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Review Article

A Review on Carbon Cloth and Nickel Foam-Based Electrodes for High-Performance Supercapacitors

Yüksek Performanslı Süperkapasitörler İçin Karbon Kumaş ve Nikel Köpük Tabanlı Elektrotlara Yönelik Bir Derleme

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Abstract
The growing demand for sustainable and high-performance energy storage has intensified interest in supercapacitors, which offer fast charge–discharge rates, long cycle life, and environmental safety. While most studies focus on active electrode materials and electrolytes, the role of current collectors remains underexplored. This review addresses that gap by examining how current collector properties—such as conductivity, surface area, and flexibility—affect overall device performance. It focuses on two widely used and structurally contrasting collectors: nickel foam and carbon cloth. Nickel foam enables high capacitance and suits high-power applications due to its porous and conductive structure. In contrast, carbon cloth offers mechanical flexibility and long-term stability, making it ideal for wearable devices. By comparing their electrochemical behavior and practical trade-offs, this study provides guidance for selecting suitable current collectors and supports the design of next-generation energy storage systems.

Key Words
Current Collector, Supercapacitor, Electrode Design, Energy Storage, Carbon Cloth, Nickel Foam, Electrochemical Performance, Specific Capacitance.

Öz
Sürdürülebilir ve yüksek performanslı enerji depolama ihtiyacının artmasıyla birlikte, hızlı şarj-deşarj oranları, uzun çevrim ömrü ve çevre dostu yapısıyla öne çıkan süperkapasitörlere olan ilgi de giderek artmaktadır. Çoğu çalışma aktif elektrot malzemeleri ve elektrolitlere odaklansa da akım toplayıcıların rolü hâlâ yeterince araştırılmamıştır. Bu derleme, bu boşluğu doldurmayı amaçlayarak; iletkenlik, yüzey alanı ve esneklik gibi akım toplayıcı özelliklerinin cihaz performansını nasıl etkilediğini incelemektedir. Çalışma, yapı bakımından farklılık gösteren ve yaygın olarak kullanılan iki akım toplayıcıya odaklanmaktadır: nikel köpük ve karbon kumaş. Nikel köpük, gözenekli ve iletken yapısı sayesinde yüksek kapasitans sağlar ve yüksek güçlü uygulamalara uygundur. Buna karşılık, karbon kumaş mekanik esneklik ve uzun vadeli stabilite sunarak giyilebilir cihazlar için ideal bir seçenektir. Bu çalışma, bu iki malzemenin elektrokimyasal davranışlarını ve pratik kullanım açısından getirdiği avantaj–dezavantajları karşılaştırarak, uygun akım toplayıcı seçimine yönelik rehberlik sunmakta ve yeni nesil enerji depolama sistemlerinin tasarımını desteklemektedir.

Anahtar Kelimeler
Akım kolektörü, Süperkapasitör, Elektrot Tasarımı, Enerji Depolama, Karbon Kumaş, Nikel Köpük, Elektrokimyasal Performans, Spesifik Kapasitans.

1. Introduction

With the growing demand for sustainable and high-performance energy storage systems in applications ranging from portable electronics to electric vehicles and grid stabilization, extensive research has been directed toward the development of electrochemical energy storage devices (Aghmadi and Mohammed 2024; Njema, Ouma, and Kibet 2024; Ozen et al. 2021). Although batteries offer high energy density, their slow charge–discharge rates and limited cycle life have driven the pursuit of alternative technologies. In this context, supercapacitors have emerged as promising candidates due to their ability to deliver rapid charge/discharge capability, high power density, excellent cycling stability, and environmental safety.

Supercapacitors store energy through either electrostatic charge accumulation (electric double-layer capacitors) or fast surface redox reactions (pseudocapacitors), depending on the nature of the active electrode materials (Karthikeyan et al. 2021). The performance of these devices is governed by the synergistic interaction of key components: electrode materials, electrolytes, separators, and most critically, current collectors (Volfkovich 2021). Among them, the electrode structure and composition have traditionally received considerable attention, with numerous studies focusing on carbon-based materials, transition metal oxides (Abbas et al. 2022; Mbebou, Polat, and Zengin 2023), and conducting polymers to enhance specific capacitance and charge transfer kinetics (Akbar et al. 2023; Polat 2021b). For instance, MnO_2-based electrodes synthesized on Ni foam have reached specific capacitances exceeding 1300 F/g, while Fe_3O_4-based systems often report values above 500 F/g but suffer from cycling degradation over time (Abbas et al. 2022). Conducting polymers like polyaniline or PEDOT have demonstrated fast response and high capacitance yet show mechanical instability after repeated cycles (Polat 2021b). In addition, low-dimensional materials such as reduced graphene (Ke et al. 2023), carbon nanotubes (CNTs) (Singh, Akhtar, and Kar 2018), and MXene (Ghaemi, Masoudpanah, and Heidari 2023) have also been widely employed due to their high surface area, excellent electrical conductivity (Mohajer et al. 2023; Niftaliyeva et al. 2018; Xue et al. 2023), and tunable surface chemistry, which further enhances charge storage capability and ion transport efficiency. MXene-based composites, for example, have shown energy densities up to 40 Wh/kg and excellent rate performance, although their synthesis often requires complex conditions and strict atmospheric control (Ghaemi et al. 2023). Similarly, CNT-integrated electrodes can improve charge mobility but may lead to non-uniform dispersion unless properly functionalized (Singh et al. 2018). However, the efficient integration of these active materials heavily depends on the type of current collector employed. The surface characteristics, conductivity, flexibility, and chemical stability of the current collector influence not only the charge transport pathway but also the synthesis, adhesion, and distribution of the active layer (Polat 2021a; Zhang et al. 2020). Particularly in situ or direct-growth approaches, the choice of current collector can dictate the resulting microstructure and electrochemical behavior of the electrode (Duboviks et al. 2015; Lefdhil, Polat, and Zengin 2023; Polat, Mohammed, and Mashrah 2025; Shah et al. 2018). Hence, despite often being considered a passive component, the current collector plays a vital and active role in determining the final performance of a supercapacitor device.

Current collectors used in supercapacitor electrodes can be broadly categorized into metal-based, carbon-based, and hybrid or functionalized types, each offering distinct structural and electrochemical characteristics (Patel et al. 2024). Metal-based current collectors, such as nickel foam, copper foil, and aluminium foil, are widely preferred due to their high electrical conductivity and mechanical robustness (Verma et al. 2020). Among these, nickel foam (Ni foam) stands out with its three-dimensional porous network, which facilitates efficient electrolyte infiltration and provides a large surface area for active material deposition (Li et al. 2019). These features make it a benchmark material for high-performance electrodes in supercapacitor research. However, these current collectors are often rigid and susceptible to corrosion in certain electrolytic environments, which can limit their long-term stability.

In contrast, carbon-based current collectors like carbon cloth, carbon paper, and activated carbon fibre offer greater mechanical flexibility, chemical stability, and moderate conductivity (S. Chen, Qiu, and Cheng 2020). Their fibrous structure allows uniform coating of active materials and can adapt to bending or deformation, making them ideal for flexible or wearable supercapacitor systems (S. Chen et al. 2020; Hassan et al. 2020). Among them, carbon cloth has emerged as a particularly promising candidate for flexible energy storage devices, due to its high surface area, compatibility with diverse active materials, and ability to sustain mechanical deformation without performance degradation.

Additionally, the high surface area of some carbon textiles enhances electrode–electrolyte interactions, contributing to improved capacitance and cycle life (León et al. 2022). These differences underline the need to systematically examine how current collector type affects electrode structure and overall device performance, particularly in terms of capacitance, energy density, and cycling stability. A clear understanding of these distinctions is essential for selecting the appropriate current collector based on the target application and operational constraints.

Nickel foam and carbon cloth, two of the most widely used and structurally contrasting current collectors, are selected as the primary focus of this review. Their differing conductivity, surface morphology, and mechanical properties offer distinct advantages in various supercapacitor applications. This review systematically compares their roles in influencing electrode architecture and electrochemical performance, drawing on recent experimental studies. The originality of this work lies in its targeted evaluation of these two materials under diverse operational scenarios, rather than providing a broad but shallow overview. By consolidating current findings, the study offers practical insights into collector–material compatibility and contributes to the rational design of high-performance, application-oriented supercapacitor systems.

2. Current Collector Types and Their Characteristics

Current collectors play a pivotal role in the performance of supercapacitor electrodes by providing a conductive platform and physical support for active materials (Kumar, Pradhan, and Jena 2022). Their material composition, surface morphology, electrical conductivity, and mechanical properties influence the charge transport efficiency and overall stability of the device (Liu et al. 2025). Current collectors are generally classified into three major categories: metal-based, carbon-based, and hybrid/functional current collectors. A comparative summary of commonly used current collectors and their key physical attributes is presented below in Table 1.

2.1. Metal-Based Current Collectors

Metal foams, meshes, and foils, such as nickel foam (Jadhav et al. 2018; Polat and Mashrah 2022), stainless steel mesh (Salleh and Mohamad 2020), copper foil (Pilathottathil et al. 2019), and aluminum foil (Yang and Laforgue 2019), are commonly used as current collectors due to their excellent electrical conductivity and mechanical robustness. Among these, nickel foam (Ni foam) stands out for its 3D porous architecture, which offers a large surface area and facilitates efficient electrolyte penetration (Polat and Faris 2022). However, metal-based current collectors are generally rigid and prone to corrosion in certain electrolytes, which may limit their long-term stability (Mashrah and Polat 2023; Verma et al. 2020).

2.2. Carbon-Based Current Collectors

Carbon-based materials such as carbon cloth (CC), carbon paper, and activated carbon fiber (ACF) offer several advantages, including high flexibility, chemical stability, and moderate conductivity (Hassan et al. 2020; Verma et al. 2020). Their compatibility with flexible and wearable energy devices makes them attractive alternatives to metal foils, especially for lightweight and bendable configurations (Polat 2021c; Polat and Karakaş 2024). The porous nature and surface chemistry of carbon current collectors can also enhance the adhesion of active materials and improve accessibility.

2.3. Hybrid Current Collectors

To overcome the limitations of individual materials, hybrid or modified current collectors have been developed (Abdisattar et al. 2022; Muzaffar et al. 2019). These include metal-based current collectors coated with conductive nanomaterials (e.g., graphene, MXene, CNTs), carbon textiles decorated with metal oxides, or even polymer-derived conductive substrates (Ghaemi et al. 2023; Gul et al. 2025; Polat, Mashrah, and Maksur 2024; Singh et al. 2018). Such functionalized current collectors combine the electrical conductivity of metals with the flexibility or surface area of carbon-based materials, offering tailored properties for specific electrochemical applications.

Table 1. Basic Properties of Commonly Used Current Collectors

Current Collector Type	Material	Flexibility	Cost	Surface Area (m^2/g)	Remarks	Reference
Metal Foam	Nickel Foam	Low	Medium	High	Highly conductive, porous	(Grdeń, Alsabet, and Jerkiewicz 2012)
Carbon Cloth	Carbon Cloth	High	Medium	Moderate	Flexible, chemically stable	(León et al. 2022)
Activated Carbon Fiber	ACF	Moderate	High	Very High	Large surface area, adsorption-friendly	(Hassan et al. 2020)
Metal Foil	Cu / Al	Low	Low	Low	Flat, rigid, highly conductive	(Liu et al. 2021)

3. Mechanical, thermal and electrical properties of current collectors

The physical properties of current collectors, such as density, thickness, elastic modulus, and thermal stability, are critical parameters that influence the structural integrity, weight, and operational reliability of electrochemical energy storage devices. In particular, when designing systems intended for high-temperature environments or flexible/wearable applications, understanding these parameters becomes essential to optimize both electrochemical performance and mechanical compatibility.

Nickel foam, widely used for its high porosity and conductivity, has a relatively low density (0.45–0.62 g/cm³) and elastic modulus of around 200 MPa, offering mechanical compliance but limited stiffness (Kim et al. 2001). Its thermal stability extends to 1455 °C, making it highly suitable for high-temperature or harsh-environment applications. However, its low compressive strength (0.25 MPa) may restrict its use in mechanically demanding designs. In comparison, aluminum foam exhibits even lower elastic modulus (70 MPa) and a slightly reduced thermal range (660–800 °C), with higher density variation depending on its cellular structure (Verma et al. 2020). Stainless steel, both in foam and foil forms, provides a balance between rigidity and thermal resilience. The elastic modulus of stainless-steel foils can reach up to 190 GPa, with thermal stability around 1371–1537 °C, making them excellent candidates for structurally robust configurations (Feng et al. 2003). However, their relatively higher densities (~7.65–7.94 g/cm³) can contribute to overall device mass. Similar trends are observed for copper foil, which offers excellent conductivity and stiffness (elastic modulus: 110–128 GPa), but at the expense of high density (8.96 g/cm³) (Verma et al. 2020).

On the other hand, carbon-based current collectors, especially carbon fibre, offer a unique combination of extremely low density (1.7–2.0 g/cm³), wide thermal stability window (900–1500 °C), and superior stiffness (up to 228 GPa), making them ideal for lightweight and high-performance devices (Singh et al. 2018). These properties are especially beneficial in applications where low mass, high mechanical stability, and thermal endurance are simultaneously required. Furthermore, the compressive strength of these materials ranges significantly, from 0.005 MPa in platinum foil to over 1.65 MPa in titanium and tantalum foils, reflecting their load-bearing capabilities during cell assembly and cycling (Verma et al. 2020). The thickness of current collectors also varies widely, from ultra-thin foils (10–50 µm) in traditional setups to thick, porous foams (>1 mm) in specialized systems, directly influencing internal resistance and device footprint (Banerjee and Kar 2017; Inglehart 2024; Singh et al. 2018). In summary, the careful selection of current collector materials based on their physical and thermal properties is vital for tailoring the mechanical robustness, weight, and environmental endurance of supercapacitor and battery systems. High-modulus metals provide structural strength, while lightweight carbon-based materials offer flexibility and low thermal inertia, underscoring the importance of material choice according to specific application needs.

4. Recent Studies Employing Nickel Foam as Current Collector

The development of high-performance supercapacitor electrodes remains a critical area of research in the quest for efficient, stable, and scalable energy storage technologies. Among the various architectures investigated, nickel foam (NF)-based current collectors have garnered considerable attention due to their high electrical conductivity, low cost, open-cell 3D porous structure, and compatibility with diverse nanostructured materials. This discussion synthesizes findings from a wide range of recent studies that utilize NF substrates for electroactive material growth, highlighting the relationship between synthesis method, composite structure, and electrochemical performance, as summarized in Table 2a. Additionally, we evaluate the challenges and potential future directions that can guide further development of NF-based supercapacitor systems.

A variety of transition metal oxides and hydroxides have been integrated with nickel foam using diverse synthesis strategies to achieve improved capacitive behavior. For instance, $NiCo_2O_4$ nanowires grown via chemical bath deposition demonstrated a high specific capacity of 342.5 mAh/g at 3 A/g, with 80.7% retention after 10,000 cycles. Their integration into a $NiCo_2O_4$//graphite asymmetric device yielded an energy density of 45.8 Wh/kg and a power density of 5689 W/kg, demonstrating excellent reversibility and conductivity for practical applications9. On the other hand, a MnO_2 nanoparticle-based electrode synthesized through anodic electrodeposition using metal ions recovered from spent alkaline batteries offered a green and sustainable route. Although the performance was more modest (105 F/g, 14.7 Wh/kg), this work illustrates the growing importance of environmentally friendly synthesis and resource recovery5. $NiMn_2O_4$/GO nanocomposites, prepared using a microwave-assisted hydrothermal method, revealed that synthesis sequence significantly influences final morphology and electrochemical properties. When $NiMn_2O_4$ was deposited before the GO layer, the composite reached 700 F/g, while the pure oxide electrode achieved 802 F/g. However, over 3500 cycles, a 12.7% capacitance decay was observed, pointing to limitations in long-term diffusion efficiency through GO layers7. Structural optimization was taken a step further with the construction of NF@NT/CoNiNSs electrodes, where ZnO nanotubes were first hydrothermally grown, etched, and coated with CoNi-based nanosheets. This 3D@1D architecture provided exceptional surface area and mechanical integrity, resulting in 4.2 F/cm², energy density of 80.8 Wh/kg, and 90.7% retention after 27,500 cycles, the highest among the surveyed studies in terms of stability13. Meanwhile, functionalization of NF with cationic polyelectrolytes followed by growth of a ZnNiCo hydroxide/graphene-CNT hydrogel (GCH) composite offered a highly conductive and adhesive scaffold. The resulting electrode exhibited 1.185 mAh/cm² areal capacity and, when assembled into a hybrid device, provided 0.41 mWh/cm² energy density, showcasing the value of hybrid material design and interfacial engineering12. Other studies adopted creative heterostructures and dopant strategies. A Ni_3S_2@CdS core-shell electrode grown hydrothermally on NF delivered ultrahigh values (2100 F/g, 127.5 Wh/kg) and uniquely increased its capacity over time to 130% after 4000 cycles, suggesting redox activation during cycling20. Similarly, bismuth-doped $NiFe_2O_4$ not only served as a supercapacitor electrode (339.16 F/g, 90.76% retention) but also exhibited magnetic memory effects, pointing to the multifunctionality achievable with NF-based materials11. In terms of synthesis methods, microwave-assisted, hydrothermal, chemical bath, and electrodeposition approaches have been widely used. Each offers trade-offs between cost, scalability, and microstructural control. For example, microwave hydrothermal methods used for $NiMn_2O_4$ or Ni/Co hydroxide films improved crystallinity and interfacial contact, while CBD and electrodeposition were simpler but sometimes suffered from non-uniformity or adhesion issues.

Despite significant advancements in the development of Ni foam-based supercapacitor electrodes, several critical challenges remain that hinder their large-scale application and long-term reliability. These include limited stability under harsh operational conditions such as high temperature, mechanical stress, or prolonged cycling, especially for complex architectures like NF@NT or core–shell structures. A persistent trade-off between high mass loading and ion/electron transport efficiency also affects practical capacitance output. Moreover, interfacial issues—such as weak adhesion, swelling, or delamination in hydrogel or GO-coated systems—can degrade electrochemical performance over time. Reproducibility and scale-up of synthesis methods like hydrothermal or microwave-assisted processes also pose barriers to industrial translation. To address these, future efforts should focus on designing hierarchical architectures that balance material thickness and accessibility, reinforcing interface stability through covalent or atomic-scale engineering, and adopting scalable fabrication techniques such as roll-to-roll processing or 3D printing. Integrating self-healing, flexible, or multifunctional materials, alongside the use of eco-friendly precursors and full-cell optimization strategies, will be vital to transition these systems from laboratory studies to commercially viable energy storage solutions.

Table 2a. Electrode Performances Using Nickel Foam as Current Collector

No	Active Material	Capacitance (F/g)	Energy Density (Wh/kg)	Cycle Life (%)	Electrolyte	Reference
1	PEDOT/ZnO	139.28	37.9	91.0 (100 cycles)	0.1 mol·L^{-1} $TBAPF_6$/DCM solution	(Shao et al. 2024)
2	CuO/Co_3O_4	806.25	71.6	99.75 (2000 cycles)	3 M KOH	(Kim et al. 2017)
3	Mo-ZnO	2296	39.1	75.6 (8000 cycles)	3 M KOH	(Ali et al. 2019)
4	Co_3O_4@$NiMoO_4$	600	36.1	98.2 (8000 cycles)	3 M KOH	(Tong et al. 2022)
5	MnO_2	549	14.7	87.2 (5000 cycles)	0.5 M K_2SO_4	(Edison et al. 2019)
6	$MnFe_2O_4$	302.6	68.7	87.3 (3000 cycles)	6 M KOH	(Fei et al. 2021)
7	$NiCo_2O_4$	1398.73	46.5	83.6 (5000 cycles)	2 M KOH	(X. Chen et al. 2020)
8	$NiCo_2O_4$@MnO_2/nickel foam/MnO_2	850	53.5	91 (30000 cycles)	6 M KOH	(Guo et al. 2019)
9	$NiCo_2O_4$	1233	45.8	80.7 (10000 cycles)	3 M KOH	(Km et al. 2022)
10	MnO_2	2790 mF/cm²	37.2	80 (1000 cycles)	1 M Na_2SO_4	(Yang et al. 2014)
11	$NiFe_2O_4$	339	4.4	90.76 (5000 cycles)	2 M KOH	(Hsu et al. 2025)
12	$NiMn_2O_4$/graphene oxide	700	-	87.3 (3500 cycles)	6 M KOH	(Wang et al. 2023)
13	NF@NT/CoNiNSs	4.2 F/cm^2	80.8 Wh/kg	97 (20000 cycles)	1 M KOH	(Tan et al. 2023)
14	VN-Qd-PC	1008 mF/cm^2	47.2	86.6 (4000 cycles)	1 M KOH	(Yang et al. 2016)
15	MOF/$Cu_{2+1}O$	1548 mF/cm^2	25.7 Wh/kg	97 (5000 cycles)	6 M KOH	(Cao et al. 2019)
16	$Ni(OH)_2$ nanoflakes	1416 F/g	18.4 Wh/kg	62 (10000 cycles)	KOH	(Alhebshi, Rakhi, and Alshareef 2013)
17	$Ni_2(CO_3)(OH)_2/Co(OH)_2$	415 mF/cm^2	30.3 Wh/kg	95 (8000 cycles)	KOH	(Tu et al. 2023)
18	ZnNiCo-GNP/CNT	1.185 mAh/cm^2	0.4 mWh/cm^2	82.6 (10000 cycles)	6 M KOH	(Lyu et al. 2021)
19	P-$Ni(OH)_2$ rods@MnO_2	5.75 F/cm^2	0.324 mWh/cm^2	100 (20000 cycles)	1 M LiOH	(Li et al. 2018)
20	Ni_3S_2@CdS	2100	127 Wh/kg	86.7 (3000 cycles)	KOH	(Wang et al. 2017)

5. Recent Studies Employing Carbon Cloth as Current Collector

Flexible energy storage systems are rapidly gaining prominence due to the increasing integration of wearable and portable electronics into daily life. Supercapacitors, in particular, offer unique advantages such as fast charge–discharge rates, long cycle life, and superior power density compared to batteries. To realize their full potential in flexible formats, the choice of current collector becomes crucial. Carbon cloth (CC) stands out among flexible substrates thanks to its woven 3D structure, high electrical conductivity, mechanical durability, and chemical stability. However, pristine CC has limited electrochemical activity, necessitating its functionalization with redox-active materials. In recent years, various studies have explored innovative combinations of transition metal oxides, conductive polymers, and carbon nanostructures anchored on CC to enhance both capacitance and stability. The following section summarizes a wide range of such strategies reported in the literature, highlighting the materials used, fabrication techniques, achieved performance metrics, and distinctive contributions of each approach.

In the literature, diverse strategies have been implemented to functionalize carbon cloth (CC) for supercapacitor applications. For instance, nanostructured Co_9S_8/polypyrrole hybrids grown directly on CC exhibited high pseudocapacitance due to the synergistic effect between the redox-active sulfide and the conductive polymer, representing a battery-type storage mechanism (1.pdf). Similarly, carbon cloth was used as a substrate for vertically aligned $NiCo_2S_4$ nanosheets, achieving enhanced cycling performance through a facile hydrothermal synthesis (2.pdf). Another approach utilized MnO_2 nanotubes directly synthesized on CC, forming binder-free flexible electrodes with 2.35 mF/cm² areal capacitance (3.pdf). To further improve redox activity and structural robustness, a hierarchical $MnMoO_4$@$CuMoO_4$ core-shell structure was designed on CC, yielding a specific capacity of 304.3 C/g and excellent reversibility (4.pdf). Likewise, γ-MnO_2 coated on CC followed by polyaniline electropolymerization delivered a high areal capacitance of 1105 mF/cm² with 86.35% retention over 2000 cycles (5.pdf). Review-based insights into CNT/MnO_2/graphene composites anchored on CC emphasized the importance of hierarchical nanoarchitecture for high mass loading and ion transport (6.pdf). Moreover, a dual-step hydrothermal strategy yielded CC@$NiCo_2O_4$@$NiMoO_4$ composites with a remarkable areal capacitance of 2.917 F/cm² and 90.6% capacity retention, attributed to the integrated conductive skeleton and hierarchical porosity (7.pdf). Ammonium pre-intercalation was employed in δ-MnO_2 grown on CC to expand the operating voltage window up to 1.1 V, resulting in 181.4 F/g capacitance and 81.2% retention over 10,000 cycles (8.pdf). Additionally, a PEDOT/MnO_2 composite electrode on heat-activated CC achieved 1882.5 mF/cm² capacitance and retained 94.6% capacity after 10,000 cycles under a wide 1.8 V window (9.pdf). In terms of carbon–oxide synergy, MnO@rGO nanohybrids anchored on CC exhibited 831.25 mF/cm² capacitance with 97.2% retention over prolonged cycling (10.pdf). Similarly, a flower-like NiS_2@CC hybrid delivered 1166.3 F/g and 34.1 Wh/kg energy density in a flexible asymmetric configuration, maintaining 96% stability after 8000 cycles (11.pdf). A PEDOT-coated MnO_2/ACC system confirmed the synergistic benefit of polymer–oxide networks on CC, ensuring mechanical flexibility and electrochemical durability (12.pdf). Potassium doping in MnO_2@CC was shown to expand the potential window and boost energy density, by stabilizing interlayer structures (13.pdf). In another strategy, graphene hydrogels were first anchored onto CC, followed by PPy electrodeposition, yielding up to 1462.5 mF/cm² capacitance and scalability up to 6556.3 mF/cm² while maintaining flexibility (14.pdf). A ternary $MnCo_2O_4$@$CuCo_2O_4$ nanosphere array synthesized on CC further enhanced redox synergy, achieving 62 Wh/kg at 747.2 W/kg (15.pdf). Beyond metal oxides, cryopolymerized PANI hydrogels fabricated on CC created superelastic and deformation-tolerant supercapacitor electrodes with robust mechanical compliance (16.pdf). At the atomic level, CoAl-layered double hydroxide arrays grown on CC showed rate-capable performance via electronic structure modulation (17.pdf). Likewise, porous Fe_2O_3 nanospheres integrated into activated CC for symmetric devices exhibited 49.1 F/g specific capacitance and cycling stability (18.pdf). Ni_2P structures grown on activated CC achieved high surface area and improved conductivity, enhancing the rate performance in hybrid devices (19.pdf). Finally, a textile-based PEDOT:PSS-coated carbon cloth enabled real-life wearable supercapacitors operating under sweat, highlighting the biocompatibility and environmental adaptability of CC-based platforms (20.pdf).

Despite notable advances in CC-based supercapacitor electrodes, key challenges remain in achieving high-performance and durable flexible devices. A primary concern is the mechanical instability of active materials under deformation or prolonged cycling, which can lead to detachment, cracking, or loss of conductivity—particularly in thick or poorly bonded layers. Additionally, the trade-off between high areal capacitance and device flexibility remains unresolved, as denser architectures often hinder ion diffusion and mechanical compliance. Future efforts should focus on engineering hierarchical or core–shell structures with improved interfacial adhesion, elasticity, and ion accessibility. Scalable and low-temperature fabrication methods, such as 3D printing or in-situ polymerization, combined with eco-friendly or recycled carbon textiles, may pave the way for sustainable device production. Furthermore, the integration of smart diagnostics and data-driven design tools holds promise for optimizing performance and predicting long-term behavior in next-generation flexible energy storage systems.

Table 2b. Electrode Performances Using Carbon Cloth as Current Collector

No	Active Material	Capacitance (F/g)	Energy Density (Wh/kg)	Cycle Life (%)	Electrolyte	Reference
1	MnO_2/PEDOT	1882 mF/cm^2	0.25 mWh/cm^2	94.6 (10000 cycles)	1.5 M LiCl	(Akbar et al. 2023)
2	$MnFe_2O_4$@PPy	1169	73.6	87.6 (5000 cycles)	1 M H_2SO_4	(Devi et al. 2024)
3	WS2@$NiCo_2O_4$	1224	45.67	85.59 (5000 cycles)	3 M KOH	(Li et al. 2020)
4	δ-MnO_2	263	180	94 (5000 cycles)	1M $Zn(NO_3)_2$	(Wang et al. 2024)
5	γ-MnO_2	540	1962.26 Wh/kg	90 (5000 cycles)	0.5 M H_2SO_4	(Zhu et al. 2022)

6	$NiCo_2O_4$	1476	-	94.25 (5000 cycles)	6 M KOH	(Abbas et al. 2022)
7	$NiCo_2O_4$@$NiMoO_4$	1458	-	90.6 (2000 cycles)	3 M KOH	(Huang et al. 2016)
8	MnO_2	181	63.49	81.2 (10000 cycles)	1 M Li_2SO_4	(Zheng et al. 2024)
9	$MnFe_2O_4$@C	824	27	93.9 (10000 cycles)	2 M KOH	(Geng et al. 2019)
10	MnO@rGO	831	17.320	97.2 (10000 cycles)	1 M Na_2SO_4	(Ke et al. 2023)
11	Fe_2O_3@PPy/CC	615	-	79.3 (5000 cycles)	1 M Na_2SO_4	(Wu et al. 2023)
12	Fe_2O_3@NiO	800	-	96.8 (16000 cycles)	3 M KOH	(Zhang et al. 2020)
13	PANI–CC	691	-	94 (2000 cycles)	1 M H_2SO_4	(Ahirrao et al. 2021)
14	SWCNF–$Co_2(OH)_2CO_3$	408	28.6	90.7 (5000 cycles)	1 M KOH	(Zhu et al. 2023)vv
15	MnO_2/PEDOT	1882 mF/cm^2	0.25 mWh/cm^2	96 (10000 cycles)	1.5 M LiCl	(Akbar et al. 2023)
16	Graphene-CF	5.1 mF/cm^2	86.6 µWh/cm^2	100 (20000 cycles)	1 M H_2SO_4	(Yao et al. 2023)
17	CC@rGO	522 mF/cm^2	14.6 mWh/cm^2	99 (5000 cycles)	1 M H_2SO_4	(Zhang et al. 2022)
18	Redox-etching	4035 mF/cm^2	6.5 mWh/cm^3	72.1 (5000 cycles)	5 M NaCl	(Han et al. 2022)
19	$MnCo_2O_4$@$CuCo_2O_4$	1241	62 Wh/kg	92 (10000 cycles)	KOH	(Chen et al. 2021)
20	NiS_2/CC	1166	34.1 Wh/kg	96 (8000 cycles)	KOH	(Fu et al. 2022)

6. Comparative Insights into Ni Foam and Carbon Cloth Current Collectors

The choice of current collector plays a pivotal role in the design of high-performance supercapacitors, directly influencing charge transport, mechanical stability, device architecture, and long-term reliability. Among the most widely explored conductive substrates, nickel foam (NF) and carbon cloth (CC) stand out due to their complementary structural and electrochemical characteristics. While both materials provide three-dimensional porosity and excellent electrical conductivity, they differ significantly in terms of mechanical behavior, compatibility with flexible devices, cost, and scalability. This section offers a comparative assessment of recent studies utilizing NF and CC as current collectors, aiming to delineate their respective strengths, limitations, and the future directions necessary to overcome common challenges.

Nickel foam offers a rigid, open-cell 3D metallic network that supports high mass loading and strong mechanical adhesion of pseudocapacitive materials, making it ideal for applications requiring high areal or volumetric capacitance. For instance, advanced architectures such as NF@NT/CoNiNSs have achieved remarkable metrics—up to 4.2 F/cm² and 80.8 Wh/kg—while maintaining over 90% capacity after 27,500 cycles, owing to their structural integrity and high electrical conductivity. Similarly, hydrothermal or microwave-assisted deposition on NF facilitates well-defined nanostructures with controllable morphology, such as $NiMn_2O_4$/GO or Ni_3S_2@CdS core-shell systems, pushing the limits of power density and cycle stability. However, NF's rigidity limits its application in flexible or wearable electronics. Additionally, adhesion issues at oxide–metal interfaces and degradation under long-term cycling or high-temperature conditions remain concerns.

In contrast, carbon cloth's soft, flexible textile form factor is exceptionally well-suited for next-generation bendable and wearable energy storage devices. Although CC has lower intrinsic strength than NF, its woven, porous structure allows conformal coating of active materials and good electrolyte accessibility. Functionalization with materials such as MnO_2, $NiCo_2O_4$, PEDOT, or PPy has enabled CC-based electrodes to achieve competitive performance—for example, PEDOT/MnO_2/CC achieving 1882.5 mF/cm^2 with 94.6% retention over 10,000 cycles (9.pdf). The added benefit of compatibility with conductive polymers and bio-derived or textile-based substrates further enhances CC's potential for environmentally sustainable devices. Nevertheless, CC electrodes are often constrained by issues like poor adhesion of thick coatings, material delamination under stress, and a trade-off between flexibility and high mass loading. Furthermore, while CC excels in flexibility and processability, it generally falls behind NF in terms of raw current-handling capacity and mechanical robustness under static compression.

In summary, NF and CC offer distinct advantages tailored to different supercapacitor use cases: NF is superior for rigid, high-power applications where structural support and current density are critical, while CC is ideal for lightweight, flexible, and wearable formats. Moving forward, bridging the performance gap between these two systems will require hybrid solutions—such as CC reinforced with conductive scaffolds or NF modified for improved flexibility. Future research should focus on universal challenges like enhancing interfacial adhesion, optimizing hierarchical structures for ion/electron transport, and scaling up synthesis techniques without sacrificing material integrity. Combining the mechanical adaptability of CC with the electrochemical performance of NF-inspired nanostructures, possibly through 3D-printed composites or textile-metal hybrids, may unlock new classes of multifunctional and industrially viable supercapacitor systems.

7. Conclusion

This review highlights the critical influence of current collectors on the electrochemical performance of supercapacitor electrodes. Among the available options, nickel foam and carbon cloth have emerged as two of the most extensively studied and practically relevant platforms, each offering distinct advantages. Nickel foam, with its high electrical conductivity and porous 3D network, supports efficient charge transfer and facilitates high specific capacitance—exceeding 1300 F/g in some configurations—while maintaining stable cycling performance (typically above 85% after several thousand cycles). In contrast, carbon cloth offers superior mechanical flexibility and chemical stability, making it highly compatible with various hybrid electrode materials. It has achieved capacitance values over 1000 F/g and excellent long-term durability, with retention up to 96% after 16,000 cycles.

Overall, the findings indicate that the selection of a current collector should be tailored to the specific application context. For high-power systems where conductivity and active material integration are critical, such as industrial or grid-related storage, nickel foam is advantageous. Conversely, for portable, flexible, or wearable electronics, where mechanical adaptability and chemical robustness are key, carbon cloth proves more suitable. This comparative evaluation underscores that no single current collector is universally optimal; performance maximization requires aligning collector properties with operational demands.

Moreover, the integration of current collectors with advanced electrode materials plays a pivotal role in determining overall energy and power metrics. Their surface morphology, conductivity, and interfacial behavior directly affect the synthesis, adhesion, and charge storage capability of the active layer. Therefore, current collectors should be treated as active components in device architecture, rather than passive supports.

To further advance the field, future research should focus on hybrid current collector systems that combine the strengths of both metal- and carbon-based substrates—such as metal-coated textiles or flexible metallic meshes. Additionally, there is a need for scalable, low-cost fabrication techniques, corrosion-resistant surface modifications, and customized designs for emerging applications (e.g., stretchable or miniaturized electronics). A deeper understanding of interfacial charge transfer dynamics and mechanical–electrochemical coupling will be key to guiding the next generation of high-performance and flexible supercapacitors.

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