr. 2020, doi: 10.1007/s42452-020-2515-8.

[13] M. Ergin, F. Blaabjerg, and A. Sangwongwanich, "A review on supercapacitor materials and developments," 2020.

[14] Z. Yu, L. Tetard, L. Zhai, and J. Thomas, "Supercapacitor electrode materials: nanostructures from 0 to 3 dimensions," *Energy Environ. Sci.*, vol. 8, no. 3, pp. 702–730, 2015, doi: 10.1039/C4EE03229B.

[15] S. Ratha and A. K. Samantara, *Supercapacitor: Instrumentation, Measurement and Performance Evaluation Techniques*. in SpringerBriefs in Materials. Singapore: Springer Singapore, 2018. doi: 10.1007/978-981-13-3086-5.

[16] Q. Guo, C. Sun, Y. Li, K. Li, and X. Tai, "Recent Advances of Electrode Materials Applied in an Electrochromic Supercapacitor Device," *Molecules*, vol. 30, no. 1, p. 182, Jan. 2025, doi: 10.3390/molecules30010182.

[17] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[18] A. G. Patel, L. Johnson, R. Arroyave, and J. L. Lutkenhaus, "Design of multifunctional supercapacitor electrodes using an informatics approach," *Mol. Syst. Des. Eng.*, vol. 4, no. 3, pp. 654–663, 2019, doi: 10.1039/C8ME00060C.

[19] S. Mandal *et al.*, "Recent advancement and design in supercapacitor hybrid electrode materials: Bridging the gap between energy and power density," *Chemical Engineering Journal Advances*, vol. 21, p. 100690, Mar. 2025, doi: 10.1016/j.ceja.2024.100690.

[20] L. Zhang, X. Hu, Z. Wang, F. Sun, and D. G. Dorrell, "A review of supercapacitor modeling, estimation, and applications: A control/management perspective," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1868–1878, Jan. 2018, doi: 10.1016/j.rser.2017.05.283.

[21] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[22] Z. Zhang, "Comparative Study of Supercapacitor, Battery and Supercapattery," *HSET*, vol. 29, pp. 289–297, Jan. 2023, doi: 10.54097/hset.v29i.4843.

[23] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[24] P. Simon and Y. Gogotsi, "Charge storage mechanism in nanoporous carbons and its consequence for electrical double layer capacitors," *Phil. Trans. R. Soc. A.*, vol. 368, no. 1923, pp. 3457–3467, July 2010, doi: 10.1098/rsta.2010.0109.

[25] R. Burt, G. Birkett, and X. S. Zhao, "A review of molecular modelling of electric double layer capacitors," *Phys. Chem. Chem. Phys.*, vol. 16, no. 14, p. 6519, 2014, doi: 10.1039/c3cp55186e.

[26] H. Ji *et al.*, "Capacitance of carbon-based electrical double-layer capacitors," *Nat Commun*, vol. 5, no. 1, p. 3317, Feb. 2014, doi: 10.1038/ncomms4317.

[27] E. Lim, C. Jo, and J. Lee, "Mini review of designed mesoporous materials for energy-storage applications: from electric double-layer capacitors to hybrid supercapacitors".

[28] P. Simon and Y. Gogotsi, "Materials for electrochemical capacitors," *Nature Mater*, vol. 7, no. 11, pp. 845–854, Nov. 2008, doi: 10.1038/nmat2297.

[29] K. Mazloomian, H. J. Lancaster, C. A. Howard, P. R. Shearing, and T. S. Miller, "Supercapacitor Degradation: Understanding Mechanisms of Cycling-Induced Deterioration and Failure of a Pseudocapacitor,"

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

*Batteries & Supercaps*, vol. 6, no. 8, p. e202300214, Aug. 2023, doi: 10.1002/batt.202300214.

[30] C. Costentin and J.-M. Savéant, “Energy storage: pseudocapacitance in prospect,” *Chem. Sci.*, vol. 10, no. 22, pp. 5656–5666, 2019, doi: 10.1039/C9SC01662G.

[31] S. Fleischmann *et al.*, “Pseudocapacitance: From Fundamental Understanding to High Power Energy Storage Materials,” *Chem. Rev.*, vol. 120, no. 14, pp. 6738–6782, July 2020, doi: 10.1021/acs.chemrev.0c00170.

[32] C. Costentin and J.-M. Savéant, “Energy storage: pseudocapacitance in prospect,” *Chem. Sci.*, vol. 10, no. 22, pp. 5656–5666, 2019, doi: 10.1039/C9SC01662G.

[33] T. Schoetz, L. W. Gordon, S. Ivanov, A. Bund, D. Mandler, and R. J. Messinger, “Disentangling faradaic, pseudocapacitive, and capacitive charge storage: A tutorial for the characterization of batteries, supercapacitors, and hybrid systems,” *Electrochimica Acta*, vol. 412, p. 140072, Apr. 2022, doi: 10.1016/j.electacta.2022.140072.

[34] N. R. Chodankar *et al.*, “True Meaning of Pseudocapacitors and Their Performance Metrics: Asymmetric versus Hybrid Supercapacitors,” *Small*, vol. 16, no. 37, p. 2002806, Sept. 2020, doi: 10.1002/smll.202002806.

[35] A. D. Su *et al.*, “Hierarchical porous nickel oxide–carbon nanotubes as advanced pseudocapacitor materials for supercapacitors,” *Chemical Physics Letters*, vol. 561–562, pp. 68–73, Mar. 2013, doi: 10.1016/j.cplett.2013.01.023.

[36] T. Kadyk and M. Eikerling, “Charging Mechanism and Moving Reaction Fronts in a Supercapacitor with Pseudocapacitance,” *J. Electrochem. Soc.*, vol. 161, no. 3, pp. A239–A246, 2014, doi: 10.1149/2.018403jes.

[37] Q. Jiang, N. Kurra, M. Alhabeb, Y. Gogotsi, and H. N. Alshareef, “All Pseudocapacitive MXene-$RuO_2$ Asymmetric Supercapacitors,” *Advanced Energy Materials*, vol. 8, no. 13, p. 1703043, May 2018, doi: 10.1002/aenm.201703043.

[38] R. Liang *et al.*, “Transition Metal Oxide Electrode Materials for Supercapacitors: A Review of Recent Developments,” *Nanomaterials*, vol. 11, no. 5, p. 1248, May 2021, doi: 10.3390/nano11051248.

[39] M. G. Bakker *et al.*, “Perspectives on supercapacitors, pseudocapacitors and batteries,” *Nanomaterials and Energy*, vol. 1, no. 3, pp. 136–158, May 2012, doi: 10.1680/nme.11.00007.

[40] Z. Han, R. Fang, D. Chu, D.-W. Wang, and K. (Ken) Ostrikov, “Introduction to Supercapacitors,” *Nanoscale Adv.*, vol. 5, no. 16, pp. 4015–4017, 2023, doi: 10.1039/D3NA90074F.

[41] Z. Yan, S. Luo, Q. Li, Z. Wu, and S. (Frank) Liu, “Recent Advances in Flexible Wearable Supercapacitors: Properties, Fabrication, and Applications,” *Advanced Science*, vol. 11, no. 8, p. 2302172, Feb. 2024, doi: 10.1002/advs.202302172.

[42] K. Xu *et al.*, “Computational Insights into Charge Storage Mechanisms of Supercapacitors,” *Energy & Environ Materials*, vol. 3, no. 3, pp. 235–246, Sept. 2020, doi: 10.1002/eem2.12124.

[43] Y. Xu *et al.*, “Recent progress in electrode materials for micro-supercapacitors,” *iScience*, vol. 27, no. 2, p. 108786, Feb. 2024, doi: 10.1016/j.isci.2024.108786.

[44] A. Muzaffar, M. B. Ahamed, K. Deshmukh, and J. Thirumalai, “A review on recent advances in hybrid supercapacitors: Design, fabrication and applications,” *Renewable and Sustainable Energy Reviews*, vol. 101, pp. 123–145, Mar. 2019, doi: 10.1016/j.rser.2018.10.026.

[45] H. Wang, M. Wang, and Y. Tang, “A novel zinc-ion hybrid supercapacitor for long-life and low-cost energy storage applications,” *Energy Storage Materials*, vol. 13, pp. 1–7, July 2018, doi: 10.1016/j.ensm.2017.12.022.

[46] R. Genc *et al.*, “High-Capacitance Hybrid Supercapacitor Based on Multi-Colored Fluorescent Carbon-Dots,” *Sci Rep*, vol. 7, no. 1, p. 11222, Sept. 2017, doi: 10.1038/s41598-017-11347-1.

[47] Y. Ma, H. Chang, M. Zhang, and Y. Chen, “Graphene-Based Materials for Lithium-Ion Hybrid Supercapacitors,” *Advanced Materials*, vol. 27, no. 36, pp. 5296–5308, Sept. 2015, doi: 10.1002/adma.201501622.

[48] M. Khalid, “A Review on the Selected Applications of Battery-Supercapacitor Hybrid Energy Storage Systems for Microgrids,” *Energies*, vol. 12, no. 23, p. 4559, Nov. 2019, doi: 10.3390/en12234559.

[49] Y. Y. Chia, L. H. Lee, N. Shafiabady, and D. Isa, “A load predictive energy management system for supercapacitor-battery hybrid energy storage system in solar application using the Support Vector Machine,” *Applied Energy*, vol. 137, pp. 588–602, Jan. 2015, doi: 10.1016/j.apenergy.2014.09.026.

[50] “qt5ps0k488 (1).”

[51] M. Kroupa, G. J. Offer, and J. Kosek, “Modelling of Supercapacitors: Factors Influencing Performance,” *J. Electrochem. Soc.*, vol. 163, no. 10, pp. A2475–A2487, 2016, doi: 10.1149/2.0081613jes.

[52] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, “Electrode Materials for Supercapacitors: A Review of Recent Advances,” *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[53] Y. Y. Kannangara *et al.*, “The electrochemical performance of various NiCo2O4 nanostructures in hybrid supercapacitors: Investigating the

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

impact of crystalline defects," *Journal of Energy Storage*, vol. 84, p. 110717, Apr. 2024, doi: 10.1016/j.est.2024.110717.

[54] J. Liu *et al.*, "$MnO_2$ -based materials for supercapacitor electrodes: challenges, strategies and prospects," *RSC Adv.*, vol. 12, no. 55, pp. 35556–35578, 2022, doi: 10.1039/D2RA06664E.

[55] D. S. Dmitriev, A. V. Nashchekin, and V. I. Popkov, "The interfacial surface of an electrode for a supercapacitor as a factor affecting the capacitance and energy density," *Applied Surface Science*, vol. 501, p. 144216, Jan. 2020, doi: 10.1016/j.apsusc.2019.144216.

[56] J. Wang *et al.*, "$MnO_2$ /Porous Carbon Nanotube/$MnO_2$ Nanocomposites for High-Performance Supercapacitor," *ACS Appl. Nano Mater.*, vol. 3, no. 11, pp. 11152–11159, Nov. 2020, doi: 10.1021/acsanm.0c02163.

[57] O. Barbieri, M. Hahn, A. Herzog, and R. Kötz, "Capacitance limits of high surface area activated carbons for double layer capacitors," *Carbon*, vol. 43, no. 6, pp. 1303–1310, May 2005, doi: 10.1016/j.carbon.2005.01.001.

[58] Y. Anil Kumar *et al.*, "Carbon Materials as a Conductive Skeleton for Supercapacitor Electrode Applications: A Review," *Nanomaterials*, vol. 13, no. 6, p. 1049, Mar. 2023, doi: 10.3390/nano13061049.

[59] G. Wang, L. Zhang, and J. Zhang, "A review of electrode materials for electrochemical supercapacitors," *Chem. Soc. Rev.*, vol. 41, no. 2, pp. 797–828, 2012, doi: 10.1039/C1CS15060J.

[60] Y. Zhao, Y. Zhang, Y. Wang, D. Cao, X. Sun, and H. Zhu, "Versatile zero- to three-dimensional carbon for electrochemical energy storage," *Carbon Energy*, vol. 3, no. 6, pp. 895–915, Nov. 2021, doi: 10.1002/cey2.137.

[61] P. Kadyan, S. Sharma, K. Sharma, V. Singh, and R. K. Sharma, "Zero Dimensional Hydrophilic Carbon Nano-Onions derived from Waste Flaxseed Oil for Symmetric Supercapacitor Device".

[62] K. Kamalasanan *et al.*, "'Zero-Dimensional' Single-Walled Carbon Nanotubes," *Angew Chem Int Ed*, vol. 52, no. 43, pp. 11308–11312, Oct. 2013, doi: 10.1002/anie.201305526.

[63] Z. Yu, L. Tetard, L. Zhai, and J. Thomas, "Supercapacitor electrode materials: nanostructures from 0 to 3 dimensions," *Energy Environ. Sci.*, vol. 8, no. 3, pp. 702–730, 2015, doi: 10.1039/C4EE03229B.

[64] C. Du and N. Pan, "High power density supercapacitor electrodes of carbon nanotube films by electrophoretic deposition," *Nanotechnology*, vol. 17, no. 21, pp. 5314–5318, Nov. 2006, doi: 10.1088/0957-4484/17/21/005.

[65] L. G. H. Staaf, P. Lundgren, and P. Enoksson, "Present and future supercapacitor carbon electrode materials for improved energy storage used in intelligent wireless sensor systems," *Nano Energy*, vol. 9, pp. 128–141, Oct. 2014, doi: 10.1016/j.nanoen.2014.06.028.

[66] N. Muralidharan *et al.*, "Carbon Nanotube Reinforced Structural Composite Supercapacitor," *Sci Rep*, vol. 8, no. 1, p. 17662, Dec. 2018, doi: 10.1038/s41598-018-34963-x.

[67] C. Portet, P. L. Taberna, P. Simon, and E. Flahaut, "Influence of carbon nanotubes addition on carbon–carbon supercapacitor performances in organic electrolyte," *Journal of Power Sources*, vol. 139, no. 1–2, pp. 371–378, Jan. 2005, doi: 10.1016/j.jpowsour.2004.07.015.

[68] J. R. McDonough, J. W. Choi, Y. Yang, F. La Mantia, Y. Zhang, and Y. Cui, "Carbon nanofiber supercapacitors with large areal capacitances," *Applied Physics Letters*, vol. 95, no. 24, p. 243109, Dec. 2009, doi: 10.1063/1.3273864.

[69] A. Izadi-Najafabadi *et al.*, "Extracting the Full Potential of Single-Walled Carbon Nanotubes as Durable Supercapacitor Electrodes Operable at 4 V with High Power and Energy Density," *Advanced Materials*, vol. 22, no. 35, Sept. 2010, doi: 10.1002/adma.200904349.

[70] J. Xu *et al.*, "Preparing two-dimensional microporous carbon from Pistachio nutshell with high areal capacitance as supercapacitor materials," *Sci Rep*, vol. 4, no. 1, p. 5545, July 2014, doi: 10.1038/srep05545.

[71] P. Forouzandeh and S. C. Pillai, "Two-dimensional (2D) electrode materials for supercapacitors," *Materials Today: Proceedings*, vol. 41, pp. 498–505, 2021, doi: 10.1016/j.matpr.2020.05.233.

[72] P. K. Panda, A. Grigoriev, Y. K. Mishra, and R. Ahuja, "Progress in supercapacitors: roles of two dimensional nanotubular materials," *Nanoscale Adv.*, vol. 2, no. 1, pp. 70–108, 2020, doi: 10.1039/C9NA00307J.

[73] Y. Y. Kannangara *et al.*, "The electrochemical performance of various NiCo2O4 nanostructures in hybrid supercapacitors: Investigating the impact of crystalline defects," *Journal of Energy Storage*, vol. 84, p. 110717, Apr. 2024, doi: 10.1016/j.est.2024.110717.

[74] Y. Y. Kannangara *et al.*, "The electrochemical performance of various NiCo2O4 nanostructures in hybrid supercapacitors: Investigating the impact of crystalline defects," *Journal of Energy Storage*, vol. 84, p. 110717, Apr. 2024, doi: 10.1016/j.est.2024.110717.

[75] Y. Y. Kannangara *et al.*, "The electrochemical performance of various NiCo2O4 nanostructures in hybrid supercapacitors: Investigating the impact of crystalline defects," *Journal of Energy Storage*, vol. 84, p. 110717, Apr. 2024, doi: 10.1016/j.est.2024.110717.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

[76] H.-L. Hsu, M. Miah, S. K. Saha, J.-H. Chen, L.-C. Chen, and S.-Y. Hsu, "Three-dimensional bundle-like multiwalled carbon nanotubes composite for supercapacitor electrode application," *Materials Today Chemistry*, vol. 22, p. 100569, Dec. 2021, doi: 10.1016/j.mtchem.2021.100569.

[77] M. Yang and Z. Zhou, "Recent Breakthroughs in Supercapacitors Boosted by Nitrogen-Rich Porous Carbon Materials," *Advanced Science*, vol. 4, no. 8, p. 1600408, Aug. 2017, doi: 10.1002/advs.201600408.

[78] Z. Pan *et al.*, "Recent Advances in Porous Carbon Materials as Electrodes for Supercapacitors," *Nanomaterials*, vol. 13, no. 11, p. 1744, May 2023, doi: 10.3390/nano13111744.

[79] L. Zhang, Y. Jiang, L. Wang, C. Zhang, and S. Liu, "Hierarchical porous carbon nanofibers as binder-free electrode for high-performance supercapacitor," *Electrochimica Acta*, vol. 196, pp. 189–196, Apr. 2016, doi: 10.1016/j.electacta.2016.02.050.

[80] Y. Wang *et al.*, "Recent progress in carbon-based materials for supercapacitor electrodes: a review," *J Mater Sci*, vol. 56, no. 1, pp. 173–200, Jan. 2021, doi: 10.1007/s10853-020-05157-6.

[81] Z. Pan *et al.*, "Recent Advances in Porous Carbon Materials as Electrodes for Supercapacitors," *Nanomaterials*, vol. 13, no. 11, p. 1744, May 2023, doi: 10.3390/nano13111744.

[82] B. Li *et al.*, "Nitrogen-doped Activated Carbon for High Energy Hybrid Supercapacitor".

[83] W. Lee and J. H. Moon, "Monodispersed N-Doped Carbon Nanospheres for Supercapacitor Application," *ACS Appl. Mater. Interfaces*, vol. 6, no. 16, pp. 13968–13976, Aug. 2014, doi: 10.1021/am5033378.

[84] X. Chen *et al.*, "A novel hierarchical porous nitrogen-doped carbon derived from bamboo shoot for high performance supercapacitor," *Sci Rep*, vol. 7, no. 1, p. 7362, Aug. 2017, doi: 10.1038/s41598-017-06730-x.

[85] A. Ilnicka, M. Skorupska, M. Szkoda, Z. Zarach, and J. P. Lukaszewicz, "N-doped carbon materials as electrodes for highly stable supercapacitors," *Materials Research Letters*, vol. 11, no. 3, pp. 213–221, Mar. 2023, doi: 10.1080/21663831.2022.2139163.

[86] Y. Wang *et al.*, "Supercapacitor Devices Based on Graphene Materials," *J. Phys. Chem. C*, vol. 113, no. 30, pp. 13103–13107, July 2009, doi: 10.1021/jp902214f.

[87] Y. B. Tan and J.-M. Lee, "Graphene for supercapacitor applications," *J. Mater. Chem. A*, vol. 1, no. 47, p. 14814, 2013, doi: 10.1039/c3ta12193c.

[88] S. R. C. Vivekchand, C. S. Rout, K. S. Subrahmanyam, A. Govindaraj, and C. N. R. Rao, "Graphene-based electrochemical supercapacitors," *Journal of Chemical Sciences*, vol. 120, no. 1, pp. 9–13, Jan. 2008, doi: 10.1007/s12039-008-0002-7.

[89] M. P. Down, S. J. Rowley-Neale, G. C. Smith, and C. E. Banks, "Fabrication of Graphene Oxide Supercapacitor Devices," *ACS Appl. Energy Mater.*, vol. 1, no. 2, pp. 707–714, Feb. 2018, doi: 10.1021/acsaem.7b00164.

[90] F. T. Johra and W.-G. Jung, "Hydrothermally reduced graphene oxide as a supercapacitor," *Applied Surface Science*, vol. 357, pp. 1911–1914, Dec. 2015, doi: 10.1016/j.apsusc.2015.09.128.

[91] L. L. Zhang, R. Zhou, and X. S. Zhao, "Graphene-based materials as supercapacitor electrodes," *J. Mater. Chem.*, vol. 20, no. 29, p. 5983, 2010, doi: 10.1039/c000417k.

[92] T. Fan *et al.*, "Fabrication of high-quality graphene oxide nanoscrolls and application in supercapacitor," *Nanoscale Res Lett*, vol. 10, no. 1, p. 192, Dec. 2015, doi: 10.1186/s11671-015-0894-3.

[93] X. Li *et al.*, "Self-supporting activated carbon/carbon nanotube/reduced graphene oxide flexible electrode for high performance supercapacitor," *Carbon*, vol. 129, pp. 236–244, Apr. 2018, doi: 10.1016/j.carbon.2017.11.099.

[94] M. Yanilmaz, M. Dirican, A. M. Asiri, and X. Zhang, "Flexible polyaniline-carbon nanofiber supercapacitor electrodes," *Journal of Energy Storage*, vol. 24, p. 100766, Aug. 2019, doi: 10.1016/j.est.2019.100766.

[95] J. R. McDonough, J. W. Choi, Y. Yang, F. La Mantia, Y. Zhang, and Y. Cui, "Carbon nanofiber supercapacitors with large areal capacitances," *Applied Physics Letters*, vol. 95, no. 24, p. 243109, Dec. 2009, doi: 10.1063/1.3273864.

[96] S. Kandambeth, V. S. Kale, O. Shekhah, H. N. Alshareef, and M. Eddaoudi, "2D Covalent-Organic Framework Electrodes for Supercapacitors and Rechargeable Metal-Ion Batteries," *Advanced Energy Materials*, vol. 12, no. 4, p. 2100177, Jan. 2022, doi: 10.1002/aenm.202100177.

[97] Q. Ke and J. Wang, "Graphene-based materials for supercapacitor electrodes – A review," *Journal of Materiomics*, vol. 2, no. 1, pp. 37–54, Mar. 2016, doi: 10.1016/j.jmat.2016.01.001.

[98] A. Ramadoss, K.-Y. Yoon, M.-J. Kwak, S.-I. Kim, S.-T. Ryu, and J.-H. Jang, "Fully flexible, lightweight, high performance all-solid-state supercapacitor based on 3-Dimensional-graphene/graphite-paper," *Journal of Power Sources*, vol. 337, pp. 159–165, Jan. 2017, doi: 10.1016/j.jpowsour.2016.10.091.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

[99] D. Zhang, C. Tan, W. Zhang, W. Pan, Q. Wang, and L. Li, “Expanded Graphite-Based Materials for Supercapacitors: A Review,” *Molecules*, vol. 27, no. 3, p. 716, Jan. 2022, doi: 10.3390/molecules27030716.

[100] S. M. Jung, D. L. Mafra, C.-T. Lin, H. Y. Jung, and J. Kong, “Controlled porous structures of graphene aerogels and their effect on supercapacitor performance,” *Nanoscale*, vol. 7, no. 10, pp. 4386–4393, 2015, doi: 10.1039/C4NR07564A.

[101] L. Manjakkal, W. T. Navaraj, C. G. Núñez, and R. Dahiya, “Graphene–Graphite Polyurethane Composite Based High-Energy Density Flexible Supercapacitors,” *Advanced Science*, vol. 6, no. 7, p. 1802251, Apr. 2019, doi: 10.1002/advs.201802251.

[102] S. Gadipelli *et al.*, “Structure-guided Capacitance Relationships in Oxidized Graphene Porous Materials Based Supercapacitors,” *Energy & Environ Materials*, vol. 6, no. 4, p. e12637, July 2023, doi: 10.1002/eem2.12637.

[103] F. Ahmad *et al.*, “Recent developments in transition metal oxide-based electrode composites for supercapacitor applications,” *Journal of Energy Storage*, vol. 81, p. 110430, Mar. 2024, doi: 10.1016/j.est.2024.110430.

[104] P. Simon and Y. Gogotsi, “Materials for electrochemical capacitors,” *Nature Mater*, vol. 7, no. 11, pp. 845–854, Nov. 2008, doi: 10.1038/nmat2297.

[105] M. G. Joysi *et al.*, “Exploring ternary metal oxides MnO2/CuO/ZrO2 composites for supercapacitor applications,” *Results in Chemistry*, vol. 10, p. 101682, Aug. 2024, doi: 10.1016/j.rechem.2024.101682.

[106] K. I. Ozoemena and S. Chen, Eds., *Nanomaterials in Advanced Batteries and Supercapacitors*. in Nanostructure Science and Technology. Cham: Springer International Publishing, 2016. doi: 10.1007/978-3-319-26082-2.

[107] W. Qian *et al.*, “Surfactant-free hybridization of transition metal oxidenanoparticles with conductive graphene for high-performance supercapacitor,” *Green Chem.*, vol. 14, no. 2, pp. 371–377, 2012, doi: 10.1039/C1GC16134B.

[108] C. An, Y. Zhang, H. Guo, and Y. Wang, “Metal oxide-based supercapacitors: progress and prospectives,” *Nanoscale Adv.*, vol. 1, no. 12, pp. 4644–4658, 2019, doi: 10.1039/C9NA00543A.

[109] Y. Peng *et al.*, “Hierarchical manganese oxide/carbon nanocomposites for supercapacitor electrodes,” *Nano Res.*, vol. 4, no. 2, pp. 216–225, Feb. 2011, doi: 10.1007/s12274-010-0072-y.

[110] S. J. Uke, V. P. Akhare, D. R. Bambole, A. B. Bodade, and G. N. Chaudhari, “Recent Advancements in the Cobalt Oxides, Manganese Oxides, and Their Composite As an Electrode Material for Supercapacitor: A Review,” *Front. Mater.*, vol. 4, p. 21, Aug. 2017, doi: 10.3389/fmats.2017.00021.

[111] J. Gu *et al.*, “Mesoporous manganese oxide with large specific surface area for high-performance asymmetric supercapacitor with enhanced cycling stability,” *Chemical Engineering Journal*, vol. 324, pp. 35–43, Sept. 2017, doi: 10.1016/j.cej.2017.05.014.

[112] C.-K. Lin, K.-H. Chuang, C.-Y. Lin, C.-Y. Tsay, and C.-Y. Chen, “Manganese oxide films prepared by sol–gel process for supercapacitor application,” *Surface and Coatings Technology*, vol. 202, no. 4–7, pp. 1272–1276, Dec. 2007, doi: 10.1016/j.surfcoat.2007.07.049.

[113] A. N. Redkin, A. A. Mitina, and E. E. Yakimov, “Binder-Free MnO2/MWCNT/Al Electrodes for Supercapacitors,” *Nanomaterials*, vol. 12, no. 17, p. 2922, Aug. 2022, doi: 10.3390/nano12172922.

[114] J. P. Cheng, X. Chen, J.-S. Wu, F. Liu, X. B. Zhang, and V. P. Dravid, “Porous cobalt oxides with tunable hierarchical morphologies for supercapacitor electrodes,” *CrystEngComm*, vol. 14, no. 20, p. 6702, 2012, doi: 10.1039/c2ce26057c.

[115] P. Sivakumar, M. Jana, M. Kota, M. G. Jung, A. Gedanken, and H. S. Park, “Controllable synthesis of nanohorn-like architectured cobalt oxide for hybrid supercapacitor application,” *Journal of Power Sources*, vol. 402, pp. 147–156, Oct. 2018, doi: 10.1016/j.jpowsour.2018.09.026.

[116] Annu, S.-S. Park, M. N. Alam, M. Yewale, and D. K. Shin, “Unraveling the Electrochemical Insights of Cobalt Oxide/Conducting Polymer Hybrid Materials for Supercapacitor, Battery, and Supercapattery Applications,” *Polymers*, vol. 16, no. 20, p. 2907, Oct. 2024, doi: 10.3390/polym16202907.

[117] S. Sagadevan *et al.*, “Reduced graphene/nanostructured cobalt oxide nanocomposite for enhanced electrochemical performance of supercapacitor applications,” *Journal of Colloid and Interface Science*, vol. 558, pp. 68–77, Jan. 2020, doi: 10.1016/j.jcis.2019.09.081.

[118] B. Heng, C. Qing, D. Sun, B. Wang, H. Wang, and Y. Tang, “Rapid synthesis of CuO nanoribbons and nanoflowers from the same reaction system, and a comparison of their supercapacitor performance,” *RSC Adv.*, vol. 3, no. 36, p. 15719, 2013, doi: 10.1039/c3ra42869a.

[119] S. P. Jahromi *et al.*, “Influence of particle size on performance of nickel oxide nanoparticle-based supercapacitor”.

[120] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, “Electrode Materials for Supercapacitors: A Review of Recent Advances,” *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: 10.3390/catal10090969.

[121] B. Vidhyadharan *et al.*, “High performance supercapacitor electrodes from electrospun nickel oxide nanowires,” *Journal of Alloys and*

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

*Compounds*, vol. 610, pp. 143–150, Oct. 2014, doi: 10.1016/j.jallcom.2014.04.211.

[122] School of Physical Sciences, PAH Solapur University Solapur (Maharashtra), 413255, S. G. Randive, H. M. Pathan, Department of Physics, Savitribai Phule Pune University, Pune, B. J. Lokhande, and School of Physical Sciences, PAH Solapur University Solapur (Maharashtra), 413255, "Ingredient-Dependent Nickel Oxide Synthesis for Supercapacitor Application," *ES Energy Environ.*, 2023, doi: 10.30919/esee8c877.

[123] J. El Nady, A. Shokry, M. Khalil, S. Ebrahim, A. M. Elshaer, and M. Anas, "One-step electrodeposition of a polypyrrole/NiO nanocomposite as a supercapacitor electrode," *Sci Rep*, vol. 12, no. 1, p. 3611, Mar. 2022, doi: 10.1038/s41598-022-07483-y.

[124] P. Lorkit, M. Panapoy, and B. Ksapabutr, "Iron Oxide-based Supercapacitor from Ferratrane Precursor via Sol–gel-Hydrothermal Process," *Energy Procedia*, vol. 56, pp. 466–473, 2014, doi: 10.1016/j.egypro.2014.07.180.

[125] P. M. Kulal, D. P. Dubal, C. D. Lokhande, and V. J. Fulari, "Chemical synthesis of Fe2O3 thin films for supercapacitor application," *Journal of Alloys and Compounds*, vol. 509, no. 5, pp. 2567–2571, Feb. 2011, doi: 10.1016/j.jallcom.2010.11.091.

[126] S. Shivakumara, T. R. Penki, and N. Munichandraiah, "Synthesis and Characterization of Porous Flowerlike -Fe2O3 Nanostructures for Supercapacitor Application," *ECS Electrochemistry Letters*, vol. 2, no. 7, pp. A60–A62, Apr. 2013, doi: 10.1149/2.002307eel.

[127] M. Gaire, N. Khatoon, B. Subedi, and D. Chrisey, "Flexible iron oxide supercapacitor electrodes by photonic processing," *Journal of Materials Research*, vol. 36, no. 22, pp. 4536–4546, Nov. 2021, doi: 10.1557/s43578-021-00346-8.

[128] M. Tarek, F. Yasmeen, and M. A. Basith, "DyFeO3 electrode material with ultra-wide voltage window for aqueous symmetric supercapacitors," Feb. 15, 2024, *arXiv*: arXiv:2403.13814. doi: 10.48550/arXiv.2403.13814.

[129] M. Yu *et al.*, "Valence-Optimized Vanadium Oxide Supercapacitor Electrodes Exhibit Ultrahigh Capacitance and Super-Long Cyclic Durability of 100 000 Cycles," *Adv Funct Materials*, vol. 25, no. 23, pp. 3534–3540, June 2015, doi: 10.1002/adfm.201501342.

[130] M. Lee *et al.*, "One-step hydrothermal synthesis of graphene decorated V2O5 nanobelts for enhanced electrochemical energy storage," *Sci Rep*, vol. 5, no. 1, p. 8151, Jan. 2015, doi: 10.1038/srep08151.

[131] M. Yu *et al.*, "Valence-Optimized Vanadium Oxide Supercapacitor Electrodes Exhibit Ultrahigh Capacitance and Super-Long Cyclic Durability of 100 000 Cycles," *Adv Funct Materials*, vol. 25, no. 23, pp. 3534–3540, June 2015, doi: 10.1002/adfm.201501342.

[132] K. I. Ozoemena and S. Chen, Eds., *Nanomaterials in Advanced Batteries and Supercapacitors*. in Nanostructure Science and Technology. Cham: Springer International Publishing, 2016. doi: 10.1007/978-3-319-26082-2.

[133] R. Liang *et al.*, "Transition Metal Oxide Electrode Materials for Supercapacitors: A Review of Recent Developments," *Nanomaterials*, vol. 11, no. 5, p. 1248, May 2021, doi: 10.3390/nano11051248.

[134] V. V. N. Obreja, "Supercapacitors specialities - Materials review," presented at the REVIEW ON ELECTROCHEMICAL STORAGE MATERIALS AND TECHNOLOGY: Proceedings of the 1st International Freiberg Conference on Electrochemical Storage Materials, Freiberg, Germany, 2014, pp. 98–120. doi: 10.1063/1.4878482.

[135] C. An, Y. Zhang, H. Guo, and Y. Wang, "Metal oxide-based supercapacitors: progress and prospectives," *Nanoscale Adv.*, vol. 1, no. 12, pp. 4644–4658, 2019, doi: 10.1039/C9NA00543A.

[136] P. H. Patil, V. V. Kulkarni, and S. A. Jadhav, "An Overview of Recent Advancements in Conducting Polymer–Metal Oxide Nanocomposites for Supercapacitor Application," *J. Compos. Sci.*, vol. 6, no. 12, p. 363, Dec. 2022, doi: 10.3390/jcs6120363.

[137] A. Tundwal *et al.*, "Developments in conducting polymer-, metal oxide-, and carbon nanotube-based composite electrode materials for supercapacitors: a review," *RSC Adv.*, vol. 14, no. 14, pp. 9406–9439, 2024, doi: 10.1039/D3RA08312H.

[138] Md. S. Islam, M. Mubarak, and H.-J. Lee, "Hybrid Nanostructured Materials as Electrodes in Energy Storage Devices," *Inorganics*, vol. 11, no. 5, p. 183, Apr. 2023, doi: 10.3390/inorganics11050183.

[139] L. Liu and S. Choi, "A High-Performance Photo-Biosupercapacitor Based on Manganese Oxide/Carbon Nanotube/PEDOT:PSS Nanocomposites," in *2020 IEEE 33rd International Conference on Micro Electro Mechanical Systems (MEMS)*, Vancouver, BC, Canada: IEEE, Jan. 2020, pp. 554–557. doi: 10.1109/MEMS46641.2020.9056378.

[140] Department of Electronic Science & PG Center, Poona College of Arts, Science and Commerce, Camp, Pune, India. *et al.*, "Nano-Metal Oxide Based Supercapacitor Via Electrochemical Deposition," *ES Energy Environ.*, 2019, doi: 10.30919/esee8c211.

[141] J. Rodriguez-Romero, I. Ruiz De Larramendi, and E. Goikolea, "Nanostructured Manganese Dioxide for Hybrid Supercapacitor Electrodes," *Batteries*, vol. 8, no. 12, p. 263, Nov. 2022, doi: 10.3390/batteries8120263.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

[142] C. Zhong, Y. Deng, W. Hu, J. Qiao, L. Zhang, and J. Zhang, "A review of electrolyte materials and compositions for electrochemical supercapacitors," *Chem. Soc. Rev.*, vol. 44, no. 21, pp. 7484–7539, 2015, doi: 10.1039/C5CS00303B.

[143] B. Pal, S. Yang, S. Ramesh, V. Thangadurai, and R. Jose, "Electrolyte selection for supercapacitive devices: a critical review," *Nanoscale Adv.*, vol. 1, no. 10, pp. 3807–3835, 2019, doi: 10.1039/C9NA00374F.

[144] A. Mendhe and H. S. Panda, "A review on electrolytes for supercapacitor device," *Discov Mater*, vol. 3, no. 1, p. 29, Oct. 2023, doi: 10.1007/s43939-023-00065-3.

[145] K. C. Lethesh, M. O. Bamgbopa, and R. A. Susantyoko, "Prospects and Design Insights of Neat Ionic Liquids as Supercapacitor Electrolytes," *Front. Energy Res.*, vol. 9, p. 741772, Oct. 2021, doi: 10.3389/fenrg.2021.741772.

[146] Y. Zhang, L. Wei, X. Liu, W. Ma, J. Wang, and S. Fan, "N/O co-enriched graphene hydrogels as high-performance electrodes for aqueous symmetric supercapacitors," *RSC Adv.*, vol. 11, no. 32, pp. 19737–19746, 2021, doi: 10.1039/D1RA01863A.

[147] A. Mendhe and H. S. Panda, "A review on electrolytes for supercapacitor device," *Discov Mater*, vol. 3, no. 1, p. 29, Oct. 2023, doi: 10.1007/s43939-023-00065-3.

[148] C. Zhong, Y. Deng, W. Hu, J. Qiao, L. Zhang, and J. Zhang, "A review of electrolyte materials and compositions for electrochemical supercapacitors," *Chem. Soc. Rev.*, vol. 44, no. 21, pp. 7484–7539, 2015, doi: 10.1039/C5CS00303B.

[149] S. S. Shah and Md. A. Aziz, "Properties of Electrode Materials and Electrolytes in Supercapacitor Technology," *JCE*, pp. 1–45, Feb. 2024, doi: 10.56946/jce.v3i1.309.

[150] M. Tomić, M. Šetka, L. Vojkůvka, and S. Vallejos, "VOCs Sensing by Metal Oxides, Conductive Polymers, and Carbon-Based Materials," *Nanomaterials*, vol. 11, no. 2, p. 552, Feb. 2021, doi: 10.3390/nano11020552.

[151] P. Azaïs *et al.*, "Causes of supercapacitors ageing in organic electrolyte," *Journal of Power Sources*, vol. 171, no. 2, pp. 1046–1053, Sept. 2007, doi: 10.1016/j.jpowsour.2007.07.001.

[152] A. Mendhe and H. S. Panda, "A review on electrolytes for supercapacitor device," *Discov Mater*, vol. 3, no. 1, p. 29, Oct. 2023, doi: 10.1007/s43939-023-00065-3.

[153] N. Hillier, S. Yong, A. Cruden, and S. Beeby, "Acetonitrile-Free Organic Electrolyte for Textile Supercapacitor Applications," *J. Electrochem. Soc.*, vol. 168, no. 8, p. 080520, Aug. 2021, doi: 10.1149/1945-7111/ac1a58.

[154] S. Shahzad *et al.*, "Ionic Liquids as Environmentally Benign Electrolytes for High-Performance Supercapacitors," *Global Challenges*, vol. 3, no. 1, p. 1800023, Jan. 2019, doi: 10.1002/gch2.201800023.

[155] L. Yu and G. Z. Chen, "Ionic Liquid-Based Electrolytes for Supercapacitor and Supercapattery," *Front. Chem.*, vol. 7, p. 272, Apr. 2019, doi: 10.3389/fchem.2019.00272.

[156] L. Yu and G. Z. Chen, "Ionic Liquid-Based Electrolytes for Supercapacitor and Supercapattery," *Front. Chem.*, vol. 7, p. 272, Apr. 2019, doi: 10.3389/fchem.2019.00272.

[157] A. Mendhe and H. S. Panda, "A review on electrolytes for supercapacitor device," *Discov Mater*, vol. 3, no. 1, p. 29, Oct. 2023, doi: 10.1007/s43939-023-00065-3.

[158] X. Chen and R. Holze, "Polymer Electrolytes for Supercapacitors".

[159] L. Zhang *et al.*, "A Review of Redox Electrolytes for Supercapacitors," *Front. Chem.*, vol. 8, p. 413, June 2020, doi: 10.3389/fchem.2020.00413.

[160] H. Gupta, M. Kumar, D. Sarkar, and P. W. Menezes, "Recent technological advances in designing electrodes and electrolytes for efficient zinc ion hybrid supercapacitors," *Energy Adv.*, vol. 2, no. 9, pp. 1263–1293, 2023, doi: 10.1039/D3YA00259D.

[161] K. Gautam, M. Bhatt, A. Verma, and A. K. Sinha, "Biomass-derived carbon electrodes from sugarcane bagasse for supercapacitor applications," *Biomass Conv. Bioref.*, Mar. 2025, doi: 10.1007/s13399-025-06799-9.

[162] M. Bilal, J. Li, and K. Landskron, "Activated Carbon Electrodes with Improved Sorption Capacity for Supercapacitive Swing Adsorption of Carbon Dioxide".

[163] A. Ahmad *et al.*, "Preparation and Characterization of Physically Activated Carbon and Its Energetic Application for All-Solid-State Supercapacitors: A Case Study," *ACS Omega*, vol. 8, no. 24, pp. 21653–21663, June 2023, doi: 10.1021/acsomega.3c01065.

[164] S. J. Zou, M. D. Patel, L. M. Smith, E. Cha, S. Q. Shi, and W. Choi, "Pecan Shell-Derived Activated Carbon for High-Electrochemical Performance Supercapacitor Electrode," *Materials*, vol. 17, no. 13, p. 3091, June 2024, doi: 10.3390/ma17133091.

[165] N. Duraisamy, K. Shenniangirivalasu Kandasamy, E. Dhandapani, K. Kandiah, S. J. Panchu, and H. C. Swart, "Biomass Derived 3D Hierarchical Porous Activated Carbon for Solid-State Symmetric

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

Supercapacitors,” *J Inorg Organomet Polym*, July 2025, doi: 10.1007/s10904-025-03837-x.

[166] P. Chomkhuntod, S. Kornnum, S. Arayawate, B. Wang, and P. Iamprasertkun, “Ultra-Fast Electrochemical Expansion for Rapid Enhancement of Graphite Paper Electrode,” *ACS Phys. Chem Au*, vol. 5, no. 4, pp. 318–326, July 2025, doi: 10.1021/acsphyschemau.5c00014.

[167] N. Kumar, K. Guru Prasad, A. Sen, and T. Maiyalagan, “Enhanced pseudocapacitance from finely ordered pristine α-MnO2 nanorods at favourably high current density using redox additive,” *Applied Surface Science*, vol. 449, pp. 492–499, Aug. 2018, doi: 10.1016/j.apsusc.2018.01.025.

[168] V. Dubey *et al.*, “Eco-Friendly Fabrication of Cr2V4O13 Nanoparticles: A Promising Material for Photocatalysis, Electrochemical Sensing, and Supercapacitor Applications,” *J Clust Sci*, vol. 36, no. 1, p. 9, Feb. 2025, doi: 10.1007/s10876-024-02720-y.

[169] F. Hamade, E. Radich, and V. A. Davis, “Microstructure and electrochemical properties of high performance graphene/manganese oxide hybrid electrodes,” *RSC Adv.*, vol. 11, no. 50, pp. 31608–31620, 2021, doi: 10.1039/D1RA05323J.

[170] X. Liu, B. Liang, X. Hong, and J. Long, “Electrochemical Performance of MnO2/Graphene Flower-like Microspheres Prepared by Thermally-Exfoliated Graphite,” *Front. Chem.*, vol. 10, p. 870541, Apr. 2022, doi: 10.3389/fchem.2022.870541.

[171] J. Liu *et al.*, “Bi2S3 nanosheet/ZnCo2O4 nanosphere arrays on Ni foam for high- performance battery-supercapacitor hybrid device”.

[172] R. Kumar, R. K. Nekouei, and V. Sahajwalla, “In-situ carbon-coated iron oxide (ISCC-Fe3O4) as an efficient electrode material for supercapacitor applications,” *Ceramics International*, vol. 51, no. 9, pp. 12312–12320, Apr. 2025, doi: 10.1016/j.ceramint.2025.01.071.

[173] “ssrn-5077509 (1).”

[174] N. M. Shinde and M. Pumera, “High Performance MXene/$MnCo_2$ $O_4$ Supercapacitor Device for Powering Small Robotics,” *ACS Appl. Electron. Mater.*, vol. 6, no. 10, pp. 7339–7345, Oct. 2024, doi: 10.1021/acsaelm.4c01204.

[175] H. Li *et al.*, “A manganese oxide/biomass porous carbon composite for high-performance supercapacitor electrodes,” *Electrochimica Acta*, vol. 473, p. 143514, Jan. 2024, doi: 10.1016/j.electacta.2023.143514.

[176] R. Shafique *et al.*, “Copper chromite/graphene oxide nanocomposite for capacitive energy storage and electrochemical applications,” *Int. J. Environ. Sci. Technol.*, vol. 19, no. 8, pp. 7517–7526, Aug. 2022, doi: 10.1007/s13762-021-03616-4.

[177] J. A. Rajesh, S.-J. Kwon, R. Manikandan, S.-H. Kang, and K.-S. Ahn, “Design of Co0.85Se Microsphere-like Architectures for High-Performance Hybrid Supercapacitors,” *Crystals*, vol. 15, no. 3, p. 217, Feb. 2025, doi: 10.3390/cryst15030217.

[178] J. Liu *et al.*, “Bi2S3 nanosheet/ZnCo2O4 nanosphere arrays on Ni foam for high- performance battery-supercapacitor hybrid device”.

[179] Z. M. El-Bahy, N. AlMasoud, M. Ali, T. S. Alomar, A. A. Al-wallan, and H. M. Tahir, “A novel DyCoO3@rGO nanocomposite electrode material for hybrid supercapacitor devices,” *Journal of Alloys and Compounds*, vol. 1010, p. 178091, Jan. 2025, doi: 10.1016/j.jallcom.2024.178091.

[180] L. G. H. Staaf, P. Lundgren, and P. Enoksson, “Present and future supercapacitor carbon electrode materials for improved energy storage used in intelligent wireless sensor systems,” *Nano Energy*, vol. 9, pp. 128–141, Oct. 2014, doi: 10.1016/j.nanoen.2014.06.028.

[181] G. R. Chitnis and S. D. Pandit, “A Battery/Supercapacitor Hybrid Combination in Uninterruptible Power Supply (UPS),” vol. 2, no. 5.

[182] F. A. Inthamoussou, J. Pegueroles-Queralt, and F. D. Bianchi, “Control of a Supercapacitor Energy Storage System for Microgrid Applications,” *IEEE Trans. Energy Convers.*, vol. 28, no. 3, pp. 690–697, Sept. 2013, doi: 10.1109/TEC.2013.2260752.

[183] A. Burke, Z. Liu, and H. Zhao, “Present and future applications of supercapacitors in electric and hybrid vehicles,” in *2014 IEEE International Electric Vehicle Conference (IEVC)*, Florence: IEEE, Dec. 2014, pp. 1–8. doi: 10.1109/IEVC.2014.7056094.

[184] G. Navarro, J. Torres, M. Blanco, J. Nájera, M. Santos-Herran, and M. Lafoz, “Present and Future of Supercapacitor Technology Applied to Powertrains, Renewable Generation and Grid Connection Applications,” *Energies*, vol. 14, no. 11, p. 3060, May 2021, doi: 10.3390/en14113060.

[185] Y. Wang *et al.*, “Supercapacitor Devices Based on Graphene Materials,” *J. Phys. Chem. C*, vol. 113, no. 30, pp. 13103–13107, July 2009, doi: 10.1021/jp902214f.

[186] “High power supercapacitors enable new pulse, bridge and main power applications,” 2017.

[187] G. Oriti, N. Anglani, and A. L. Julian, “Hybrid Energy Storage Control in a Remote Military Microgrid With Improved Supercapacitor Utilization and Sensitivity Analysis,” *IEEE Trans. on Ind. Applicat.*, vol. 55, no. 5, pp. 5099–5108, Sept. 2019, doi: 10.1109/TIA.2019.2923380.

[188] Y. Su *et al.*, “Stretchable Transparent Supercapacitors for Wearable and Implantable Medical Devices,” *Adv Materials Technologies*, vol. 7, no. 1, p. 2100608, Jan. 2022, doi: 10.1002/admt.202100608.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 231-259

[189] C. Abbey and G. Joos, "Supercapacitor Energy Storage for Wind Energy Applications," *IEEE Trans. on Ind. Applicat.*, vol. 43, no. 3, pp. 769–776, 2007, doi: 10.1109/TIA.2007.895768.

[190] J. Partridge and D. I. Abouelamaimen, "The Role of Supercapacitors in Regenerative Braking Systems," *Energies*, vol. 12, no. 14, p. 2683, July 2019, doi: 10.3390/en12142683.

[191] G. Gianolio, I. Rosso, L. Mercante, F. Pedrazzo, G. Simonato, and F. Ceriani, "GreenShelter for telecom applications a new generation of shelters for telecom applications integrating fuel cell electric backup and a new cooling approach," in *INTELEC 2008 - 2008 IEEE 30th International Telecommunications Energy Conference*, San Diego, CA: IEEE, Sept. 2008, pp. 1–7. doi: 10.1109/INTLEC.2008.4664059.

[192] B. Shu, Z. Huang, W. Ren, Y. Wu, and H. Li, "Learning-Based Model Predictive Control for Legged Robots with Battery–Supercapacitor Hybrid Energy Storage System," *Applied Sciences*, vol. 15, no. 1, p. 382, Jan. 2025, doi: 10.3390/app15010382.

[193] S. S. Nardekar and S. Kim, "Untethered Magnetic Soft Robot with Ultra-Flexible Wirelessly Rechargeable Micro-Supercapacitor as an Onboard Power Source," *Advanced Science*, vol. 10, no. 28, p. 2303918, Oct. 2023, doi: 10.1002/advs.202303918.

[194] B. Shu, Z. Huang, W. Ren, Y. Wu, and H. Li, "Learning-Based Model Predictive Control for Legged Robots with Battery–Supercapacitor Hybrid Energy Storage System," *Applied Sciences*, vol. 15, no. 1, p. 382, Jan. 2025, doi: 10.3390/app15010382.

[195] R. Niestrój, T. Rogala, and W. Skarka, "An Energy Consumption Model for Designing an AGV Energy Storage System with a PEMFC Stack," *Energies*, vol. 13, no. 13, p. 3435, July 2020, doi: 10.3390/en13133435.

[196] B. Buergler *et al.*, "Towards Supercapacitors in Space Applications," *E3S Web Conf.*, vol. 16, p. 17003, 2017, doi: 10.1051/e3sconf/20171617003.

[197] G. Palissat, L. Farhat, and J. J. J. Carreira, "Supercapacitors for space applications: trends and opportunities".

[198] J. Fernando, N. Kularatna, S. Silva, and S. Silva Thotabaddadurage, "Supercapacitor assisted surge absorber technique: high performance transient surge protectors for consumer electronics," *IEEE Power Electron. Mag.*, vol. 9, no. 2, pp. 48–60, June 2022, doi: 10.1109/MPEL.2022.3171644.

[199] M. Şahin, F. Blaabjerg, and A. Sangwongwanich, "A Comprehensive Review on Supercapacitor Applications and Developments," *Energies*, vol. 15, no. 3, p. 674, Jan. 2022, doi: 10.3390/en15030674.

[200] G. Gautham Prasad, N. Shetty, S. Thakur, Rakshitha, and K. B. Bommegowda, "Supercapacitor technology and its applications: a review," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 561, no. 1, p. 012105, Oct. 2019, doi: 10.1088/1757-899X/561/1/012105.

[201] G. Navarro, J. Torres, M. Blanco, J. Nájera, M. Santos-Herran, and M. Lafoz, "Present and Future of Supercapacitor Technology Applied to Powertrains, Renewable Generation and Grid Connection Applications," *Energies*, vol. 14, no. 11, p. 3060, May 2021, doi: 10.3390/en14113060.

[202] G. Gautham Prasad, N. Shetty, S. Thakur, Rakshitha, and K. B. Bommegowda, "Supercapacitor technology and its applications: a review," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 561, no. 1, p. 012105, Oct. 2019, doi: 10.1088/1757-899X/561/1/012105.

[203] J. A. Stagner and D. S.-K. Ting, Eds., *Sustaining Resources for Tomorrow*. in Green Energy and Technology. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-030-27676-8.

[204] S. Rudra, H. W. Seo, S. Sarker, and D. M. Kim, "Supercapatteries as Hybrid Electrochemical Energy Storage Devices: Current Status and Future Prospects," *Molecules*, vol. 29, no. 1, p. 243, Jan. 2024, doi: 10.3390/molecules29010243.

*Correspondence to: Akash Indoria, Centre for Renewable Energy & Storage, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: akashindoria001@gmail.com*