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Transition Metal Chalcogenides for Supercapacitors: Design Strategies, Performance Modulation, and Future Perspectives

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ABSTRACT

The growing demand for efficient and sustainable energy storage has accelerated the development of supercapacitors as devices that bridge the performance gap between conventional batteries and dielectric capacitors. Although supercapacitors offer high power density, rapid charge–discharge rates, and long cycling stability, their performance is strongly dependent on the choice of electrode materials. Transition metal chalcogenides (TMCs) have emerged as promising candidates due to their rich redox chemistry, layered crystalline structures, tunable electronic properties, and multiple oxidation states. This review provides a critical and comprehensive analysis of the recent advances in TMC-based electrodes, including monometallic, bimetallic, and doped systems. In contrast to prior reviews, this study systematically correlates synthesis strategies, compositional tuning, and defect engineering with charge storage mechanisms to establish a unified structure-property-performance framework. Key design and synthesis approaches are evaluated in relation to their influence on electrochemical behavior, with particular emphasis on redox reactions and ion intercalation. Performance metrics such as specific capacitance, energy density, power density, and cycling stability were comparatively assessed to identify material trends. Unlike prior reviews, this study explicitly identifies the key limitations of TMC-based electrodes, including conductivity constraints, chemical instability, phase degradation, and non-standardized testing conditions, and systematically correlates these challenges with targeted material design strategies to establish a unified structure–property–performance framework. Persistent challenges, including limited conductivity, structural degradation, and scalability, are critically discussed, along with potential solutions such as hybridization and defect modulation. Finally, future research directions are outlined to enable the development of robust, high-performance, and sustainable TMC-based supercapacitor electrodes are outlined.

1. INTRODUCTION

The increasing global demand for efficient and sustainable energy storage systems, driven by the rapid expansion of renewable energy technologies, portable electronics, and electric vehicles, has intensified the need for advanced electrochemical energy storage solutions [1-3]. Conventional batteries, such as lithium-ion and sodium-ion systems, offer high energy densities; however, their performance is limited by their low power density, sluggish charge–discharge kinetics, and structural degradation during prolonged cycling [4-6]. In contrast, dielectric capacitors exhibit excellent power capability and long cycle life but suffer from inherently low energy densities [7]. Supercapacitors bridge this gap by delivering high power density, rapid charge–discharge rates, and long operational stability; however, their relatively low energy density remains a critical challenge that is strongly governed by electrode material design [8-10].

Electrochemical energy storage in supercapacitors is generally classified into three mechanisms: electric double-layer capacitance (EDLC), pseudocapacitance, and battery-type faradaic reactions. EDLC originate from electrostatic charge accumulation at the electrode–electrolyte interface and are characteristic of carbon-based materials with a high surface area and excellent cycling stability [11, 12]. Pseudocapacitance involves fast and reversible surface or near-surface redox reactions, which enable a higher capacitance with relatively rapid kinetics. In contrast, battery-type behavior is governed by diffusion-controlled faradaic reactions involving bulk phase transformations, which are

typically associated with pronounced redox peaks, slower kinetics, and limited rate capability. Importantly, many transition metal-based electrodes, including transition metal chalcogenides (TMCs), exhibit a combination of pseudocapacitive and battery-type characteristics; thus, a careful distinction between these mechanisms is essential for the accurate interpretation of electrochemical performance. A schematic comparison of pseudocapacitive/battery-type charge storage and EDLC mechanisms is illustrated in Figure 1.

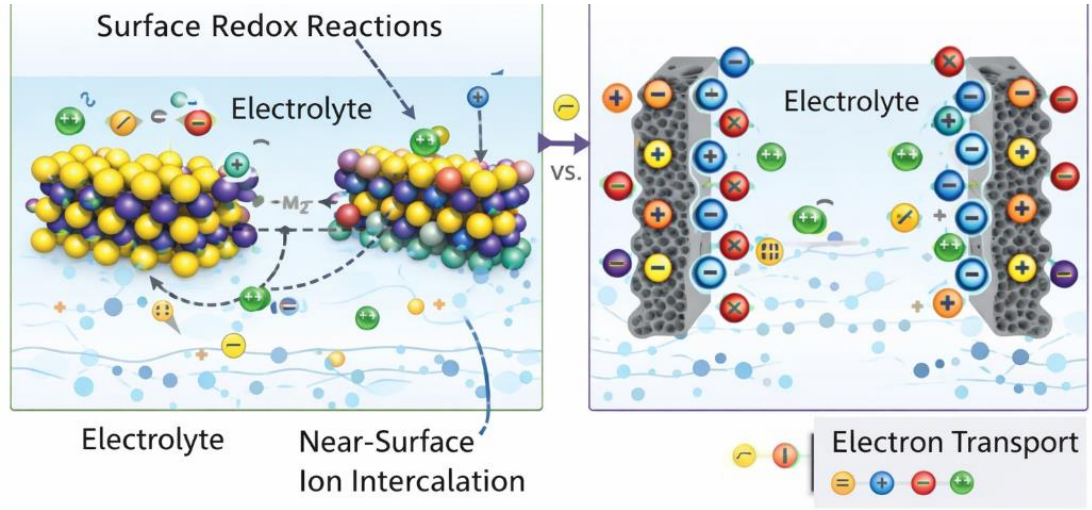

Figure 1. Sketch showing charge storage mechanisms in (a) transition metal chalcogenides and (b) electric double-layer capacitors (EDLC)

Among the emerging electrode materials, TMCs have attracted significant attention owing to their rich redox chemistry, layered crystal structures, tunable electronic properties, and multiple oxidation states [13]. Compared to transition metal oxides, TMCs generally exhibit improved electrical conductivity owing to reduced metal–chalcogen bond ionicity, which enhances the charge-transfer kinetics and pseudocapacitive behavior [14, 15]. Furthermore, their layered architectures facilitate ion diffusion and near-surface intercalation, contributing to the improved electrochemical utilization of active materials. Despite these advantages, the practical application of TMC-based supercapacitor electrodes is hindered by several critical material- and device-level challenges.

A major limitation is the insufficient electrical conductivity of many monometallic TMCs, such as MoS_2 and WS_2, which restricts electron transport and rate capability at high current densities [16-21]. Additionally, structural instability and phase degradation during repeated faradaic cycling, caused by volume expansion, lattice distortion, and surface reconstruction, lead to progressive capacitance fading, particularly in Ni- and Co-based sulfides [22-33]. Another key issue is the chemical instability of sulfide- and selenide-based systems, including oxidation and metal dissolution in aqueous electrolytes, which compromises their long-term cycling stability [34, 35]. Moreover, most reported electrochemical performances are obtained under low mass loading and idealized laboratory conditions, limiting their relevance to practical device configurations and obscuring realistic energy metrics and power. Challenges associated with scalability, synthesis reproducibility, and environmental considerations, particularly for multimetallic systems, hinder large-scale deployment.

To address these limitations, various design strategies have been explored, including nanostructuring, compositional tuning, hybridization with conductive carbon matrices and elemental doping. However, a systematic understanding of how these approaches influence the conductivity, structural stability, redox activity, and electrochemical utilization across different classes of TMCs remains limited. In particular, the comparative roles of monometallic, bimetallic/ternary, and doped systems in overcoming these intrinsic challenges require critical evaluations.

In this context, this review provides a comprehensive and structured analysis of transition metal chalcogenide-based electrodes for supercapacitor applications. The review is organized as follows: first, monometallic TMCs are discussed as model systems to understand fundamental charge storage mechanisms and inherent limitations; next, bimetallic and ternary TMCs are examined with emphasis on synergistic redox activity, improved electrical conductivity, and enhanced structural stability; subsequently, doped TMCs are analyzed in terms of defect engineering and electronic modulation; and finally, structure–property–performance relationships are established to correlate material design with electrochemical behavior. Based on this analysis, key challenges and future research directions are outlined to facilitate the development of high-performance, stable, and scalable TMC-based supercapacitor technology.

Despite the significant progress in the reported electrochemical performance, direct comparison of TMC-based electrodes across different studies remains challenging because of variations in the testing conditions. Parameters such as current density or scan rate, mass loading, electrolyte composition, voltage window, and measurement configuration (three-electrode versus full-device systems) can significantly influence the reported values of specific capacitance, energy density, and cycling stability. In many cases, high capacitance values are obtained under low mass loading and idealized three-electrode configurations, which may overestimate the practical performance. Therefore, careful consideration of the testing conditions is essential for the accurate evaluation of the structure–property–performance relationships and for assessing the true applicability of TMC-based materials in real-world supercapacitor devices.

2. CLASSIFICATION OF TRANSITION METAL CHALCOGENIDES

Transition metal chalcogenides are extensively divided into monometallic, bimetallic (ternary), and doped categories (Figure 2). The crystal structure, morphology, electronic configuration, and defect chemistry have a strong impact on their electrochemical behavior.

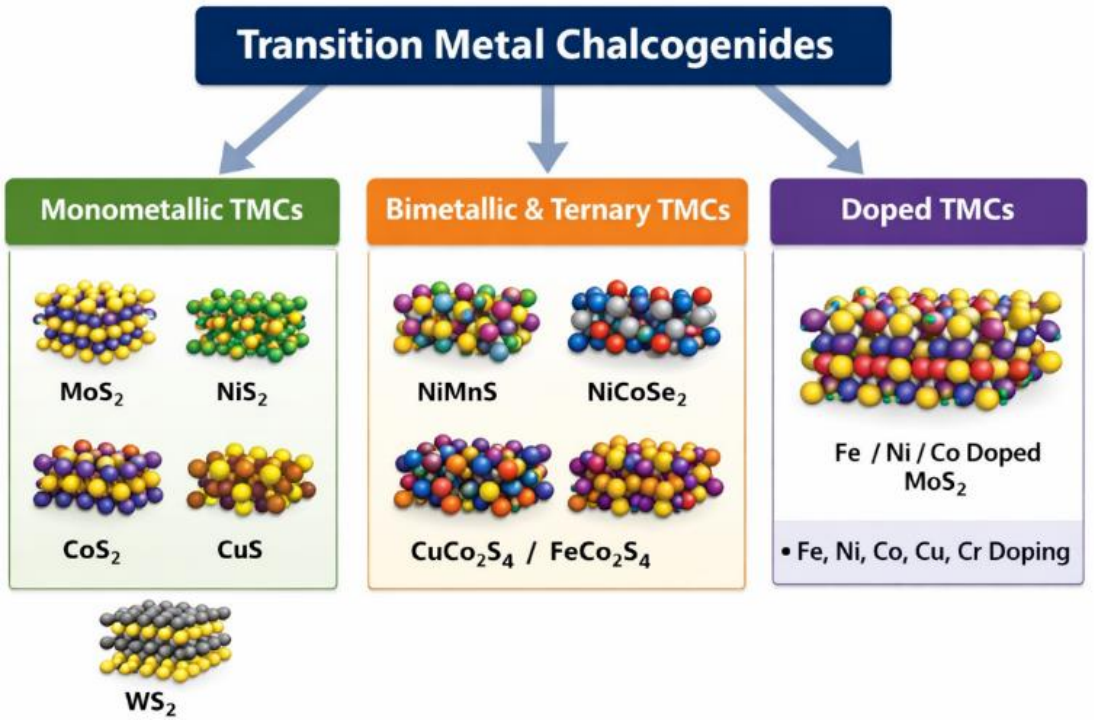

Figure 2. Types of transition-metal-chalcogenides

2.1 Monometallic transition metal chalcogenides

MoS_2, NiS_x, CoS_x, CuS, and WS_2 have also been of great interest as pseudocapacitive electrode materials because of their rich redox chemistry, structural diversity, and desirable electrochemical properties. Such materials generally have fast reversible faradaic reactions at or near the electrode surface, allowing them to have higher capacitance than charge storage mechanisms that are entirely electrostatic. The crystal structure, electronic conductivity, defect density, and morphology also have a strong effect on their electrochemical behavior and are therefore essential model systems for understanding the processes of pseudocapacitive charge storage [36-41].

Molybdenum disulfide (MoS_2) is one of the most widely studied materials among monometallic TMCs, considering its graphene-type S-Mo-S layer structure. The van der Waals interaction of adjacent layers is weak, and this allows available interlayer spaces, offering easy access to ion diffusion by electrolytes and near-surface ion intercalation to assist in higher charge storage [16]. Figures 3(a) and (a') represent the layered MoS_2 nanosheet morphology, highlighting its 2D-architecture which is favorable for pseudocapacitive behavior [42, 43]. Despite these advantages, pristine MoS_2 has an inherently low electrical conductivity and a high propensity to restack nanosheets during electrode production and operation, further decreasing the electrochemically active surface area and preventing excellent rate performance. Therefore, electrodes made with MoS_2 tend to have moderate specific capacitance values unless structural modification/ hybridization methods are adopted [44-46].

The introduction of various accessible oxidation states (e.g., Ni^{2+} /Ni^{3+} and Co^{2+} /Co^{3+}) makes nickel and cobalt sulfides (such as NiS, Ni_3S_2, NiS_2, and CoS_2) especially likely pseudocapacitive materials, which can be easily accessed with different oxidation states, allowing high theoretical capacitance [47, 48]. The intrinsic electrical conductivity of these materials is typically higher than that of MoS_2, enabling quicker electron flow and enhanced redox rates. However, frequent faradaic cycling of nickel- and cobalt-based sulfides can cause serious volume expansion, lattice deformation, and surface rearrangement, eventually causing progressive capacitance decay and cycle instability. These problems of structural degradation remain a significant hurdle to the long-term use of their structural degradation in supercapacitors.

Another group of monometallic TMCs that have been considered as supercapacitor electrodes are copper sulfide (CuS) and tungsten disulfide (WS_2). CuS is a moderately pseudocapacitive material, with surface redox reactions controlling its behavior. However, its surface conductivity is relatively poor, and the chemically active sites are relatively small, leading to a lower specific capacitance compared to nickel- and cobalt-based sulfides. Likewise, WS_2 has a layered structure like MoS_2, but with good chemical stability and often limited electrochemical performance owing to sluggish charge-transfer kinetics and restacking effects. As a result, the performance of both CuS-and WS_2 based electrodes usually necessitates incorporation with a conductive matrix or structural engineering to be competitive [17-21].

Therefore, monometallic TMCs can provide important information regarding the underlying pseudocapacitive processes. They are useful materials in many ways because of their comparatively simple structure and synthetic pathways, although their limitations in terms of electrical conductivity, structural integrity, and electrochemical utilization of active materials have been noted. Table 1 presents a comparative

overview of typically represented monometallic TMC-based electrodes, which highlights trends in performance based on different materials.

These shortcomings have led to increasing interest in more complicated systems based on materials, such as bimetallic, ternary, and doped TMCs, which counteract the inherent weaknesses of their monometallic counterparts using a synergetic electronic and structural response.

Table 1. Comparative electrochemical performance of representative monometallic transition metal chalcogenide (TMC) electrodes under reported testing conditions

Material System	Morphology (Synthesis Method)	Specific Capacitance (F g^{-1}) at Current Density (A g^{-1})	Mass Loading	Electrolyte	Cycling Stability / (Configuration)	Key Limitations	Ref.
MoS_2 (pristine)	Nanosheets, nanoflowers (Hydrothermal, CBD, sputtering)	120–350 at 1–2	Low (<1 mg cm^{-2})	KOH (1–6 M)	70–85% (3000–5000 cycles) / (3-electrode)	Low conductivity, restacking	[36-39, 49]
MoS_2-based composites	Layered hybrid networks (Hydrothermal + polymerization)	500–580 at ~1	Low	KOH / H_2SO_4	>80% (≥5000 cycles) / (3-electrode)	Polymer degradation, stability issues	[50-52]
NiS_x (NiS, Ni_3S_2, NiS_2)	Porous, hollow, nanowires (Hydrothermal, electrodeposition)	500–2000 at 1–10	Low–moderate	KOH (1–3 M)	80–97% (2000–5000 cycles) / (3-electrode/ASC)	Volume expansion, structural degradation	[22-28]
CoS_x	Hollow spheres, hierarchical networks (Hydrothermal, electrodeposition)	1000–3000 at 1–5	Low–moderate	KOH	70–90% (5000–10000 cycles) / (3-electrode/ASC)	Stoichiometric instability, phase change	[29-33]
CuS	Nanoparticles, clusters (Hydrothermal, solvothermal)	<300 at ~1	Low	KOH / Na_2SO_4	~80% (3000–5000 cycles) / (3-electrode)	Poor conductivity, limited active sites	[53-55]
WS_2	Thin films, nanosheets (Sputtering, hydrothermal)	300–500 at 1–2	Low	KOH	~80% (3000–5000 cycles) / (3-electrode)	Restacking, sluggish kinetics	[17-20, 56-59]

Note: CBD = Chemical Bath Deposition, ASC = Asymmetric Supercapacitor

2.2 Bimetallic and ternary transition metal chalcogenides

Bimetallic and ternary TMCs, including Ni–Mn sulphide, Ni–Co selenides, $CuCo_2S_4$ and $FeCo_2S_4$, have emerged as highly promising electrode materials for supercapacitor applications due to their superior electrochemical performance compared to monometallic counterparts. Ni- and Co-based sulfides adopt hierarchical architecture, as shown in Figures 3(b) and 3(b'), where nanorods, nanoparticles, or nanosheets assemble into a porous, flower-like framework. The incorporation of two or more metal cations into a single chalcogenide framework introduces synergistic effects that significantly enhance the redox activity, electrical conductivity, and structural stability. Consequently, these multimetallic systems generally exhibit higher specific capacitance, improved rate capability, and enhanced cycling durability [60-62].

The primary advantage of bimetallic and ternary TMCs is the coexistence of multiple redox-active metal centers, which broadens the accessible redox potential window and increases the density of electrochemically active sites. For instance, in Ni–Mn sulfides, the presence of both Ni^{2+}/Ni^{3+} and Mn^{2+}/Mn^{3+} redox couples enables richer faradaic reactions than single-metal sulfides, thereby contributing to a higher charge storage capacity. Similarly, Ni-Co selenides benefit from the complementary redox behavior of nickel and cobalt ions, which facilitates rapid charge transfer kinetics and improves the utilization of the active material [61, 63, 64].

In addition to enhanced redox chemistry, bimetallic and ternary TMCs often exhibit improved intrinsic electrical conductivities. The interaction between different metal cations can modify the electronic band structure, reduce the charge transfer resistance, and promote faster electron transport during electrochemical cycling. This improvement in conductivity is particularly evident in selenide-based systems, where the lower metal–chalcogen bond ionicity further enhances the electronic mobility. Consequently, these materials typically demonstrate superior rate performance, maintaining high capacitance even at elevated current densities [65-67].

Structural stability is another key advantage of multimetallic TMCs. The incorporation of multiple metal species can stabilize the crystal lattice and mitigate the volume expansion and mechanical stress associated with repeated redox cycling. For example, spinel-type structures such as $CuCo_2S_4$ and $NiCo_2S_4$ provide robust 3-D frameworks (Figures 3(c) and 3(c')) that accommodate reversible ion insertion and extraction with minimal structural degradation. This structural robustness translates into improved cycling stability, making these materials more suitable for long-term supercapacitor operation [42, 68-71].

Despite these advantages, the synthesis of bimetallic and ternary TMCs is generally more complex than that of monometallic systems, requiring precise control over the composition, phase purity, and morphology. Variations in the synthesis parameters can significantly influence electrochemical performance, highlighting the importance of optimized fabrication strategies. Furthermore, while multi-metallic systems offer enhanced performance, issues related to material cost, scalability, and environmental impact, particularly for cobalt-containing compounds, must be carefully considered [70, 71].

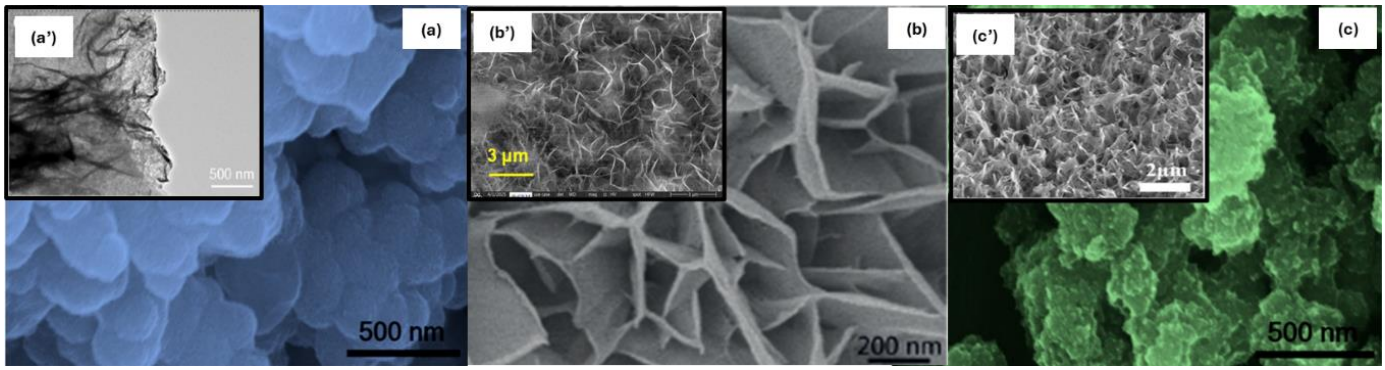

Figure 3. Representation of morphologies of transition metal chalcogenide electrodes: (a) layered MoS_2 nanosheets [42] (inset (a') [43]), (b) hierarchical Ni-Co sulfide architecture ([60]) (inset (b') ([67])), and (c) spinel-type / ($NiCo_2S_4$ [42] (inset (c') $CuCo_2S_4$ [68])

Table 2. Comparative electrochemical performance of representative bimetallic and ternary transition metal chalcogenide (TMC) electrodes under reported testing conditions

Material System	Morphological Features (Synthesis Method)	Specific Capacitance (F g^{-1}) at Current Density (A g^{-1})	Mass Loading / Electrolyte)	Cycling Stability / Configuration	Energy Density (Wh kg^{-1})	Key Advantages	Key Limitations	Ref.
Ni–Mn sulfides	Porous hierarchical structures (Sol–gel, hydrothermal)	~1000–1100 at ~1–2	Low–moderate / (KOH)	>80% (≥3000 cycles) / (ASC)	~36	Synergistic redox activity	Composition sensitivity, stability issues	[61]
Ni–Co selenides	Nanoparticles, nanorods (Hydrothermal)	~1300 C g^{-1} (~high capacity) at ~1–5	Low / (KOH / solid-state gel)	~85–90% (≥5000 cycles) / (ASC/solid-state)	~42	High conductivity, fast charge transfer	Cost, chemical instability	[62]
$CuCo_2S_4$	Hierarchical nanowire arrays (Hydrothermal)	2000–2400 at ~1–5	Moderate / (KOH)	~80–90% (≥10000 cycles) / (ASC)	~33	Fast electron transport, high capacitance	Structural degradation at high cycles	[63]
$FeCo_2S_4$	Crosslinked nanowire networks (Hydrothermal)	~337 mAh g^{-1} at ~1	Moderate / (KOH)	~80–90% (≥5000 cycles) / (ASC)	~40	Structural robustness, stable framework	Limited rate capability	[69]
Cu_2FeSnS_4 composites	Multimetallic composite framework (Solvothermal / hybrid synthesis)	~300–350 at ~1	Low / (KOH)	~80% (≥3000 cycles) / (ASC)	~73	Multiple redox centers, high energy density	Complex synthesis, scalability issues	[71]

Note: ASC = Asymmetric Supercapacitor

Overall, bimetallic and ternary transition metal chalcogenides represent a significant advancement over monometallic TMCs by combining enhanced redox activity, improved electrical conductivity, and greater structural stability. These attributes make them strong candidates for next-generation high-performance supercapacitor electrodes and provide a foundation for further performance optimization through compositional tuning and structural optimization. Table 2 shows the comparative performances of bimetallic and ternary TMC-based electrodes reported in the literature.

2.3 Doped transition metal chalcogenides

Elemental doping has also become an efficient approach for optimizing the electronic structure, defect density, and electrochemical behavior of TMCs for use in supercapacitors. Doping can be used to adjust the concentration of charge carriers, change the band structure, and create more electrochemically active sites by introducing foreign metal ions into the host chalcogenide lattice, thus improving the pseudocapacitive behavior. Relative to compositional modification via multimetallic structures, doping provides a simple and flexible method for performance adjustment without significantly changing the crystal structure. The electrochemical properties of TMC-based electrodes have been widely improved by doping with transition metals, including Fe, Ni, Co, Cu, and Cr.

These dopant ions can either replace host metal cations or replace interstitial lattice sites, resulting in lattice deformities and defects that enhance rapid ion diffusion and faster charge-transfer behavior. Dopant-induced vacancies and anisotropic edge sites increase the density of electrochemically active surface sites, thereby enhancing the specific capacitance and rate capability. Furthermore, the insertion of dopants can enhance the intrinsic electrical conductivity by altering the local electronic setup and reducing the charge-transfer resistance at the electrode-electrolyte interface [72-74].

In addition to enhancing electronic properties, elemental doping is also essential for inhibiting particle agglomeration and stabilizing nanostructured morphologies during electrochemical cycling. Dopants can also be used as structural stabilizers, preventing crystal growth and aggregation, leading to smaller particle sizes and surface areas. This morphological stabilization helps improve electrochemical usage and cycling stability, especially when the current density is high [75-77].

Regardless of these benefits, TMC-based electrodes may be

negatively impacted by high dopant concentrations on their structural integrity and long-term electrochemical stability. Excessive dopant levels can cause excessive lattice distortion, break long-range crystallinity, and cause internal strain in the crystal structure. These structural distortions can increase the rate of material degradation during long cycling, which causes fading in capacitance and a low operational life. Therefore, maximizing the dopant type, concentration, and distribution is crucial to ensure a balance between performance increase and structural stability.

In general, doped transition metal chalcogenides are an essential category of pseudocapacitive materials that can be halfway between monometallic and multimetallic. Doping can be used to boost redox activity, electrical conductivity, and morphological stability, thereby improving electrochemical performance when designed appropriately. Mechanistic dopant optimization and understanding of dopant–host interactions should be the basis of future research to ensure that the potential of doped TMCs as supercapacitor electrodes is fully realized. Table 3 presents an overview of selected studies on the effect of doping on the electrochemical performance of TMC electrodes under reported testing conditions.

It is important to note that the reported electrochemical performance metrics vary significantly depending on the experimental conditions, including the current density, scan rate, mass loading, electrolyte type, and testing configuration. As a result, direct comparison of values across different studies should be interpreted with caution, particularly when high capacitance values are obtained under low mass loading or three-electrode configurations

Table 3. Effect of doping on the electrochemical performance of Transition metal chalcogenides (TMCs) electrodes under reported testing conditions

Host TMC	Dopant(s)	Structural / Electronic Effect	Specific Capacitance (F g^{-1}) at Current Density (A g^{-1})	Mass Loading / (Electrolyte)	Cycling Stability / (Configuration)	Key Advantages	Key Limitations	Ref.
MoS_2	Cr, Fe, Mn, Co	Increased defect density, improved conductivity	>1000 at ~1	Low / (KOH)	~80–90% (≥5000 cycles) / (3-electrode)	Enhanced active sites, faster charge transfer	Structural distortion at high doping	[70, 78, 79]
MnS	Ni, Cu, Fe	Reduced particle agglomeration, improved morphology	up to ~900 at ~1–2	Low / (KOH)	~80% (≥3000 cycles) / 3-electrode	Improved surface area, better ion diffusion	Morphology non-uniformity	[72]
CuS	Ni	Increased porosity, enhanced conductivity	~40% increase over pristine at ~1	Low/ (KOH / Na_2SO_4)	~80% (≥3000 cycles) / 3-electrode	Improved charge transfer kinetics	Excess lattice strain at higher doping	[80, 81]
CuS	Fe	Increased redox activity, additional active sites	Higher capacitance at low scan rate at ~1	Low / (KOH)	Limited long-term stability 3-electrode	Enhanced faradaic reactions	Poor cycling durability	[74]
$NiSe_2$ / WSe_2	Co, Mn	Band structure tuning, improved conductivity	~800–1200 at ~1–5	Low–moderate / (KOH)	~80–90% (≥5000 cycles) / (3-electrode/ASC)	Enhanced rate capability, reduced resistance	Dopant optimization required	[75, 76]

Note: ASC = Asymmetric Supercapacitor

2.4 Structure-property-performance relationships

The relationship between the structure and performance of TMC-based electrodes is governed by the interplay between morphology, defect chemistry, and electrode architecture. These factors collectively influence the charge storage mechanisms, ion transport pathways, and electron transfer kinetics, thereby determining the overall electrochemical performance of the electrode. Nanostructuring increases electrochemical activity by enhancing the surface-to-volume ratio and shortening the ion diffusion distances in favor of surface-controlled pseudocapacitive reactions. Vacancies, edge sites, and lattice defects are other common redox-active sites that enhance charge storage kinetics when properly managed. Conductive carbonaceous materials are hybridized to create a good electron transport chain and counteract the effects of mechanical degradation during cycling. The charge-transfer kinetics and redox stability in bimetallic and doped systems are further optimized by synergistic electronic interactions to enhance the performance of bimetallic and doped systems and significantly improve cycling stability [46, 50-54].

In terms of materials chemistry, it is possible to see the clear differences between sulfide- and selenide-based systems. Selenides tend to have increased electrical conductivity and reduced ionicity of the material-chalcogen distance bond, which can provide faster kinetics of the model charge transfer. Nevertheless, most of them can be characterized by their subordination in terms of chemical stability and material cost. Conversely, sulfides are heavier and less harmful to the environment; however, they are chemically stronger and generally require defect engineering or conductive hybridization to counteract their inherent conductivity shortcomings. Correspondingly, Ni- and Co-based TMCs are more likely to provide larger contributions to pseudocapacitive than Cu- and Fe-based systems because several different oxidation states can be accessed, where structured optimization and composite design are more heavily dependent on high performance. Bimetallic and doped systems also have an added advantage of synergistic redox mechanisms and improved electronic structures.

3. OUTLOOK AND PERSPECTIVE

Transition metal chalcogenides have become a useful family of pseudocapacitive-based electrode materials with rich redox chemistry, tunable electronic structures, and structural diversity, which are incredibly appealing for advanced supercapacitors. As indicated in this review, monometallic TMCs can provide useful insights into the underlying charge-storage processes, but are typically limited by poor electrical conductivity, structural instability, and electrochemical use. Conversely, bimetallic, ternary, and doped TMC systems exhibit superior electrochemical behaviors in terms of synergistic redox interactions, optimized charge-transfer kinetics, and structural robustness.

Despite these improvements, several significant challenges remain in terms of material chemistry. Long-term sulfide and selenide systems are chemically and electrochemically stable in aqueous electrolytes, oxidation reactions, and phase changes during cycling, and the mechanical degradation caused by the volume remains a limitation for practical applications. These degradation pathways are material-dependent; layered TMCs (e.g., MoS_2) suffer from restacking, whereas Ni/Co sulfides undergo volume expansion-induced mechanical failure and metal dissolution under alkaline conditions. In addition, most of these performance measures are reported under laboratory-scale operating conditions with low mass loading, indicating the necessity of common testing procedures and realistic device-level testing.

Future rational material design strategies should focus on combining defect engineering, controlled doping, and hierarchical nanostructuring with scalable and reproducible synthesis pathways. Special focus should be paid to the study of the relationship between the electronic structure, ion pathways, and mechanical stability during extended cycling. In addition, metal and chalcogen elements and chalcogen components must be selected based on sustainability, that is, elemental abundance, toxicity, and environmental impact, which are of primary concern for large-scale energy storage.

Overall, the further development of transition metal chalcogenide-based supercapacitors relies on the ability to bridge the gap between high-performance laboratory work and operational devices. Mechanistic knowledge and chemistry-guided design principles should play a decisive role in the translation of these materials into trustworthy and commercially feasible energy storage technologies.

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REFERENCES

[1] Saleh, H.M., Hassan, A.I. (2024). The challenges of sustainable energy transition: A focus on renewable energy. Applied Chemical Engineering, 7(2): 2084. https://doi.org/10.59429/ace.v7i2.2084

[2] Dunn, B., Kamath, H., Tarascon, J. (2011). Electrical energy storage for the grid: A battery of choices. Science, 334(6058): 928-935. https://doi.org/10.1126/science.1212741

[3] Kumar, V., Khanna, R., Kumar, A., Kumar, P. (2025). A systematic review on the integration of electric vehicles in maintaining grid stability. Smart Electric and Hybrid Vehicles: Advancements in Materials, Design, Technologies, and Modeling, 2024: 127-140. https://doi.org/10.1002/9781394225040.ch4

[4] Conway, B.E. (2013). Electrochemical supercapacitors: scientific fundamentals and technological applications. Springer Science & Business Media.

[5] Miller, J.R., Simon, P. (2008). Electrochemical capacitors for energy management. Science, 321(5889): 651-652. https://doi.org/10.1126/science.1158736

[6] Yu, Z., Tetard, L., Zhai, L., Thomas, J. (2014). Supercapacitor electrode materials: Nanostructures from 0 to 3 dimensions. Energy & Environmental Science, 8(3): 702-730. https://doi.org/10.1039/c4ee03229

[7] Wang, G., Zhang, L., Zhang, J. (2012). A review of electrode materials for electrochemical supercapacitors. Chemical Society Reviews, 41(2): 797-828. https://doi.org/10.1039/c1cs15060j

[8] Simon, P., Gogotsi, Y. (2020). Perspectives for electrochemical capacitors and related devices. Nature Materials, 19(11): 1151-1163. https://doi.org/10.1038/s41563-020-0747-z

[9] Palchoudhury, S., Ramasamy, K., Han, J., Chen, P., Gupta, A. (2023). Transition metal chalcogenides for next-generation energy storage. Nanoscale Advances, 5(10): 2724-2742. https://doi.org/10.1039/d2na00944g

[10] Fic, K., Platek, A., Frackowiak, E. (2018). Sustainable materials for electrochemical capacitors. Materials Today, 21(4): 437-454. https://doi.org/10.1016/j.mattod.2018.03.005

[11] Banerjee, S., Mordina, B., Sinha, P., Kar, K.K. (2025). Recent advancement of supercapacitors: A current era of supercapacitor devices through the development of electrical double layer, pseudo and their hybrid supercapacitor electrodes. Journal of Energy Storage, 108: 115075. https://doi.org/10.1016/j.est.2024.115075

[12] Simon, P., Gogotsi, Y. (2008). Materials for electrochemical capacitors. Nature Materials, 7(11): 845-854. https://doi.org/10.1038/nmat2297

[13] Chhowalla, M., Shin, H.S., Eda, G., Li, L., Loh, K.P., Zhang, H. (2013). The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. Nature Chemistry, 5(4): 263-275. https://doi.org/10.1038/nchem.1589

[14] Liu, Y., Xiao, H., Goddard, W.A. (2016). Schottky-barrier-free contacts with two-dimensional semiconductors by surface-engineered MXenes. Journal of the American Chemical Society, 138(49): 15853-15856. https://doi.org/10.1021/jacs.6b10834

[15] Khan, S. (2023). Phase engineering and impact of external stimuli for phase tuning in 2D materials. Advanced Energy Conversion Materials, 5(1): 40-55. https://doi.org/10.37256/aecm.5120243886

[16] Santra, S., Ali, M.S., Karmakar, S., Chattopadhyay, D. (2023). Molybdenum disulfide: A nanomaterial that is paving the way toward a sustainable future. Materials Today Sustainability, 25: 100659. https://doi.org/10.1016/j.mtsust.2023.100659

[17] Georgiou, T., Jalil, R., Belle, B.D., Britnell, L.,

Gorbachev, R.V., Morozov, S.V., Kim, Y., Gholinia, A., Haigh, S.J., Makarovsky, O., Eaves, L., Ponomarenko, L. A., Geim, A.K., Novoselov, K.S., Mishchenko, A. (2012). Vertical field-effect transistor based on graphene–WS2 heterostructures for flexible and transparent electronics. Nature Nanotechnology, 8(2): 100-103. https://doi.org/10.1038/nnano.2012.224

[18] Braga, D., Lezama, I.G., Berger, H., Morpurgo, A.F. (2012). Quantitative determination of the band gap of WS2 with ambipolar ionic liquid-gated transistors. Nano Letters, 12(10): 5218-5223. https://doi.org/10.1021/nl302389d

[19] Alonso, G., Petranovskii, V., Del Valle, M., Cruz-Reyes, J., Licea-Claverie, A., Fuentes, S. (2000). Preparation of WS2 catalysts by in situ decomposition of tetraalkylammonium thiotungstates. Applied Catalysis A: General, 197(1): 87-97. https://doi.org/10.1016/s0926-860x(99)00536-0

[20] Tenne, R., Margulis, L., Genut, M., Hodes, G. (1992). Polyhedral and cylindrical structures of tungsten disulphide. Nature, 360(6403): 444-446. https://doi.org/10.1038/360444a0

[21] Tu, C., Lin, L., Xiao, B., Chen, Y. (2016). Highly efficient supercapacitor electrode with two-dimensional tungsten disulfide and reduced graphene oxide hybrid nanosheets. Journal of Power Sources, 320: 78-85. https://doi.org/10.1016/j.jpowsour.2016.04.083

[22] Pang, H., Wei, C., Li, X., Li, G., Ma, Y., Li, S., Chen, J., Zhang, J. (2014). Microwave-assisted synthesis of NiS2 nanostructures for supercapacitors and cocatalytic enhancing photocatalytic H2 production. Scientific Reports, 4: 3577. https://doi.org/10.1038/srep03577

[23] Krishnamoorthy, K., Veerasubramani, G.K., Radhakrishnan, S., Kim, S.J. (2014). One pot hydrothermal growth of hierarchical nanostructured Ni3S2 on Ni foam for supercapacitor application. Chemical Engineering Journal, 251: 116-122. https://doi.org/10.1016/j.cej.2014.04.006

[24] Wang, T., Chen, H.C., Yu, F., Zhao, X., Wang, H. (2019). Boosting the cycling stability of transition metal compounds-based supercapacitors. Energy Storage Materials, 16: 545-573. https://doi.org/10.1016/j.ensm.2018.09.007

[25] Chu, S., Cui, Y., Liu, N. (2016). The path towards sustainable energy. Nature Materials, 16(1): 16-22. https://doi.org/10.1038/nmat4834

[26] Patil, A.M., Lokhande, V.C., Lokhande, A.C., Chodankar, N.R., Ji, T., Kim, J.H., Lokhande, C.D. (2016). Ultrathin nickel sulfide nano-flames as an electrode for high performance supercapacitor; comparison of symmetric FSS-SCs and electrochemical SCs device. RSC Advances, 6(72): 68388-68401. https://doi.org/10.1039/c6ra12018k

[27] Du, N., Zheng, W., Li, X., He, G., Wang, L., Shi, J. (2017). Nanosheet-assembled NiS hollow structures with double shells and controlled shapes for high-performance supercapacitors. Chemical Engineering Journal, 323: 415-424. https://doi.org/10.1016/j.cej.2017.04.127

[28] Akbarzadeh, R., Dehghani, H. (2018). From nickel oxalate dihydrate microcubes to NiS2 nanocubes for high performance supercapacitors. Journal of Solid State Electrochemistry, 22(11): 3375-3382. https://doi.org/10.1007/s10008-018-4040-x

[29] Yu, X., Yu, L., Lou, X.W. (. (2015). Metal sulfide hollow nanostructures for electrochemical energy storage. Advanced Energy Materials, 6(3): 1501333. https://doi.org/10.1002/aenm.201501333

[30] Ji, Y., Liu, X., Liu, W., Wang, Y., Zhang, H., Yang, M., Wang, X., Zhao, X., Feng, S. (2014). A facile template-free approach for the solid-phase synthesis of CoS2 nanocrystals and their enhanced storage energy in supercapacitors. RSC Advances, 4(91): 50220-50225. https://doi.org/10.1039/c4ra08614g

[31] Liu, S., Mao, C., Niu, Y., Yi, F., Hou, J., Lu, S., Jiang, J., Xu, M., Li, C. (2015). Facile synthesis of novel networked ultralong cobalt sulfide nanotubes and its application in supercapacitors. ACS Applied Materials & Interfaces, 7(46): 25568-25573. https://doi.org/10.1021/acsami.5b08716

[32] Jia, H., Wang, Z., Zheng, X., Cai, Y., Lin, J., Liang, H., Qi, J., Cao, J., Feng, J., Fei, W. (2019). Controlled synthesis of MOF-derived quadruple-shelled CoS2 hollow dodecahedrons as enhanced electrodes for supercapacitors. Electrochimica Acta, 312: 54-61. https://doi.org/10.1016/j.electacta.2019.04.192

[33] Shi, J., Li, X., He, G., Zhang, L., Li, M. (2015). Electrodeposition of high-capacitance 3D CoS/graphene nanosheets on nickel foam for high-performance aqueous asymmetric supercapacitors. Journal of Materials Chemistry A, 3(41): 20619-20626. https://doi.org/10.1039/c5ta04464b

[34] Kong, D., Wang, H., Lu, Z., Cui, Y. (2014). CoSe2 Nanoparticles grown on carbon fiber paper: An efficient and stable electrocatalyst for hydrogen evolution reaction. Journal of the American Chemical Society, 136(13): 4897-4900. https://doi.org/10.1021/ja501497n

[35] Xu, Y., Lin, Z., Huang, X., Liu, Y., Huang, Y., Duan, X. (2013). Flexible solid-state supercapacitors based on three-dimensional graphene hydrogel films. ACS Nano, 7(5): 4042-4049. https://doi.org/10.1021/nn4000836

[36] Tang, H., Wang, J., Yin, H., Zhao, H., Wang, D., Tang, Z. (2014). Growth of polypyrrole ultrathin films on MoS2 monolayers as high-performance supercapacitor electrodes. Advanced Materials, 27(6): 1117-1123. https://doi.org/10.1002/adma.201404622

[37] Ren, L., Zhang, G., Yan, Z., Kang, L., Xu, H., Shi, F., Lei, Z., Liu, Z. (2015). Three-dimensional tubular MoS2/PANI hybrid electrode for high rate performance supercapacitor. ACS Applied Materials & Interfaces, 7(51): 28294-28302. https://doi.org/10.1021/acsami.5b08474

[38] Ansari, S.A., Cho, M.H. (2017). Simple and large scale construction of MoS2-g-C3N4 heterostructures using mechanochemistry for high performance electrochemical supercapacitor and visible light photocatalytic applications. Scientific Reports, 7: 43055. https://doi.org/10.1038/srep43055

[39] Zhu, J., Sun, W., Yang, D., Zhang, Y., Hoon, H.H., Zhang, H., Yan, Q. (2015). Multifunctional architectures constructing of PANI nanoneedle arrays on MoS2 thin nanosheets for high-energy supercapacitors. Small, 11(33): 4123-4129. https://doi.org/10.1002/smll.201403744

[40] Peng, S., Li, L., Tan, H., Cai, R., Shi, W., Li, C., Mhaisalkar, S.G., Srinivasan, M., Ramakrishna, S., Yan, Q. (2013). MS2 (M = Co and Ni) hollow spheres with tunable interiors for high-performance supercapacitors and photovoltaics. Advanced Functional Materials,

24(15): 2155-2162. https://doi.org/10.1002/adfm.201303273
[41] Ahmed, S., Gondal, M., Alzahrani, A., Almessiere, M. (2023). Critical review on transition metal selenides/graphene composite as futuristic electrode material for high performance supercapacitors. Journal of Energy Storage, 74: 109214. https://doi.org/10.1016/j.est.2023.109214
[42] Tue, L.N.M., Sahoo, S., Dhakal, G., Nguyen, V.H., Lee, J., Lee, Y.R., Shim, J. (2023). NiCo2S4/MoS2 nanocomposites for long-life high-performance hybrid supercapacitors. Nanomaterials, 13(4): 689. https://doi.org/10.3390/nano13040689
[43] Zhang, Y., Xu, J., Lu, S., Li, H., Yonar, T., Hua, Q., Liu, T., Zhang, Y. (2025). Engineering few-layer MoS2 and rGO heterostructure composites for high-performance supercapacitors. Advanced Composites and Hybrid Materials, 8: 108. https://doi.org/10.1007/s42114-024-01159-z
[44] Hu, B., Qin, X., Asiri, A.M., Alamry, K.A., Al-Youbi, A.O., Sun, X. (2013). Synthesis of porous tubular C/MoS2 nanocomposites and their application as a novel electrode material for supercapacitors with excellent cycling stability. Electrochimica Acta, 100: 24-28. https://doi.org/10.1016/j.electacta.2013.03.133
[45] Choudhary, N., Patel, M., Ho, Y., Dahotre, N.B., Lee, W., Hwang, J.Y., Choi, W. (2015). Directly deposited MoS2 thin film electrodes for high performance supercapacitors. Journal of Materials Chemistry A, 3(47): 24049-24054. https://doi.org/10.1039/c5ta08095a
[46] Kanaujiya, N., Kumar, N., Sharma, Y., Varma, G.D. (2018). Probing the electrochemical properties of flower like mesoporous MoS2 in different aqueous electrolytes. Journal of Electronic Materials, 48(2): 904-915. https://doi.org/10.1007/s11664-018-6801-9
[47] Nwaji, N., Gwak, J., Goddati, M., Kang, H., Pasanaje, A.H., Sharan, A., Singh, N., Lee, J. (2023). Defect-engineered Fe3C@NiCo2S4 nanospike derived from metal–organic frameworks as an advanced electrode material for hybrid supercapacitors. ACS Applied Materials & Interfaces, 15(29): 34779-34788. https://doi.org/10.1021/acsami.3c04635
[48] Wang, J., Zhou, R., Jin, D., Xie, K., Wei, B. (2016). Controlled synthesis of NiCo2S4 nanostructures on nickel foams for high-performance supercapacitors. Energy Storage Materials, 2: 1-7. https://doi.org/10.1016/j.ensm.2015.11.001
[49] Karade, S.S., Dubal, D.P., Sankapal, B.R. (2016). MoS2 ultrathin nanoflakes for high performance supercapacitors: Room temperature chemical bath deposition (CBD). RSC Advances, 6(45): 39159-39165. https://doi.org/10.1039/c6ra04441g
[50] Bai, L., Wang, Y., Cheng, S., Li, F., Zhang, Z., Liu, Y. (2018). Synthesis and electrochemical performance of molybdenum disulfide-reduced graphene oxide-polyaniline ternary composites for supercapacitors. Frontiers in Chemistry, 6: 218. https://doi.org/10.3389/fchem.2018.00218
[51] Ansari, S.A., Fouad, H., Ansari, S., Sk, P., Cho, M.H. (2017). Mechanically exfoliated MoS2 sheet coupled with conductive polyaniline as a superior supercapacitor electrode material. Journal of Colloid and Interface Science, 504: 276-282. https://doi.org/10.1016/j.jcis.2017.05.064
[52] Gupta, H., Mothkuri, S., McGlynn, R., Carolan, D., Maguire, P., Mariotti, D., Jain, P.K., Rao, T.N., Padmanabham, G., Chakrabarti, S. (2020). Activated functionalized carbon nanotubes and 2D nanostructured MoS2 hybrid electrode material for high-performance supercapacitor applications. Physica Status Solidi (a), 217(10): 1900855. https://doi.org/10.1002/pssa.201900855
[53] Zhao, T., Yang, W., Zhao, X., Peng, X., Hu, J., Tang, C., Li, T. (2018). Facile preparation of reduced graphene oxide/copper sulfide composite as electrode materials for supercapacitors with high energy density. Composites Part B: Engineering, 150: 60-67. https://doi.org/10.1016/j.compositesb.2018.05.058
[54] Zhao, T., Peng, X., Zhao, X., Hu, J., Jiang, T., Lu, X., Zhang, H., Li, T., Ahmad, I. (2020). Preparation and performance of carbon dot decorated copper sulphide/carbon nanotubes hybrid composite as supercapacitor electrode materials. Journal of Alloys and Compounds, 817: 153057. https://doi.org/10.1016/j.jallcom.2019.153057
[55] Pavithra, S., Sakunthala, A., Vinofia, S., Pramoda, K., Kathirvel, V., Keri, R.S. (2024). Superior performance of hierarchical 3D microflower CuS grown on carbon cloth as binder free electrode for supercapacitor applications. Materials Research Bulletin, 180: 113010. https://doi.org/10.1016/j.materresbull.2024.113010
[56] Alzaid, M., Iqbal, M.Z., Alqahtani, B., Alanazi, R., Alsohaimi, I.H., Mohamed, W.S., Hadia, N.M.A. (2023). Tailoring the interfacial surfaces of tungsten and molybdenum tungsten disulfide electrodes for hybrid supercapacitors. RSC Advances, 13(23): 15575-15585. https://doi.org/10.1039/d3ra00847a
[57] Imran, M., Afzal, A.M., Iqbal, M.W., Mumtaz, S., Alqarni, A.S. (2024). Superior electrochemical performance and cyclic stability of WS2@CoMgS//AC composite on the nickel-foam for asymmetric supercapacitor devices. Energies, 17(14): 3363. https://doi.org/10.3390/en17143363
[58] Ratha, S., Rout, C.S. (2013). Supercapacitor electrodes based on layered tungsten disulfide-reduced graphene oxide hybrids synthesized by a facile hydrothermal method. ACS Applied Materials & Interfaces, 5(21): 11427-11433. https://doi.org/10.1021/am403663f
[59] Tang, M., Wu, Y., Yang, J., Wang, H., Lin, T., Xue, Y. (2021). Graphene/tungsten disulfide core-sheath fibers: High-performance electrodes for flexible all-solid-state fiber-shaped supercapacitors. Journal of Alloys and Compounds, 858: 157747. https://doi.org/10.1016/j.jallcom.2020.157747
[60] He, S., Lu, C., Wang, G., Wang, J., Guo, H., Guo, L. (2014). Synthesis and growth mechanism of white-fungus-like nickel sulfide microspheres, and their application in polymer composites with enhanced microwave-absorption properties. Chempluschem, 79(4): 569-576. https://doi.org/10.1002/cplu.201300435
[61] Cao, J., Yuan, S., Yin, H., Zhu, Y., Li, C., Fan, M., Chen, H. (2018). One-pot synthesis of porous nickel–manganese sulfides with tuneable compositions for high-performance energy storage. Journal of Sol-Gel Science and Technology, 85(3): 629-637. https://doi.org/10.1007/s10971-018-4580-7
[62] Wang, Y., Liu, R., Sun, S., Wu, X. (2019). Facile synthesis of nickel-cobalt selenide nanoparticles as

battery-type electrode for all-solid-state asymmetric supercapacitors. Journal of Colloid and Interface Science, 549: 16-21. https://doi.org/10.1016/j.jcis.2019.04.049

[63] Du, J., Yan, Q., Li, Y., Cheng, K., et al. (2019). Hierarchical copper cobalt sulfides nanowire arrays for high-performance asymmetric supercapacitors. Applied Surface Science, 487: 198-205. https://doi.org/10.1016/j.apsusc.2019.04.275

[64] Duraivel, M., Nagappan, S., Park, K.H., Prabakar, K. (2022). Optimised Ni3+/Ni2+ and Mn3+/Mn2+ ratios in nickel manganese layered double hydroxide for boosting oxygen and hydrogen evolution reactions. ChemElectroChem, 9(19): e202200822. https://doi.org/10.1002/celc.202200822

[65] Ahmed, A., Karim, M.R.A., Usman, M. (2025). Tailoring the electrochemical performance of nickel cobalt selenides via hydrothermal zincronization for high-performance asymmetric supercapacitors. Electrochimica Acta, 531: 146351. https://doi.org/10.1016/j.electacta.2025.146351

[66] Huang, K., Tao, H., Xiong, W., Lin, J., Chen, T., Lei, M., Hu, H., He, Z., Wang, K., Jiang, K., Zhang, L., Li, S. (2025). Tuning the electronic configuration of momn bimetallic–nitrogen–carbon catalysts for advanced lithium–sulfur batteries. Advanced Functional Materials, 36(32): e26648. https://doi.org/10.1002/adfm.202526648

[67] Sagayaraj, P.J.J., Senthilkumar, A., Lee, J., Byeon, E., Kim, H., Shenoy, S., Sekar, K. (2025). Self-supported tailoring of nickel Sulfide/CuCo nanosheets into hierarchical heterostructures for boosting urea oxidation reaction. Catalysts, 15(7): 664. https://doi.org/10.3390/catal15070664

[68] Xu, J., Wang, X., Cheng, J. (2020). Supercapacitive performances of ternary CuCo2S4 sulfides. ACS Omega, 5(3): 1305–1311. https://doi.org/10.1021/acsomega.9b03865

[69] Liu, S., Xu, G., Li, J., Wang, B., Huang, Z., Chen, Q., Qi, X. (2018). Iron-Cobalt Bi-Metallic sulfide nanowires on ni foam for applications in high-performance supercapacitors. ChemElectroChem, 5(16): 2250-2255. https://doi.org/10.1002/celc.201800486

[70] Kour, P., Kour, S., Deeksha, Sharma, A., Yadav, K. (2024). Electrochemical advancements in molybdenum disulfide via different transition metal (Cr, Mn, Fe, Co) doping for hybrid supercapacitors. Journal of Alloys and Compounds, 981: 173740. https://doi.org/10.1016/j.jallcom.2024.173740

[71] Isacfranklin, M., Yuvakkumar, R., Ravi, G., Saravanakumar, B., Pannipara, M., Al-Sehemi, A.G., Velauthapillai, D. (2021). Quaternary Cu2FeSnS4/PVP/rGO composite for supercapacitor applications. ACS Omega, 6(14): 9471-9481. https://doi.org/10.1021/acsomega.0c06167

[72] Tigwere, G.A., Khan, M.D., Nyamen, L.D., de Souza, F.M., Lin, W., Gupta, R.K., Revaprasadu, N., Ndifon, P.T. (2023). Transition metal (Ni, Cu and Fe) doped MnS nanostructures: Effect of doping on supercapacitance and water splitting. Materials Science in Semiconductor Processing, 158: 107365. https://doi.org/10.1016/j.mssp.2023.107365

[73] Ebenezar, J. (2017). Recent Trends in Materials Science and Applications. Nanomaterials, Crystal Growth, Thin Films, Quantum Dots, & Spectroscopy (Proceedings ICRTMSA 2016). https://doi.org/10.1007/978-3-319-44890-9

[74] Brown, J.W., Ramesh, P.S., Geetha, D. (2018). Fabrication of mesoporous iron (Fe) doped copper sulfide (CuS) nanocomposite in the presence of a cationic surfactant via mild hydrothermal method for supercapacitors. Materials Research Express, 5(2): 024007. https://doi.org/10.1088/2053-1591/aaad55

[75] Gu, Y., Fan, L., Huang, J., Geng, C., Lin, J., Huang, M., Huang, Y., Wu, J. (2018). Hydrothermal synthesis of Co-doped NiSe2 nanowire for high-performance asymmetric supercapacitors. Materials, 11(8): 1468. https://doi.org/10.3390/ma11081468

[76] Faisal, F., Alotaibi, B., Gassoumi, A., Alyousef, H.A., Alrowaily, A., Al-Harbi, N., Khan, M.J., Ahmad, K. (2024). Facile fabrication of Mn doped WSe2 as an electrode material for supercapacitor application. Electrochimica Acta, 505: 144876. https://doi.org/10.1016/j.electacta.2024.144876

[77] Tomar, A., Choudhary, N., Malik, G., Chandra, R. (2024). WSe2 nanoflakes on graphite sheets for flexible symmetric supercapacitors. ACS Applied Nano Materials, 7(22): 26111-26125. https://doi.org/10.1021/acsanm.4c05378

[78] Xie, J., Zhang, H., Li, S., Wang, R., Sun, X., Zhou, M., Zhou, J., Lou, X.W., Xie, Y. (2013). Defect-rich MoS2 ultrathin nanosheets with additional active edge sites for enhanced electrocatalytic hydrogen evolution. Advanced Materials, 25(40): 5807-5813. https://doi.org/10.1002/adma.201302685

[79] Lukowski, M.A., Daniel, A.S., Meng, F., Forticaux, A., Li, L., Jin, S. (2013). Enhanced hydrogen evolution catalysis from chemically exfoliated metallic MoS2 nanosheets. Journal of the American Chemical Society, 135(28): 10274-10277. https://doi.org/10.1021/ja404523s

[80] Podili, S., Geetha, D., Ramesh, P.S. (2018). Electrochemical studies on Ni doped CuS nanostructures with cationic surfactant synthesized through a hydrothermal route. Journal of Materials Science: Materials in Electronics, 29(13): 11167-11177. https://doi.org/10.1007/s10854-018-9202-1

[81] Qasim, B., Jabbour, K., Ouladsmane, M., Waheed, M.S., Abdullah, M., Bano, N., Manzoor, S., Sillanpää, M., Ashiq, M.N. (2024). Effect of Ni dopant on the capacitive behavior of CuS for supercapacitor application. Journal of Materials Science: Materials in Electronics, 35: 445. https://doi.org/10.1007/s10854-024-12235-x