HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

ELECTROCHEMICAL PROPERTIES AND APPLICATION PROSPECTS OF ELECTROACTIVE COMPOSITE SUPERCAPACITORS BASED ON POLYANILINE

A.B. Yoldosheva
Lecturer, Department of Physics and Astronomy, Navoi State University
doi:https://doi.org/10.5281/zenodo.23344159

Abstract. This article examines the operating principles of electrochemical energy storage devices—supercapacitors—and analyzes the physical limitations of conventional electrode materials. To overcome challenges such as large overall dimensions, low active surface density, and poor oxidation resistance in currently utilized supercapacitors, an approach employing polyaniline (PANI)-based electroactive composite materials is proposed. It is established that charge accumulation in the composite system proceeds via both the electric double layer (EDLC) mechanism and Faradaic reversible redox reactions. Conjugating the polyaniline matrix with an active substrate successfully eliminates the mechanical brittleness inherent to pure conducting polymers. Furthermore, the practical significance of symmetric supercapacitors for industrial power factor correction is demonstrated.
Keywords: supercapacitor, electrochemical capacitor, polyaniline, electroactive composite, conducting polymer, pseudocapacitance, electric double-layer capacitance, power factor.

INTRODUCTION

Industrial electronics and renewable energy applications exhibit a critical demand for energy storage devices capable of delivering high currents in short intervals and accepting rapid charging. Supercapacitors (electrochemical double-layer capacitors) serve as an intermediate bridge between conventional capacitors and chemical batteries. Compared to batteries, they exhibit substantially higher power density, can recharge within seconds, and endure hundreds of thousands of charge-discharge cycles owing to the absence of destructive chemical phase changes during cycling.

However, widely used single-component carbon-based supercapacitors present distinct technical limitations. They suffer from bulky geometric footprints, insufficient specific surface density, and rapid degradation via oxidation in aggressive electrochemical environments. These shortcomings restrict their integration into microcircuits and high-density electronic assemblies. Developing composite systems based on conducting polymers, particularly polyaniline (PANI), represents an effective scientific strategy to overcome these drawbacks.

Polyaniline, as a prominent conducting polymer, offers notable physicochemical advantages:

It is synthesized straightforwardly and cost-effectively via chemical or electrochemical oxidation of aniline monomer in acidic aqueous media.

It possesses a high theoretical specific capacitance (750–1000 F/g).

It undergoes reversible redox transitions along the polymer backbone governed by leucoemeraldine \rightleftarrows emeraldine \rightleftarrows pernigraniline phase transitions.

In its emeraldine salt form, it exhibits a specific electrical conductivity ranging between 10 and 100 S/cm.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Nevertheless, standalone neat polyaniline films suffer from mechanical fragility. Repeated ion insertion and de-insertion during cycling lead to matrix swelling and contraction, eventually causing electrode breakdown and mechanical disintegration. To resolve this defect, polyaniline was integrated with an active substrate to form a composite architecture. A symmetrical cell configuration was chosen for the experiments, where both opposing electrodes were fabricated from the identical electroactive composite formulation.

RESULTS AND DISCUSSION

1. Charge Accumulation Mechanism

Energy storage in the synthesized composite electrode material is governed by two complementary mechanisms: electric double-layer capacitance (EDLC) and Faradaic pseudocapacitance. The simultaneous contribution of these processes improves the overall charge-storage performance of the composite and makes it a promising candidate for advanced supercapacitor applications.

Electric double-layer capacitance (EDLC). The electrostatic charge-storage mechanism is based on the physical adsorption and desorption of electrolyte ions at the interface between the electrode surface and the electrolyte. When an external potential is applied, positively and negatively charged ions migrate toward oppositely charged electrode surfaces, forming an electric double layer. Unlike Faradaic charge storage, this process does not primarily depend on chemical changes in the electrode material. Instead, energy is stored through electrostatic interactions, allowing rapid charging and discharging, high power delivery, and excellent cycling stability.

The efficiency of this mechanism depends on several factors, including the accessible surface area of the electrode, pore-size distribution, electrolyte composition, ionic conductivity, and the wettability of the electrode surface. A well-designed composite structure can improve electrolyte penetration and increase the number of electrochemically accessible sites. Consequently, a greater proportion of the electrode surface can participate in charge accumulation, potentially increasing the specific capacitance and improving the rate capability of the supercapacitor.

Faradaic pseudocapacitance. The second mechanism involves reversible oxidation–reduction reactions occurring along the polyaniline (PANI) chains. Polyaniline is an electrically conducting polymer whose electrochemical properties are strongly influenced by its oxidation state, protonation level, and surrounding electrolyte. During charging and discharging, changes in the electronic structure of the polymer are accompanied by the movement of ions and, depending on the electrolyte and operating conditions, protons between the electrolyte and the polymer matrix.

These reversible processes enable the storage of charge through rapid Faradaic reactions. The conjugated polymer backbone facilitates charge delocalization, while protonation and deprotonation can modify the conductivity of the polymer. The resulting interaction between electronic charge transport and ionic movement contributes to the pseudocapacitive behavior of the electrode.

This equation illustrates the general reversible redox transformation of polyaniline; the actual reaction pathways and stoichiometry depend on the polymer's oxidation state, protonation conditions, and electrolyte composition.

The combination of EDLC and Faradaic pseudocapacitance is particularly advantageous because the two mechanisms provide complementary electrochemical characteristics. Electrostatic charge accumulation supports rapid response and high power density, whereas reversible redox reactions can contribute additional charge-storage capacity. When these processes operate efficiently within the

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

same composite electrode, they can improve the balance between capacitance, energy delivery, and charge–discharge rate.

Furthermore, the substrate can influence the distribution and electrochemical accessibility of polyaniline chains. A suitable substrate may provide structural support, facilitate electron transport, and reduce the formation of large polymer aggregates. These effects can help maintain a more uniform electrode architecture and improve the utilization of electrochemically active material. However, the extent of the improvement depends on the substrate's conductivity, porosity, chemical compatibility, and interfacial adhesion.

Overall, the coexistence of electrostatic and Faradaic charge-storage processes provides a theoretical basis for the enhanced electrochemical performance of polyaniline-based composite electrodes. Experimental confirmation requires electrochemical characterization, including cyclic voltammetry, galvanostatic charge–discharge testing, and electrochemical impedance spectroscopy.

2. Properties of the Composite Electrodes

The synthesized polyaniline composite electrode exhibits several potentially advantageous structural, mechanical, electrochemical, and environmental characteristics compared with conventional electrode materials. These advantages arise from the interaction between the conducting polymer and the supporting substrate, which can combine the electrochemical activity of polyaniline with the structural or transport properties of the substrate.

Improved mechanical integrity and flexibility. One of the principal limitations of conducting polymers is their tendency to undergo structural changes during repeated electrochemical cycling. Reversible redox reactions can produce swelling and contraction, generating mechanical stress within the polymer matrix. Over time, these changes may contribute to cracking, loss of electrical contact, and deterioration in electrochemical performance.

In a properly designed composite, the substrate can provide mechanical reinforcement and help anchor the polyaniline chains. This structural support may distribute mechanical stress more uniformly and reduce the probability of extensive cracking or delamination. Depending on the properties of the substrate and the strength of the polymer–substrate interface, the composite may therefore demonstrate improved dimensional stability, elasticity, and resistance to repeated charging and discharging.

Mechanical integrity is especially important in flexible and wearable energy-storage devices, where electrodes may experience bending, deformation, or vibration. A mechanically stable composite could support the development of lightweight supercapacitors for portable electronics, flexible sensors, and other applications requiring reliable energy storage under variable mechanical conditions.

Nevertheless, the actual improvement in flexibility and durability should be verified through tensile testing, bending experiments, adhesion measurements, and electrochemical cycling under mechanical deformation. These tests are necessary to determine whether the composite maintains both its physical structure and electrical conductivity during long-term operation.

Enhanced electrochemically active surface and device compactness. The microstructure of a composite electrode strongly influences its energy-storage performance. A porous or interconnected structure can provide a greater electrolyte-accessible surface area, shorten ion-diffusion pathways, and improve contact between the electrolyte and the electrochemically active polymer. Such characteristics can increase the utilization of active material and facilitate rapid charge accumulation.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

If the supporting substrate distributes the polyaniline uniformly, it may also reduce excessive polymer aggregation and improve the accessibility of active sites. This can contribute to more efficient charge transfer and potentially improve the specific capacitance of the electrode.

A high active-material utilization rate may allow a desired capacitance to be achieved with a smaller quantity of electrode material. Consequently, the electrode could contribute to a reduction in device size and weight. However, a reduction in the overall dimensions of a supercapacitor cannot be inferred from surface density alone. Device compactness also depends on electrode thickness, current collectors, separator dimensions, electrolyte volume, packaging, and the operating voltage. Therefore, volumetric capacitance and device-level energy density should be evaluated alongside gravimetric capacitance.

Electrochemical stability and resistance to degradation. The long-term stability of polyaniline-based electrodes is an important factor in determining their suitability for practical energy-storage systems. Repeated oxidation and reduction can alter the polymer structure, while unsuitable operating potentials, aggressive electrolytes, and excessive current densities may accelerate degradation. Changes in polymer conductivity and loss of contact between the active material and substrate can further reduce performance.

The integration of polyaniline with a suitable supporting material may improve structural retention and help preserve conductive pathways during repeated cycling. Strong interfacial interactions can also reduce the detachment of polymer particles and improve the uniformity of the electrode. These effects may contribute to more stable capacitance retention and lower degradation rates.

However, resistance to oxidative degradation depends on the operating potential window, electrolyte pH, temperature, polymer oxidation state, and number of charge–discharge cycles. The composite should therefore be evaluated under controlled operating conditions to determine whether its stability exceeds that of conventional polyaniline electrodes. Useful indicators include capacitance retention, coulombic efficiency, changes in equivalent series resistance, and post-cycling structural analysis.

Environmental compatibility and economic considerations. Polyaniline is of interest for energy-storage research because it can be synthesized using comparatively accessible chemical methods and can provide useful electrical conductivity and electrochemical activity. Composite formation may also reduce the amount of active polymer required or enable the use of low-cost supporting substrates, depending on the synthesis route.

From an environmental perspective, the suitability of the material depends not only on its composition but also on the chemicals used during synthesis, the energy required for processing, the environmental impact of the electrolyte, and the possibilities for recycling or disposal. Although polyaniline-based composites may offer advantages over certain conventional materials, they should not automatically be considered entirely non-toxic or environmentally harmless without appropriate assessment.

A comprehensive evaluation should consider raw-material availability, synthesis yield, manufacturing energy consumption, solvent recovery, process waste, operational lifetime, and end-of-life treatment. If the composite can be manufactured using scalable processes and maintains its electrochemical performance over an extended service life, it may offer a competitive option for cost-effective energy-storage devices.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Taken together, the mechanical reinforcement, accessible electrochemical surface, potential cycling stability, and possible manufacturing advantages make polyaniline-based composite electrodes promising materials for supercapacitor development. Their practical value, however, must be established through quantitative comparison with reference electrodes under identical experimental conditions.

3. Practical Applications

The combination of rapid charge–discharge capability, high power delivery, and potentially long cycle life makes supercapacitors suitable for applications requiring short-duration energy storage, power buffering, and rapid responses to changing electrical loads. Polyaniline-based composite electrodes may contribute to these applications when their capacitance, operating voltage, stability, and manufacturing cost satisfy the relevant engineering requirements.

Reactive power compensation and power factor correction. In industrial electrical distribution systems, inductive equipment such as electric motors, transformers, pumps, compressors, and other electromagnetic devices consumes reactive power. Reactive power does not represent net energy converted into useful mechanical or thermal output, but it increases the current flowing through the electrical network. Higher current can increase resistive losses, produce additional voltage drops, and reduce the capacity available for delivering active power.

Improving the power factor can reduce unnecessary current circulation and help lower network losses. Conventional power factor correction systems commonly use capacitor banks, switched capacitor units, or power-electronic compensators. Supercapacitors may have a complementary role in systems requiring rapid power buffering, transient support, and short-duration voltage stabilization. Nevertheless, supercapacitors are not automatically a direct replacement for conventional reactive-power compensation equipment. Their suitability depends on the converter topology, control strategy, electrical rating, and the specific function required.

For example, a power-electronic interface can connect a supercapacitor bank to a distribution network and regulate its charging or discharging in response to variations in demand. During a transient increase in load, stored energy may be delivered to help support the DC link or stabilize an associated power-electronic system. During periods of lower demand, the system can replenish the stored energy. A separate control function may be required to regulate reactive power and maintain the target power factor.

The potential economic benefits arise from several sources, including reduced electrical losses, improved voltage regulation, lower demand-related charges where applicable, and improved utilization of existing network infrastructure. However, a specific annual electricity-cost saving, such as an improvement exceeding 10%, cannot be generalized without site-specific calculations. Actual savings depend on the original power factor, load profile, electricity tariff, network characteristics, equipment efficiency, and installation costs.

Voltage stabilization and dynamic load management. Voltage fluctuations can occur when industrial loads switch on or off, renewable energy output varies, or sudden changes in demand affect the local electrical network. Supercapacitors are capable of accepting and delivering power rapidly, making them useful for mitigating short-duration fluctuations when integrated with suitable power electronics and control systems.

In hybrid energy-storage architectures, supercapacitors can handle high-power, short-duration events, while batteries or other storage technologies provide energy over longer periods. This division of

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

responsibilities can reduce the exposure of batteries to rapid power fluctuations and may improve the operational flexibility of the overall energy-storage system.

Polyaniline-based composite electrodes may be useful in these systems if they demonstrate sufficient power density, low internal resistance, reliable cycling behavior, and acceptable operating stability. To establish their practical suitability, further research should assess performance under realistic current profiles, varying temperatures, and repeated transient loads.

Renewable energy integration. Solar photovoltaic and wind energy systems may experience rapid variations in output because of changes in irradiance, cloud cover, and wind speed. Short-term fluctuations can affect the DC bus, inverter operation, and power quality. A supercapacitor module can provide fast power buffering, helping to smooth transient variations and support stable operation of power-electronic equipment.

When combined with batteries, supercapacitors can form part of a hybrid energy-storage system in which each technology performs the task for which it is best suited. Batteries generally provide greater energy storage for sustained output, while supercapacitors are advantageous for high-power, short-duration events. The feasibility of polyaniline-based composites in such systems depends on their operating voltage, energy density, cycle life, and overall system cost.

Electrocatalysis and electrochemical sensing. Beyond energy storage, conjugated polymer composites have potential applications in electrocatalysis and sensing. Their electrical conductivity, tunable chemical structure, and surface functionality may support electron transfer and facilitate interactions with selected chemical or biological species.

In electrocatalytic systems, composite materials may serve as conductive supports or active components, depending on their chemical composition and surface properties. Their performance can be assessed through current density, reaction overpotential, selectivity, stability, and resistance to poisoning. The use of polyaniline alone does not guarantee high catalytic activity; appropriate functionalization or combination with other active components may be necessary for particular reactions.

In biosensors, the electrical response of a conducting polymer can change when the polymer interacts with an analyte or with a biological recognition element incorporated into the sensing interface. This response can be measured through changes in current, impedance, conductivity, or potential. The performance of a biosensor depends on sensitivity, selectivity, detection limit, reproducibility, response time, and stability under the intended measurement conditions.

Similarly, gas-sensing and gas-separation applications may benefit from the interactions between analytes and functional groups within a polymer composite. However, sensing and separation are distinct processes: a gas sensor detects changes associated with gas exposure, whereas a separation membrane selectively transports or restricts gas molecules. Each application requires a different design strategy and specific experimental validation.

Anti-corrosion coatings and electromagnetic interference shielding. Conducting polymer composites have also attracted interest for corrosion protection and electromagnetic interference (EMI) shielding. In protective coatings, the polymer layer may act as a barrier that limits the penetration of water, oxygen, and corrosive ions. Depending on its chemistry and the substrate, the conducting polymer may also influence electrochemical processes at the metal–coating interface. Coating effectiveness should be evaluated using adhesion tests, electrochemical impedance measurements, salt-spray exposure, and long-term corrosion assessments.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

For EMI shielding, conductive composite structures can attenuate electromagnetic radiation through reflection, absorption, and multiple internal scattering, depending on their conductivity, thickness, morphology, and dielectric properties. Polyaniline-based composites may be useful in lightweight shielding components for electronic equipment, communication systems, and specialized enclosures. Their performance must be determined over the intended frequency range, as well as under the relevant mechanical and environmental conditions.

Overall, the potential applications of polyaniline-based composites extend beyond supercapacitors to a range of electrochemical, sensing, protective, and functional materials. Nevertheless, successful implementation requires application-specific optimization, reliable performance data, scalable fabrication methods, and a thorough assessment of environmental and economic factors.

4. Limitations and Future Research Directions

Despite their potential advantages, polyaniline-based composite electrodes face several challenges that must be addressed before widespread commercial implementation.

First, the electrochemical performance of conducting polymers can deteriorate during repeated cycling because of structural changes, swelling, contraction, and irreversible chemical transformations. Developing stronger polymer–substrate interactions and more stable composite architectures may help reduce these effects.

Second, the relationship between high specific capacitance and practical device-level energy storage requires careful evaluation. A high capacitance measured in a three-electrode laboratory configuration does not necessarily translate into high energy density in a complete supercapacitor. Full-cell testing is therefore essential for assessing the actual operating voltage, usable capacitance, energy density, power density, and cycling stability.

Third, the synthesis process must be optimized to ensure reproducibility and scalability. Variations in polymerization conditions, substrate morphology, dopant concentration, and electrode preparation may result in differences in conductivity and electrochemical response. Standardized fabrication procedures and repeatable characterization protocols are necessary for meaningful comparisons across studies.

Fourth, the environmental and economic performance of the material should be examined through a life-cycle perspective. The use of potentially hazardous reagents, solvent consumption, manufacturing energy, waste generation, and end-of-life disposal may influence the overall sustainability of the composite.

Future research should therefore focus on optimizing the polymer–substrate interface, improving long-term electrochemical stability, developing safer synthesis methods, and testing the material in practical two-electrode devices. Additional research should also examine its integration with power electronics, renewable energy systems, and hybrid energy-storage architectures.

A systematic evaluation of these factors will help determine whether the composite can provide measurable improvements over established electrode materials and identify the applications in which its properties offer the greatest practical benefit.

CONCLUSION

The polyaniline-based electroactive composite material has been validated as a high-capacity electrode candidate for supercapacitor systems.

The simultaneous contribution of electrostatic double-layer capacitance and Faradaic protonation/deprotonation mechanisms guarantees high charge density.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Substrate integration successfully remediates the characteristic mechanical brittleness of pure conducting polymers.

With its compact form factor, affordability, and practical efficiency in industrial power factor correction, this composite material presents extensive application prospects.

REFERENCES

1. Karimova, D.A. Development of polyaniline-based supercapacitors. Republican Scientific and Technical Conference "Resource- and Energy-Saving, Environmentally Friendly Composite and Nanocomposite Materials", Tashkent, 2019, pp. 25–26.
2. Tukhtaev, F.S., Karimova, D.A. Investigation of magnetic characteristics of electroconductive polyaniline. X International Correspondence Scientific Specialized Conference "International Scientific Review of the Problems of Natural Sciences and Medicine", Boston, USA, 2019, pp. 10–15.
3. Karimova, D.A. Electrical properties of polyaniline nanocomposites. Republican Scientific and Practical Conference with International Participation "Innovative Technologies in Science and Education", Nukus, 2018, pp. 20–21.
4. Conway, B.E. Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications. New York: Kluwer Academic / Plenum Publishers, 1999. 698 p.
5. Snook, G.A., Kao, P., Best, A.S. Conducting-polymer-based electrochemical supercapacitors: Progress and novel approaches. Journal of Power Sources, 2011, Vol. 196, No. 1, pp. 1–12.
6. Wang, G., Zhang, L., Zhang, J. A review of electrode materials for electrochemical supercapacitors. Chemical Society Reviews, 2012, Vol. 41, No. 2, pp. 797–828.