Review Article

Recent Research Trends on Zeolitic Imidazolate Framework-8 and Zeolitic Imidazolate Framework-67-Based Hybrid Nanocomposites for Supercapacitor Application

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Recently, Zeolitic Imidazolate Frameworks (ZIFs) and their hybrid composites have incited a lot of interest in the research community and have shown promising potential in supercapacitors owing to their excellent conductivity, high surface area, tunable structure, rich redox chemistry, composition diversity, etc. Even though many ZIFs are being studied for the advancement of electrode materials used for energy storage applications, in this review, we are focused on ZIF-8 and ZIF-67 only. The electrochemical performance of pure ZIFs is poor due to low electronic conductivity and poor cycling life. To counter this, ZIFs are mixed with other materials like conducting polymers, other transitional metals composites, and activated carbons to prepare hybrid composites. Furthermore, the highly porous structure and large surface area of the ZIFs cage act as an ideal template for designing composites with excellent supercapacitor applications. This review is focus on the synthesis and electrochemical performance of such materials. This review is divided into two main parts: the design and synthesis of ZIF-8 and ZIF-67 derivatives for supercapacitor applications and the electrochemical performance of ZIF-8 and ZIF-67-based derivatives in three-electrode and two-electrode setups. Lastly, the challenges and obstacles encountered while employing ZIF-8 and ZIF-67-based composites in supercapacitors will be reviewed and commented on.

1. Introduction

Worldwide demand for energy storage is growing by the day. Batteries and supercapacitors are some of the significant technologies for electrical energy storage due to their portability and small size [1]. Supercapacitors are a category of energy storage devices with a high power density and good sustainability [2–5]. Even though supercapacitors have many times more power than that of batteries, they cannot store the same amount of charge. As a result, supercapacitors may account for specific applications requiring power outbursts but not those requiring high energy storage capac-
parallel plate capacitor. Carbon-based electrode materials in EDLCs include carbon nanotubes, active carbon, and graphene [13]. However, compared to lithium-ion batteries (LIB), EDLC has a lower magnitude of energy storage, confining their pervasive use in applications requiring high power density. Pseudocapacitors, on the other hand, store charge via fast and reversible surface redox reactions (Faraday’s reaction is seen in pseudocapacitors). It offers high power density and energy density than EDLC [14]. Undoubtedly, pseudocapacitors frequently suffer from relatively poor loops and partially irreversible reactions because of Faradaic processes [11, 15]. In pseudocapacitive materials, energy is stored due to redox reactions occurring on the surface of the electrode but not due to the separation of ions. Much research has been and continues to be done on pseudocapacitors, but due to the presence of electrochemical reactions, increasing energy density leads to power and lifetime reduction of the cell, which has yet to be solved [16–18]. Moreover, hybrid supercapacitors use both charge-storage mechanisms found in EDLCs and pseudocapacitors, i.e., it employs both Faradaic and non-Faradaic processes, resulting in better cycling stability than pseudocapacitors and higher capacitance than EDLCs [19–22]. Likewise, their energy density increases without sacrificing power density [23]. Meanwhile, it is important to keep in mind that hybrid supercapacitors differ significantly from asymmetric supercapacitors. The hybrid composite can be fabricated with one EDLC and other battery-like redox materials. Asymmetric supercapacitors (ASC), on the other hand, have different electrode configurations, i.e., they have different types of anode and cathode. Also, ASC exhibits triangular-shaped GCD curve and rectangular-shaped CV curve. Conversely, the hybrid capacitors, owing to their two different charge storage mechanisms, show distinct redox peaks in CV and charge-discharge plateau in GCD curve [24–26] Recently reported efficient hybrid supercapacitors with high energy density, power density, and long cycling stability are essential for developing capable energy storage and conversion systems [27, 28]. The outline performance of various supercapacitors with batteries is presented in Table 1.

There is a high demand for advanced energy storage systems to meet the requirement of daily norms. Materials like graphene, N-doped graphite, carbon nanotubes (CNTs), transitional metal oxides (TMOs), transition metal sulfides (TMSs), metal-organic frameworks (MOFs), MXene, and conducting polymers (CPs) are widely used with various modifications and conversions into their respective derivatives for the development of the electrode materials for the energy storage systems [34–36]. This review focuses on the metal-organic frameworks (MOFs) based on supercapacitors. More than 20,000 MOFs have been known to exist to date, and many more are being unraveled daily [37–41]. Among them, zeolitic imidazolate frameworks (ZIFs) are extensively studied MOFs and were first discovered by Yaghi and Li in 1995 [42]. Among the MOF-based electrode materials, ZIF-based composites are well known for their excellent electrochemical performance. From various ZIFs, the ZIF-8 (Zn-based ZIF) and ZIF-67 (Co-based ZIF) are widely used for the fabrication of efficient electrode materials for supercapacitor applications owing to the rich active metal center, nanoporous carbon, tunability, structural regularity, adjustable surface functionality, high porosity, tunable pore size, and excellent thermal and chemical stability and wide ranges of derivatives. ZIF-based materials offer notable advantages in overcoming the challenges related to the limited charging voltage window and restricted rate capability observed in energy storage applications. These materials provide potential solutions for enhancing the performance and efficiency of energy storage systems, thereby addressing key limitations and expanding the possibilities for their practical implementation. Their high surface area facilitates the availability of abundant active sites, leading to enhanced electrochemical performance. Moreover, the tunable pore size of ZIFs allows for precise control over ion diffusion and storage, further improving their capacitance capabilities. Additionally, the excellent stability exhibited by ZIF materials, even in harsh environmental conditions, highlights their potential for the long-term operation of supercapacitor devices.[43–45]. The advancements made in ZIF-8- and ZIF-67-based nanocomposites have shown promise in mitigating the challenges associated with the lack of a wide charging voltage window and limited rate capability. These materials provide opportunities for the development of high-performance supercapacitors with improved energy storage and power delivery characteristics, bringing us closer to realizing the full potential of supercapacitors in various applications.

ZIF-8 is the classic and most well-known member of the ZIF family. ZIF-8 is widely used because of its high stability in long-term use [46]. Also, zinc motifs can be easily removed by high temperatures or acid dissolution from ZIF-8 to prepare nanoporous materials [47]. ZIF-8 (Zn(mIm)2, where mIm is 2-methylimidazole) displays a 3D sodalite ( sod) topography with a space group of interconnected six-membered rings with a pore size of 11.6 Å and a diameter of 3.4 Å. ZIF-8 is found to have 276 atoms in each unit cell [48]. Three-dimensional structure of ZIF-8 in the cubic unit cell is presented in Figure 1, and ZIF-8 consist of 2-methyl-imidazolate (MeIm) groups linking tetra-coordinated Zn2+ metal ions [49].

On the other hand, ZIF-67 is isostructural to ZIF-8, consisting of cobalt ion (Co2+) linked by imidazole anion resulting in sodalite topology exhibiting cubic crystal symmetry.

<table>
<thead>
<tr>
<th>Energy storage devices</th>
<th>Energy density</th>
<th>Power density</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>EDLCs</td>
<td>Low</td>
<td>High</td>
<td>[29,30]</td>
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<tr>
<td>Pseudocapacitors</td>
<td>Moderate</td>
<td>High</td>
<td>[31]</td>
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<td>Hybrid supercapacitors</td>
<td>High</td>
<td>Moderate to high</td>
<td>[32]</td>
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<tr>
<td>Batteries</td>
<td>Very high</td>
<td>Low to moderate</td>
<td>[33]</td>
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Due to the large surface area (SBET > 1700 m² g⁻¹), rich active sites, and the micropore (diameter≈0.34 nm), it has a greater affinity for guest molecules [51]. These properties make them potential candidates for electrochemical applications. However, the poor electrical conductivity of ZIF-67 restricts its use in energy applications in its pristine form [52]. Hence, ZIF-67 is used as a template or precursor to prepare different electrode materials like metal oxide, porous carbon, nitrogen-doped carbon, and metal incorporated n doped carbon. Such materials have enhanced ion/ electron conductivity and can be used as efficient electrode materials for supercapacitors [53–56]. Three-dimensional structure of ZIF-67 in the cubic unit cell is presented in Figure 2, and ZIF-67 consist of 2-methyl-imidazolate (MeIM) groups linking tetra-coordinated Co²⁺ metal ions [49].

According to the nature of Zn and 2-methylimidazole, which prior and later are considered junctional acids and soft N-donor ligands, respectively, the hard and soft acid base theory (HSAB) suggests that the ZIF-8 has very high stability owing to the strong bond between Zn²⁺ and soft N-donor ligand [57, 58]. Cai et al. synthesized ZIF-8, ZIF-8 melamine composite (ZM), and melamine-assisted carbonized ZIF-8 (ZM-C-800), of which FTIR spectra can be seen in Figure 3(a). The peaks at 3135 and 2928 cm⁻¹ represent the aromatic and aliphatic C–H stretching of imidazole, respectively. The peak at 1584 cm⁻¹ represents C=N stretching, and the spectral region 600-1500 cm⁻¹ corresponds to the bending or stretching of the entire ring [59]. Adding to the physical stability, the exceptional thermal and chemical stability of ZIF-8 and ZIF-67 are considerably enhanced by the addition of melamine, as shown by the estimated BET-specific area of 558 m² g⁻¹, which is larger than that of Z-C-800 (420 m² g⁻¹), as shown in Figures 3(e) and 3(f). High specific surface area is a plus point for the supercapacitor application.

Furthermore, it avoids aggregation problems due to its polyhedron structure during electrode fabrication [61]. Thus, ZIF-8-derived nanoporous electrodes can store a considerable charge and be the best alternative for various energy storage systems. Figure 3(g) shows the overall XPS analysis spectrum along with N 1s and C 1s peaks for the pristine Z-C-800 sample show a good presence of nitrogen functional group derived from imidazole linker [59]. At the same time, melamine incorporation during carbonization seems to increase the nitrogen concentration substantially. Nonetheless, the presence of nitrogen greatly enhances the pseudocapacitive nature of energy storage and increases the overall capacitive property of the material [10]. Similarly, Figure 3(h) shows the XPS of Co 2p XPS spectra of Se0.6@CPNA-ACFT (ZIF-67 derivative), which shows the Co²⁺/Co³⁺ for the redox reaction during the charging and discharging of supercapacitors. Moreover, the N₂ adsorption-desorption isotherms with pore size distribution curves, XRD, and FTIR of the ZIF-67 derivatives are presented in Figures 3(i)–3(l), respectively [62, 63]. ZIF-67-derived porous carbon and hybrid composites with high surface area, abundant porosity, tunable properties, and redox behavior due to the presence of cobalt-based compounds in the form of oxide, sulfides, phosphides, and selenides are widely used for the supercapacitor application. Hence, various characterizations shown here greatly support the
Figure 3: Continued.
Figure 3: (a) FTIR spectra of ZIF-8, ZM, and ZM-C-800. (b) TG curves of ZIF-8, ZM, and melamine. (c) XRD patterns of ZIF-8, ZM, and ZM-C-800. (d) Raman spectra of ZM-C samples prepared at different temperatures. (e) N₂ adsorption-desorption isotherm. (f) Pore-size distributions of Z-C-800 and ZM-C-800. (g) Full XPS spectra of ZM-C-800 and Z-C-800 (reproduced from Ref. [59] with permission). (h) XPS of Co at Co₃O₄-PANI@ZIF-8NPC nanocomposites. (i, j) N₂ adsorption-desorption isotherm and pore-size distributions of ZIF-67 derivatives (reproduced from Ref. [62] with permission). (k, l) XRD patterns and FTIR spectra of ZIF-67 derivatives (reproduced from Ref. [63] with permission).
energy storage ability of ZIF-8-derived composites, making them viable for supercapacitor application.

Pristine ZIF-8 and ZIF-67 have limited electrical conductivity and inadequate cycle stability, limiting their usage in energy storage devices. Recently, ZIF derivatives have been extensively used in energy storage. Its exceptional electrochemical properties and unique nanostructure have caught the eye of many researchers. Pure ZIFs have low electrical conductivity, so researchers are focusing primarily on introducing carbon-based materials or conductive polymers into ZIFs and encapsulating redox-active materials like polyanion or oxometalates into the framework of ZIFs to increase their electrical conductivity and overall electrochemical performance [64, 65]. Nevertheless, because of its high porosity and surface area, ZIF with a cage structure serves to design high-performance electrode materials. Nanocomposites prepared using ZIFs as templates can be advantageous to the original components and provide synergistic effects for different components with enhanced energy storage performance [66]. Figure 4 shows the schematic of the essential properties of the ZIF-8 and ZIF-67 derivatives for the supercapacitor applications.

Much research has been focused on producing several MOF- and ZIF-based materials that exhibit outstanding electrochemical performance in supercapacitor devices [67–71]. Consequently, this review article sheds light on the most recent advancements in ZIF-8- and ZIF-67-derived composite materials for supercapacitor applications. Furthermore, the electrochemical and capacitive performance of the materials is investigated on a three-electrode and two-electrode system separately to highlight the concerns that must be addressed in the future to build highly robust supercapacitor materials. Additionally, the outcomes of this discussion were summarized by comparing the resulting electrode materials, electrolyte, specific capacitance, energy density, power density, and cyclic stability of each ZIF-8- and ZIF-67-derived material in a three-electrode and two-electrode systems separately with challenges and future perspectives.

2. Different Synthesis Techniques of ZIF Derivative for Supercapacitor Applications

Figure 5 illustrates some of the synthesis techniques of ZIF-derived electrode materials for supercapacitor applications which are in practice.

2.1. Hydrothermal/Solvothermal Method. The hydrothermal method is a synthesis process in which chemical reagents and water are heated inside a high-pressure steel vessel called an autoclave. Hydrothermal synthesis of ZIFs involves heating a mixture of organic linkers and metal salt in an aqueous environment inside a sealed vessel at high temperature and pressure. The solvothermal method is similar to the hydrothermal method, except that instead of water, organic solvents such as ethanol, methanol, isopropyl alcohol, N, and N-dimethyl formaldehyde (DMF) are used [72, 73]. Long et al. grew a hydrophobic layer of ZIF-8 on the bare zinc metal by solvothermal method to avoid corrosion and dendrite growth in the zinc-ion hybrid supercapacitor. First, they took zinc foil, polished it, and kept it in an autoclave with zinc nitrate and 2-methylimidazole in the presence of methanol as solvent and heated the mixture at 100°C for 8 h in an oven to obtain ZIF-8/Zn [74]. Rabani et al. prepared ZIF-8 using the solvothermal method and then used the synthesized ZIF to fabricate cerium oxide incorporated ZIF-8 composite material, i.e., Ce-MOF [75]. Li et al. prepared ZIF-67@ZIF-8 from ZIF-67 by using a hydrothermal method in the presence of zinc ions and 2-methylimidazole (2-MeIM). The thus prepared material was carbonized in thiourea (as a sulfur source) to obtain CNTs interconnected with NiS@Co containing porous carbon for the supercapacitor applications, as presented in Figure 6 [76].

Tahir et al. produced ZIF-67 in the aqueous phase by using a hydrothermal method and utilized it as a sacrificial template for the solvothermal fabrication of homogeneous three-dimensional (3D) hierarchical hexagonal flower-like nickel-cobalt-layered double hydroxides (NiCo-LDH) for supercapacitor applications as presented in Figure 7 [77].

Liu et al. prepared a 3D CNTs/graphene network supported by a CoZnNiS nanosheet derived from ZIF-67 and ZIF-8 (CoZnNiS@CNTs@rGO) by using hydrothermal Vulcanization and ion exchange process to study its electrochemical performance [78]. Hou et al. synthesized hollow dodecahedral Co3S4@NiO. They prepared Co3S4 from the ZIF-67 template using the hydrothermal method using TAA as a sulfur source and then grew NiO sheets on the surface of Co3S4 to produce Co3S4@NiO for supercapacitor application [79].

To summarize, the hydrothermal/solvothermal techniques employed in the works discussed here have inherent advantages such as environmental benignity and ease of synthesis. With relatively moderate operating conditions (reaction temperatures of under 300°C), cheap cost, a one-step synthetic approach, environmental stewardship, and excellent dispersion in solution, hydrothermal/solvothermal synthesis offers several benefits. It has various uses in producing MOF-derived heteroatom-doped materials because of its strong reactivity, controllability, and distinctive condensed phase of reactants [80]. New materials’ chemical and physical transformations are possible in high-temperature, high-
pressure liquid environments. Additionally, uniform doping is feasible under hydrothermal circumstances [81]. Furthermore, highly controllable reaction parameters such as reaction temperature and time and organic linker selection result in the synthesis of morphologically diverse MOFs with different shapes and sizes [82]. The availability of such a diverse choice of materials is undoubtedly beneficial for supercapacitor applications.

2.2. Sonochemical Method. In the sonochemical method, ultrasonic sound waves initiate a chemical reaction. High temperature and pressure are generated in this process as a result of high heating and cooling rates due to the phenomena known as acoustic cavitation. Compared to the solvothermal method, high-energy ultrasound travels through the reaction mixture, resulting in faster nucleation, smaller and more homogeneous particle sizes, and a shorter crystallization period. As a result, it is one of the most widely used techniques for synthesizing ZIF. Zhang et al. prepared N-Co3S4-GN/CNT for a high-performance supercapacitor. First, they prepared ZIF-67 from cobalt nitrate hexahydrate and 2-methylimidazoles (2mIM) by sonication and then mixed ZIF-67 powder with melamine and heated it at 500°C, which converted melamine into g-C3S4, and at 800°C, 3D-N-CO-GN/CNT was obtained. Thus, obtained material was oxidized and, under sulfurization treatment, converted to N-Co3S4-GN/CNT, as presented in Figure 8 [83].

Lu and Chen prepared polyvinylidene fluoride/ZIF-8 (PVDF/ZIF-8) polyelectrolyte for a high-performance supercapacitor. In this experiment, ZIF-8 was synthesized by...
solvothermal method, PVDF powder and ZIF-8 materials were added to DMF, and the mixture was dispersed sonochemically under an ice bath for 1 h. Then, it was heated in a Teflon vessel for 3 h at 60°C to obtain sea-island nanostructured PVDF/ZIF-8 polyelectrolyte [84]. Zhang et al. prepared ZIF-8/GO and ZIF-67/GO nanocomposite by facile ultrasonication method at room temperature [64]. Hosseinian et al. synthesized ZIF-67 and reduced graphene oxide (ZIF-67/rGO) nanocomposite via a simple and facile ultrasonication method at room temperature and studied its electrochemical performance [85].

Sonochemical synthesis benefits from shorter reaction durations, phase selectivity, and smaller particle sizes. In contrast to traditional procedures, primarily characterized

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**Figure 7:** Schematic illustration of the NiCo-LDH synthesis route [77] (reproduced from Ref. [77] with permission).

**Figure 8:** Schematic diagram of the construction of N-Co$_3$S$_4$-GN/CNT nanostructure [83] (reproduced from Ref. [83] with permission).
by high temperatures and lengthy reaction times, the use of ultrasounds in ZIF research has reduced the gap to smaller particle sizes with relatively moderate circumstances. On the other hand, this method is based on the phenomenon known as acoustic cavitation, which is the sequential development, growth, and collapse of bubbles in a hot region. These circumstances make it possible to employ ultrasonic irradiation to generate reactions that were previously difficult to accomplish using conventional techniques, even macroscopically at room temperature [86]. Hence, as mentioned earlier, the cavitation phenomena generated by sonication help easier deposition of organic or inorganic materials on the smaller core to produce uniformly dispersed MOF nanostructures in a reaction solution eliminating any chance of agglomeration. The elimination of agglomeration leads to a smaller size nanomaterial, which in turn is highly beneficial for supercapacitor application [84].

2.3. Microwave/Ultrasonic Wave-Assisted Techniques. In this method, microwave radiation is used to prepare the ZIFs. The electromagnetic irradiation frequency ranging from 0.2 to 300 GHz rapidly transfers the energy to reaction precursors making this method faster than others such as hydrothermal and solvothermal [87]. Yao et al. show a mild and efficient ultrasound-assisted synthetic method to prepare ZIF-8, ZIF-67, and Co/ZIF-8 with well-designed particle size and morphology. The bimetallic Zn/Co-ZIF shows a hierarchical porous structure with modified physicochemical properties [88]. The schematic diagram for synthesizing ZIF-8 derivative using a microwave-assisted technique is presented in Figure 9.

Mahmoodi et al. prepared ZIF-67@Fe3O4@ESM (ESM-eggshell membrane) composite by using the microwave-assisted or ultrasound-assisted method. The microwave technique increased the circulation of the reaction system and thus reduced the coordination time from 6 h to 3 h [90].

Due to its straightforward, rapid, inexpensive, and economically viable procedures, microwave-assisted synthesis has become more and more popular. In contrast to traditional techniques, microwave irradiation crystallization achieved a greater yield, used less ligand and solvent, and did not need to utilize deprotonators [91]. Microwave absorption may cause atoms and molecules to oscillate, converting mechanical energy to thermal energy and effectively initiating chemical processes [92]. Furthermore, it has been observed that the microwave synthesis of MOF partially carbonizes the organic linkers, which generate a large number of defects and enhance the stability and charge-storing ability of MOF by potentially increasing active sites [93]. Hence, the microwave synthesis method is widely used for the green synthesis of ZIFs with the benefits of accelerating crystal formation, enhancing selectivity, and lowering reaction temperature and reaction time [69].

2.4. Electrochemical Method. In this method, the anodic dissolution of metal gives the metal ion, which is then supplied to the reaction mixture containing the organic linker and electrolyte, where the formation of ZIFs takes place [94]. Wang et al. synthesized ZIF-67 crystals on the carbon cloth (CC) surface and electrodeposited PANI on the cloth to create a porous PANI-ZIF-67-CC composite with interwoven PANI chains and ZIF-67 crystals [95]. Zhang et al. deposited the ZIF-8 layer on the surface of multiwalled carbon nanotubes (MWCNT) using the electrochemical method to prepare ZIF-8@MWCNT. The synthesized material was then carbonized to obtain C-ZIF-8@MWCNT. The C-ZIF-8@MWCNT had a necklace-like structure and had high conductivity and surface area. The material exhibited excellent electrochemical properties [96]. The schematic diagram of the electrodeposition of ZIF-8 in MWCNT is presented in Figure 10.

Compared to other approaches, electrochemical methods provide several benefits, such as quicker and smoother synthesis conditions. Additionally, it permits direct control over the reaction, providing greater control and enabling to do the synthesis consistently. Additionally, the confined character of electrochemical processes makes it possible to generate guided thin films without the usual need for surface pretreatment. In addition to reducing the impacts of thermally induced film cracking, a significant problem with hydrothermal techniques, low temperatures are also employed throughout the synthesis. Recent studies have shown the effectiveness of the electrochemical approach for synthesizing thin films in particular and for fine-tuning crystal shapes [97]. The electrochemical method can be subdivided into several synthesis methods, such as anodic and cathodic synthesis, electrophoretic and indirect bipolar deposition, and electroplating substitution [98]. All of these methods promote faster MOF synthesis with diverse morphology and excellent porosity. Hence, the electrochemical approach with several advantages, including shorter synthesis time, moderate conditions, a simple synthesis process, faster morphological modification, and high faradaic efficiency, is one of the promising methods for ZIF synthesis [99].

2.5. Coprecipitation Method. Coprecipitation is the simultaneous precipitation of soluble and microcomponents from the same solution by adsorption, encapsulation, or mechanical trapping to form mixed crystals [100]. Coprecipitation, in other terms, is the process of precipitating a metal hydroxide from its salt precursor in a solvent with the help of a base. Chhetri et al. prepared nanoporous carbon (NPC) from ZIF-8 (prepared by the coprecipitation method) and modified ZIF-8NPC by controlled polymerization of PANI and Co3O4 nanoflakes on the surface of the ZIF-8NPC to form Co3O4-PANI@ZIF-8NPC nanocomposite and studied its practical application in asymmetric supercapacitor [101]. The graphical outline of the synthesis of Co3O4-PANI@ZIF-8NPC nanocomposite is presented in Figure 11.

Luo et al. constructed a layered core-sheath architecture with porous Co-Ni LDH nanocages uniformly interlaced by MnO2NW (MnO2@Co-Ni LDH) using a two-step solution-phase synthesis technique and investigated its potential application in supercapacitors [102]. The schematic of the preparation process for MnO2@Co-Ni LDH is presented in Figure 12.

The coprecipitation technique benefits from other chemical and physical processes, such as simplicity in preparation, controllability of experimental variables, high purity, and capacity for producing a product in higher numbers. However,
this technique calls for the use of premium solvents, water for washing, and extended drying times [103]. This procedure uses a base to precipitate a metal hydroxide from its salt precursor in a solvent. The advantages of the coprecipitation method are high product purity, excellent productivity, no need for organic solvents, easy reproducibility, and low cost. Thus, due to these advantages, this method is widely used for synthesizing ZIFs and their derivatives. Furthermore, compared to other hydrothermal methods, the coprecipitation method is preferable due to faster reaction kinetics and more accessible and milder experimental conditions [87].

2.6. Annealing/Carbonization Method. Annealing is a high-temperature procedure that alters the material’s physical and sometimes chemical characteristics to improve its ductility and enhance its uses in various applications. Jiang et al. prepared N-doped carbon from ZIF-8@CTAB (CTAB-cetyltrimethylammonium bromide). They first prepared ZIF-8@CTAB from CTAB micelle in an aqueous system; then, they carbonized the material at 1,000°C in an N₂ atmosphere to obtain N-doped carbon [104]. Huang et al. prepared N-doped carbon sheets by high-temperature carbonization and KOH chemical activation of ZIF-8@ZnO composite [105]. The synthesis method of NPCs with a hierarchical porous structure is shown in Figure 13.

Wang et al. prepared N-doped porous carbon from ZIF-8/polypyrrole by carbonization, anchored it on carbon nanotubes to obtain PC-CNTs, and studied its electrochemical
properties for high-performance EDLC supercapacitors [106]. Zhang et al. synthesized N-doped porous carbon by carbonizing heterogeneous core-shell ZIF-L(Zn)@ZIF-67 nanoleaves under an argon atmosphere. Highly porous amorphous carbon@graphite carbon shell nanoleaves with high nitrogen content carbon nanotubes (N-C@GC/CNTs) were obtained [107]. Zhong et al. prepared carbon-ZS from nitrogen-containing ZIF-8 and an additional carbon source, i.e., sucrose, via carbonization at 950°C. Carbon-ZS thus prepared had high nitrogen content and excellent electrochemical performance [108]. Gayathri et al. prepared cobalt phosphide-draped N-doped carbon/graphene hybrid (CoP-NPC/GS), obtained by in situ carbonization and phosphatization of ZIF-67 precursor [53]. Zhang et al. prepared graphene and CNT-wrapped cobalt derivatives by annealing the complex of ZIF-67 and graphene oxide. Thus, prepared Gr-CNT@Co showed excellent conductivity, a large surface area, and many active sites [109]. The schematic diagram for preparing Gr-CNT@Co is presented in Figure 14.

The ZIFs can be converted from different synthesis techniques into various types of electrode materials for the supercapacitor application. ZIF-derived carbon-based materials such as metal carbides, nanoporous carbon, graphitized carbon, N-doped carbon, and CNTs are well known for their long cyclic stability. ZIF-converted and ZIF-mixed nano-composites such as metal hydroxides, metal sulfides, metal phosphides, metal selenides, metal nitrides, rGO, CNTs, graphene, and conducting polymers can be prepared from the abovementioned different techniques for the supercapacitor applications [81]. To readily control sample size and shape while still allowing for accurate analysis of the synthesized material’s active site, researchers may employ the carbonization process. MOFs, especially ZIFs, often contain a significant amount of carbon and do not need the addition of excess carbon sources.

Consequently, the atom type and structure of ZIFs often determine their electrochemical properties. The environment and temperature, which both may significantly affect the end products of the calcined ZIF precursor, are the two primary components of this process. The final product produced in an inert gas varies significantly from that produced in air, but annealing in various atmospheres may produce final compositions with various final properties [62]. The annealing of ZIFs helps produce nanoporous carbon (NPC), N-doped carbon, CNTs, etc. ZIFs have carbon-based organic linkers and pores; thus, they can be used as precursors/templates for synthesizing porous carbon material. It is essential to remember that the metal components
present in ZIFs must be removed to prepare porous carbon. Because of their high conductivity, excellent chemical and mechanical robustness, large surface area, and tunable structure, porous carbons are widely studied for their potential application in supercapacitor devices [69].

3. ZIF-8-Derived Hybrid Materials for Supercapacitors

3.1. ZIF-8-Derived Hybrid Materials for Supercapacitor in a Three-Electrode System.

ZIF-8-derived hybrid materials are found to give good results for three-electrode systems. Chhetri et al. combined Co3O4 nanoflakes with polyaniline (PANI) in a controlled in situ polymerization on the ZIF-8-nanoporous carbon (NPC) surface and developed a Co3O4-PANI@ZIF-8 NPC nanocomposite. Thus, formed nanocomposite has a high specific capacitance of 1407 F g\(^{-1}\) at 1 A g\(^{-1}\), which gives excellent rate capability and cyclic stability [101]. The electrochemical performances and FE-SEM images of Co3O4-PANI@ZIF-8 NPC nanocomposite are presented in Figure 15.

Ahmad et al. employed a bimetallic approach to preparing ZIF-8/ZIF-67-derived Co-Zn-nanoporous carbon-sulfide material for supercapacitor. Such materials show the specific capacitance of 583 F g\(^{-1}\) at 1 A g\(^{-1}\) with around 83% cyclic stability after 5000 cycles [110]. Zhang et al. developed a novel necklace-like ZIF-8@MWCNT composite. The electrode material shows a high specific surface area of 1063.2 m\(^2\) g\(^{-1}\). The C-ZIF-8@MWCNT electrode material for the supercapacitor showed a high specific capacitance of 259.2 F g\(^{-1}\) at the current density of 0.5 A g\(^{-1}\). Additionally, the capacitance retention reached 92% after 5000 cycles under the current density of 15 A g\(^{-1}\) [96]. Han et al. prepared a 3D hierarchically porous ZIF-8-derived carbon/LDH core-shell composite for supercapacitors. The prepared electrode materials, 3D ZIF-8-C@NiAl-LDH, show a high specific capacitance of 1370 F g\(^{-1}\) at the current density of 1 A g\(^{-1}\) with 77% capacitance retention after 1000 cycles at 4 A g\(^{-1}\) [111]. Tang et al. developed carbon tube arrays connected to N-doped carbon bubbles (CTA@NCB) using ZnO@ZIF-8 as a template. Thus, synthesized CTA@NCB showed excellent microstructure. In a three-electrode system, the CTA/NCB revealed a specific capacitance of 244 F g\(^{-1}\) at 0.67 A g\(^{-1}\) in 1 M H\(_2\)SO\(_4\). Furthermore, the designed device offered specific capacitance retention of 98.5% after 10,000 cycles [112]. Moreover, Li et al. designed a multi-walled carbon nanotube/nitrogen-doped porous carbon composite (MWCNT/NPC). Deposition of ZIF-8 onto the surface of MWCNT yielded the precursor. The initial conditions were then tightly monitored to construct the preferred structure with high electrochemical properties. The MWCNT/NPC electrode demonstrated a specific capacitance of 332 F g\(^{-1}\) at a scan rate of 5 mV s\(^{-1}\) using a 1 M H\(_2\)SO\(_4\) solution [113]. Bao et al. studied 3D hybrid-porous carbon derived from microsized ZIF-8 with distinct porous networks and a high specific surface area. The resulting 3D hybrid-porous carbon demonstrated excellent EDLC behavior, with a high specific capacitance of 332 F g\(^{-1}\) at 0.5 A g\(^{-1}\) and excellent specific capacitance consolidation of 100% at 5 A g\(^{-1}\) for 10,000 cycles. The 3D hybrid-porous carbon was unearthed to have a unique porous framework that aids ion movement [114]. The electrochemical performances and FE-SEM images of 3D hybrid-PC are presented in Figure 16.

Shang et al. prepared the N-doped carbon composite derived from ZIF-8/polyaniline@cellulose-derived carbon aerogel for the supercapacitor. The ZIF-8-derived porous carbon (ZC)/PANI@CA (ZPCA) shows 388 F g\(^{-1}\) specific capacitance at 0.5 A g\(^{-1}\) and excellent specific capacitance consolidation of 91.2% at 1 A g\(^{-1}\) for 2,000 cycles [115]. Kong et al. created a graphitic carbon nitride composite/N-decorated carbon nanoparticles (g-CN/NCP) by calcinating a mixture of ZIF-8, urea, and glucose in an inert nitrogen atmosphere and then washing it with HCl. The produced
Figure 15: Continued.
g-CN/NCPP composite material then demonstrated good supercapacitor properties, with a specific capacitance of 495 and 188 F g$^{-1}$ at 0.1 and 20 A g$^{-1}$, respectively, using H$_2$SO$_4$ electrolyte. Following that, a cyclic stability test at 10 A g$^{-1}$ revealed that the specific capacitance maintenance of the g-CN/NCPP composite electrode was increased to more than 100%, possibly due to high electrolyte ion diffusion through porous carbon texture [116]. Yu et al. created a ZIF-8@graphene quantum dot composite to prepare C/GQD material for supercapacitor applications. At 2 A g$^{-1}$, the specific capacitance of the C/GQD electrode was 130 F g$^{-1}$. Furthermore, after 9,999 cycles at 2 A g$^{-1}$, the prepared carbon electrode retains 100% of the specific capacitance [117]. Cai et al. created a broccoli-like porous carbon nitride (ZM-C-800) by carbonizing a ZIF-8@melamine composite at 800°C. Using a 6 M KOH electrolyte, this ZM-C-800 material had a specific capacitance of 359.1 F g$^{-1}$ at 1 A g$^{-1}$. Meanwhile, the cyclic test demonstrated that it could maintain 98.3% of specific capacitance over 10,000 cycles at 1 A g$^{-1}$ [59]. By manufacturing ZIF-8 on polyelectrolyte decorated silica
Figure 16: Continued.
PP-SiO₂) and developing ZIF-8/PP-SiO₂, Li et al. elucidated the creation and structure-property coupling for the first time of a novel 3D carbon framework. Thus, formed material was transformed again into unusual N-rich hollow carbon shell frameworks (NHCSFs). The study on alkaline supercapacitor was transformed into unusual N-rich hollow carbon.

Discharge curve at different current densities. (c) Specific capacitance calculated from charge/discharge curve at different current densities. (d) Cyclic stability in 1 M KOH solution. (e) FE-SEM image of 3D hybrid porous carbon. (f–h) TEM images of 3D hybrid porous carbon at different magnifications. (i) TEM image of the edge of 3D hybrid porous carbon [114] (reproduced from Ref. [114] with permission).

The selected three-electrode material discussed above shows the various electrochemical signatures of supercapacitors. Among them, Co₃O₄-PANI@ZIF-8NPC, ZnO/C@fMWCNT, and g-CN/NCPP displayed high specific capacitance of 1407 F g⁻¹ at 1 A g⁻¹, 650 F g⁻¹ at 1 A g⁻¹, and 495 F g⁻¹ at 0.1 A g⁻¹, respectively, due to the presence of transitional metal oxides in the electrode materials from the conversion of ZIF-8. Likewise, MC, 3D hybrid-PC, g-CN/NCPP, and C/GQD displaced the highest cyclic stability due to highly porous (micropores and mesopores) carbon derived from the ZIF-8. Despite these good electrochemical characteristics, ZIF-8-based materials in three-electrode systems still have room for improvement regarding their electrochemical performance, which is discussed below in Section 5.

3.2. ZIF-8-Derived Hybrid Materials for Supercapacitor in a Two-Electrode System. ZIF-8-derived hybrid materials are extensively used as electrode materials in two-electrode systems. Xue et al. created self-doped nanoporous carbon with excellent electrochemical performance by pyrolyzing NaCl-filled ZIF-8. The specific capacitance in the two-electrode system is 359.1 F g⁻¹ at 0.5 A⁻¹ and delivers an excellent energy density of 21.1 Wh kg⁻¹ at a power density of 211.3 W kg⁻¹. Moreover, it has high cyclic stability (97.5%, 8500 cycles) [122]. The electrochemical performances and FE-SEM images of ZIF-8-derived hybrid materials are presented in Figure 18.

Yang et al. used direct heating of a ZIF-8 and ZIF-L(Co) mixture to develop a coating method for preparing stratified porous carbon with carbon nanotubes (CNTs). The electrode was found to have good N content and adjusted pore-size distribution along with high specific capacitance of 204 F g⁻¹ at 1 A g⁻¹ and energy density of 6.99 Wh kg⁻¹ and 4.58 Wh kg⁻¹ at power densities of 0.262 kW kg⁻¹ and 4.711 kW kg⁻¹, respectively [123]. Li et al. invented an MWNT/NPC (multiwalled carbon nanotube/nitrogen-doped porous carbon composite). The precursor was obtained by depositing ZIF-8 onto the surface of MWNT. Then, to produce the ideal structure with good electrochemical characteristics, the preparation circumstances were constantly monitored. The MWNT/NPC symmetric two-electrode cell produced a specific capacitance of 112.4 F g⁻¹ at 0.5 A g⁻¹ and an energy density of 12.65 Wh kg⁻¹ at 225.1 W kg⁻¹ [113]. Huang et al. demonstrated the formation of an N-doped porous carbon nanosheet (NPCS) via carbonization followed by KOH activation of a ZIF-8/ZnO composite using ZnO nanorods as a template. In the two electrodes, a device with an NPCS electrode displayed a specific capacitance of 44 and 35 F g⁻¹ at 0.5 and 50 A g⁻¹, correspondingly. Furthermore, it supplied energy...
Figure 17: Continued.
Figure 17: Continued.
densities of 6.12 and 4.86 Wh kg\(^{-1}\) at 250 W kg\(^{-1}\) and 25,000 W kg\(^{-1}\), respectively [105]. Ding et al. prepared carbon nanosheets (ZCN) from 2D ZIF-8 MOF using a porous ZnO nanosheet as a self-template and shape controller. The following material had a graphene-like structure and good capacitive behavior. Using a 6 M KOH electrolyte, a symmetrical two-electrode system with this ZCN produced high specific capacitance of 220 and 177 F g\(^{-1}\) at 0.5 and 20 A g\(^{-1}\). Furthermore, the charge-discharge cyclic stability test results indicated that the symmetric device has a superb specific capacitance of 97% over 5,000 cycles at 2 A g\(^{-1}\). As an outcome, nitrogen doping improves the electrochemical capacitance of electrode materials, which is especially important for supercapacitors [124]. By calcining a mixture of ZIF-8, urea, and glucose in an inert nitrogen atmosphere and then washing with HCl, Kong et al. created a graphitic carbon nitride composite/N-decorated carbon nanoparticles (g-CN/NCPP). The resulting g-CN/NCPP composite material exhibited excellent supercapacitor properties. For the two-electrode system, the specific capacitance reached 349.7 and 261.2 F g\(^{-1}\) at 0.5 and 5 A g\(^{-1}\), and the energy density and power density of the g-CN/NCPP composite electrode-based device were 11.89 Wh kg\(^{-1}\) and 247.4 W kg\(^{-1}\), respectively [116]. Moreover, Young et al. developed a nanoporous carbon (NPC) material for supercapacitors using a simple thermal treatment of ZIF-8 at 900°C. The specific capacitance of the NPC was 219 F g\(^{-1}\) at 5 mV s\(^{-1}\) in the 1 M H\(_2\)SO\(_4\) electrolyte. The assembled electrode in a symmetrical two-electrode device had a

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**Table 2: Comparison of various parameters of ZIF-8-derived different electrode materials in three-electrode systems for supercapacitor applications.**

<table>
<thead>
<tr>
<th>S.N.</th>
<th>ZIF-8-derived electrode materials</th>
<th>Potential window (V)</th>
<th>Electrolyte</th>
<th>Specific capacitance</th>
<th>Cyclic stability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Co(_3)O(_2)-PANI@ZIF-8NPC</td>
<td>-0.2-0.5 V</td>
<td>3 M KOH</td>
<td>1407 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>88.43% over 10,000 cycles</td>
<td>[101]</td>
</tr>
<tr>
<td>2.</td>
<td>C-Zn/Co/S</td>
<td>0.0-0.5 V</td>
<td>2 M KOH</td>
<td>583 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>83% over 5000 cycles</td>
<td>[110]</td>
</tr>
<tr>
<td>3.</td>
<td>C-ZIF-8@MWNT</td>
<td>0.0-1.0 V</td>
<td>1 M H(_2)SO(_4)</td>
<td>259.2 F g(^{-1}) @ 0.5 A g(^{-1})</td>
<td>92% over 5000 cycles</td>
<td>[96]</td>
</tr>
<tr>
<td>4.</td>
<td>3-D ZIF-8-C@LDH</td>
<td>0.0-0.5 V</td>
<td>EMITFSI</td>
<td>1370 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>77% over 1000 cycles</td>
<td>[111]</td>
</tr>
<tr>
<td>5.</td>
<td>CTA@NCB</td>
<td>0.0-1.0 V</td>
<td>1 M H(_2)SO(_4)</td>
<td>244 F g(^{-1}) @ 0.67 A g(^{-1})</td>
<td>98.5% over 10,000 cycles</td>
<td>[112]</td>
</tr>
<tr>
<td>6.</td>
<td>MWNT/N</td>
<td>0.0-0.9 V</td>
<td>1 M H(_2)SO(_4)</td>
<td>293.4 F g(^{-1}) @ 5 mV s(^{-1})</td>
<td>95.8% over 10,000 cycles</td>
<td>[113]</td>
</tr>
<tr>
<td>7.</td>
<td>3D hybrid-PC</td>
<td>0.0-1.0 V</td>
<td>6 M KOH</td>
<td>332 F g(^{-1}) @ 500 mA g(^{-1})</td>
<td>100% over 10,000 cycles</td>
<td>[114]</td>
</tr>
<tr>
<td>8.</td>
<td>ZC/PANI@CA (ZPCA)</td>
<td>-1.0-0.0 V</td>
<td>2 M KOH</td>
<td>388 F g(^{-1}) @ 0.5 A g(^{-1})</td>
<td>91.2% over 2,000 cycles</td>
<td>[115]</td>
</tr>
<tr>
<td>9.</td>
<td>g-CN/NCPP</td>
<td>-0.2-0.8 V</td>
<td>1 M H(_2)SO(_4)</td>
<td>495 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>100% over 9999 cycles</td>
<td>[116]</td>
</tr>
<tr>
<td>10.</td>
<td>C/GQD</td>
<td>-1.0-0.0 V</td>
<td>6 M KOH</td>
<td>130 F g(^{-1}) @ 2 A g(^{-1})</td>
<td>t 100% over 9999 cycles</td>
<td>[117]</td>
</tr>
<tr>
<td>11.</td>
<td>ZM-C800</td>
<td>-1.0-0.0 V</td>
<td>6 M KOH</td>
<td>359.1 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>98.3% over 10,000 cycles</td>
<td>[59]</td>
</tr>
<tr>
<td>12.</td>
<td>NHCSF</td>
<td>0.0-1.6 V</td>
<td>6 M KOH</td>
<td>253.6 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>92.1% over 20,000 cycles</td>
<td>[118]</td>
</tr>
<tr>
<td>13.</td>
<td>Ce@ZIF-8</td>
<td>-0.1-0.6 V</td>
<td>3 M KOH</td>
<td>132 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>90% over 5000 cycles</td>
<td>[75]</td>
</tr>
<tr>
<td>14.</td>
<td>ZnO/C@fMWCNT</td>
<td>0.0-0.5 V</td>
<td>3 M KOH</td>
<td>652 F g(^{-1}) @ 1 A g(^{-1})</td>
<td>70% over 5000 cycles</td>
<td>[119]</td>
</tr>
<tr>
<td>15.</td>
<td>NiCo-NFA from ZIF-8</td>
<td>0.0-0.45 V</td>
<td>6 M KOH</td>
<td>971.4 F g(^{-1}) @ 1.9 A g(^{-1})</td>
<td>94.1% over 5,000 cycles</td>
<td>[121]</td>
</tr>
</tbody>
</table>

Figure 18: Continued.
specific capacitance of 53.8 F g\(^{-1}\) at 0.1 A g\(^{-1}\) [125]. Cai et al. developed a broccoli-like porous carbon nitride (ZM-C-800) by carbonizing a ZIF-8@melamine composite at 800°C. The ZM-C-800-based symmetric supercapacitors device then provided an energy density of 11.4 Wh kg\(^{-1}\) at 498.5 W kg\(^{-1}\) [59]. The electrochemical performances and FE-SEM images of broccoli-like porous carbon nitride (ZM-C-800) are presented in Figure 19.

Wang et al. used ZIF-8/polypyrrole nanotube composite as a precursor to creating N-doped porous carbon nanotube (PC-CNT) material for supercapacitors at 250 W kg\(^{-1}\). The symmetric two-electrode device with a PC-CNT electrode provided an energy density of 8.42 Wh kg\(^{-1}\) [106]. Zhang et al. found a strategy to synthesize ZIF-8 decorated on wood (ZIF-8@Wood). The carbonized/activated ZIF-8@Wood-derived hierarchical porous composites (C-ZIF-8@ACW) display high areal specific capacitances of 12.52 and 8.95 F cm\(^{-2}\) at the current densities of 1 and 20 mA cm\(^{-2}\), respectively. The assembly of two identical C-ZIF-8@ACW electrodes achieved a superior energy density of 0.55 mWh cm\(^{-2}\) at a power density of 0.5 W cm\(^{-2}\) while retaining 96.8% of initial capacitance after 10,000 cycles [126]. Shang et al. used marine crustacean derivatives and chitin nanofibers (ChNF) as bio-templates of zeolitic imidazolate frameworks (ZIF-8) to form ChNF@ZIF-8 nanocomposites. This material in a biobased N-doped hierarchically porous carbon (N-HPC) electrode improved electrochemical performance and enhanced capacitive performance of specific capacity (128.5 F g\(^{-1}\) at 0.2 A g\(^{-1}\)) with good electrochemical stability even after 5000 cycles [127].

Shang et al. synthesized cellulose-derived carbon aerogel (CA) coated with polyaniline (PANI) on the surface and made ZIF-8-derived porous carbon (ZC)/PANI@CA (ZPCA) hybrid carbon composite through a facile process which served as an electrode for supercapacitor. The ZPCA electrode achieved a capacitance of 388 F g\(^{-1}\) at 0.5 A g\(^{-1}\) and excellent cycling performance. The symmetric supercapacitor-based ZPCA achieved a high energy density of 13.4 Wh kg\(^{-1}\) at a power density of 250 W kg\(^{-1}\) with a 2 M KOH aqueous solution. The ultrahigh energy density of 81.8 Wh kg\(^{-1}\) at a power density of 950 W kg\(^{-1}\) was found later with Et₄NBF₄/AN electrolyte [115]. The electrochemical performances and FE-SEM images of ZPCA are presented in Figure 20.

Cui et al. synthesized rGO/Ni₂ZnS₄ composite with graphene oxide (GO) and ZIF-8. They grew ZIF-8 in situ on the...
Figure 19: Continued.
GO surface and used it as a template. The rGO/Ni2ZnS4 composite as electrode material shows a specific capacitance of 1150 F g\(^{-1}\) at a current density of 1 A g\(^{-1}\). The asymmetric supercapacitor with the electrode material gave an energy density of 31.06 Wh kg\(^{-1}\) when the power density was 750.44 W kg\(^{-1}\). When the high power density was 7489.18 W kg\(^{-1}\), the energy density remained at 12.69 Wh kg\(^{-1}\) [128]. Likewise, Deng et al. workers used direct pyrolysis and KOH activation to create porous honeycomb-like carbon frameworks from (ZIF-8)/poly(vinylpyrrolidone) (PVP) composite. The symmetric supercapacitor assembled with 1-ethyl-3-methylimidazolium tetrafluoroborate (EMIMBF4) electrolyte exhibits significant specific capacitance of 174 F g\(^{-1}\) at 1 A g\(^{-1}\) and delivers an excellent energy density of 74 Wh kg\(^{-1}\) at a power density of 872 W kg\(^{-1}\) [129]. Moreover, Li et al. developed cobalt-containing porous nanocarbon (CoNC) obtained from ZIFs as a supporting base for designing a hybrid structure. The NiS@Co-NC nanocomposite electrode demonstrated a high specific capacitance of 1116.6 F g\(^{-1}\) when the current density was 1 A g\(^{-1}\). The fabricated hybrid supercapacitor delivered an energy density of 21.6 Wh kg\(^{-1}\) at 799.9 W kg\(^{-1}\) and coulombic efficiency of 90.177% and 14.22 Wh kg\(^{-1}\) at a high power density of 7999.9 W kg\(^{-1}\) [76]. The comparison of various parameters of ZIF-8-derived different electrode materials in two-electrode systems for supercapacitor applications is presented in Table 3.
Figure 20: Continued.
Figure 20: Performance of ZPCA in 2 M KOH and 1 M Et₄NBF₄/AN electrolyte: (a) CV curves at the scan rate of 5–200 mV s⁻¹. (b) GCD curves at current densities of 0.5–5 A g⁻¹ in KOH electrolyte at 1.0 V. (c) CV curves at different scan rates. (d) GCD curves at different current densities in Et₄NBF₄/AN electrolyte at 3.8 V. (e) Nyquist plot. (f) Specific capacitances at various current densities. (g) Ragone plot (inset displays a red LED light-up by assembled ZPCA supercapacitor using Et₄NBF₄/AN electrolyte). (h) Cycling stability at 5 A g⁻¹ for 10,000 cycles of ZPCA-based symmetric supercapacitor at different electrolytes. (i) A digital photograph of cellulose hydrogel, cellulose aerogel, and CA. (j) SEM and (k) TEM images of CA. (l) SEM image of PCA. (m, n) SEM images of ZPCA [115] (reproduced from Ref. [115] with permission).
Table 3: Comparison of various parameters of ZIF-8-derived different electrode materials in two-electrode systems for supercapacitor applications.

<table>
<thead>
<tr>
<th>S. N.</th>
<th>Electrode material</th>
<th>Potential window (V)</th>
<th>Electrolyte</th>
<th>Energy density</th>
<th>Power density</th>
<th>Cyclic stability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N-doped carbon CZ-900//CZ-900</td>
<td>0.0-1.3</td>
<td>1 M H₂SO₄</td>
<td>21.1 Wh kg⁻¹</td>
<td>211.3 W kg⁻¹</td>
<td>97.5% over 8,500 cycles</td>
<td>[122]</td>
</tr>
<tr>
<td>2</td>
<td>Carbonized CZ-6//CZ-6</td>
<td>-1.0-0.0</td>
<td>6 M KOH</td>
<td>6.99 Wh kg⁻¹</td>
<td>262 W kg⁻¹</td>
<td>96% over 10,000 cycles</td>
<td>[123]</td>
</tr>
<tr>
<td>3</td>
<td>MWCNT/NPC//MWCNT/NPC</td>
<td>0.0-0.9</td>
<td>1 M H₂SO₄</td>
<td>12.65 Wh kg⁻¹</td>
<td>225.1 W kg⁻¹</td>
<td>95.8% over 10,000 cycles</td>
<td>[113]</td>
</tr>
<tr>
<td>4</td>
<td>NPCs/NPCS</td>
<td>0.0-1.0</td>
<td>1 M H₂SO₄</td>
<td>6.12 Wh kg⁻¹@250 W kg⁻¹ and 4.86 Wh kg⁻¹@25,000 W kg⁻¹</td>
<td>250 W kg⁻¹@6.12 Wh kg⁻¹ and 25 kW kg⁻¹@4.86 Wh kg⁻¹</td>
<td>94% over 10,000 cycles</td>
<td>[105]</td>
</tr>
<tr>
<td>5</td>
<td>NiCo-NFA//AC</td>
<td>0.0-1.7</td>
<td>6 M KOH</td>
<td>52.1 Wh kg⁻¹</td>
<td>16.5 kW kg⁻¹</td>
<td>NA</td>
<td>[121]</td>
</tr>
<tr>
<td>6</td>
<td>g-CN/NCPP//g-CN/NCPP</td>
<td>0.0-1.0</td>
<td>1 M H₂SO₄</td>
<td>11.89 Wh kg⁻¹</td>
<td>247.40 W kg⁻¹</td>
<td>100% after 2,500 GCD cycle</td>
<td>[116]</td>
</tr>
<tr>
<td>7</td>
<td>S-900//S-900</td>
<td>0.0-1.4</td>
<td>1 M H₂SO₄</td>
<td>6.44 mWh cm⁻³</td>
<td>0.031 W cm⁻³</td>
<td>NA</td>
<td>[125]</td>
</tr>
<tr>
<td>8</td>
<td>ZM-C-800//ZM-C-800</td>
<td>0.0-1.0</td>
<td>6 M KOH</td>
<td>11.4 Wh kg⁻¹</td>
<td>498.5 W kg⁻¹</td>
<td>98.3% over 10,000 cycles</td>
<td>[59]</td>
</tr>
<tr>
<td>9</td>
<td>PC-CNT//PC-CNT</td>
<td>0.0-1.0</td>
<td>6 M KOH</td>
<td>8.42 Wh kg⁻¹</td>
<td>250 W kg⁻¹</td>
<td>97.3% over 3,000 cycles</td>
<td>[106]</td>
</tr>
<tr>
<td>10</td>
<td>C-ZIF-8@ACW//C-ZIF-8@ACW</td>
<td>0.0-1.0</td>
<td>PVA/KOH</td>
<td>0.55 mWh cm⁻²</td>
<td>0.5 W cm⁻²</td>
<td>96.8% over 1,000 cycles</td>
<td>[126]</td>
</tr>
<tr>
<td>11</td>
<td>N-HPC//N-HPC</td>
<td>-1.0-0.0</td>
<td>6 M KOH</td>
<td>4.46 Wh kg⁻¹</td>
<td>50 W kg⁻¹</td>
<td>90% over 5,000 cycles</td>
<td>[127]</td>
</tr>
<tr>
<td>12</td>
<td>ZPCA//ZPCA</td>
<td>0.0-1.0</td>
<td>2 M KOH</td>
<td>13.4 Wh kg⁻¹</td>
<td>250 W kg⁻¹</td>
<td>91.2% over 10,000 cycles</td>
<td>[115]</td>
</tr>
<tr>
<td>13</td>
<td>rGO/Ni₉Zn₄S₄//AC</td>
<td>0.0-1.5</td>
<td>6 M KOH</td>
<td>31.06 Wh kg⁻¹</td>
<td>750.44 W kg⁻¹</td>
<td>59.7%</td>
<td>[128]</td>
</tr>
<tr>
<td>14</td>
<td>HHCF//HHCF</td>
<td>0.0-3.5</td>
<td>EMIMBF₄</td>
<td>74 Wh kg⁻¹</td>
<td>872 W kg⁻¹</td>
<td>95.81% over 10,000 cycles</td>
<td>[129]</td>
</tr>
<tr>
<td>15</td>
<td>NiS@Co-NC//AC</td>
<td>0.0-1.6</td>
<td>6 M KOH</td>
<td>21.6 Wh kg⁻¹@799.9 W kg⁻¹ and 14.22 Wh kg⁻¹@7999.9 W kg⁻¹</td>
<td>799.9 W kg⁻¹@21.6 Wh kg⁻¹ and 7999.9 W kg⁻¹@14.22 Wh kg⁻¹</td>
<td>89.95% over 5,000 cycles</td>
<td>[76]</td>
</tr>
</tbody>
</table>

The abovementioned two-electrode material displays various electrochemical signatures of supercapacitors. Among them, NiS@Co-NC, rGO/Ni$_2$ZnS$_x$/AC, and ZPCA/ZPC displays high specific capacitance of 1116.6 F g$^{-1}$ at 1 A g$^{-1}$, 1150 F g$^{-1}$ at 1 A g$^{-1}$, and 388 F g$^{-1}$ at 0.5 A g$^{-1}$, respectively. Likewise, NiS@Co-NC//AC, HHCF//HHCF, and rGO/ Ni$_2$ZnS$_x$/AC showed high energy density and power density, i.e., 21.6 Wh kg$^{-1}$ @ 799.9 W kg$^{-1}$, 74 Wh kg$^{-1}$ @ 872 W kg$^{-1}$, and 31.06 Wh kg$^{-1}$ @ 750.4 W kg$^{-1}$, respectively. Moreover, CZ-6/CZ-6, ZCN/ZCN, g-CN/NCP/g-CN/NCP, and ZM-C-800/ZM-C-800 showed excellent cyclic stability.

Recently, researchers have shown much interest in extracting hybrid material using ZIF-8 for supercapacitors. It is significant to note that several hybrid materials produced from ZIF-8 have shown promise for improving the electrochemical performance of supercapacitors. Hence, different synthesis methods of ZIF-derived MOFs and their metal oxide/carbon framework counterparts were discussed, along with their respective two-electrode and three-electrode supercapacitor applications [130]. Besides these, the energy storage property of ZIF-derived MOFs can also be elaborated according to their dimensionalities, such as 0D, 1D, 2D, and 3D. It is believed that the lower dimensional material has a larger surface area and a shorter reactant or electrolyte diffusion distance, resulting in better utilization of MOF active sites [5]. This further highlights the importance of synthesis methods, as only with the tailored methodology can the desired dimension of MOF be obtained.

Despite these characteristics, the electrochemical performance of ZIF-8-based material in two-electrode systems can be enhanced. Those opportunities and challenges are discussed below in Section 5.

4. ZIF-67-Derived Hybrid Materials for Supercapacitors

4.1. ZIF-67-Derived Hybrid Materials for Supercapacitors in a Three-Electrode System. Hou et al. synthesized hollow dodecahedral Co$_3$S$_4$@NiO and studied its electrochemical activity. They use the facile hydrothermal method to transform the ZIF-67 template into Co$_3$S$_4$ with TAA as a sulfur source. Ultimately, NiO sheets were grown on the surface of Co$_3$S$_4$ to produce a hollow dodecahedron Co$_3$S$_4$@NiO. The electrochemical performance of synthesized material was studied using three-electrode systems in 6 M KOH electrolyte. The composite material exhibited the specific capacitance of 1877.93 F g$^{-1}$ at the specific current of 1 A g$^{-1}$. Co$_3$S$_4$@NiO showed good cyclic stability with 92.6% capacity retention after 1000 cycles at the specific current of 5 A g$^{-1}$. The porous structure of Co$_3$S$_4$@NiO provided more active sites, accelerated the electrolyte transport, accelerated the electron transfer in the electrochemical process, and enhanced the capacitance [79].

Ezeigwe et al. synthesized ZIF-67-derived ternary zinc-nickel-cobalt hollow polyhedron (ZNC ZIF-67) using a facile route using ZIF-67 as both cobalt precursors and sacrificial template and studied its potential for use in supercapacitor electrode material. ZNC ZIF-67 has active sites, internal porous channels, and a diversified composition of interlinked nanoparticles that helps to increase a material’s specific surface area. Because of these properties ternary, ZNC ZIF-67 shows excellent capacitance compared to binary MOF-derived ZnCo$_2$O$_4$ [131]. The electrochemical performance of the synthesized composite was studied using three-electrode systems with Pt foil as a counter electrode, calomel as a reference electrode, and 6 M KOH as an aqueous electrolyte. The cyclic voltammetry was performed under the potential window of 0-0.5 V, and GCD was performed in a potential range of 0-0.4. ZNC ZIF-67 shows enhanced capacitance with a specific capacitance of 247 F g$^{-1}$ at a current density of 0.1 A g$^{-1}$. This electrode material shows outstanding cyclic stability of 99% over 5000 cycles.

Wang et al. synthesized N-Co$_3$S$_4$-GN/CNT for a high-performance cycling stable supercapacitor. N-Co$_3$S$_4$-GN/CNT is ZIF-67 derived; nitrogen-doped graphene-coated carbon nanotube (CNT) interlinked 3D Co$_3$S$_4$/C conductive network. Transition metal sulfide (TMS) electrode materials, i.e., Co$_3$S$_4$, have high capacitance but still have poor cyclic stability due to significant volume changes during charging and discharging and poor conductivity. This problem can be solved by mixing TMS with conductive materials such as graphene and carbon nanotubes (CNT). Thus, N-Co$_3$S$_4$-GN-CNT has excellent cycling stability [132, 133]. The electrochemical performance of synthesized material is studied using a three-electrode cell where calomel is used as reference electrode and Pt foil as counter electrode and working electrode of synthesized materials. 6 M KOH is used as an electrolyte. The CV is performed within the potential window of 0-0.6. NCSC-211 nanocomposite with a mass ratio of 2 : 1 : 1 for ZIF-67, melamine, and g-C$_3$N$_4$ shows enhanced electrochemical performance. NCSC-211 shows a specific capacitance of 1158 F g$^{-1}$ and excellent cyclic stability with 97.2% capacity retention after 5000 cycles at a current density of 5 A g$^{-1}$ [83]. Ahmad et al. prepared Co/NC/S@NH to study its electrochemical performance in supercapacitors. Co/NC/S@NH is a cobalt-based MOF nanosheet arrangement made up of ZIF-67-based nitrogen-doped nanotubes (Co/NC) and sulfur hosted in Ni foam by using Ni(OH)$_2$ nanoparticles. Thus, synthesized Co/NC/S@NH electrodes offer several advantages, such as a ZIF-derived nanotube providing excellent conductivity and the 3D porosity among interlinked nanotubes reducing the ion transfer pathway and offering tremendous free space for the dwelling of active sulfur ions [134]. The electrochemical tests were performed in 6 M KOH using three-electrode systems; calomel is used as reference electrode and Pt foil as counterelectrode, and working electrode is fabricated from synthesized material. The CV is performed within the potential window of 0-0.6. This composite shows the improved specific capacitance of 1636 F g$^{-1}$ at 1 A g$^{-1}$ and shows the cyclic stability of 94% over 5000 cycles. The electrochemical performances and FE-SEM images of Co/NC/S@NH are presented in Figure 21.

Kumar et al. synthesized polyoxometalate (POM)/ZIF-67 composite to study its electrochemical property [63]. The first main transition series with a higher oxidation state forms POMs [135]. POMs have the unique ability to undergo quick and reversible multielectron transfer while retaining their structural integrity [136]. They are known as electron sponges.
Figure 21: Continued.
due to their tendency to gain or lose up to 24 electrons. However, their application in electrochemical cells is confined due to their high solubility in aqueous and polar organic solvents [137]. To solve this problem, POMs are mixed with ZIF-67. When POMs are added to ZIF, POMs are encapsulated inside the ZIF cavity, which helps to prevent the dissolution of POMs. The electrochemical tests were performed using three-electrode cells with 1 M Na2SO4 as electrolyte. The CV is performed within the potential window of -0.2 to 0.6 V. The integrated electrode (ZADV@LSC) shows a maximum capacitance of 250.1 F g\(^{-1}\). The electrode material shows cyclic stability of 89% after 5000 cycles [63].

Lou et al. prepare coupled carbon quantum dots/NiCo-LDHs nanosheets on carbon cloth as electrode material for flexible supercapacitors [138]. One of the most promising electrode materials for supercapacitors is nickel–cobalt–layered double hydroxides (NiCo-LDHs) [139]. However, NiCo-LDHs’ low conductivity and volume change limit their use in supercapacitors. Thus, NiCo-LHDs and carbon quantum dot nanosheets are prepared to solve this problem. The electrochemical tests were conducted using three-electrode cells with 1 M Na2SO4 as electrolyte. The CV is performed within the potential window of -0.2 to 0.6 V. The integrated electrode (ZADV@LSC) shows a maximum capacitance of 250.1 F g\(^{-1}\). The electrode material shows cyclic stability of 89% after 5000 cycles [63].

Sundriyal et al. intercalate nickel in ZIF-67/rGO composite to enhance the electrochemical performance of the composite. Reduced graphene oxide (rGO) has a limited surface area but excellent electric conductivity. As a result, ZIF-67 is combined with porous ZIF-67. Reduced graphene oxide stores charge by an EDLC mechanism, whereas ZIF stores charge via a pseudocapacitive mechanism, resulting in a hybrid material. The high surface area of ZIF-67, the better conductivity of rGO nanosheets, and the improved expression of the redox process due to Ni-doping have resulted in outstanding electrochemical performance. A final composite, i.e., Ni33/ZIF-67/rGO20, was used as supercapacitor material, and a specific capacitance of 304 F g\(^{-1}\) was achieved. CV of synthesized material was performed at the potential window of 0-0.5 V using three-electrode cells and 1 M H2SO4 as electrolyte. This material exhibits a cycling stability of 87% after 4000 cycles [140].

Zhang et al. synthesized the polypyrrole nanotube-interconnected NiCo-LDH nanocages derived from ZIF-67 to study its potential application as a supercapacitor electrode. In PNT@NiCo-LDH composite, the higher specific surface area and active sites of NiCo-LDH result in better supercapacitor performance of ZIF derivatives. Meanwhile, NiCo-hollow LDHs’ cavities and pores reduced volume shrinkage while charging and discharging. The use of polypyrrole avoids the agglomeration of ZIF-derived nanoparticles. Also, the hydrophilic porous structure helps to increase electrolyte penetration and diffusion of ions [141].

Jian et al. interconnected carbon nanotubes with cobalt sulfide hybrid nanocage (CNT/CoS nanocage) derived from ZIF-67 to study its potential application in supercapacitors. The CV curves for given materials were obtained at a potential window of -0.07 to 0.63 V, where calomel is used as a reference electrode. CNT/CoS nanocage shows a specific capacitance of 2173.41 F g\(^{-1}\) and cyclic stability of 91% over 1000 cycles [142].

Chhetri et al. demonstrate controlled selenium infiltration of cobalt phosphide nanostructure arrays as a self-supported electrode for flexible quasisolid-state asymmetric supercapacitors using a two-dimensional cobalt metal-organic framework (ZIF-67). In this work, 2D Co-MOF arrays are successfully grown on an activated carbon fiber textile (ACFT) and converted into Sex@CPNA-ACFT through successive phosphidization and selenium infiltration processes under optimized conditions. In the three-electrode system, Se0.6@CPNA-
Figure 22: Continued.
Figure 22: (a, b) SEM images. (c, d) FE-SEM images. (e, f) TEM images. (g, h) HR-TEM images (the inset in (g) shows the SAED pattern) of Se0.6@CPNA-ACFT at different magnifications. (i) Comparative CV curves at 50 mA cm\(^{-2}\). (j) Comparative GCD curves at 1 mA cm\(^{-2}\). (k) Specific capacity as a function of the current density. (l) Nyquist plots (inset: equivalent circuit diagram) [62] (reproduced from Ref. [62] with permission).
ACFT shows a higher specific capacity of \(~302\) mAh g\(^{-1}\) and excellent cycling stability with a capacity retention of \(~93.8\)% after 10,000 cycles [55]. The electrochemical performances and FE-SEM images of Sex@CPNA-ACFT are presented in Figure 22.

Shrivastav et al. combined a hollow sphere of \(\text{Co}_3\text{S}_4\) derived from ZIF-67 with WS\(_2\) nanorods to prepare a hybrid \(\text{Co}_3\text{S}_4/{\text{WS}}_2\) material and studied its electrochemical performance. \(\text{Co}_3\text{S}_4/{\text{WS}}_2\) is the metal sulfide derived from pristine ZIF-67, and it is widely used as pseudocapacitive material in energy storage devices due to its high conductivity and redox activity. However, due to its low stability and less surface area, it has poor cycling life and charge-discharge rate. To improve this problem, Srivastav et al. combined \(\text{Co}_3\text{S}_4\) with \(\text{WS}_2\). The combination of \(\text{Co}_3\text{S}_4\) with \(\text{WS}_2\) helped to reduce the limitation of both. The material showed a specific

![Figure 23: (a–c) SEM images of TC-ZIF-67 with different magnifications. (d) CV curves. (e) GCD profile. (f) Rate capabilities of TC-ZIF-67 [145] (reproduced from Ref. [145] with permission).](image)
capacitance of 407 F g\(^{-1}\) at 1 Ag\(^{-1}\) current density and exhibited cycling stability of 94.3% after 2000 cycles in a three-electrode system [143].

He et al. synthesized Co(OH)F@NiCo-LDH using a three-step solvent-assisted technique. The synthesized material had improved mechanical stability, a large contact area, high capacitance value, and long cycling life. These properties jointly helped to enhance the electrochemical performance of the composite. The materials showed a specific capacitance of 1313.3 C g\(^{-1}\) at 1 Ag\(^{-1}\) current density and excellent cycling stability of 92.7% over 9000 cycles [144]. Ma et al. grew ZIF-67 flakes on textile carbon cloth and studied its electrochemical performance in three-electrode systems. Pristine ZIF-67 suffered from low conductivity and poor cyclic stability. To solve these problems, Ma et al. grew ZIF flakes on conductive textile cloth (TC), which enhanced the conductivity of ZIF-67 by three times and improved the cycling life. TC-ZIF-67 showed a specific capacitance of 303 F g\(^{-1}\) and cyclic stability of 103% over 15,000 cycles [145]. The electrochemical performances and FE-SEM images of ZIF flakes on conductive textile cloth are presented in Figure 23.

Rehan et al. synthesized a strip of ZIF-67 (SZIF-67) using a wet chemical technique and deposited a conducting polymer(polypropylene) on the surface of SZIF-67 by in situ polymerization to form SZIF-67@PPy. Pristine ZIF had poor conductivity, so its conductivity was enhanced by mixing it with conducting polymer. The electrochemical performance of synthesized material was studied using a three-electrode system where 1M H\(_2\)SO\(_4\) was used as an electrolyte. The material showed a specific capacitance of 220 F g\(^{-1}\) at 1 Ag\(^{-1}\) current density and cycling stability of 92% over 3000 cycles [147]. The comparison of various parameters of ZIF-67-derived different electrode materials in three electrodes system for supercapacitor applications is tabulated in Table 4.

The selected three-electrode material discussed above shows various electrochemical signatures of supercapacitors. Among them, (CQDs)/NiCo-LDHs@CC, Co\(_3\)S\(_4\)@NiO, and Co/NCl/S@NH displayed high specific capacitance of 2023 F g\(^{-1}\) 1877.93 F g\(^{-1}\), and the 1636 F g\(^{-1}\), respectively. Likewise, Co\(_3\)S\(_4\)@NiO, ZNC-ZIF-67, and CNT/CoS nanocage showed the highest cyclic stability. Despite these electrochemical characteristics, ZIF-67-based materials in three-electrode systems still have room for improvement regarding their electrochemical performance, which is discussed below in Section 5.

### Table 4: Comparison of various parameters of ZIF-67-derived different electrode materials in three-electrode system for supercapacitor applications.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Electrode materials</th>
<th>Potential window (V)</th>
<th>Electrolyte</th>
<th>Specific capacitance</th>
<th>Cyclic stability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Co(_3)S(_4)@NiO</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>1877.93 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>92.6% over 1,000 cycles</td>
<td>[79]</td>
</tr>
<tr>
<td>2.</td>
<td>ZNC-ZIF-67</td>
<td>0.0-0.4</td>
<td>6 M KOH</td>
<td>247 F g(^{-1}) @ 0.1 Ag(^{-1})</td>
<td>99% over 5,000 cycles</td>
<td>[131]</td>
</tr>
<tr>
<td>3.</td>
<td>N-Co(_3)S(_4)-GN/CNT</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>1158 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>97.2% over 5,000 cycles</td>
<td>[83]</td>
</tr>
<tr>
<td>4.</td>
<td>Co/NCl/S@NH</td>
<td>0.0-0.6</td>
<td>2 M KOH</td>
<td>1636 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>94% over 5,000 cycles</td>
<td>[134]</td>
</tr>
<tr>
<td>5.</td>
<td>ZADV@LSC</td>
<td>-0.2-0.6</td>
<td>1 M Na(_2)SO(_4)</td>
<td>250.1 F g(^{-1}) @ 0.8 Ag(^{-1})</td>
<td>89% over 5000 cycles</td>
<td>[63]</td>
</tr>
<tr>
<td>6.</td>
<td>(CQDs)/NiCo-LDHs@CC</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>2023 F g(^{-1}) @ 5 mA cm(^{-2})</td>
<td>83.1% over 5000 cycles</td>
<td>[138]</td>
</tr>
<tr>
<td>7.</td>
<td>PNT@NiCo-LDH</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>1448.2 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>84.3% over 5,000 cycles</td>
<td>[141]</td>
</tr>
<tr>
<td>8.</td>
<td>CNT/CoS nanocage</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>2173.1 F g(^{-1}) at 5 Ag(^{-1})</td>
<td>91% over 1,000 cycles</td>
<td>[142]</td>
</tr>
<tr>
<td>9.</td>
<td>Co(_3)O(_2)/NiNH</td>
<td>0.0-0.5</td>
<td>6 M KOH</td>
<td>541 C g(^{-1}) @ 4 Ag(^{-1})</td>
<td>82% over 10,000 cycles</td>
<td>[148]</td>
</tr>
<tr>
<td>10.</td>
<td>TC-ZIF-67</td>
<td>0.0-0.45</td>
<td>2 M KOH</td>
<td>303 F g(^{-1})</td>
<td>103% over 15,000 cycles</td>
<td>[145]</td>
</tr>
<tr>
<td>11.</td>
<td>Co(_3)S(_4)/WS(_2)</td>
<td>0.0-1.0</td>
<td>1 M H(_2)SO(_4)</td>
<td>407.3 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>94.3% over 2,000 cycles</td>
<td>[143]</td>
</tr>
<tr>
<td>12.</td>
<td>Co(OH)F@NiCo-LDH</td>
<td>0.0-0.45</td>
<td>3 M KOH</td>
<td>1313.3 C g(^{-1}) @ 1 Ag(^{-1})</td>
<td>92.7% over 7,000 cycles</td>
<td>[144]</td>
</tr>
<tr>
<td>13.</td>
<td>Cu(Co-Ni)(_3)S(_4) NTs/Ni</td>
<td>0.0-0.4</td>
<td>1 M KOH</td>
<td>1819 mAh g(^{-1}) @ 2 mA cm(^{-2}) (specific capacity)</td>
<td>96.2% over 5000 cycles</td>
<td>[146]</td>
</tr>
<tr>
<td>14.</td>
<td>Se(_{0.6})/CPNA-ACFT</td>
<td>0.0-0.5</td>
<td>3 M KOH</td>
<td>302 mAh g(^{-1}) @ 1 mA cm(^{-2}) (specific capacity)</td>
<td>93.8% over 10,000 cycles</td>
<td>[62]</td>
</tr>
<tr>
<td>15.</td>
<td>SZIF-67@PPy</td>
<td>-0.4-0.6</td>
<td>1 M H(_2)SO(_4)</td>
<td>220 F g(^{-1}) @ 1 Ag(^{-1})</td>
<td>92% over 3,000 cycles</td>
<td>[147]</td>
</tr>
</tbody>
</table>

Thus, an asymmetric capacitor with activated carbon as a negative electrode and Co-ZIF-R3 as a positive electrode was fabricated. The specific capacitance of the supercapacitor at the current density of 0.25 A g\(^{-1}\) was 32 C g\(^{-1}\), and cyclic stability was 87\% over 2500 cycles. The fabricated supercapacitor’s energy and power densities were 23 Wh Kg\(^{-1}\) and 218 W Kg\(^{-1}\), respectively [149]. The electrochemical performances in the two-electrode system and FE-SEM images of Co-ZIF-R3 are presented in Figure 24.

Cai et al. synthesized a hollow cage of nickel-cobalt sulfide derived from ZIF-67 to study it as electrode material in a supercapacitor. The cages of NiCo\(_2\)S\(_4\) consist of hollow cavities and mesoporous assembly, which accelerate the ion diffusion and provide more active sites. Cai et al. fabricated an asymmetric supercapacitor with NiCo\(_2\)S\(_4\) as a positive electrode and AC as a negative electrode to study its practical application in energy storage devices. The potential window used was 0−1.5 V. The ASC delivered the capacitance of 113 F g\(^{-1}\) at 1 A g\(^{-1}\) current density. The energy and power density obtained were 35.3 Wh Kg\(^{-1}\) and 750 W Kg\(^{-1}\), respectively [150].

Zhou et al. prepared an N-doped carbon skeleton from ZIF-67 and grew manganese dioxide (MnO\(_2\)) and vanadium nitrogen (VN) on the surface of the N-doped carbon skeleton to prepare N-C@MnO\(_2\) and N-C@VN. Carbon nanotube films supported the synthesized N-C frameworks to prepare CTF/N-C@MnO\(_2\) and CTF/N-C@VN. The all-solid-state asymmetric tandem all-in-one supercapacitor with CTF/N-C@MnO\(_2\) as the negative electrode and CTF/N-C@VN as the positive electrode was built to investigate the practical applicability of the designed material. The device showed a specific capacitance of 336.7 mF cm\(^{-2}\) at 2 mA cm\(^{-2}\) and an energy density of 2032.8 μWh cm\(^{-2}\) at the power density of 6583.6 μW cm\(^{-2}\). The device showed cyclic stability of 97.2\% over 6000 cycles [151].

Li et al. prepared C-LDH/Co\(_9\)S\(_8\) nanocage. C-LDH/Co\(_9\)S\(_8\) is composed of two components, i.e., Co\(_9\)S\(_8\) and NiCo-LDH derived from ZIF-67-C. ZIF-67-C was obtained by annealing ZIF-67. Poor conductivity and weak mechanical strength of nickel-cobalt double hydroxide (NiCo-LDH) limit its use in electrochemical devices. Thus, the combination of NiCo-LDH with Co\(_9\)S\(_8\) greatly enhances the
electrochemical performance of the material. The ASC with C-LDH/Co9S8 anode and AC cathode was developed to investigate the practical applicability of the synthesized material. The device had a specific capacitance of 151.2 F g\(^{-1}\) at 2 A g\(^{-1}\) and an 80.87 percent cycling stability over 10,000 cycles. At a power density of 1505 W Kg\(^{-1}\), the energy density displayed was 47.3 Wh Kg\(^{-1}\) [152].

Zhang et al. created graphene and carbon nanotube-encased cobalt derivative (Gr-CNT@Co) by heating ZIF-67 and graphene oxide complex. The all-solid-state asymmetric supercapacitor (ASSC) was fabricated with Gr-CNT@Co as an anode and N-doped graphene oxide (N-doped rGO) as a cathode to investigate the practical application of synthesized material in a supercapacitor device. At 1 A g\(^{-1}\) current density, the device had a specific capacitance of 140.2 F g\(^{-1}\) and cycling stability of 78% over 6000 cycles. At a power density of 685.3 W Kg\(^{-1}\), the device delivered 35.6 Wh Kg\(^{-1}\) of energy density [109].

Wang et al. prepared a CoNi\(_2\)S\(_4\) nanocage using ZIF-67 as a template. During the nanocage sulfuration reactions of induced Ni\(^{2+}\), template synthesis, nanosheet assemblies were produced on the nanocage surface, accelerating electrochemical reactions and increasing the number of active sites. An asymmetric supercapacitor (ASC) with CoNi\(_2\)S\(_4\) as the cathode and a yolk-shell structure carbon sphere (YS-CS) as the anode was created to investigate the practical application of electrode material in 2 M KOH electrolyte. The operating voltage was from 0 to 1.6 V. The ASC showed the specific capacitance of 98 F g\(^{-1}\) at the current density of 1 A g\(^{-1}\) and the cyclic stability of 63.28% over 5000 cycles. Fabricated ASC's energy and power densities were 35 Wh Kg\(^{-1}\) and 640 W Kg\(^{-1}\), respectively [153]. The electrochemical performances in the two-electrode system and FE-SEM images of ZIF-67-derived CoNi\(_2\)S\(_4\) nanocage are presented in Figure 25.

Li et al. combined vanadium oxide with a ZIF-67 nanocube as a template to obtain a hollow nanocube of Co\(_2\)V\(_2\)O\(_7\)/(CoVO-HNC). An asymmetric supercapacitor (ASC) was fabricated to study the practical application of CoVO-HNC. For the fabrication of asymmetric supercapacitors, AC was used as the cathode, and CoVO-HNC was used as the anode. The asymmetric supercapacitor had a specific capacitance of 71.11 F g\(^{-1}\) at 1 A g\(^{-1}\) current density and an energy density of 25.28 Wh Kg\(^{-1}\) when the power density was 801.24 W Kg\(^{-1}\). The cyclic performance of the device was 78% over 10,000 cycles [154].

Hong et al. synthesized layered Co\(_2\)O\(_4\)/NiNH composite and studied its electrochemical performance. First, they synthesized ZIF-67 by calcination process at 350°C in an inert atmosphere. The layered sandwich structure was created by fragmenting rhombic Co\(_2\)O\(_4\) into Co\(_2\)O\(_4\) particles, which provide sites for forming Ni\(_2\)(NO\(_3\))\(_2\)(OH)\(_4\) nanostructures, i.e., NiNH. The layered structure of Co\(_2\)O\(_4\)/NiNH and the large oxygen vacancies facilitated charge transport within Co\(_2\)O\(_4\)/NiNH and at the electrolyte contact. To study the potential application of Co\(_2\)O\(_4\)/NiNH in supercapacitors, an ASC was fabricated with Co\(_2\)O\(_4\)/NiNH anode and AC cathode. This device showed an energy density of 42.6 Wh Kg\(^{-1}\) at a power density of 823 W Kg\(^{-1}\) and cyclic stability of 82.3% over 10,000 cycles. The CV was performed within the potential window of 0-1.6 V. The specific capacitance of the device at 1 A g\(^{-1}\) was 187 C g\(^{-1}\) [148].

Le et al. synthesized Co\(_2\)V\(_2\)O\(_7\)/graphene nanocomposite. This composite had hollow nanocages of Co\(_2\)V\(_2\)O\(_7\) equally scattered on the sheets of graphene. The distinct structure of Co\(_2\)V\(_2\)O\(_7\) nanocage and graphene’s excellent conductivity accelerated the ion and electron transfer and increased the number of electroactive sites. In order to study its practical application, ASC with Co\(_2\)V\(_2\)O\(_7\)/graphene cathode and rGO anode with 1 M KOH was fabricated. ASC showed the specific capacitance of 86 F g\(^{-1}\) at 1 A g\(^{-1}\) and energy density of 25.7 Wh Kg\(^{-1}\) at the power density of 663.5 W Kg\(^{-1}\) [155].

Xie et al. combine nickel-cobalt sulfide and oxides from Ni\(_2\)CoS\(_8\)/ZIF-67 to prepare the α-Ni(Co)S@NiCoO\(_2\) composite. This nanocomposite had a core-shell structure with excellent pseudocapacitive behavior. An ASC with α-Ni(Co)S@NiCoO\(_2\) cathode and AC anode was built with 2 M KOH as the electrolyte to examine its practical applicability in supercapacitors. At 1 A g\(^{-1}\) current density, the device had a specific capacitance of 205.4 F g\(^{-1}\). The device showed an energy density of 82.4 Wh Kg\(^{-1}\) at a power density of 847.5 W Kg\(^{-1}\) and cyclic stability of 63.7% over 10,000 cycles [156].

Chu et al. used facile dipping and hydrothermal techniques to grow 3D flower-like CoWO\(_4\) composite from ZIF-67 on nickel foam (3D-HCoWO\(_4\)/NF). This composite has a large specific area and sufficient active sites. During the charge/discharge process, it can withstand significant volume change. Also, its 3D-hollow structure allowed it to transport ions/electrons rapidly. These properties help to enhance the electrochemical performance of 3D-HCoWO\(_4\)/NF. To study its potential application in a supercapacitor, ASC was fabricated where 3D-HCoWO\(_4\)/NF and AC were used as anode and cathode, respectively, with 2 M KOH as electrolyte. The potential window of ASC was 0-1.6 V. The specific capacitance obtained was 81 F g\(^{-1}\); ASC provided an energy density of 29.0 Wh Kg\(^{-1}\) when the power density was 404 W Kg\(^{-1}\) [157].

Qiu et al. synthesized NiO/Co\(_2\)O\(_4\) heterostructure by the pyrolysis of nickelocene (NiCp\(_2\)) packed with ZIF-67. The cohering of nickel on cobalt helped to accelerate the ion and electron transfer during the electrochemical process. In order to study its potential application in energy storage devices, an asymmetric capacitor (ASC) with NiO/Co\(_2\)O\(_4\) heterostructure anode and AC cathode was fabricated. Here, 6 M KOH was used as an electrolyte. The potential window for the device was taken from 0 to 1.5 V. The device shows the specific capacitance of 76 F g\(^{-1}\) at 1 A g\(^{-1}\) and delivered 97.9% cyclic stability over 1000 cycles. The ASC showed an energy density of 23.8 Wh Kg\(^{-1}\) and a power density of 750 W Kg\(^{-1}\) [158]. The electrochemical performances in the two-electrode system and SEM images of nickelocene-ZIF-67 are presented in Figure 26.

Tahir et al. synthesized microflowers of nickel cobalt and layered double hydroxide(NiCo-LDH) derived from ZIF-67 using hydrothermal methods. Here, the aqueous solution of ZIF-67 was used as a sacrificial template from which flower-like nanostructures of NiCo-LDH were synthesized, where 2,3,5,6-tetrafluoroterephthalic acid (H\(_2\)tfbdc) and hexamethylenetetramine (HMT) were used as additives. NiCo-
Figure 25: Continued.
LDH prepared had a large surface area and outstanding conductivity. Hierarchical microflower morphology increases the metal centers and enhances the pseudocapacitive behavior. An asymmetric supercapacitor was constructed with NiCo-LDH and AC as anode and cathode, respectively, to investigate the practical application of electrode material. Here, 6 M KOH was used as an electrolyte. The CV was performed within the potential window of 1.1 to 1.6 V. The specific capacitance obtained from ASC was 171 F g\(^{-1}\) at 1 A g\(^{-1}\) current density. Moreover, the cyclic stability obtained was 84.3\% over 6000 cycles. The energy and power density obtained were 53.31 Wh Kg\(^{-1}\) and 749.7 W Kg\(^{-1}\), respectively [77].

Hu et al. prepared ZIF-67@amorphousZIF electrode material for a high-performance asymmetric supercapacitor. The ASC had ZIF-67@amorphousZIF anode and AC cathode and displayed the specific capacitance of 65.9 F g\(^{-1}\) at 0.5 A g\(^{-1}\) and cyclic stability of 100\% over 2000 cycles. The excellent cyclic stability of the device was due to the core-shell structure of ZIF-67@amorphousZIF. The device delivered an energy density of 23.4 Wh Kg\(^{-1}\) at 0.48 kW Kg\(^{-1}\) power density [159]. The comparison of specific capacitances of ZIF-67-derived various electrode materials in two-electrode systems for supercapacitor applications is tabulated in Table 5.

The abovementioned two-electrode material displays various electrochemical performances of supercapacitors. It is worth noting that some ZIF-67-derived hybrid materials have been shown to boost the electrochemical performance of supercapacitors. Among them, α-Ni(Co)S@NiCoO\(_2\)//AC, NiCo-LDH/AC, and CoP-NPC/YS-CS displayed a high specific capacitance of 205.4 F g\(^{-1}\) @ 1 A g\(^{-1}\), 171 F g\(^{-1}\) @ 1 A g\(^{-1}\), and 151 F g\(^{-1}\) at 1 A g\(^{-1}\) respectively. Likewise, α-Ni(Co)S@NiCoO\(_2\)//AC, NiCo-LDH@AC, and C-LDH/CoS\(_2\)//AC showed high energy and power density, i.e., 82.4 Wh Kg\(^{-1}\) and 847.5 W Kg\(^{-1}\), 53.31 Wh Kg\(^{-1}\) and 749.7 W Kg\(^{-1}\), and 47.3 Wh Kg\(^{-1}\) and 1505 W Kg\(^{-1}\), respectively. Moreover, CoP-NPC/GS//CoP-NPC showed excellent cyclic stability. The combination of (CQDs)/NiCo-LDHs@CC, CoS\(_2@\)NiO, and Co/NC@NH materials uplifted specific capacitance to 2023 F g\(^{-1}\), 1877.93 F g\(^{-1}\), and the 1636 F g\(^{-1}\), respectively. These results also reveal that the prepared hybrid composite material with a porous architecture had remarkable cycling stability with very high specific capacitance, emphasizing the importance of developing ZIF-67-based hybrid materials for energy-storage devices. Similarly, CoS\(_2@\)NiO, ZNC-ZIF-67, and CNT/Co nanocage boosted the cyclic stability to a greater extent. α-Ni(Co)S@NiCoO\(_2\)//AC, NiCo-LDH//AC, and C-LDH/CoS\(_2//AC showed high energy and power density, i.e., 82.4 Wh Kg\(^{-1}\) and 847.5 W Kg\(^{-1}\), 53.31 Wh Kg\(^{-1}\) and 749.7 W Kg\(^{-1}\), and 47.3 Wh Kg\(^{-1}\) and 1505 W Kg\(^{-1}\), respectively. The high charge carrier motilities of QDs, NPCs, LDH, and transition metals made them responsible for enhancing their properties of storing charge, thus becoming a material with development prospects for supercapacitors application.

As a result, several synthesis techniques for metal oxide/ carbon framework counterparts of ZIF-derived MOFs and their two- and three-electrode supercapacitor applications were described. In addition, ZIF-derived MOFs’ energy storage capability may also be developed in terms of their dimensionailities, including 0D, 1D, 2D, and 3D. According to theory, the reduced dimensional material uses its MOF active sites more effectively since it has a higher surface area and a shorter reactant or electrolyte diffusion distance [5]. This emphasizes the significance of synthesis techniques even more since the necessary MOF dimension can only be achieved via a customized process. Despite these characteristics, the electrochemical performance of ZIF-67-based material in the two-electrodes system can be enhanced, and those opportunities are discussed below in Section 5.

5. Opportunities and Challenges

Supercapacitors are stellar energy storage systems because of their quick charge-discharge, excellent long-term stability,
Figure 26: (a, b) SEM images of ZIF-67. (c, d) SEM images nickelocene@ZIF-67. (e) Cyclic voltammetry curves at scan rates of 100 mVs$^{-1}$. (f) Galvanostatic charge-discharge curves. (g) Nyquist plots. (h) Ragone plots of the ASCs (NiO/Co$_3$O$_4$/AC and Co$_3$O$_4$/AC)[158] (reproduced from Ref. [158] with permission).
end high power density. The attractiveness of supercapacitors is set to expand as their unique combination of features makes them suited for most of the expected energy storage growth areas. Their electrochemical performance largely depends on the electrode material they possess, electrolytes employed, specific capacitance they show, assembling procedure, and long cycle life. Thus, selecting suitable electrode materials can account for better electrochemical performance. ZIFs offer an intriguing opportunity in this regard. The hollow and porous structure of ZIF-derived metal composite can provide a way to diffuse electrolyte ions, enhancing the reaction kinetics. Their conjugation with graphene, reduced graphene oxides, MXenes, and carbon nanotubes/rods can enhance their cyclic stability. Pure ZIF, on the other hand, has several drawbacks, including low cycling stability and discharge capacity. Because conductive polymers can improve overall electrical conductivity and make all of ZIF’s surfaces approachable to the electrolyte, mixing ZIF with conductive polymers was a more effective strategy for improving ZIF’s electrochemical performance. Nonetheless, the material’s low cycling stability and limited potential window prevent it from being used as an efficient electrode for supercapacitors. Encasing active species such as polyoxometalates within the cages of ZIFs or

<table>
<thead>
<tr>
<th>S. N.</th>
<th>Electrode material</th>
<th>Potential window</th>
<th>Electrolyte</th>
<th>Energy density</th>
<th>Power density</th>
<th>Cyclic stability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Co-ZIF-R3//AC</td>
<td>0.0-1.7 V</td>
<td>1 M KOH</td>
<td>23 Wh Kg⁻¹</td>
<td>218 W Kg⁻¹</td>
<td>87% over 2500 cycles</td>
<td>[149]</td>
</tr>
<tr>
<td>2</td>
<td>NiCo₂S₄ Hollow cage//AC</td>
<td>0.0-1.5 V</td>
<td>2 M KOH</td>
<td>35.3 Wh Kg⁻¹</td>
<td>700 W Kg⁻¹</td>
<td>79% over 10,000 cycles</td>
<td>[150]</td>
</tr>
<tr>
<td>3</td>
<td>YS-CS//CoNi₂S₄ Nanocage</td>
<td>0.0-1.6 V</td>
<td>2 M KOH</td>
<td>35 Wh Kg⁻¹</td>
<td>640 W Kg⁻¹</td>
<td>63.28% over 5000 cycles</td>
<td>[153]</td>
</tr>
<tr>
<td>4</td>
<td>α-Ni(Co)S@NiCoO₂//AC</td>
<td>0.0-1.7 V</td>
<td>2 M KOH</td>
<td>82.4 Wh Kg⁻¹</td>
<td>847.5 W Kg⁻¹</td>
<td>63.7% over 10,000 cycles</td>
<td>[156]</td>
</tr>
<tr>
<td>5</td>
<td>3D-HCoWO₄/NF//AC</td>
<td>0.0-1.6 V</td>
<td>2 M KOH</td>
<td>29.0 Wh Kg⁻¹</td>
<td>404 W Kg⁻¹</td>
<td>78% over 10,000 cycles</td>
<td>[157]</td>
</tr>
<tr>
<td>6</td>
<td>CoVO-HNC//AC</td>
<td>0.0-1.6 V</td>
<td>3 M KOH</td>
<td>25.28 Wh Kg⁻¹</td>
<td>801.24 W Kg⁻¹</td>
<td>82.3% over 10,000 cycles</td>
<td>[154]</td>
</tr>
<tr>
<td>7</td>
<td>Co₃O₄/NiNH//AC</td>
<td>0.0-1.6 V</td>
<td>2 M KOH</td>
<td>42.6 Wh Kg⁻¹</td>
<td>823 W Kg⁻¹</td>
<td>88% over 10,000 cycles</td>
<td>[148]</td>
</tr>
<tr>
<td>8</td>
<td>rGO//Co₃V₂O₇/graphene</td>
<td>0.0-1.5 V</td>
<td>1 M KOH</td>
<td>25.7 Wh Kg⁻¹</td>
<td>663.5 W Kg⁻¹</td>
<td>97.9% over 1000 cycles</td>
<td>[155]</td>
</tr>
<tr>
<td>9</td>
<td>NiO/Co₃O₄//AC</td>
<td>0.0-1.5 V</td>
<td>6 M KOH</td>
<td>23.8 Wh Kg⁻¹</td>
<td>750 W Kg⁻¹</td>
<td>84.3% over 6000 cycles</td>
<td>[158]</td>
</tr>
<tr>
<td>10</td>
<td>NiCo-LDH//AC</td>
<td>0.0-1.5 V</td>
<td>6 M KOH</td>
<td>53.31 Wh Kg⁻¹</td>
<td>749.7 W Kg⁻¹</td>
<td>97.2% over 6000 cycles</td>
<td>[77]</td>
</tr>
<tr>
<td>11</td>
<td>CTF/N-C@VN//CTF/ N-C@MnO₂</td>
<td>0-6.6 V</td>
<td>Gel LiCl/ PVA</td>
<td>2032.8 μWh cm⁻²</td>
<td>6583.6 μW cm⁻²</td>
<td>97.2% over 6000 cycles</td>
<td>[151]</td>
</tr>
<tr>
<td>12</td>
<td>CoP-NPC/GS // CoP-NPC</td>
<td>0-1.4 V</td>
<td>2 M KOH</td>
<td>10 Wh Kg⁻¹</td>
<td>700 W Kg⁻¹</td>
<td>100% over 11,000 cycles</td>
<td>[153]</td>
</tr>
<tr>
<td>13</td>
<td>C-LDH/Co₃S₈ //AC</td>
<td>0-1.5 V</td>
<td>3 M KOH</td>
<td>47.3 Wh Kg⁻¹</td>
<td>1505 W Kg⁻¹</td>
<td>80.87% over 10,000 cycles</td>
<td>[152]</td>
</tr>
<tr>
<td>14</td>
<td>Gr-CNT@Co//N-doped rGO</td>
<td>0-1.6 V</td>
<td>PVA/ KOH gel</td>
<td>36.5 Wh Kg⁻¹</td>
<td>685.3 W Kg⁻¹</td>
<td>78% over 6000 cycles</td>
<td>[109]</td>
</tr>
<tr>
<td>15</td>
<td>ZIF-67@amorphousZIF //AC</td>
<td>0-1.6 V</td>
<td>6 M KOH</td>
<td>23.4 Wh Kg⁻¹</td>
<td>0.48 kW Kg⁻¹</td>
<td>100% over 2000 cycles</td>
<td>[159]</td>
</tr>
</tbody>
</table>

Note: YS-CS: yolk shell carbon sphere; CTF: carbon nanotube film.
Materials and composites derived from ZIFs are becoming increasingly important in the innovation of high-performance supercapacitors. ZIFs should be prepared simply and primarily in the air, resulting in lower manufacturing costs and greater market availability. The electrochemical signature of ZIFs and derived materials should be enhanced, as this is critical for supercapacitor performance. Metal incorporation and doping of heteroatoms, metal oxides/hydroxides/sulfides, polymers, and heteroatoms improve their electrochemical performance, and their derived materials are promising strategies for improving the electrochemical performance of composite electrodes. Even with the discovery of numerous types and morphologies of ZIFs materials with excellent electrochemical properties, they still lag behind other energy storage materials. As a result, their morphology, manufacturing strategies, and reaction chemistry should be researched to achieve cost-effective, scalable manufacturing and high-performance electrode materials for highly desirable energy storage technologies. Despite numerous challenges, recent research on the rapid evolution of ZIF-derived materials has paved the way for a prosperous future for countless functional materials for energy storage technologies.

Data Availability
The research data supporting this review paper are from previously reported studies, which have been clearly cited.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Authors’ Contributions
Kisan Chhetri, Anup Adhikari, and Jyotendra Kunwar wrote the original draft; Kisan Chhetri, Debendra Acharya, Roshan Mangal Bhattarai, Young Sun Mok, and Achyut Adhikari wrote and edited the paper and conducted the literature review; Kisan Chhetri, Amar Prasad Yadav, and Hak Yong Kim proof-read, conceptualized, wrote, reviewed, and edited the manuscript. Anup Adhikari and Jyotendra Kunwar contributed equally to this work.

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