

Conductive polymers as electrochemical investigation for enhanced supercapacitor performance: Review

M. Vanitha Sri^{1,2}, V. T. Jeielayaganga³, D. Sakthilatha¹

¹ Department of Chemistry, Kandaswami Kandar's College, P. Velur, Namakkal, Affiliated to Periyar University, Salem 636011, Tamil Nadu, India

² Department of Chemistry, Government Arts College for Women, Salem, Affiliated to Periyar University, Salem 636011, Tamil Nadu, India

³ Department of Physics, K.S. Rangasamy College of Arts and Science (Autonomous), Tiruchengode, Namakkal, Affiliated to Periyar University, Salem 636011, Tamil Nadu, India

Corresponding author: D. Sakthilatha (sakthichem@gmail.com)

Received 23 January 2025 ♦ Accepted 26 November 2025 ♦ Published 23 April 2026

Citation: Vanitha Sri M, Jeielayaganga VT, Sakthilatha D (2026) Conductive polymers as electrochemical investigation for enhanced supercapacitor performance: Review. *Modern Electronic Materials* 12(1): 53–61. <https://doi.org/10.3897/j.moem.12.1.147738>

Abstract

This review explores the role of conductive polymers in enhancing the performance of electrochemical supercapacitors, a promising solution for sustainable energy storage. Supercapacitors close the distance between batteries and conventional capacitors, providing quick charge-discharge cycles, a high energy density, and extended cycle life. The study delves into key types of supercapacitors, including electric double-layer capacitors, pseudocapacitors, and hybrid systems. Conductive polymers like polyaniline, polypyrrole, polythiophene, and poly (3,4-ethylene dioxathiophene) are emphasized for having exceptional electrochemical qualities, flexibility, and cost-effectiveness. However, these materials face challenges related to mechanical stability, cycle life, and ion transport efficiency. Future opportunities lie in developing hybrid materials, nanostructured designs, and scalable synthesis methods to enhance conductivity, stability, and storage capacity. This comprehensive review underscores the potential of conductive polymers in advancing next-generation energy storage technologies to meet growing global energy demands.

Keywords

polymer, electrochemical, electrode, cyclic stability

1. Introduction

Environmental degradation and energy scarcity are the two biggest threats to human sustainability. Efficient energy consumption and the search for clean, renewable energy sources are viable solutions to these issues; thus, there is a pressing need for low-cost, effective energy storage technologies, including the synthesis of novel materials and effective preparation techniques. Numerous useful and efficient devices that store energy, such as fuel cells, batteries, and electrochemical supercapacitors (SCs), have been studied as science and technology have advanced

[1]. The greater energy density of electrochemical capacitors has drawn a lot of interest in recent years. These advanced energy storage devices, also known as SCs, have gained recognition for their remarkable electrochemical properties. In addition, they have a longer cycle life and a better power density than conventional secondary batteries. Ultracapacitors are therefore widely used in a variety of industries, including automotive systems and portable electronics [2]. Furthermore, encouraged by the market need for wearable electronics as well as breakthroughs in nanomaterials and nanotechnologies, building highly flexible SCs with integrated functionality employing

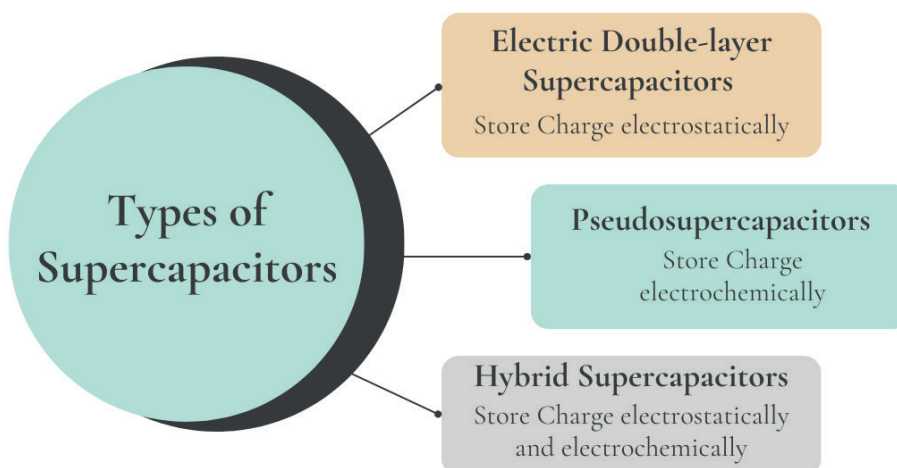


Figure 1. Types of supercapacitors

compliant materials becomes an overpowering trend [3]. The material used for the electrodes is crucial to the electrochemical performance of SCs, which are made up of an electrolyte, a separator, and two electrodes [4]. When voltage is given to a current collector, it attracts oppositely charged ions, and the ions from the electrolyte are collected on both surfaces of the current collector, resulting in the formation of the charge. Supercapacitors consist of current collectors (metal plates), electrodes, an electrolyte, and a separator. Supercapacitors have different structures compared to conventional capacitors and batteries. Activated carbon increases surface area, leading to higher capacitance values. Additionally, electrolytes with low internal resistance enhance power density. Supercapacitors can store and release energy fast because of these two qualities.

Conventional capacitors and SCs operate on similar underlying principles. However, they use electrodes with large surface areas and thin dielectrics to minimize electrode distances. Supercapacitors can achieve comparable power densities. They provide several advantages over fuel cells and electrochemical batteries, including faster charging, longer cycle and shelf life, and higher power density [5]. Supercapacitors have the potential to overcome the drawbacks of traditional energy storage technologies like lithium-ion batteries due to their high power density and energy density [6]. As a result of this, the majority of research focused on developing electrode materials with bigger or more ion-accessible surface areas aims to increase the energy storage capacity of SCs. However, obtaining a high energy density has been difficult [7]. Higher storage capacity, excellent power and energy densities, and superior cyclability are characteristics of the perfect electrical energy storage device. By operating at a greater specific power than most batteries and with the ability to reversibly store more energy than ordinary capacitors, electrochemical SCs fill the performance gap between standard batteries and capacitors. Supercapacitors also have a high energy density, operate in a broad temperature range, are environmentally

benign, and provide quick charging and discharging as well as a long cycle life [8].

2. Types of supercapacitors

Supercapacitors are classified according to their charge and discharge mechanisms: electric double-layer supercapacitors (EDLCs), pseudosupercapacitors (PSCs), and hybrid SCs [9] are shown in Fig. 1.

2.1. Electric double-layer supercapacitors

In terms of power and energy density, electrochemical double-layer capacitors (EDLCs), also known as supercapacitors or ultracapacitors, are fast energy delivery and storage devices that fall somewhere between batteries/fuel cells, which have a large energy storage capacity, and conventional dielectric capacitors, which offer a high power output. They can be utilized as supplementary or alternative power sources in several applications, such as electric hybrid cars, portable electronics, standby power systems, and telecommunications equipment [10]. As memory backup devices, EDLCs are used due to their long lifespans and high cycle efficiencies. The charge-discharge mechanism (electrosorption) in an electric double layer on porous electrodes serves as their foundation [11]. Ordered mesoporous carbons (OMCs), which have accelerated ionic mobility inside particles, have demonstrated high capacitance and exceptional rate capability as active materials in EDLC systems. Additionally, OMC electrodes have given researchers a platform to conduct fundamental and methodical investigations of electrochemistry, including the impact of electrode shape on ionic and electronic transports [12]. The electrolyte in an EDLC can be an aqueous or non-aqueous liquid or a solid substance such as a conducting polymer. The charged ions are organized in an array at the electrode surface following Helmholtz [13]. Helmholtz established the theoretical basis for the double-layer phenomena. It is utilized

in all electrochemical capacitors to store electrical energy. The word “double layer” was first used by Helmholtz in 1853 to refer to two layers of charge at the interface of two distinct metals. He contrasted the metal-to-metal contact and the metal-to-aqueous solution interface in 1879 [14]. The Helmholtz model is the most straightforward technique for estimating the spatial charge distribution at double-layer interfaces. Ions of opposite signs at a distance of d neutralize the charge of a solid electronic conductor. This idea offsets charges from the solid via stiff layers using a parallel plate capacitor model. According to the Gouy-Chapman or diffuse model, opposing ions concentrate in a liquid around a charged solid rather than being permanently affixed to its surface [15]. Charging and discharging are very reversible due to the non-faradaic electrical system. This allows for reliable cycling up to 10^6 cycles or more and rapid charging and discharging. Finally, there's little depletion. Since EDLCs require highly conductive electrodes, their primary drawback is the scarcity of electrode materials [16].

2.2. Pseudosupercapacitors

In 1941, David C. Grahame proposed the word “pseudocapacitance”, which was later used by Conway and Gileadi in the 1960s to describe electrochemically reversible capacitance not related to EDLCs [17]. Pseudocapacitors are asymmetric supercapacitors that use carbon cathodes and conducting polymers or metal oxides as anodes [18]. When a voltage is applied to the two electrodes of a supercapacitor, electrolyte ions travel to the oppositely charged electrodes, creating two layers at the point of interface. As a result of pseudocapacitor, the electrolyte's precisely adsorbed ions penetrate the double layer and transmit charge to the electrodes [19]. It uses redox active materials to store electrical charge and energy, unlike EDLCs. The majority of charge transfer and storage is handled by faradaic processes, whereas the EDLC only contributes a minor portion of the charge [20]. Polymer-based electrodes often have less cycle stability than carbon-based electrodes. When doped, polymers can enhance conductivity on the one hand, but they can alter volume, producing swelling and an increase in electrode thickness, which is a risk for any device [16]. Metal oxides (e.g. RuO_2 and MnO_2) and electrically conducting polymers (e.g. polyanilines, polypyrroles, and polythiophenes) are the most often utilized materials for pseudocapacitors [21].

2.3. Hybrid supercapacitors

Hybrid supercapacitors, also known as asymmetric supercapacitors, transcend the limitations of EDLCs and pseudocapacitors to give superior performance. Hybrid supercapacitors store energy using both pseudocapacitances (faradaic technique) and double-layer capacitances (non-faradaic approach) [22]. The study focuses on improving combinations to improve the efficiency of EDLCs while maintaining their extended cycle life. The

goal is to combine the power capabilities of traditional capacitors with the benefits of pseudocapacitors, lowering cost barriers and boosting certain performance metrics such as energy density, bringing them closer to battery performance. This strategy aims to bridge the gap between capacitors' quick charge/discharge capabilities and batteries' larger energy storage capacity [23]. As portable and wearable technology becomes increasingly prevalent, there is an increased need for multi-functional hybrid gadgets. Combining SCs with energy-collecting devices to form a hybrid device is an efficient way to harvest and store energy. To date, all self-charging hybrid SCs employing renewable energy sources such as mechanical, thermal, hydroelectric, solar, piezoelectric, and triboelectric have been thoroughly investigated [24].

3. Conducting polymers in supercapacitor

Polymers are either artificial or natural elements composed of huge molecules or macromolecules that are repeats of smaller chemical-building elements known as monomers [25]. Conducting polymers is often popular because of their high charge density and inexpensive cost (compared to the greater cost of metal oxides). One important disadvantage of these materials is that they produce very low power (or charge-discharge rates) due to the slow transition of ions inside the electrode's bulk [26]. Conductive polymers (CPs) such as polyaniline (PANI), polypyrrole (PPy), polythiophene (PTh), and poly 3,4-ethylene dioxythiophene (PEDOT) are considered prospective pseudo-capacitive materials because of their high specific capacitance and the characterization of multiple active sites [27]. Supercapacitor electrodes produced from these materials offer various advantages, including high conductivity, flexibility, cheap cost, and ease of production [28].

3.1. Polyaniline

Polyaniline, often known as black aniline, is produced by 1- and 4-coupling of aniline monomers in various oxidation states. Its structure is defined by changing benzenoid and quinonoid ratios, which are investigated using FT-IR spectroscopy, revealing its distinct electrochemical capabilities and usefulness for a wide range of applications [29]. Polyaniline is a highly conductive polymer commonly utilized as a cost-effective agent in electrochemical capacitors due to its changeable oxidation state, stoichiometric composition, ability to become strongly doped and de-doped, and assignment of the largest specific pseudo capacitance [30]. Polyaniline is a key polymer in advanced materials research due to its electron-rich structure, high electrical conductivity, and processing flexibility. Over the last decade, it has received attention for its varied qualities, which make it perfect for

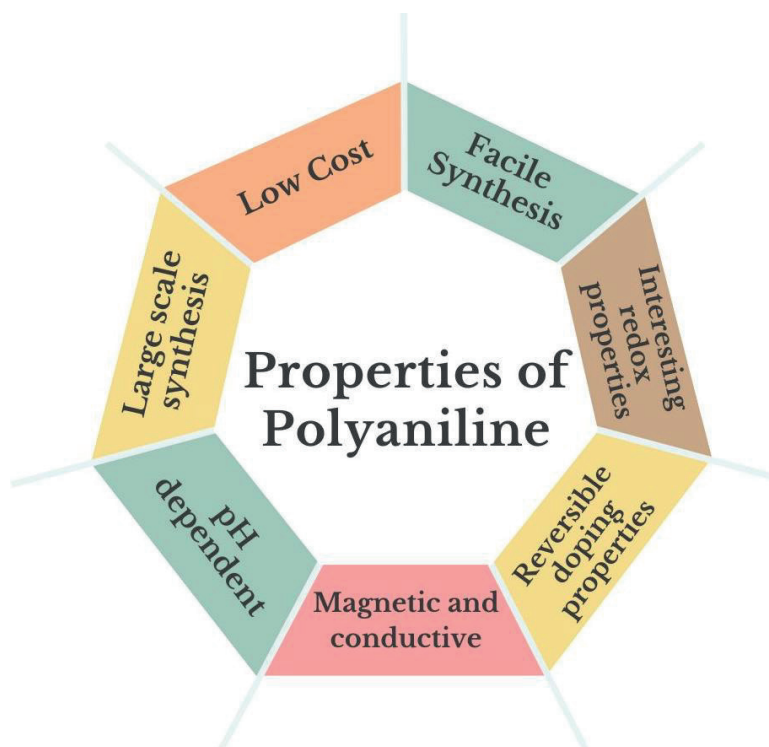


Figure 2. Properties of polyaniline

use in electronics, sensors, SCs, and other cutting-edge technologies [31]. Polyaniline is widely used in industrial and biomedical applications due to its easy synthesis, affordability, excellent electrical conductivity, biocompatibility, low toxicity, and environmental stability. However, it faces challenges such as low solubility in standard solvents, infusibility, poor processability, and a gradual decline in conductivity over time. To address these issues, various strategies have been developed, including redoping with functionalized organic acids, copolymerizing with PANI derivatives or other polymers, and creating blends or nanocomposites with other materials [32]. The properties of polyaniline are shown in Fig. 2 [33].

Polyaniline has been one of the most actively researched conductive polymers in recent years, owing to its ease of manufacture and great thermal stability. PANI can be produced using chemical polymerization by oxidation or electrochemical polymerization. Its characteristics vary depending on its synthesis methods and protonation

state. Polyaniline comes in two forms: reduced (leucoemeraldine) and oxidized (pernigraniline). Emeraldine base is the neutral form, which is half reduced and half oxidized. Emeraldine salt, a highly conductive polymer, is produced when proton-doped polyaniline is made with acids. Emeraldine salt is frequently produced via oxidative polymerization in acidic conditions (pH 1–3) using oxidants like potassium dichromate and ammonium persulfate (APS) [32]. Emeraldine is the most conductive kind of PANI. Because EB is semiconducting, it has a lesser conductivity than ES, which is metallic. When the emeraldine base is protonated to generate the emeraldine salt, a structural alteration occurs as a result of proton-induced spin unpairing. As a result, the band becomes half-filled, possibly leading to a metallic state in which each repeating unit has a positive charge owing to protonation, as well as an accompanying counter ion. The conductivity is also modified by the synthesis procedures and settings used. The conductivity of EB has been shown to increase with acid doping [34]. The chemical characteristics of PANI do not change with the dopant since it does not make any connection with the main polymer chain; nevertheless, the dopant just remains near the polymer chain to enable carrier activity [35]. The chemical specifications for polyaniline are mentioned in Table 1 [36].

Table 1. Chemical specifications for polyaniline

Chemical formula	$C_6H_5NH_2$
Specific density	1.02 g/cm ³
Molecular weight	93.13 h/Mol
PH value	8.8
The state in which the polymer is available	Liquid
Color	Light blue
Boiling temperature	184 °C

3.2. Polypyrrole

Heterocyclic organic conjugated polymers include PPy. Its monomer structure is a ring with five members. One atom is swapped out for a nitrogen atom in the five-membered conjugated carbon ring. The 1960s saw the first re-

ports of PPy. Pyrrole's nitrogen atom also had a role in this material's conjugation. It is an amorphous polymer with weak strength and solubility characteristics [37]. Due to its low cost and favorable electrical characteristics, PPy is the most often used naturally conducting polymer in energy producers (batteries and solar cells) and in other fields including sensors, actuators, and the biomedical industry [38]. A pyrrole monomer was first chemically oxidized with hydrogen peroxide to produce PPy, a black powdered material. Polypyrrole has insulating qualities when it is undoped and pure. Even though it is doped with halogenic electron acceptors such as iodine or bromine, its conductivity remains constant at 10^{-5} s/m. Bulk PPy possesses 15 % crystallinity, with the crystalline component in the monoclinic phase, despite being non-crystalline and amorphous. Electrochemically generated PPy is 1 μm thick and yellow-black. The polymer changes and becomes more stable in air and thermally stable up to 300 °C as the protonation concentration rises. However, the loss of impurity anions may result in heat deterioration [39]. The properties of PPy are shown in Fig. 3. [40]

Conductive polymers are an interesting family of materials distinguished by their ability to transmit electricity, which is uncommon among typical organic polymers. This conductivity is due to their unique molecular structure, the polymer backbone is made up of a conjugated structure of alternating single and double bonds. This conjugation delocalizes π -electrons, allowing charge carriers like electrons or holes to flow freely throughout the material.

Because of its potential for broad and creative applications, this distinct trait has caught the interest of researchers and scientists from a variety of fields, including academia and industry. Polypyrrole is a particularly remarkable conducting polymer. Its broad usage in a variety of applications is because of its high electrical conductivity, environmental stability, and simplicity of synthesis. PPy has found applications in the production of electrical devices like as transistors and diodes, as well as the development of sophisticated sensors capable of detecting chemical or biological molecules with great sensitivity.

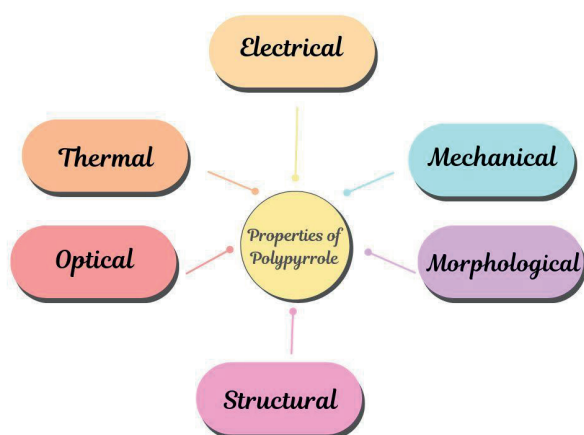


Figure 3. Properties of polypyrrole

It is also used in batteries as a conductive material for energy storage, as well as microactuators, which use electrical energy to generate mechanical motion on a small size. PPy is also utilized in antielectrostatic coatings, which minimize static electricity accumulation, and in biomedical applications, including as drug delivery systems and bioactive scaffolds for tissue engineering. PPy may be manufactured utilizing a variety of processes, the most frequent being the polymerization of its monomer, pyrrole. This process can take place by electrochemical oxidation, in which an electric current drives the polymerization reaction, or through chemical oxidation, in which chemical oxidants are used to start and promote the reaction. These methods can be carried out in a range of solvents, including organic solvents and aqueous media, offering versatility in tailoring the properties of the resulting polymer for specific applications. This versatility and PPy's intrinsic features confirm its position as a critical material in advancing basic research and commercial applications [41].

3.3. Polythiophene

Polythiophenes are polymers of sulfur heterocycles. Polythiophenes has the formula $(\text{C}_4\text{H}_2\text{S})_n$ and is solid in color and insoluble. The rings are connected at locations 2 and 5. The alkyl substituents in positions 3 and 4 are composed of poly(alkyl thiophene)(s). These are likewise colorful solids, but they dissolve in organic solvents [42]. Polythiophene shares some structural similarities with PPy. The main distinction is that PTh has a sulfur-substituted group, whereas PPy contains NH. Polythiophene is a low-bandgap semiconductor material. Polythiophene has excellent electrical conductivity, thermal consistency, environmental stability, and processability. Furthermore, the transparency of PTh has resulted in unexpected optical properties, such as photoluminescence. Polythiophene is an intrinsic conducting polymer, featuring conjugated double bonds in the middle [43]. Researchers and industry are very interested in PTh polymer because of its excellent environmental stability, low band gap energy, and better thermal stability. Additionally, the PTh composites attracted a lot of interest due to their fascinating characteristics, which comprised electrical, semiconducting, and optical activity, in addition to their exceptional mechanical properties and processing simplicity. Due to their enhanced interaction with metal electrodes and environmental resilience, they are frequently used in solar cells. Combining the two allowed for the creation of a unique hybrid variety with enhanced electrical characteristics since n-type semiconducting particles are more efficient at transporting holes than PTh matrix. The transparency of PTh also provides notable optical properties [44]. It has been shown that the structure of the thiophene molecules affects the band gap and optical characteristics of completely conjugated cyclo[n]thiophenes, which have been investigated both experimentally and theoretically. Furthermore, it is anticipated that electronic mem-

ory devices will make use of PTh and its derivatives. For the past two decades, these materials have been the primary emphasis. In this class of materials, it is simple to inject electrons from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO) [45]. The polymerization process is complicated by the inert sulfur present in the thiophene ring, which has a high oxidation potential. PTh has typically been created using three methods: chemical oxidative polymerization, metal-catalyzed coupling reaction, and electropolymerization. Nevertheless, there are benefits to chemical oxidative polymerization over other techniques, such as the ability to choose different monomers and an appropriate catalyst that promotes high yield, simplicity of synthesis, and optimal electrical conductivity. The characteristics of the materials in chemical oxidative synthesis are determined by the type of dopant anion and the reaction circumstances. High electrical conductivity for PTh with iodine vapor postdoping was observed in several experiments [46]. The role of PTh in various fields is shown in Fig. 4.

3.4. Poly 3,4-ethylene dioxithiophene

For SC electrodes, poly(3,4-ethylenedioxythiophene) (PEDOT) is a very appealing conducting polymer because of its superior electrical conductivity, stability, and electrochemical performance. PEDOT is perfect for advanced energy applications because it works in concert with other conductive materials like graphene or carbon nanotubes to improve energy storage capacity, charge transfer efficiency, and overall electrode durability [47]. Poly(3,4-ethylenedioxythiophene) undergoes oxidative polymerization using an electrochemical current or suitable oxidants (chemically). Of the several possible morphologies of nanostructures, the anisotropic transport and

optical characteristics of fibers and tubes have drawn special attention. Using a porous alumina substrate, PEDOT nanowires and nanotubes were created using electrochemical polymerization [48]. Poly (3,4-ethylene dioxithiophene) has higher cycle stability than typical π -conjugated polymers such as polyaniline and polypyrrole due to its lower structural flaws. The ethylenedioxy group replaces the two β H atoms in 3,4-ethylene dioxithiophene (EDOT), allowing polymerization to occur exclusively at the α -site. Unfortunately, PEDOT's high relative molecular weight yields a low theoretical specific capacitance. Furthermore, the agglomeration of synthesized PEDOT due to the poor solubility of EDOT monomer in the polymerization system utilizing water as a solvent causes a significantly lower observed specific capacitance than the predicted specific capacitance [49]. PEDOT is a polymer that is insoluble in water. By doping polystyrene sulfonate, a water-soluble polyelectrolyte, during the polymerization of PEDOT and creating the conjugated polymer PEDOT/PSS, the solubility issue of PEDOT was resolved [42]. In order to create a hydrophilic polyelectrolyte system that can form films, PEDOT polymers are usually *p*-doped. Sodium polystyrene sulfonate, a typical doping agent, acts as a charge-balancing counter-ion to PEDOT for polymerization. The *p*-doped PEDOT/PSS improves conductivity and thermal stability while increasing PEDOT dispersion in aqueous solution. PEDOT's great cytocompatibility and high charge delivery capability make it a potential material for tissue regeneration [50]. Because of their electrochemical characteristics, conductive polymers are widely used in applications such as drug delivery systems, electrochemical transistors, actuators, electrochromic devices, and smart membranes. Nevertheless, little is known about the basic physical and chemical processes that underlie the doping and dedoping procedures, which modify conduc-

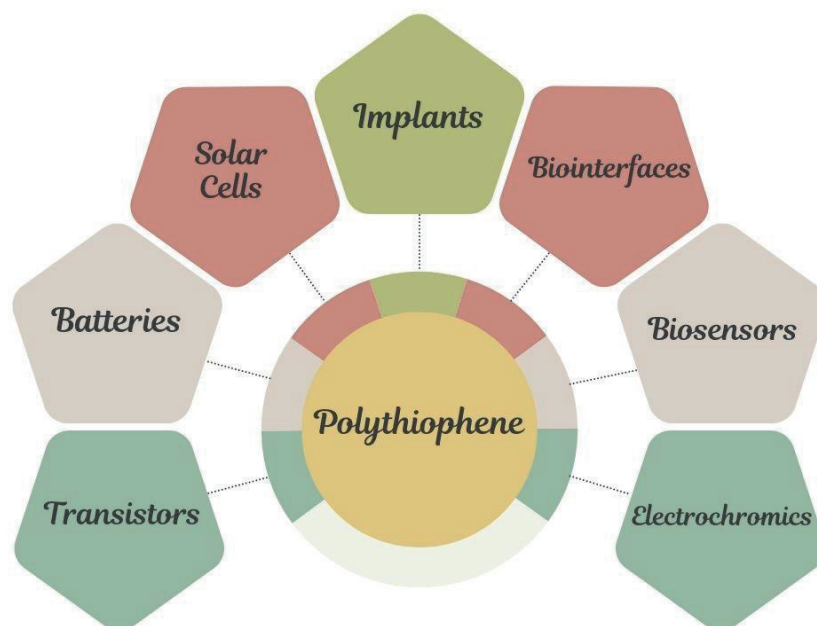


Figure 4. Role of polythiophene

tivity by adding or removing charge carriers. To maximize the functionality and dependability of conductive polymer-based devices and increase their potential uses in cutting-edge technologies, it is imperative to clarify these intricate processes [51].

4. Future opportunities and limitations

Because of their excellent electrical conductivity, environmental reliability, and ease of functionalization, conductive polymers have enormous potential for improving SC performance. In order to achieve better energy storage capacity, cycling stability, and charge-discharge rates, future opportunities will be found in creating innovative polymer composites and hybrid materials that combine the qualities of conductive polymers with those of other nanostructured materials, examples include metal oxides and carbon-based compounds. Their use in commercial SC technologies may be accelerated by developments in scalable and economical synthesis methods, including as 3D printing and green chemistry strategies. Furthermore, problems like limited mechanical stability and decreased electrochemical efficiency during extended usage can be addressed by investigating polymers with programmable redox activity and customizing their nanostructures. Although these possibilities, there are still difficulties in comprehending and managing the mechanisms behind charge storage, doping-dedoping, and degradation routes in conductive polymers. Even while their inherent conductivity is excellent, it frequently falls short of that of conventional electrode materials, requiring further tuning. To guarantee sustainable adoption, concerns like scalability, material prices, and the effects on the environment during manufacture and disposal must also be addressed. Conductive polymers can make a substantial contribution to next-generation energy storage technologies that effectively and sustainably fulfill the world's energy demands by overcoming these constraints through interdisciplinary research and development.

5. Conclusion

Due to their special blend of high electrical conductivity, chemical adaptability, and environmental durability, conductive polymers have become viable materials for improving the efficiency of supercapacitors. These substances, which involve polypyrrole, polyaniline, poly-

thiophene, and poly(3,4-ethylenedioxythiophene), have outstanding electrochemical characteristics, including rapid charge-discharge cycles, high capacitance, and effective charge storage. Conductive polymers are excellent choices for supercapacitor electrodes because they provide effective charge transfer and storage processes by utilizing their conjugated molecular architectures. Additionally, the creation of hybrid systems with synergistic performance gains is made possible by their customizable chemical characteristics and compatibility with a variety of nanostructured materials, including metal oxides and carbon-based materials. However, issues including poor long-term performance brought on by volumetric changes during doping and dedoping, limited cycle stability, and mechanical deterioration continue to be significant obstacles. To solve these problems, efforts are being made to integrate conductive polymers with durable materials, develop novel structural designs, and employ advanced synthesis processes. All things considered, the adaptability and promise of conductive polymers in supercapacitor technology underscore their important contribution to the creation of next-generation energy storage systems, helping to meet the rising demand for scalable, sustainable, and high-performance energy solutions.

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

The authors confirm contribution to the paper as follows: Study conception, design, draft manuscript preparation, Guidance, analysis and interpretation of results: M. Vanitha Sri.; Analysis and interpretation of results: V.T. Jeielayaganga; Data collection, analysis and interpretation of results: D. Sakthilatha; All authors reviewed the results and approved the final version of the manuscript.

Data availability

Not applicable.

Funding

No funding was received to assist with the preparation of this manuscript.

Reference

1. Meng Q., Cai K., Chen Y., Chen L. Research progress on conducting polymer based supercapacitor electrode materials. *Nano Energy*. 2017; 36: 268–285. <https://doi.org/10.1016/j.nanoen.2017.04.040>
2. Su D.Y., Liu Z.G., Jiang L., Hao J., Zhang Z.J., Ma J. Conducting polymers in supercapacitor application. *IOP Conference Series*

- Earth and Environmental Science*. 2019; 267(4): 042048. <https://doi.org/10.1088/1755-1315/267/4/042048>
3. Wang Z., Zhu M., Pei Z., Xue Q., Li H., Huang Y., Zhi C., Polymers for supercapacitors: Boosting the development of the flexible and wearable energy storage. *Materials Science and Engineering R: Reports*. 2020; 139: 100520. <https://doi.org/10.1016/j.mser.2019.100520>
 4. Xu Z., Zhang Z., Yin H., Hou S., Lin H., Zhou J., Zhuo S. Investigation on the role of different conductive polymers in supercapacitors based on a zinc sulfide/reduced graphene oxide/conductive polymer ternary composite electrode. *RSC Advances*. 2020; 10: 3122–3129. <https://doi.org/10.1039/C9RA07842H>
 5. Jalal N.I., Ibrahim R.I., Oudah M.K. A review on supercapacitors: types and components. *Journal of Physics: Conference Series*. 2021; 1973(1): 012015. <https://doi.org/10.1088/1742-6596/1973/1/012015>
 6. Rahman Md.M., Joy P.M., Uddin Md.N., Bin Mukhlis M.Z., Khan M.M.R. Improvement of capacitive performance of polyaniline based hybrid supercapacitor. *Heliyon*. 2021; 7(7): e07407. <https://doi.org/10.1016/j.heliyon.2021.e07407>
 7. Kim H.J., Lee S.-Y., Sinh L.H., Yeo C.S., Son Y.R., Cho K.R., Song Y., Ju S., Shin M.K., Park S.-J., Park S. Maximizing volumetric energy density of all-graphene-oxide-supercapacitors and their potential applications for energy harvest. *Journal of Power Sources*. 2017; 346: 113–119. <https://doi.org/10.1016/j.jpowsour.2017.02.040>
 8. Afzal A., Abulilwi F.A., Habib A., Awais M., Waje S.B., Atieh M.A. Polypyrrole/carbon nanotube supercapacitors: Technological advances and challenges. *Journal of Power Sources*. 2017; 352: 174–186. <https://doi.org/10.1016/j.jpowsour.2017.03.128>
 9. Shokry A., Karim M., Khalil M., Ebrahim S., El Nady J. Supercapacitor based on polymeric binary composite of polythiophene and single-walled carbon nanotubes. *Scientific Reports*. 2022; 12: 11278. <https://doi.org/10.1038/s41598-022-15477-z>
 10. Lei C., Markoulidis F., Ashtaka Z., Lekakou C. Reduction of porous carbon/Al contact resistance for an electric double-layer capacitor (EDLC). *Electrochimica Acta*. 2013; 92: 183–187. <https://doi.org/10.1016/j.electacta.2012.12.092>
 11. Shiraishi S. Electric double layer capacitors. In: *Carbon alloys*. Elsevier; 2003. P. 447–457. <https://doi.org/10.1016/B978-008044163-4/50027-9>
 12. Lim E., Jo C., Lee J. A mini review of designed mesoporous materials for energy-storage applications: from electric double-layer capacitors to hybrid supercapacitors. *Nanoscale*. 2016; 8: 7827–7833. <https://doi.org/10.1039/C6NR00796A>
 13. Staaf L.G.H., Lundgren P., Enoksson P. Present and future supercapacitor carbon electrode materials for improved energy storage used in intelligent wireless sensor systems. *Nano Energy*. 2014; 9: 128–141. <https://doi.org/10.1016/j.nanoen.2014.06.028>
 14. Afif A., Rahman S.M., Tasfiah Azad A., Zaini J., Islan M.A., Azad A.K. Advanced materials and technologies for hybrid supercapacitors for energy storage – A review. *Journal of Energy Storage*. 2019; 25: 100852. <https://doi.org/10.1016/j.est.2019.100852>
 15. Goikolea E., Mysyk R. Nanotechnology in electrochemical capacitors. In: *Emerging nanotechnologies in rechargeable energy storage systems*. Elsevier; 2017. P. 131–169. <https://doi.org/10.1016/B978-0-323-42977-1.00004-2>
 16. Najib S., Erdem E. Current progress achieved in novel materials for supercapacitor electrodes: Mini review. *Nanoscale Advances*. 2019; 1(8): 2817–2827. <https://doi.org/10.1039/C9NA00345B>
 17. Panchu S.J., Raju K., Swart H.C. Emerging two-dimensional intercalation pseudocapacitive electrodes for supercapacitors. *ChemElectroChem*. 2024; 11(15): e202300810. <https://doi.org/10.1002/celec.202300810>
 18. Pottathara Y.B., Tiyyagura H.R., Ahmad Z., Sadasivuni K.K. Graphene based aerogels: fundamentals and applications as supercapacitors. *Journal of Energy Storage*. 2020; 30: 101549. <https://doi.org/10.1016/j.est.2020.101549>
 19. Choudhary R.B., Ansari S., Purty B. Robust electrochemical performance of polypyrrole (PPy) and polyindole (PIn) based hybrid electrode materials for supercapacitor application: A review. *Journal of Energy Storage*. 2020; 29: 101302. <https://doi.org/10.1016/j.est.2020.101302>
 20. Sarno M. Nanotechnology in energy storage: the supercapacitors. In: *Studies in surface science and catalysis*; 2020. Vol. 179. P. 431–458. <https://doi.org/10.1016/B978-0-444-64337-7.00022-7>
 21. Zhou L., Li C., Liu X., Zhu Y., Wu Y., van Ree T. Metal oxides in supercapacitors. In: *Metal oxides in energy technologies*. Elsevier; 2018. P. 169–203. <https://doi.org/10.1016/B978-0-12-811167-3.00007-9>
 22. Engineered nanomaterials for energy applications. In: *Handbook of nanomaterials for industrial applications*. Elsevier; 2018. P. 751–767. <https://doi.org/10.1016/B978-0-12-813351-4.00043-2>
 23. Shaikh S.F., Ubaidullah M., Mane R.S., Al-Enizi A.M. Types, synthesis methods and applications of ferrites. In: *Spinel ferrite nanostructures for energy storage devices*. Elsevier; 2020. P. 51–82. <https://doi.org/10.1016/B978-0-12-819237-5.00004-3>
 24. Gao D., Luo Z., Liu C., Fan S. A survey of hybrid energy devices based on supercapacitors. *Green Energy & Environment*. 2023; 8(4): 972–988. <https://doi.org/10.1016/j.gee.2022.02.002>
 25. Tadesse M.G., Ahmmed A.S., Lübben J.F. Review on conductive polymer composites for supercapacitor applications. *Journal of Composites Science*. 2024; 8(2): 53. <https://doi.org/10.3390/jcs8020053>
 26. Snook G.A., Kao P., Best A.S. Conducting-polymer-based supercapacitor devices and electrodes. *Journal of Power Sources*. 2011; 196(1): 1–12. <https://doi.org/10.1016/j.jpowsour.2010.06.084>
 27. Xu Z., Zhang Z., Yin H., Hou S., Lin H., Zhou J., Zhuo S. Investigation on the role of different conductive polymers in supercapacitors based on a zinc sulfide/reduced graphene oxide/conductive polymer ternary composite electrode. *RSC Advances*. 2020; 10: 3122–3129. <https://doi.org/10.1039/C9RA07842H>
 28. Meng Q., Cai K., Chen Y., Chen L. Research progress on conducting polymer based supercapacitor electrode materials. *Nano Energy*. 2017; 36: 268–285. <https://doi.org/10.1016/j.nanoen.2017.04.040>
 29. Beygisangchin M., Baghdadi H.A., Kamarudin K.S., Rashid A.S., Jakmunee J., Shaari N. Recent progress in polyaniline and its composites; Synthesis, properties, and applications. *European Polymer Journal*. 2024; 210: 112948. <https://doi.org/10.1016/j.eurpolymj.2024.112948>
 30. Khan J., Khan A., Rubab B., Jamshaid F., Al-Kahtani A.A., Dahshan A. Exploring the progression of energy storage toward flexibility: Metal-organic framework and conducting polymer aspects. *Applied Materials Today*. 2023; 34: 101906. <https://doi.org/10.1016/j.apmt.2023.101906>
 31. Majeed A.H., Mohammed L.A., Hammoodi O.G., Sehgal S., Alheety M.A., Saxena K.K., Dadoosh S.A., Mohammed I.K., Jasim M.M., Salmaan N.U. A review on polyaniline: synthesis, properties, nano-

- composites, and electrochemical applications. *International Journal of Polymer Science*. 2022; 2022(5): 9047554(1–19). <https://doi.org/10.1155/2022/9047554>
32. Zare E.N., Makvandi P., Ashtari B., Rossi F., Motahari A., Perale G. Progress in conductive polyaniline-based nanocomposites for biomedical applications: A review. *Journal of Medicinal Chemistry*. 2020; 63(1): 1–22. <https://doi.org/10.1021/acs.jmedchem.9b00803>
 33. Giri H., Dowell T.J., Almtiri M., Scott C.N. Polyaniline derivatives and their applications. In: Năstase F. (ed.). *Trends and developments in modern applications of polyaniline*. IntechOpen; 2023. <https://doi.org/10.5772/intechopen.1001940>
 34. Yadav A.K., Mohammad N., Chamanehpour E., Mishra Y.K., Khanna P.K. Polyaniline (PANI) nanocomposites with Se, Te and their metal chalcogenides: A review. *RSC Applied Polymers*. 2024;2:775–794. <https://doi.org/10.1039/D4LP00093E>
 35. Sharma N., Singh A., Kumar N., Tiwari A., Lal M., Arya S. A review on polyaniline and its composites: from synthesis to properties and progressive applications. *Journal of Materials Science*. 2024; 59: 6206–6244. <https://doi.org/10.1007/s10853-024-09562-z>
 36. Mansoor R.D., Rasheed L.M. A study on the conductivity of polyaniline polymers. *IOP Conference Series: Materials Science and Engineering*. 2019; 571: 012087. <https://doi.org/10.1088/1757-899X/571/1/012087>
 37. Kausar A. Perspectives on nanocomposite with polypyrrole and nanoparticles. In: *Conducting polymer-based nanocomposites*. Elsevier; 2021. P. 103–128. <https://doi.org/10.1016/B978-0-12-822463-2.00006-3>
 38. Zare E.N., Agarwal T., Zarepour A., Pinelli F., Zarrabi A., Rossi F., Ashrafizadeh M., Maleki A., Shahbazi M.-A., Maiti T.K., Varma R.S., Tay F.R., Hamblin M.R., Mattoli V., Makvandi P. Electroconductive multi-functional polypyrrole composites for biomedical applications. *Applied Materials Today*. 2021; 24: 101117. <https://doi.org/10.1016/j.apmt.2021.101117>
 39. Mahmood J., Arsalani N., Naghash-Hamed S., Hanif Z., Geckeler K.E. Preparation and characterization of hybrid polypyrrole nanoparticles as a conducting polymer with controllable size. *Scientific Reports*. 2024; 14: 11653. <https://doi.org/10.1038/s41598-024-61587-1>
 40. Singh N. Polypyrrole-based emerging and futuristic hybrid nanocomposites. *Polymer Bulletin*. 2022; 79: 6929–7007. <https://doi.org/10.1007/s00289-021-03840-5>
 41. Yussuf A., Al-Saleh M., Al-Enezi S., Abraham G. Synthesis and characterization of conductive polypyrrole: the influence of the oxidants and monomer on the electrical, thermal, and morphological properties. *International Journal of Polymer Science*. 2018; 2018(22): 1–8. <https://doi.org/10.1155/2018/4191747>
 42. Parmar V., Solanki N., Patel G. Conductive hydrogels for tissue engineering applications. In: *Hydrogels for tissue engineering and regenerative medicine*. Elsevier; 2024. P. 249–264. <https://doi.org/10.1016/B978-0-12-823948-3.00022-1>
 43. Kausar A. Emerging hybrids derived from polythiophene and grapheme. In: *Conducting polymer-based nanocomposites*. Elsevier; 2021. P. 129–156. <https://doi.org/10.1016/B978-0-12-822463-2.00002-6>
 44. Singh S.K., Shukla R., Dixit C. Synthesis of polythiophene and their application. *International Journal of Physics and Mathematics*. 2022; 4(1 Pt A): 76–79. <https://doi.org/10.33545/26648636.2022.v4.i1a.66>
 45. Kaloni T.P., Schreckenbach G., Freund M.S. Band gap modulation in polythiophene and polypyrrole-based systems. *Scientific Reports*. 2016;6:36554. <https://doi.org/10.1038/srep36554>
 46. Thanasamy D., Jesuraj D., Konda kannan S.K., Avadhanam V. A novel route to synthesis polythiophene with great yield and high electrical conductivity without post doping process. *Polymer*. 2019; 175: 32–40. <https://doi.org/10.1016/j.polymer.2019.03.042>
 47. Bashir S., Hasan K., Hina M., Ali Soomro R., Mujtaba M.A., Ramesh S., Ramesh K., Duraisamy N., Manikam R., Conducting polymer/graphene hydrogel electrodes based aqueous smart Supercapacitors: A review and future prospects. *Journal of Electroanalytical Chemistry*. 2021; 898: 115626. <https://doi.org/10.1016/j.jelechem.2021.115626>
 48. Feng Z.-Q., Wu J., Cho W., Leach M.K., Franz E.W., Naim Y.I., Gu Z.-Z., Corey J.M., Martin D.C. Highly aligned poly(3,4-ethylene dioxythiophene) (PEDOT) nano- and microscale fibers and tubes. *Polymer*. 2013; 54(2): 702–708. <https://doi.org/10.1016/j.polymer.2012.10.057>
 49. Du Y., Cao D., Li B., Lü H., Shen Y. Stable conge red doped poly (3,4-ethylene dioxythiophene)/graphene oxide composite as electrode material for high-performance asymmetric supercapacitors. *Electrochimica Acta*. 2021; 395: 139201. <https://doi.org/10.1016/j.electacta.2021.139201>
 50. Tomaskovic-Crook E., Higginbottom S.L., James E.C., Rathbone S.J.C., Crook J.M., Electroceuticals for neural regenerative nanomedicine. In: *Neural regenerative nanomedicine*. Elsevier; 2020. P. 213–257. <https://doi.org/10.1016/B978-0-12-820223-4.00007-3>
 51. Marzocchi M., Gualandi I., Calienni M., Zironi I., Scavetta E., Castellani G., Fraboni B. Physical and electrochemical properties of PEDOT:PSS as a tool for controlling cell growth. *ACS Applied Materials & Interfaces*. 2015; 7: 17993–18003. <https://doi.org/10.1021/acsami.5b04768>