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An Overview of the Advances in Polymer-Based Electrode Materials in Supercapacitors

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Abstract: A special family of polymers known as conducting polymers (CPs) is able to carry charge via conjugated double bonds. CPs are intricate dynamic structures that capture the interest of those working in the field of intelligent materials. Electrical stimulation can cause significant changes in the electrical, mechanical, and chemical features of CPs. Nanocomposites made of CPs have been used in sensors, batteries, flexible electronics, and supercapacitors (SCs). A supercapacitor is a device used to store electrical charge through electrostatic and electrochemical processes. They have the potential to replace conventional batteries and capacitors. They have been used in the automotive, railways, military, renewable, and power industries. The development of electrical parameter models, reliability testing, and industry norms are all challenges that SCs are now dealing with. In this article, the introduction of supercapacitors (SCs), the potential of different types of CPs-based nanocomposite materials in the electrode material of SCs, current studies, future perspectives, opportunities, and challenges have been discussed.

Keywords: CPs; CPs-based nanocomposites; SCs; electrode materials.

1. Introduction

Clean energy sources are now needed to protect natural resources and regulate global energy usage. Supercapacitors (SCs) are known for their high power, long life cycle, and environmental safety. Hybrid cars, electric transit vehicles, and transportable electronic devices have all employed them [1]. They function as a link between fuel cells or batteries and regular capacitors. Fuel cells/batteries have a lot of power, while regular capacitors show high energy storage [2]. They have been used in renewable and electrical devices and for high power density and exceptional reversibility [1,2]. Electrodes are essential to SCs, and electrode performance is based on the surface area, the conductivity of materials, and porosity [3]. A nanocomposite material is made up of several phases that have at least one nanometer-scale dimension. The structure-property relationship is significantly influenced by the proportion between surface area and volume of reinforced material utilized in nanocomposite synthesis [4]. A polymer is a natural or artificial material composed of large molecules named macromolecules that seem to be multiples of smaller chemical units known as monomers. Conducting polymers (CPs) have been attracted to their utilization in different fields of science and technology due to their characteristic features such as ease of synthesis, environmental durability, high mechanical and optical properties, adjustable electrical properties, and ease of fabrication [5-8]. Polymer nanocomposites (PNCs) are polymers in which only a few weight percentages uniformly disperse modest amounts of nanoparticles (1 to 100 nm). Because of these small scales, a large specific surface area is formed, emphasizing the importance of polymer-nanoparticle interactions [9]. Individual components working individually cannot achieve the physicochemical features that PNCs possess. PNCs have been attracted to their potential in various applications, such as electromagnetic absorption, sensing, water remediation, transportation and safety, catalysts, information technology, and energy storage. PNCs have generated much interest in overcoming environmental and energy problems [9,10]. We have discussed a brief introduction to SCs, a general discussion of polymers and CPs, the role of CPs-based nanocomposites in energy storage, and some relevant and current studies and future perspectives.

2. Supercapacitors (SCs)

A high-capacity capacitor is referred to as a supercapacitor or ultracapacitor. With a much larger capacitance than typical capacitors but less stringent voltage requirements, it serves as the bridge between electrolytic capacitors and rechargeable batteries. In comparison to batteries, SCs can hold 1,000 times the power of batteries, making them ideal options for usage in a range of devices when power bursts are required. Transition metal oxides (TMOs), carbon materials, and CPs are generally employed as electrode materials in SCs [11-13]. SCs are electrochemical energy storage systems that work on the simple principle of ions from an electrolyte adsorbing on a large surface area electrode [14,15]. A Ragone plot (Figure 1) demonstrates the efficiency of several energy storage devices. Because SCs take up space between batteries and capacitors, it has a distinct benefit that makes them important for applications requiring high power delivered quickly [16].

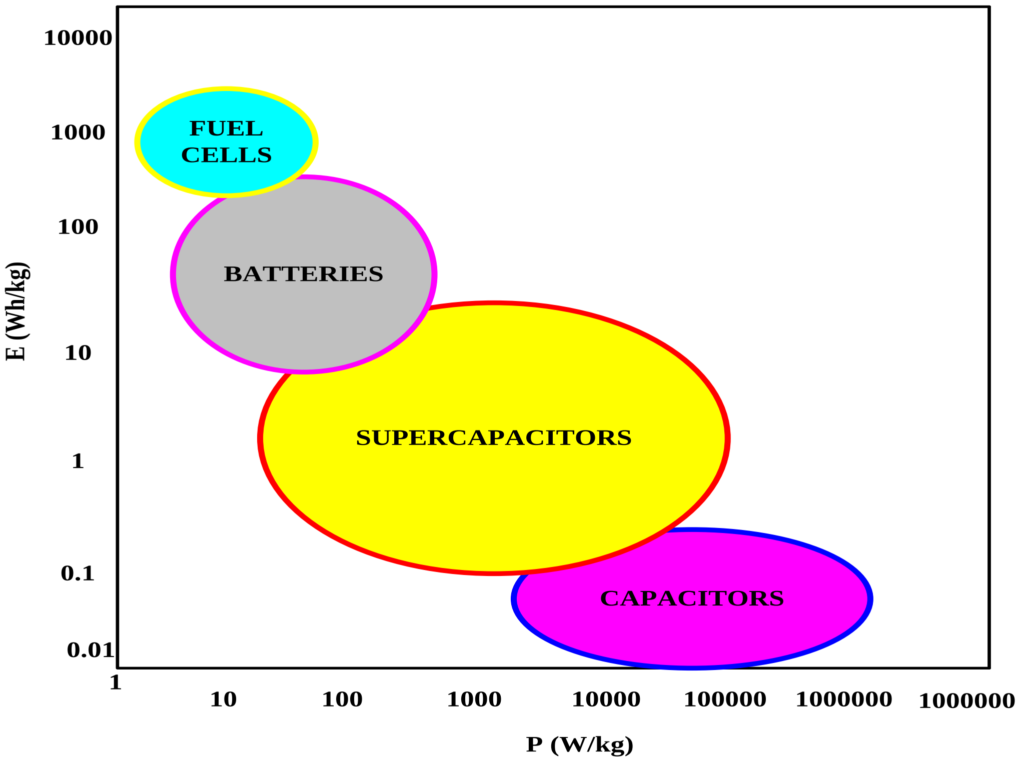

Figure 1. Ragone plot for energy storage devices.

Anode, cathode, separator, and electrolyte constitute SCs.The anode is the negative terminal and is associated with oxidative chemical reactions. The cathode, or positive electrode, is related to reductive chemical reactions. Electrolytes provide ionic conductivity between anode and cathode electrodes; a separator is generally a physical barrier between both electrodes. In the battery environment, separators must be permeable to ions and inert [17]. SCs are made up of two parallel electrodes separated by a separator. A separator is a conducting material impregnated with an electrolyte; ions present in the electrolyte are attached to the surface of the electrode after the voltage is applied. Due to charge accumulation and contact with the surface of the electrode, an electrostatic double layer (EDL) is formed. The EDL formation procedure is reversible and produces efficient charge-discharge processes (Figure 2). It results in high power in SCs. The high cyclic stability is due to the low degradation of materials [15].

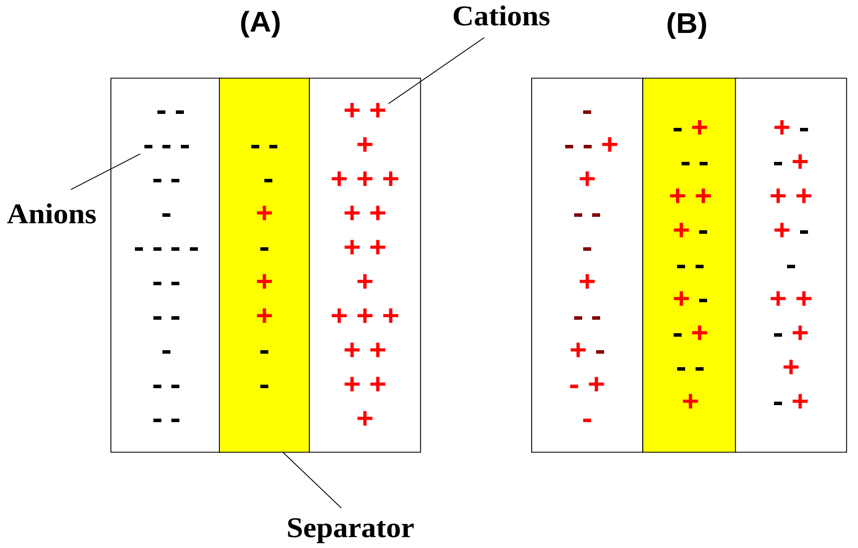

Figure 2. Charged and discharged SCs.

The main advantages of SCs are efficient charging rate, backup, power, high power density, good storage ability, long life cycle, environmentally feasible, etc. (Figure 3) [18-21]. In many applications, SCs are currently considered one of the biggest and most efficient energy storage devices, replacing batteries. They have been used in transportation, vehicles, and the military, aerospace, biomedical, and electronics industries [19,20]. Electrostatic double-layer capacitors, pseudocapacitors, and hybrid capacitors are the different types of SCs (Figure 3). Electrochemical double-layer capacitors (EDLC) are also known as ultracapacitors. They act similarly to conventional capacitors, and there is no faradaic process. Energy storage involves simple charge separation. An EDLC system is a form of energy storage based on electrostatic interactions between two carbon electrodes with a high specific area per volume. The electrodes are submerged in an electrolyte, and a separator is employed between them [15,22-24]. Pseudocapacitors, also known as faradaic SCs, differ from EDLCs in that they generate pseudocapacitance by quick and reversible faradaic processes or redox reactions. The flow of charge across the double layer is based on the faradaic current which passes through the supercapacitor cell. Pseudocapacitors have a low power density and lack cycling stability [25-27]. Hybrid SCs have a high capacitance as well as a high energy storage capacity. They have received a lot of attention because of their propensity to integrate their components' characteristics. The asymmetric behavior of hybrid SCs, which are a combination of an EDLC and a pseudocapacitor, functions as a capacitance booster [21] (Figure 4).

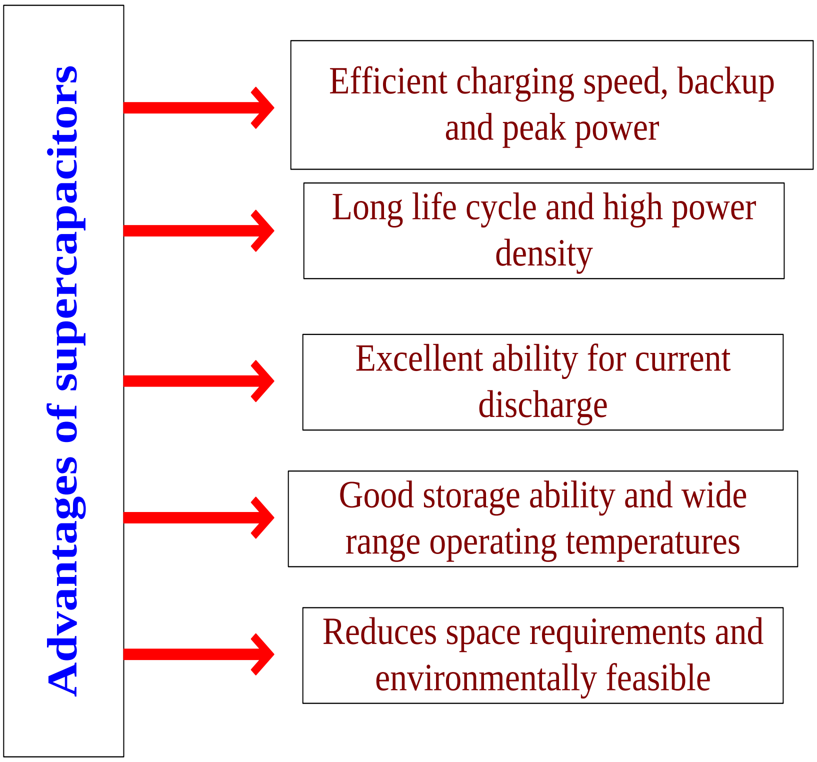

Figure 3. Main advantages of SCs.

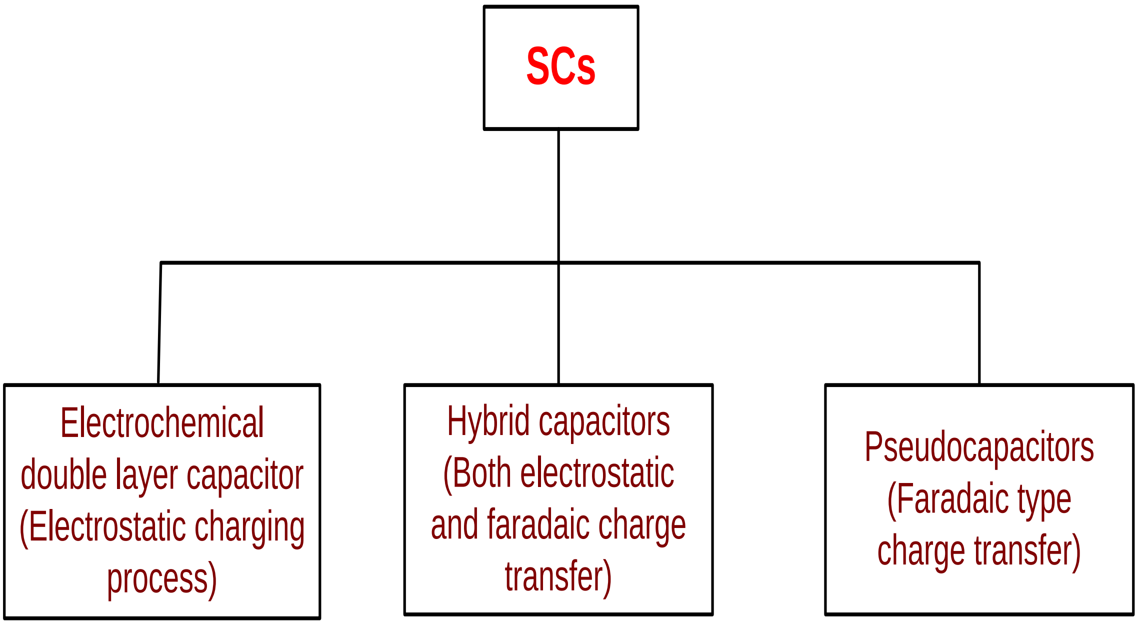

Figure 4. Classification of SCs.

3. Electrode Materials used in SCs

The supercapacitive performance is based on the selection of suitable electrode material. The electrode material should be thermally, chemically, and electrically stable. Such materials should have corrosion resistance, high electrical conductivity, and adequate surface wettability. Cost-effectiveness and environmental friendliness are also important considerations [28,29]. The device's capacitance is enhanced by a large surface area, proper pore size, pore size dispersion, and the presence of functional groups [30]. The electrode materials are classified into carbon materials, transition metal oxides (TMOs), CPs, and some nanocomposite-based materials (Figure 5) [30,31]. Carbon is one of nature's most abundant elements. Carbon-based materials are good choices for energy storage devices because of their excellent electrical conductivity, mechanical strength, high electron mobility, excellent stability, large surface area, and tunable properties. Graphene, carbon nanotubes, and activated carbon can satisfy this need [31].

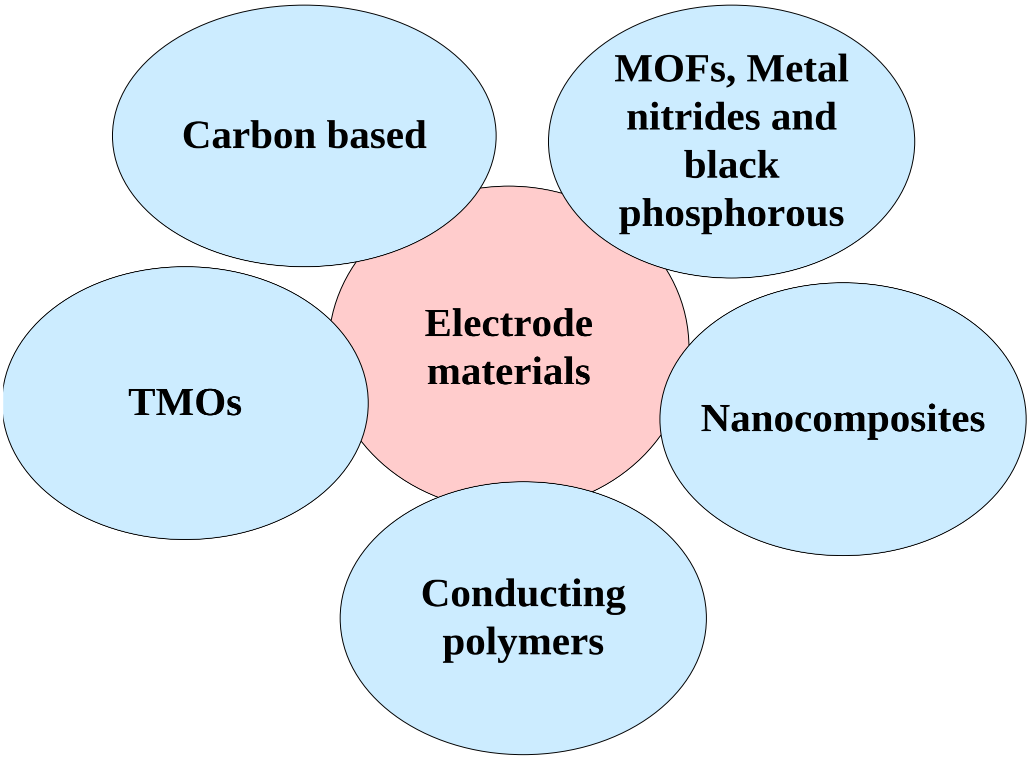

Figure 5. Some common electrode materials.

Some other carbon-based materials are carbon aerogel, carbon quantum dots, and doped materials [32]. Transition metal oxides have received much attention in the energy storage and conversion field due to their numerous valence state shifts for high pseudocapacitances [33]. Metal oxide materials' composition, production of innovative nanostructures, electro-conductivity, and oxygen vacancies have all improved the properties of metal oxides in terms of chemical stability, electrical conductivity, surface area, and electroactive sites, respectively [34]. Carbon nanotubes (CNTs) have generated much interest because of their fascinating and possibly valuable electrical, mechanical, and structural properties. When a graphite sheet is curled into cylinders, CNTs are generated, including single-walled CNTs (SWCNT) and multi-walled CNTs (MWCNT). CNTs show a large surface area, good stability, and low resistance. They have appeared to be perfect materials for polarizable electrodes based on these characteristics. SWCNTs and MWCNTs have both been explored as electrochemical supercapacitor electrodes because of their unique properties [35]. Because of their rapid and reversible oxidation and reduction processes, high electrical conductivity, and low cost, CPs are the second class of good candidates for redox pseudocapacitors. When compared to carbon-based electrode materials, CPs revealed increased capacitance, conductivity, and lower equivalent series resistance [25]. The nanocomposite-based materials of graphene, metal oxides, conducting materials, and others have also attracted great attention in storage devices, especially SCs [36,37]. Metal-organic frameworks, MXenes, black phosphorus, metal nitrides, and other materials are also important for electrode materials in SCs [38].

4. Electrochemical Aspects of SCs

The key supercapacitor specifications are determined via cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). In three or two-electrode configurations, an electrochemical workstation is used to measure critical parameters such as current, voltage, equivalent series resistance (ESR), and capacitance. The energy and power values can also be computed using mathematical equations based on the measurement findings [39].

4.1. Cyclic voltammetry (CV).

CV (cyclic voltammetry) is a potent and extensively used electrochemical tool for determining molecular species' reduction and oxidation processes. The investigation of chemical processes involving electron transfer is also assisted by CV. Cyclic voltammetry, like other types of voltammetry, employs a three-electrode system with a reference, counter electrode, and working electrodes. A potentiostat sweeps the potential between the working and reference electrodes linearly until something hits a specified limit, which is swept back the other way. CV has a wide range of applications for both inorganic and organic substances. It can also be used to assess other types of traits indirectly. During a scan, this process repeats numerous times, and the device measures the changing current between the working and counter probes in real time; the result is a cyclic voltammogram [40].

4.2. Galvanostatic charge-discharge (GCD).

The experimental "reverse" of cyclic voltammetry is galvanostatic cycling, in which the supercapacitor is charged and discharged at a constant current between two specified voltage points. This type of procedure is more practical. When the supercapacitor's main charging source is unplugged, the supercapacitor begins to lose charge due to the high internal resistance. This is known as the self-discharge trait. It is a voltage decrease in a charged capacitor following a period of no load [41].

4.3. Electrochemical impedance spectroscopy (EIS).

The preferred method for detecting the ESR of SCs is electrochemical impedance spectroscopy (EIS). EIS can also detect capacitance and non-ideality in capacitors. Electrochemical impedance spectroscopy (EIS) is one of the most powerful approaches for better understanding the physicochemical phenomena involved in SCs. Impedance spectroscopy has been utilized to examine the energy storage mechanism in SCs [42].

5. Conducting Polymer-based Nanocomposites

A polymer is a natural or manufactured substance made up of large molecules termed macromolecules that are multiples of smaller chemical units known as monomers. Polymers can be found naturally in plants and animals (natural polymers) or created artificially (synthetic polymers). Polymers contain a variety of physiochemical characteristics that permit them to be used in daily life. Polymers were regarded as insulators before the invention of CPs. However, such organic polymers may have special electrical and optical characteristics comparable to those of inorganic semiconductors. The electrical and optical characteristics of a conjugated carbon chain, which is made up of alternating single and double bonds, are caused by the highly delocalized, polarised, and electron-dense links. The common CPs are polyaniline (PANI), polythiophene (PTH), polypyrrole (PPy), polyfuran (PF), polyacetylene (PA), poly (phenylenevinylene) (PPV), etc. CPs have been used in various applications, including energy storage devices, EMI shielding, transistors, water remediation, coatings, biomedical devices, and sensors [5,42-44]. Figure 6 depicts several applications of CPs [5-8].

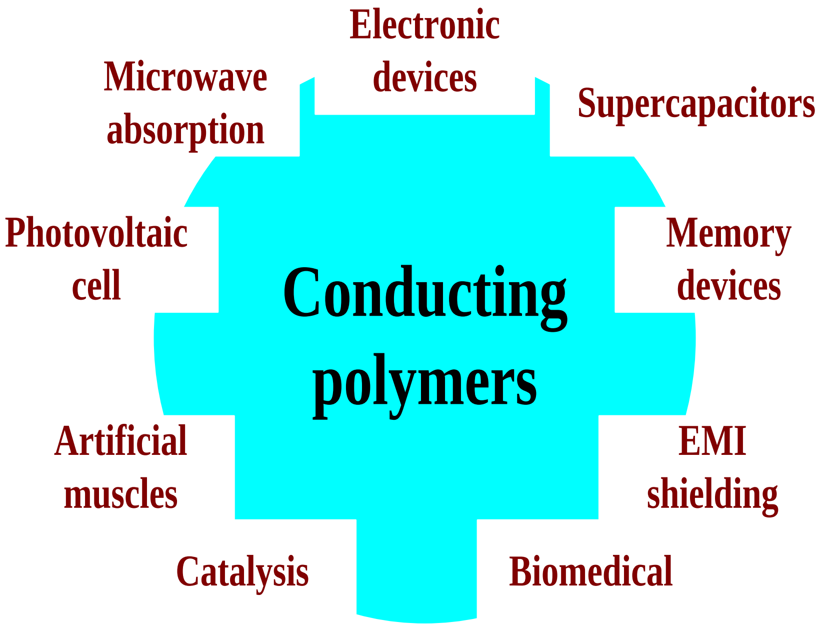

Figure 6. Different applications of CPs.

A nanocomposite material is heterogeneous in nature and made up of at least one nano-scale phase (nanofiller), which is dispersed into another phase (matrix). The structure-property relationship is directly influenced by the surface area ratio to reinforced material volume utilized during nanocomposite manufacture [4]. Nanocomposite materials provide unique mechanical properties, barrier qualities, weight reduction, and long-term performance in terms of wear, heat, and scratch resistance. However, conductive polymers may be more biocompatible than traditional metals or semi-conductive materials. Polymer-based nanocomposite materials have received great attention because of their utilization in many recognized fields. They have been used in adhesives, paints, artificial muscles, EMI shielding, conductive films, photovoltaics, energy storage devices, water purification, protective clothes, LEDs, sensors, anticorrosion, and electronic devices [45,46].

6. CPs-based Nanocomposites as Electrode Materials for SCs

CPs-based nanocomposite materials with inorganic metals, metal oxides, carbon, graphene, and others have been recognized as excellent electrode materials for SCs. These mixtures may be binary, ternary, and quaternary, respectively (Fig. 7).

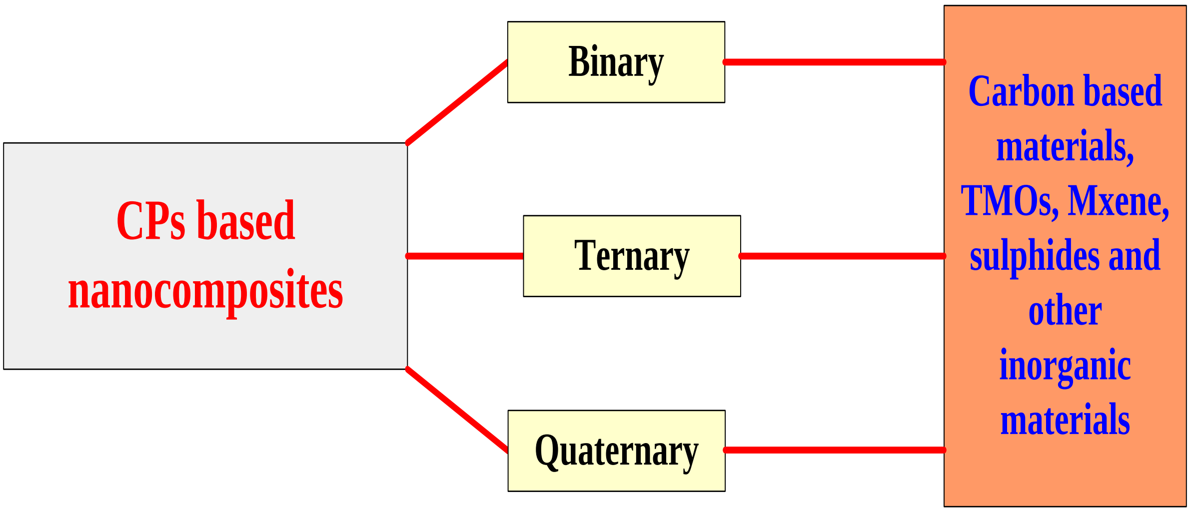

Figure 7. CPs-based nanocomposites for electrode materials of SCs.

6.1. Binary composites.

The general binary composites for applications as electrodes are synthesized by treating metal oxides, graphene, carbons, CNTs, and others with CPs [47-51]. The TMO-based pseudocapacitor exhibits high specific capacity, energy density, and an efficient charge-discharge process. These materials involve faradaic redox reactions at the interface between electrode and electrolyte and have excellent conductivity and high surface area [52]. Garrido *et al*. [53] have reported the suitability of TMOs for SCs under different voltage windows. TMOs show high thermal and chemical stability and ion exchange capability [54]. The major issue with CPs is their cyclic stability, which needs to be resolved. TMOs play an essential role in enhancing volume change, mechanical stability, and specific capacitance of the CPs [2]. The supercapacitive performances of CPs and TMO-based nanocomposite materials is shown in table 1.

Table 1. Supercapacitive performances of CPs-Metal based nanocomposites

Nanocomposite	Specific capacitance	Cyclic stability	Energy density	Power density	References
PANI/Fe_3O_4	242.9 F/g at 0.5 A/g	73 % after 1000 cycles	-	-	[54]
PPY/Fe_3O_4	290.2 F/g at 1 A/g	84 % after 5000 cycles	26.6 Wh/ kg	700 W/ kg	[55]
Poly(3,4-ethylenedioxythiophene) (PEDOT)/CuO	198.89 F/g at 5 mV/S	68.55 % after 500 cycles	-	-	[56]
PTh/MnO_2	290 F/g at 1 A/g	97.3 % after 1000 cycles	-	-	[57]
PPY/NiO	3468.6 F/g at 3 A/g	-	333.3 Wh/ kg	2399.99 W/kg	[58]
PANI/MnO_2	417F/g at 5 mV/s	94.3 % after 2000 cycles	7.2 Wh/kg	11.4 W/kg	[59]
PPY/MnO_2	141.6 F/g at 2 A/g	-	12.6 Wh/ kg	34 W/kg	[60]
RuO_2/PEDOT	1217 F/g at 5 mA cm^2	-	28 Wh/kg	20 kW/ kg	[61]
PANI/RuO_2	830 at 5 mV/s	85 % after 5000 cycles	216 Wh/ kg	4.16 kW/ kg	[62]
PTh/TiO_2	632 F/g at 2 A/g	89 % after 1000 cycles	237 Wh/kg	2100 W/ kg	[63]

Carbon materials have widely been used as supercapacitor electrodes due to their many advanced features, such as excellent conductivity, large surface area, compatibility, and environmental friendliness. Carbon materials can be combined with CPs to achieve excellent capacitive performance [46]. Graphene derivatives are very common electrode materials for SCs due to their high conductivity, surface area, and easy fabrication process. The introduction of graphene to CPs increases the rate of faradaic reaction and capacitive performance [64]. The conjugated structures oxidize to p-type CPs or reduce to form n-type CPs [65]. Graphene is synthesized through graphite microchemical breakage, hydrocarbon chemical vapor deposition, graphite dispersion in organic solvents, and epitaxial growth of silicon carbide. Graphene oxide (GO) and reduced graphene oxide (r-GO) are the oxidizing forms of graphene. Due to their increased water dispersion and the fact that they both have reactive oxygen groups, they appear to be more well-liked than pure graphene [66]. Because of the positive synergistic affection between CPs and graphene, binary composites with CPs and graphene have higher stability and electrical conductivity than individual components [67]. Table 2 shows the supercapacitive performances of some selected CPs-Graphene-based materials.

Table 2: Supercapacitive performances of CPs-Graphene nanocomposites.

Nanocomposite	Specific capacitance	Cyclic stability	Energy density	Power density	References
GO/PANI	1095 F/g at 1 A/g	-	24.3 Wh/ kg	28.1 kW/kg	[68]
GO/PPY	1532 mF/cm^2 at 0.88 mA/cm^2	90 % after 1000 cycles	70 µWh/ cm^2	500 µW/cm^2	[69]
r-GO/PEODT	471 F/g at 0.2 A/g	98.7 % after 20,000 cycles	48.18 Wh/ kg	1.4 kW/kg	[70]
PANI/r-GO	420 F/g at 0.2 A/g	80% after 6000 cycles	9.3 Wh/ kg	11.6 kW/kg	[71]
PPy/r-GO	9300 mF/cm^2 at 1 mA/cm^2	94.47% after 10,000 cycles	167 µWh/ cm^2	1.20 mW/cm^2	[72]
Reduced graphene oxide/poly(pyrrole-co-thiophene)	417 F/g at 0.81 A/g	65 % after 1000 cycles	86.4 Wh/kg	630 W/kg	[73]
r-GO/PPY	685 mF/cm^2 at 2 mA/cm^2	92.8 % after 5000 cycles	147 µWh/ cm^2	-	[74]

Activated carbon has also been extensively used as an electrode in SCs due to its simplicity in synthesis, excellent electrical conductivity, and low price. The less effective specific surface area of activated carbon is brought on by the existence of haphazardly linked micropores with a diameter of less than 2 nm. It makes them challenging for electrolyte ions to access. However, this limits these advantages [75]. Conventional chemical and physical activation methods, as well as a combination of these methods, template-based methods, porous materials made from carbides, and other techniques, have all been used to create porous carbon materials. To fully understand the capability of porous materials for supercapacitor applications, fundamental physical aspects, including pore size, electrical conductivity, specific surface area, shape, and distribution, are being carefully investigated. In industrial and scientific contexts, porous carbon compounds produced by pyrolysis are often used. Many fields, including supercapacitor research, have given carbon compounds produced from biomass a lot of attention [32]. Rawal *et al*. [76] studied the synthesis of an activated carbon/polyaniline (AC/PANI) composite and its performance as a supercapacitor electrode. The electrochemical analyses of the samples showed that the electrochemical performance of the AC/PANI composite has improved. The electrochemical activity of the AC/PANI-based nanocomposite has significantly increased despite a reduction in the specific surface area due to the synergistic interaction between the pseudocapacitance and double-layer capacitance. It was found that the highest specific capacitance was 1021 F/g, which was greater than PANI's (389 F/g) and AC's (253 F/g), respectively. Tian and others [77] have reported the supercapacitive performance of activated carbon/polyaniline (AC/PANI) and the influence of Ni after introducing it to AC/PANI and to form Ni/AC/PANI. The content of Ni in the composite was detected using atomic absorption spectroscopy. The final composite's specific capacitance was observed to be 535 F/g, and its cyclic stability increased by 32% as compared to AC/PANI. Jia *et al*. [78] studied the supercapacitive activity of N-doped mesoporous carbon in the electrolytic solution of H_2SO_4. At 0.2 A/g, a high capacitance of 396.5 F/g was observed. A capacitance retention of 95.9 % was observed after 2000 cycles. Inal *et al*. [79] have reported the specific capacitance of 228 F/g at 1.5 mA/cm^2 for the AC/PANI composite. The composite has been prepared after the polymerization of aniline and its incorporation into AC. The effect of polyaniline content in the composite was also studied to optimize supercapacitive behavior. Kong *et al*. [80] studied the effect of carbonized bacterial cellulose on the supercapacitive performance of PANI. The prepared CBC/PANI composite achieved a specific capacitance of 324.8 F/g at 1 A/g. The CBC/PANI showed long-life cycling, high-rate performance, and promising electrode material for SCs. The electrochemical performance of polypyrrole/activated carbon (PPY/AC)-based nanocomposites was investigated by Reis et al. [81]. The eggshell-based activated carbon incorporated material showed a capacitance of 172.5 mF/cm^2, an energy density of 4.73 Wh/kg, and power density of 320.8 W/kg, and 60 % retention after 1000 cycles. Bellow *et al*. [82] have described the synthesis of porous carbon materials for use in SCs applications using the polymerization as well as carbonization of pyrrole. The symmetric SCs devices fabricated from this carbon have also been analyzed in different electrolytes, such as 1 M $NaNO_3$, 6 M KOH, and 1 M Na_2SO_4, respectively. In terms of capacitive effectiveness, the 1 M Na_2SO_4 medium had a greater specific capacitance than the other two electrolytes (which had specific capacitances of 108 F/g in 6 M KOH and 94 F/g in 1 M $NaNO_3$).The distinctive characteristics of the three electrolytes, such as conductivity and different ion solvation sizes, are related to the variations in capacitance observed in each one. In SCs electrodes, carbon nanotubes (CNTs) and CPs have been suggested as composite materials. CNTs have a large surface area and stable double-layer capacitance. CNTs are also considered low-cost and efficient materials for electrochemical applications. They also have good cyclic stability and high electric conductivity [83]. Carbon atoms are structured in a sequence of condensed benzene rings to form tubular structures known as CNTs. On the basis of a number of layers, CNT structures are categorized into two parts: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). A single graphene cylinder with a diameter ranging from 0.4 to 2 nm makes up each SWCNT, which is the hexagonal close-packed bundle. A single sheet of graphene around a hollow core makes up each of the two to several coaxial cylinders that make up an MWCNT. MWCNTs range in size from 0.2 to several micrometers in length, with an outer diameter of 2 to 100 nm and an inner diameter of 1 to 3 nm [84]. Che and others [85] have reported the synthesis of CNTs and PANI-based composites (CNT/PANI) for electrochemical studies. The specific capacitance of 1266 A/g was found at 1 A/g. The cyclic stability was found to be 83 % after 10,000 cycles. The remarkable effectiveness of the composite material is demonstrated by its excellent electrochemical performance. Qureshi *et al*. [86] studied the electrochemical study of polythiophene/CNT (PTh/CNT); they focused on the feasibility of this type of composite for supercapacitor applications. Analysing the collected data, it can be said that the preferred choice that does have an impact on the supercapacitor's overall performance is the weight percentage of CNTs in the composite. Afzal and other workers [87] discussed the development of a polypyrrole/CNT (PPY/CNT) composite for the electrode material of SCs. The PPY/CNT was distinguished by its long cycle life, high charge-discharge, and high storage capability. The PPY/CNT offers high specific capacitance and improved energy density and stability. Canobre *et al*. [88] have reported the advantages of the PPY/CNT nanocomposite for SCs applications. The main advantages included ease of synthesis, cost-effectiveness, easy handling, and high electric conductivity. After 50 charge-discharge cycles, the specific capacitance was measured to be 530 F/g with 99.2 % retention. The incorporation of metal sulfides also improves the change in volume during repeated redox cycles and also increases the specific capacitance and mechanical stability of the CPs. These materials also enhance the energy density and cyclic stability of SCs [46,89,90].

Mesoporous, porous, and other 3D carbon materials have drawn a lot of attention as supercapacitor electrode materials attributable to their outstanding advantages, such as superior conductivity, a greater surface area, and excellent electrolyte accessibility. 3D carbon materials with organized pores will be able to achieve their maximal capacitance due to the precise alignment of hole diameters and electrolyte ion sizes [91-94]. Incorporating MXene into CPs is a hot topic for supercapacitor applications. On the basis of mass load, flexibility, excellent mechanical properties, and surface area, CPs/MXene composites have received a lot of attention to become highly efficient electrode materials [95-98]. Liang and Zhitomirsky [99] reported a polypyrrole/MXene (PPY/MXene) composite for supercapacitive performance. The application of a conceptually novel method for *in-situ* polymerization of PPY on the MXene surface is based on using an effective catecholate-type surfactant for electrostatic dispersion of MXene, which is one of the important elements for the improved negative electrode performance. The adsorbed dispersion stimulates PPY polymerization on the MXene surface by acting as an anionic dopant for PPY. The MXene/PPY nanocomposite demonstrated exceptional cycle stability, with an energy density of 21.61 Wh/kg and a power density of 499.9 W/kg.

6.2. Ternary and quaternary composites.

Nowadays, ternary and quaternary nanocomposites that combine three or four components from carbon nanomaterials, inorganic materials (metals, metal oxides, etc.), and CPs have attracted the interest of many researchers due to their superior performance compared to binary systems. In terms of electrochemistry, numerous components can compensate for individual deficiencies and enhance their overall performance. Quaternary composites of CPs with graphene are expected to have greater capacity and service life. Some synergistic effects were revealed when adopting a ternary structural design as the electrode material for EDLC. [46]. Dong [98] studied the synthesis, characterization, and electrochemical study of a MnO_2/MoS_2/PPY ternary composite. The ternary composite has performed as a pseudocapacitor; at a current density of 1 A/g, it was found that the specific capacitance was 490 F/g. The cyclic stability was found to be 90 % after 1000 cycles. Pan *et al*. [100] have incorporated PANI nanowires into Ag nanoparticles and MnO_2 nanoflakes to form the ternary composite Ag/PANI/MnO_2. Ag/PANI/MnO_2 has been utilized as an electrode material for SCs. At 0.1 A/g, a high specific capacitance of 518 F/g was found, and after 1600 cycles, the cyclic stability was 88.4%. Huang *et al*. [101] have synthesized MnO_2/PANI/MWCNTs through a facile chemical method. The MnO_2/PANI/MWCNTs were utilized for electrochemical behavior. A specific capacitance of 395 F/g at 1 A/g with 72% retention after 1000 cycles has been observed for the material. Table 3 lists some additional ternary composites.

Table 3. Supercapacitive performances of CPs-based ternary nanocomposites.

Nanocomposite	Specific capacitance	Cyclic stability	Energy density	Power density	References
CNT/PPY/MnO_2	325 F/g at 2 mV/s	90.2 after 500 cycles	-	-	[102]
PANI/PEDOT/AC	611 F/g at 1 A/g	90 % after 10000 cycles	2094 Wh/kg	2160 W/kg	[103]
PANI/PPY/AC	586 F/g at 1 A/g	92 % after 10000 cycles	40 Wh/kg	44 Wh/kg	[103]
GO/PANI/$CuCo_2O_4$	741.3 F/g at 1 mV/s	84.2 % after 5000 cycles	62.5 Wh/kg	5997.6 W/kg	[104]
RGO/PEDOT/PSS	367 F/g at 1 A/g	80% after 30,000 cycles	50.7 Wh/ kg	1014 W/kg	[105]
PANI/MnO_2/r-GO	762 F/g at 1.4 A/g	75% after 10000 cycles	-	-	[106]
SiO_2/Graphene/PANI	727 F/g at 20 mA/g	90% after 3500 cycles	2.6 Wh/kg	30.6 W/kg	[107]

Gottam and Srinivasan [108] have developed a highly efficient quaternary composite comprising mesoporous carbon (MC), PANI, MoO_3, and SiO_2 components. The synthesized MoO_3-MC-SiO_2-PANI has been utilized as an electrode material in a symmetric electrode configuration. After 250,000 charge-discharge cycles, a retention of 57% has been observed. The energy and power densities were found to be 31 Wh/Kg and 155 W/Kg, respectively. Golikand *et al*. [109] have also developed a quaternary composite made up of PANI, graphene nanosheets (GNS), CNT, and Pt nanoparticles. A remarkable specific capacity of 3450 C/g was found for PANI/GNS/CNT/Pt nanocomposites. The PANI/GNS/CNT/Pt showed a long-life cycle with 84.8% retention after 1000 cycles.

7. Current Studies

SCs are considered one of the most exciting energy storage systems for various commercial and defense applications. Conducting polymer nanocomposites are novel functional materials appropriate for SCs because of the synergistic effects of the various constituents. The previous industrial sector, which was based on using large amounts of fossil fuels, had a detrimental effect, as well as an energy crisis and serious environmental issues. Consequently, sustainable, eco-friendly, and regenerative new energy sources have been increasingly employed, and new energy storage technology has advanced quickly. Electrode materials are considered the main area of interest in supercapacitor research since they form the system's heart [110-112].

Table 4. Supercapacitive performances of currently used CPs-based nanocomposites (year 2022).

Nanocomposite	Maximum specific capacitance	Cyclic stability	Energy density	Power density	References
NiCoP/CNT/PPy	1686.3 F/g at 20 A/g	75% capacitance retained after 8000 cycles	34.8 Wh/kg	700 W/kg	[110]
$NiCo_2S_4$/PPy	2554.9 F/g at 2.54 A/g	>97 % after 10000 cycles	35.17 Wh/ kg	1472 W/kg	[113]

Nanocomposite	Maximum specific capacitance	Cyclic stability	Energy density	Power density	References
PANI/CNT/e-MoS_2	532 F/g at 1 A/g	83% after 1000 cycles	11.8 Wh/kg	3785 W/kg	[114]
PANI/PbS	625 F/g at 0.4 A/g	95.5 % after 5000 cycles	4.168 Wh/ kg	196.03 W/kg	[115]
MXene/PANI/MWCNTs	414 F/g at 1 A/ g	90.4% for 10 000 cycles	-	-	[116]
Carbon cloth/PANI/MnO_2	634 F/ g at 1 A/ g	83% after 4000 cycles	47.25 μWh/ cm^2	2.40 mW/ cm^2	[117]
Polypyrrole/Gum Arabic	368.5 F/g at 1 A/g	85 % after 1000 cycles	73.6 Wh/ kg	599.6 W/kg	[118]
polypyrrole/polydopamine	1920 mF/cm^2	100% capacitance after 10,000 cycles	-	-	[119]

Recently, efficient and compatible CPs-based composites have been introduced for electrode materials of SCs by different researchers, such as NiCoP/CNT/PPy, $NiCo_2S_4$/PPy, PANI/CNT/e-MoS_2, MXene/PANI/MWCNTs, Carbon cloth/PANI/MnO_2, and others [110-119]. The supercapacitive performances of these nanocomposite-based materials are illustrated in table 4.

8. Possibilities for the Future, Challenges, and Conclusions

Energy storage systems are becoming increasingly popular each day as a result of the increasing demand for electrical power for portable devices. SCs are regarded as the most promising and environmentally friendly energy storage devices. Since their inception, SCs have advanced significantly, and contemporary technology has unquestionably shown practical uses for traditional electrical architecture. They offer everything else, from backup power for mobile phones to battery life extensions for gadgets that sometimes require short bursts of power. The SCs batteries that can be used separately are very close. Researchers successfully developed an innovative supercapacitor battery that charges more efficiently and consumes less space than lithium-ion cells. Combining existing energy-storage technology with a double-layer charging interface represents the most potential future for SCs. SCs' retention capacity can be improved by modernizing manufacturing processes and technology. However, trying to find new electrode materials and electrolytes with improved electrochemical performance will be challenging and time-consuming in the long run. Nevertheless, SCs have the potential for advancement to be used as an eco-friendly and non-volatile energy storage source in the future. They allow additional downsizing possibilities without compromising the transfer rate and high energy storage capacity [118-123].

Researchers have recently focused on CPs-based nanocomposites for the electrode materials in SCs due to their remarkably improved electrochemical properties. Nanostructured CPs are easier to process than other conducting materials, making them more effective at creating dynamic interfaces inside the nanocomposites and enhancing their vital electrical functions. The morphology of CPs impacts how they work electrochemically; they have been used in various ways, such as nanosheets, nanopowder, and nanowalls. High porosity and high surface area, surface interactions, and specific conducting routes make them more functional in electrochemical fields. Redox materials based on CPs are transforming possibilities for flexible pseudocapacitors. The potential for novel, lightweight, low-cost, and very flexible devices in the future of CPs-based flexible energy storage devices is much higher. In light of recent efforts, it is still hard to formulate new approaches for developing novel nanocomposite materials based on CPs. The goal is to increase the efficiency of CPs-based composite materials in the fields of energy storage devices [49,123,124].

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Conflicts of Interest

The authors declare that they have no conflict of interest in the publication of this article.

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