

Research Progress on Preparation of Polyaniline Materials and Their Application in Supercapacitors

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Abstract. With the rapid development of grid-connected renewable energy, portable electronic devices and flexible wearable devices, supercapacitors featuring high power density, fast charge-discharge performance and long cycle life have attracted extensive attention. As a typical conductive polymer, polyaniline (PANI) possesses advantages including easily available raw materials, mild synthesis conditions, tunable doping states and prominent pseudocapacitance contribution, and it serves as a key research subject for supercapacitor electrode materials. This paper reviews the preparation of polyaniline materials and their applications in supercapacitors. It first outlines the device configuration, conduction process and energy-storage mechanism of supercapacitors. Then it summarizes preparation approaches including chemical oxidative polymerization, electrochemical polymerization, in-situ composite synthesis, template/scaffold-assisted construction and doping functionalization, and compares the performance of polyaniline-based composite electrodes in terms of specific capacitance, energy density and cycling stability. Existing studies indicate that the construction of conductive scaffolds, pore channel regulation and interface stabilization can improve charge transport and ion diffusion of polyaniline. Nevertheless, volume variation during charge-discharge cycles and degradation of active layers remain critical bottlenecks restricting practical applications.

Keywords: polyaniline, conductive polymer, preparation method, supercapacitor

1. Introduction

Against the backdrop of rapid advances in grid-connected renewable energy, traffic energy recovery, portable electronic devices and flexible wearable devices, energy-storage devices are required not only to deliver considerable energy output, but also to complete charge-discharge within short periods and maintain long service life. Situated between conventional electrostatic capacitors and secondary batteries, supercapacitors combine high power density, rapid response and long cycle life, and thus hold high application value in instantaneous power compensation, pulse energy supply and small-scale energy-storage units [1, 2]. However, supercapacitors generally exhibit lower energy density compared with battery systems. How to raise stored charge capacity while retaining favourable fast-kinetics characteristics remains a persistent concern in relevant research [1, 3]. Supercapacitor performance is jointly determined by electrodes, electrolytes, separators, current collectors and electrode-electrolyte interfaces. Electrode materials undertake the primary charge-

storage function. Their specific surface area, conductive networks, pore structures and active sites directly affect specific capacitance, rate capability and cycle retention rate. Electrolytes govern ion-transport capacity and stable voltage windows. Separators and current collectors are responsible for device safety and electron-transport efficiency respectively [1-3]. Accordingly, understanding supercapacitors should not be limited to the properties of individual materials; their energy-storage behaviours ought to be analysed from the perspective of device structures and interfacial processes. Polyaniline (PANI) is a typical conductive polymer. It has easily accessible raw materials, mild synthesis conditions and doping-tunable conductive states. Amino and imine groups on its molecular chains can participate in reversible redox reactions and deliver pseudocapacitance for supercapacitors [1, 3, 4]. Still, repeated charge-discharge cycles trigger chain expansion-shrinkage, active-layer cracking and deteriorated interfacial contact for polyaniline, which degrades its cycling stability [4, 5]. In recent years, polyaniline-based materials have evolved from single-polymer electrodes toward conductive-scaffold composites, three-dimensional porous architectures and functional interface modulation [6-9]. On this basis, this paper first describes supercapacitor devices and their energy-storage principles, and then discusses preparation methods and electrochemical research progress of polyaniline materials.

2. Supercapacitors and their energy-storage devices

Supercapacitors represent an important energy-storage form bridging conventional capacitors and secondary batteries. Their application value stems not only from fast charge-discharge capability, but also from the flexible design of device structures for diverse application scenarios. Therefore, before discussing specific electrode materials, it is necessary to clarify the basic concepts, constituent units and performance evaluation metrics of supercapacitors.

2.1. Brief introduction to supercapacitors

Also known as electrochemical capacitors, supercapacitors store energy through charge separation at electrode-electrolyte interfaces or rapid surface redox reactions. Compared with conventional capacitors, they possess larger effective energy-storage areas and higher capacitance. Different from batteries, their charge-storage processes generally do not rely on deep bulk-phase reactions, so faster charge-discharge rates and longer cycle life can be achieved [1, 2]. Featuring high power output, long service life and rapid response, they are suitable for scenarios such as vehicle braking energy recovery, backup power supplies, smart-grid peak-shaving and instantaneous energy supply for electronic equipment.

2.2. Energy-storage devices of supercapacitors

From the device perspective, a supercapacitor is not a simple stack of single electrode materials. It is an electrochemical energy-storage unit assembled with positive and negative electrodes, electrolyte, separator, current collector and packaging structure. During operation, electrons travel through the external circuit while ions migrate inside the electrolyte. The separator prevents direct contact between positive and negative electrodes and permits ion passage. Pore channels, functional groups and conductive pathways on electrode surfaces determine whether charges can quickly reach active regions. Ion size, concentration and electrochemical window of electrolytes govern the tolerable voltage and energy density of devices [1, 2].

Supercapacitors are comprehensively evaluated by specific capacitance, energy density, power density, rate performance and cycling stability. Specific capacitance reflects the charge-storage capacity of materials per unit mass, area or volume. Energy density is correlated with capacitance and operating voltage, whereas power density describes the capacity of devices to release energy within short periods [1, 3]. In practical applications, pursuing merely one high parameter is often insufficient. High specific capacitance may be accompanied by slow ion diffusion, and high energy density could sacrifice power output or cycle life. Accordingly, the core of supercapacitor research lies in balancing material structures, electrode fabrication processes and device parameters. See Figure 1 for the corresponding schematic illustration.

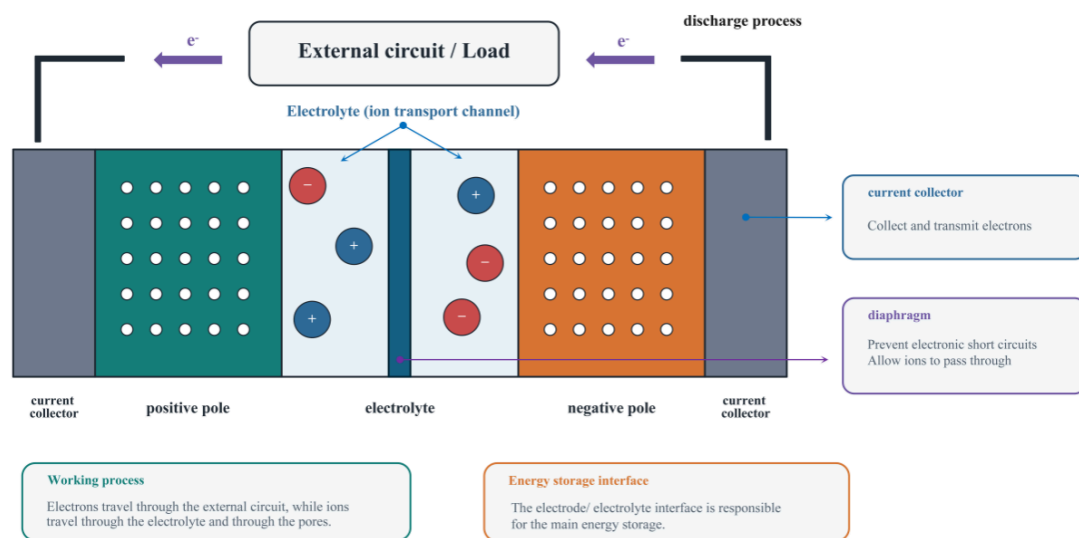


Figure 1. Schematic diagram of supercapacitor

3. Components, conduction mechanisms and energy-storage principles of supercapacitor devices

The electrochemical behaviours of supercapacitors are jointly determined by device components, electron-ion transport pathways and electrode interfacial reactions. Different components undertake distinct functions during charge-discharge cycles, and their synergy directly influences rate performance, energy density and cycling stability of devices. This section elaborates on structural components, conductive pathways and two major energy-storage mechanisms.

3.1. Device composition and conduction mechanism of supercapacitors

Typical supercapacitor components include electrodes, electrolyte, separator and current collectors. Electrodes serve as core sites for charge storage, and are generally required to have large specific surface area, favourable conductivity and stable pore structures. As ion-transport media, electrolytes need to balance ionic conductivity, electrochemical stability window and safety performance. Separators should feature insulation property, chemical stability and good wettability to avoid short-circuit and sustain ion migration. Current collectors transfer electrons from external circuits to electrode active layers, and are expected to have low resistance, corrosion resistance and firm bonding with electrode layers [1, 2].

During charging, electrons enter one electrode and exit the other through the external circuit. Cations and anions in the electrolyte migrate toward electrode surfaces with opposite charges. Since the separator blocks direct electron passage inside the device, electron conduction and ion conduction take separate paths: electrons move mainly along current collectors and electrode conductive networks, while ions diffuse within electrolytes and electrode pore channels. Mismatch between electrode pore size and electrolyte ion dimension, or excessively thick active layers leading to tortuous and complicated channels, will increase ion-migration resistance and further impair rate performance and power output [1, 2].

3.2. Energy-storage principle of electric double-layer capacitors

According to energy-storage mechanisms, supercapacitors are classified into electric double-layer capacitors, pseudocapacitors and hybrid capacitors combining both mechanisms. Electric double-layer capacitors store charges primarily via electrostatic adsorption-desorption between electrode surfaces and electrolyte ions. This process exhibits good reversibility and fast reaction kinetics, hence delivering high power density and long cycle life. Nevertheless, limited active sites per unit mass restrict its energy density [1, 2]. See Figure 2 for the corresponding schematic illustration.

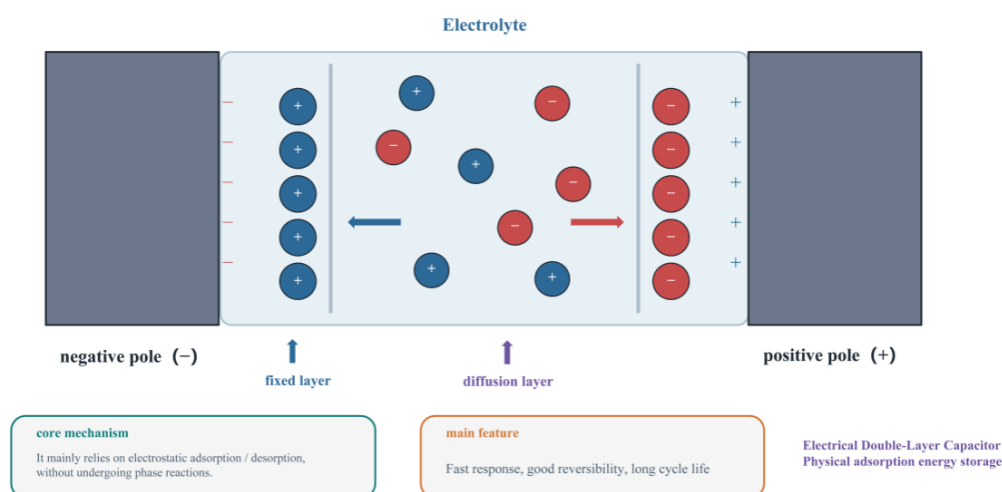


Figure 2. Schematic diagram of double-layer energy storage

3.3. Energy-storage principle of pseudocapacitors

Pseudocapacitance originates from fast and reversible Faradaic reactions on or near electrode surfaces. It introduces extra charge-storage sites and raises specific capacitance as well as energy density. However, material stability may decline when ion intercalation, valence-state variation or structural stress occurs [1, 3]. For this reason, ideal electrodes are supposed to possess open ion channels, continuous electron pathways and stable interfacial structures simultaneously. See Figure 3 for the corresponding schematic illustration.

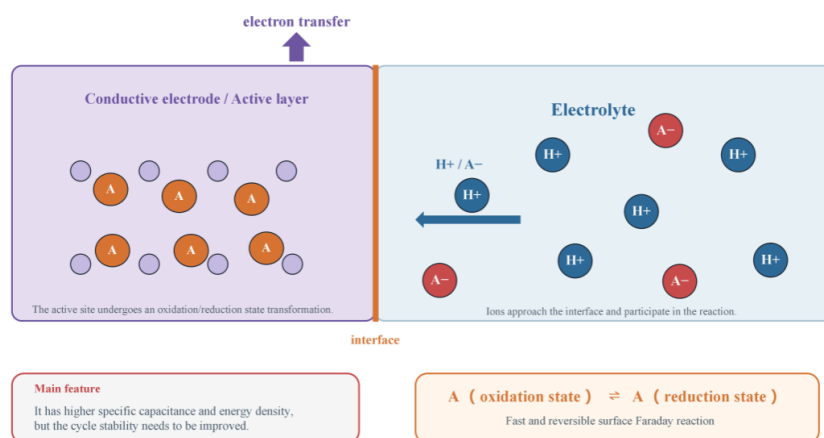


Figure 3. Schematic diagram of pseudocapacitor energy storage

4. Preparation of polyaniline materials

Polyaniline is formed by oxidative polymerization of aniline monomers. Its molecular chains contain structural units including benzene rings, quinone rings, amino groups and imine groups. Different oxidation and doping states significantly affect its electrical conductivity and electrochemical activity. Among them, proton-acid-doped emeraldine salt is the most widely studied form for supercapacitor electrodes [1, 4]. From the preparation perspective, the challenge for polyaniline lies not in realizing polymerization, but in controlling its morphology, thickness, pore features and interfacial bonding. Such control enables full exposure of active sites, while preventing polymer agglomeration, detachment and excessive expansion during charge-discharge processes [4, 5].

Common preparation routes include chemical oxidative polymerization, electrochemical polymerization, in-situ composite polymerization, template/scaffold-assisted construction, and doping-based functional modification. Chemical oxidative polymerization features simple procedures and easy scale-up, suitable for producing powders and composite materials. Electrochemical polymerization can directly form polyaniline films on conductive substrates, facilitating the control of loading mass and interfacial contact. In-situ composite polymerization allows uniform growth of polyaniline on the surface of carbon materials, MXene, MOF or natural polymer scaffolds, so as to optimize conductive networks and cycling stability [6-8, 10]. Key features of different methods are summarised in Table 1.

Table 1. Main preparation methods for polyaniline materials

No.	Preparation Method	Basic Process	Structural Characteristics	Applicable Systems	References
1	ChemicalOxidativePolyme rization	Polymerization is initiated byadding oxidants such asammonium persulfate and FeCl ₃ into acidic media with aniline asmonomer.	Mature approach with mildconditions; morphology ofparticles, fibres or coatinglayers can be readilyadjusted.	Polyaniline powder, carbon/PANI composites.	[3, 5, 11, 12]

Table 1. (continued)

2	Electrochemical Polymerization / Deposition	Potential or current is applied on conductive substrates to realize in-situ film formation of aniline on electrode surfaces.	Controllable film thickness and loading mass; favourable interfacial bonding; reduced binder interference.	Carbon cloth, 3D-printed carbon electrodes, flexible electrodes.	[2, 9, 13]
3	In-situ Composite Polymerization	Conductive scaffolds or porous supports are pre-fabricated, followed by aniline polymerization on their surfaces or within pore channels.	Favours the formation of continuous conductive networks and buffers volume variation of polyaniline.	MXene/PANI, rGO/PANI, MOF/PANI, cellulose/PANI.	[6-8, 10]
4	Template / Scaffold-Assisted Construction	Foams, mesoporous materials, three-dimensional carbon frameworks or natural polymers are adopted as supporting structures	Open pore channels and self-supported structures can be obtained, improving electrolyte wetting and ion diffusion.	Three-dimensional porous electrodes, flexible or solid-state devices.	[7, 8, 11, 13]
5	Doping and Functional Modification	Electron and proton transport are tuned via acid doping, sulfonation, main-chain copolymerization or surface functional-group regulation	Improved hydrophilicity, conductivity and interfacial stability; excessive modifications should be avoided to prevent activity loss	Polyaniline electrodes with high cycling stability, devices matched with gel electrolytes.	[4, 6, 9]

Overall, the selection of polyaniline preparation methods should match target devices. Chemical oxidative polymerization shows cost advantages when high mass loading is required. For flexible, self-supported devices with stable interfaces, electrochemical deposition or in-situ composite polymerization deliver prominent structural merits. To achieve long-term cycling life, priority should be given to controlling polyaniline layer thickness, pore openness and mechanical strength of supporting scaffolds [4, 5, 9]. Accordingly, further research should not merely pursue higher polyaniline content. Instead, preparation routes should be optimised from two perspectives: accessible active sites and stable charge-transport interfaces.

5. Electrochemical performance of polyaniline-based materials for supercapacitors

When applied in supercapacitors, polyaniline exhibits prominent advantages of considerable pseudocapacitance contribution and fast redox response. Its drawbacks mainly involve chain expansion-shrinkage, conductive network disruption and deteriorated active-layer stability upon repeated cycling [4, 5]. For this reason, recent studies tend to composite polyaniline with MXene, graphene, activated carbon, mesoporous silica, MOF, nanocellulose or conductive carbon black. Conductive scaffolds provide electron pathways, porous structures facilitate ion diffusion, and interfacial interactions constrain polyaniline deformation [6, 8, 9, 14]. Representative performance of several recently reported polyaniline-based electrodes and devices is listed in Table 2.

Table 2. Performance, advantages and drawbacks of polyaniline-based materials

No.	Material System	Performance				Advantages and Features	Limitations and Challenges	References
		Specific Capacitance	Cycling Stability	Power Density	Energy Density			
1	CDP-MX/PANI Composite	523.8 F/g (1 A/g)	5000 cycles, 86.5% retention	700 W/kg	27.7 Wh/kg	CDP induces the uniform growth of PANI on the MXene surface, suppressing self-aggregation and enabling more sufficient ion access.	The process involves MXene and CDP functionalization, making the interfacial regulation steps relatively complex.	[6]
2	PANI/RGO/MF Flexible Electrode	806.2 mF/cm ² (0.5 mA/cm ²)	Nearly 100% retention after bending from 0° to 180°, with good cycling stability	200 μ W/cm ²	26.6 μ Wh/cm ²	The foam skeleton provides three-dimensional channels while offering flexibility, self-supporting capability, and high areal capacitance.	PANI loading and foam thickness affect volumetric energy density and batch-to-batch consistency.	[7]
3	PANI-MOF5@SBA-15-NH ₂	757 F/g (1 A/g)	98.8% retention after 8000 cycles	128 W/kg	27 Wh/kg	The mesoporous silica/MOF5/PANI hierarchical composite provides abundant active sites and high capacity retention during cycling.	The construction of the support and surface functionalization involve multiple steps, and the cost of large-scale production requires further consideration.	[8]
4	Sulfonated PANI/MXene and PVAA/MXene Gel Device	549 F/g for the electrode; 153.13 F/g for the device	87% retention for the electrode and 93.51% retention for the device after 10,000 cycles	399.67 W/kg	13.61 Wh/kg	Sulfonic acid groups can serve as proton reservoirs, while the gel electrolyte improves flexibility, compressive resistance, and low-temperature adaptability.	The electrode and gel systems are relatively complex, and additional processing steps such as solvent exchange increase the manufacturing difficulty.	[9]

Table 2. (continued)

5	BNNC/PANI/ZnO Ternary Composite	571.42 F/g (0.1 A/g); 40.2 F/g for the device	97.84% retention after 5000 cycles	540.29 W/kg	14.84 Wh/kg	The synergistic combination of nanocellulose, PANI, and ZnO achieves a balance between high specific capacitance and cycling stability.	The device-specific capacitance is significantly lower than that of the individual electrode, and the conductive network still requires further optimization.	[10]
6	Bark-Derived Activated Carbon/PANI-FeCl ₃ Composite	414.0 F/g (0.5 A/g)	74.7% retention after 5000 cycles	1872 W/kg	5.2 Wh/kg	Biomass-derived activated carbon is low-cost, while FeCl ₃ serves both oxidation and doping functions, improving electrical conductivity.	The energy density is relatively low at high power, and variations in biomass feedstocks may affect stability.	[11]
7	PANI/Acetylene Black (8:1) Composite	388.6 F/g (0.5 A/g)	Approximately 88% retention after 2300 cycles; 80% retention at 10 A/g	700 W/kg; up to 14 kW/kg	24.2 Wh/kg; 13.7 Wh/kg at high power	Acetylene black constructs a conductive network, resulting in excellent rate capability and high-power output performance.	The long-term cycling data cover a relatively short period, and performance is relatively sensitive to the PANI/AB ratio.	[12]
8	3D-Printed Carbon/MXene//3D-Printed Carbon@PANI Solid-State Asymmetric Device	24.42 mF/cm ² (0.28 mA/cm ²)	74% retention after 20,000 cycles	317.10 μ W/cm ²	5.10 μ Wh/cm ²	The three-dimensionally printed electrodes are self-supporting, enabling the construction of solid-state asymmetric devices and expansion of the voltage window.	The evaluation primarily uses areal metrics, while the PANI positive electrode still suffers from cycling degradation and thickness-control issues.	[13]
9	rGO/PANI//WO ₃ Aqueous Asymmetric Device	97 F/g for the device; 1130 F/g for the electrode	82% retention after 5000 cycles	732 W/kg	23 Wh/kg	Chemical bath deposition enables direct film formation, while rGO improves the electrical conductivity of PANI and broadens its applications in asymmetric devices.	The device-specific capacitance is lower than that of the individual electrode, and long-term cycling stability still requires improvement.	[14]

As can be seen from Table 2, performance improvement of polyaniline-based materials generally does not stem from a single factor. Instead, it originates from the synergistic effect of conductive scaffolds, active polymers and electrolyte interfaces. MXene and graphene can reduce electron-transport resistance. Foam or porous scaffolds help maintain ion channels. MOFs and mesoporous materials improve the dispersion of active components. Sulfonation modification and gel electrolytes further boost proton supply and the stability of flexible devices [6-9]. Meanwhile, test setups, mass loading, areal capacitance or gravimetric capacitance adopted in different literatures are not entirely consistent. Units, test current, device types and cycling conditions should be taken into account for direct horizontal comparisons.

Overall, research priorities of polyaniline for supercapacitors have shifted from "achieving high specific capacitance" to "striking a balance among high specific capacitance, fast mass transport and long service life". Promising future directions include constructing thin and continuous polyaniline active layers to avoid ion-diffusion limitations caused by thick films; introducing stable conductive scaffolds to buffer volume variation during redox reactions; developing gel or solid-state electrolytes compatible with polyaniline to enhance safety and environmental adaptability of flexible devices; unifying test standards and attaching importance to full-device energy density and long-term cycling retention [4, 5, 9, 12]. Solutions to these issues will determine whether polyaniline-based supercapacitors can evolve from high-performance laboratory specimens toward practical stable applications.

6. Conclusions

This paper reviews the fundamentals of supercapacitor devices, energy-storage mechanisms, preparation of polyaniline materials and their electrochemical performance. Supercapacitor performance is not determined by electrode materials alone. It arises from the combined effects of electrodes, electrolytes, separators, current collectors and interfacial structures. Electric double-layer energy-storage relies more on rapid ion adsorption and long-term cycling stability, while pseudocapacitive energy-storage enhances charge-storage capacity through fast surface redox reactions. As a typical conductive polymer, polyaniline features relatively mild synthesis conditions, tunable doping states and prominent pseudocapacitance contribution. It remains a research subject of great value for high-capacitance electrodes and flexible energy-storage devices.

In terms of the correlation between preparation methods and performance, chemical oxidative polymerization is suitable for large-scale production. Electrochemical polymerization favours the fabrication of tightly bonded film electrodes. In-situ composite and template-assisted strategies deliver more prominent advantages in structural design. Recent studies demonstrate that compositing polyaniline with MXene, graphene, activated carbon, MOFs, mesoporous materials, nanocellulose and conductive carbon black can improve electron transport, ion diffusion and interfacial stability, so as to increase specific capacitance, energy density and cycling retention. The introduction of three-dimensional porous scaffolds, flexible self-supported electrodes and functional gel electrolytes also drives polyaniline-based materials from simple material optimization toward device-oriented development for practical application scenarios.

Nevertheless, polyaniline still suffers from chain expansion-shrinkage, active-layer cracking, pore blockage and degraded interfacial contact under repeated charge-discharge cycles. These problems directly restrict its long-term cycling life and practical device stability. Follow-up research shall further regulate polyaniline loading mass, film thickness and growth sites, and establish more stable conductive scaffolds and interfacial bonding modes. Besides, unified test criteria for full devices should be emphasised, and material performance shall not be judged merely by the high specific

capacitance of single electrodes. If a reasonable balance among structural stability, scalable preparation and standardized performance evaluation can be realized, polyaniline-based materials will hold favourable prospects for high-power, flexible and miniaturized supercapacitors.

References

- [1] Shah, S. S., Oladepo, S., Ehsan, M. A., et al. (2024). Recent progress in polyaniline and its composites for supercapacitors. *The Chemical Record*, 24(1), e202300105. <https://doi.org/10.1002/tcr.202300105>.
- [2] Shanmuganathan, M. A. A., Raghavan, A., & Ghosh, S. (2023). Recent progress in polyaniline-based composites as electrode materials for pliable supercapacitors. *Physical Chemistry Chemical Physics*, 25(11), 7611–7628. <https://doi.org/10.1039/D2CP05217B>.
- [3] Heme, H. N., Alif, M. S. N., Rahat, S. M. S. M., et al. (2021). Recent progress in polyaniline composites for high capacity energy storage: A review. *Journal of Energy Storage*, 42, 103018. <https://doi.org/10.1016/j.est.2021.103018>.
- [4] Okafor, O. B., Popoola, A. P. I., Popoola, O. M., et al. (2024). Review of advances in improving thermal, mechanical and electrochemical properties of polyaniline composite for supercapacitor application. *Polymer Bulletin*, 81(1), 189–246. <https://doi.org/10.1007/s00289-023-04710-y>.
- [5] Okafor, O. B., Popoola, A. P. I., Popoola, O. M., et al. (2025). Review on the recent development on polyaniline and transition metal oxides composite electrode for supercapacitor application. *Next Materials*, 6, 100389. <https://doi.org/10.1016/j.nxmate.2024.100389>.
- [6] He, T., Li, X., Sun, B., et al. (2024). Preparation of cyclodextrin polymer-functionalized polyaniline/MXene composites for high-performance supercapacitor. *RSC Advances*, 14(19), 13685–13693. <https://doi.org/10.1039/d4ra02542c>.
- [7] Han, K., Tao, J., Li, L., et al. (2024). Melamine foam scaffolded 3D porous polyaniline/reduced graphene oxide composite electrode for flexible supercapacitor. *Polymer*, 309, 127454. <https://doi.org/10.1016/j.polymer.2024.127454>.
- [8] Alizadeh, A., & Ahmadi, E. (2025). Polyaniline and MOF5 functionalized mesoporous silica composite as electrode for high performance symmetric supercapacitor. *Scientific Reports*, 15(1), 40233. <https://doi.org/10.1038/s41598-025-24044-1>.
- [9] Zhou, X., Fu, Y., Yang, J., et al. (2026). Sulfonation-modified polyaniline electrodes and three-dimensional PVAA/MXene gel electrolytes for a highly cycle-stable multifunctional flexible supercapacitor. *Journal of Energy Storage*, 164, 121561. <https://doi.org/10.1016/j.est.2026.121561>.
- [10] Chutia, S., & Phukan, K. (2026). High-performance supercapacitor electrode from betel nut nanocellulose/polyaniline/ZnO ternary nano-composite. *Next Materials*, 10, 101359. <https://doi.org/10.1016/j.nxmate.2025.101359>.
- [11] Yu, T., Zhang, P., Chen, L., et al. (2025). Preparation of high-performance supercapacitors using bark activated carbon/polyaniline composite electrode. *Biomass and Bioenergy*, 197, 107813. <https://doi.org/10.1016/j.biombioe.2025.107813>.
- [12] Mandal, S., Kaibarta, B., & Dasmahapatra, A. K. (2025). Polyaniline/acetylene black binary nanocomposites for high performance supercapacitor electrode. *Future Batteries*, 5, 100054. <https://doi.org/10.1016/j.fub.2025.100054>.
- [13] Mappoli, S., Ghosh, K., & Pumera, M. (2024). MXene and polyaniline coated 3D-printed carbon electrode for asymmetric supercapacitor. *Virtual and Physical Prototyping*, 19(1), e2361139. <https://doi.org/10.1080/17452759.2024.2361139>.
- [14] Pawar, D. C., Bagde, A. G., Thorat, J. P., et al. (2024). Synthesis of reduced graphene oxide (rGO)/polyaniline (PANI) composite electrode for energy storage: Aqueous asymmetric supercapacitor. *European Polymer Journal*, 218, 113366. <https://doi.org/10.1016/j.eurpolymj.2024.113366>.