Sustainable Chemistry for Energy Materials 2 (2025) 100024

Contents lists available at ScienceDirect

Sustainable Chemistry for Energy Materials

journal homepage: www.elsevier.com/locate/scenem

Advancements in ceramic materials for high-performance supercapacitors: Strategies, challenges, and opportunities

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A R T I C L E I N F O

Keywords:
Ceramic electrodes
Structure design
Ceramic material, Specific capacitance
Supercapacitors

A B S T R A C T

Supercapacitors (SCs) are emerging as efficient and long-lasting energy storage devices, and ceramic materials have gained popularity due to their thermal stability, wide operating range, and structural strength. However, factors such as low specific surface area (SSA), poor intrinsic conductivity, and limited surface activity limit their performance. Recent advances in ceramic electrodes, including metal oxides (MOs), hydroxides, sulfides, carbides, nitrides, MXenes, and ceramic-based hybrids, show promise in strategies such as nanostructuring, compositing with conductive carbons or metals, heterostructure design, and defect/doping engineering to improve charge storage, electron transport, and cycling stability. Despite these advancements, scalable fabrication, mechanical integrity, and long-term stability remain significant challenges. This paper critically examines existing work, highlights typical fabrication and optimization methodologies, and offers future research prospects for high-performance, sustainable, and economically viable ceramic-based SCs for advanced energy storage.

1. Introduction

The decline of traditional energy sources alarms us to investigate renewable energy resources for enhanced energy storage and conversion systems [1–3]. Energy storage involves various energies, technologies, sizes, and applications [4–7]. Portable energy storage solutions, such as batteries, fuel cells, and SCs, are becoming more significant [8,9]. Over the last decade, advances in electrochemically active materials and innovative device topologies have resulted in major advances in electrochemical energy storage (EES) devices [10]. SC technology was less widespread than hybrid electric vehicles from 1957 to the 1990s. This strategy aims to improve electrode material performance, making SCs more competitive than high ED (energy density) batteries [11]. Due to their lengthy life cycles and high PD (power density), SCs are ideal energy storage devices [12]. SCs, also known as electrochemical double-layer capacitors, have high PD and rapid charge-discharge capabilities, complementing batteries in electric cars and allowing for swift acceleration [13,14]. Their performance is determined by the charge storage method as well as electrode and electrolyte characteristics [15,16]. Unlike conventional capacitors, SCs form an electronic double layer with carbon-based separators, allowing for rapid cycles in seconds or milliseconds [17–19]. Advanced electrode designs (core--shell, heterostructures, and hierarchical structures) increase ED while maintaining high power [20]. SCs are most suited for short-term energy delivery, energy harvesting, and integration with other storage devices to increase efficiency and lifespan [21–23].

Materials science is driving the development of next-generation energy storage technologies, with polymer electrolytes (PEs) gaining popularity in SCs due to their solvent-free operation, flexibility, transparency, broad electrochemical stability, thin-film processability, and high ionic conductivity [24]. Solid-state materials, metals, polymers, and ceramics are critical in this context [25], with polymers reducing leakage [26] and ceramics providing high thermal strength, chemical inertness, and cycling stability, enabling applications in batteries, SCs, fuel cells, thermoelectrics, and energy harvesting [27–31]. Smart films improve reactivity to environmental stimuli [32–34]. SCs are known as clean, robust devices with high ED, extended lifetime, and a wide range of applications, but their performance is restricted by electrode materials [35,36] and current manufacturing and costs [37–39]. SCs, unlike dielectric ceramic capacitors with ultrafast discharge [40], work by electrochemical mechanisms. They are classed as electrochemical double-layer capacitors (EDLCs), pseudocapacitors (PCs), and hybrid

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https://doi.org/10.1016/j.scenem.2025.100024
Received 2 September 2025; Received in revised form 4 October 2025; Accepted 16 October 2025

types (Fig. 1A) [41]. Flexible SCs, designed for wearable technologies, integrate high-specific-surface-area(HSSA) electrodes including carbon nanotubes(CNTs), conductive polymers(CPs), and MOs [42,43]. They offer high PD (>10 kW kg^{-1}), rapid charge-discharge, over 100,000 cycles, safety, and adaptability in thin-film, sandwich, or planar structures [23,44–50]. Fig. 1B shows the cyclic voltammetry (CV) curves and galvanostatic charge-discharge (GCD) behavior of SCs and batteries. In Fig. 1B-a, SCs display a rectangular hysteresis curve with a nearly constant current during charging and discharging. In contrast, batteries show discrete spikes that indicate Faradaic reactions (Fig. 1B-b). The GCD curve of an SC (Fig. 1B-c) typically has a constant slope. In contrast, batteries involve Faradaic reactions, resulting in a CV curve with distinct redox peaks. Batteries maintain a consistent voltage except near full charge or discharge, as seen in the flat region of the GCD curve. SC GCD curves show high slopes and a steady gradient, whereas batteries have a rather flat charge/discharge profile under constant voltage (Fig. 1 B-d). SCs are high-power energy storage devices widely utilized in consumer electronics, smart meters, and transportation [41–43,51]. However, they have limitations such as high ED requirements and long working hours. Additionally, SCs can only store charge on the electrodes' surfaces, with lower ED than batteries. Despite these shortcomings, SCs have shown promising performance in a few applications. The ED (E, Wh.g^{-1}) of a full capacitor is determined using the formula: $E = 1/2\ CV^2$, which relates to the specific capacitance (C) (Ah.g^{-1}) of the electrode material and the voltage window (V) between the positive and negative electrodes. Porous nanoelectrode materials can boost ED by increasing the SSA. Carbon materials, recognized for their great surface area, low cost, availability, and electrical conductivity, have the potential to revolutionize the use of capacitors in various applications.

Ceramics are especially useful in batteries and SCs due to their strong ionic conductivity, thermal stability, and mechanical robustness, which inhibit dendrite formation and increase device lifetime [52,53]. Advanced ceramics, including lithium compounds, titanium dioxide (TiO_2), tin dioxide (SnO_2), barium titanate ($BaTiO_3$), and lead zirconate titanate (PZT), are being investigated as solid electrolytes, electrodes, or dielectric materials due to their high ED, strong breakdown strength, rapid charge-discharge rates, and energy storage efficiency [52–55]. TMOs, including ruthenium dioxide (RuO_2) and manganese dioxide (MnO_2), improve SC electrode performance by increasing capacitance and electrical conductivity [56]. Ceramics are also ideal for high-temperature applications such as molten salt thermal energy storage in concentrated solar power (CSP) facilities, and ceramic coatings enhance electrode safety, conductivity, and lifespan [57–59]. SC electrodes are made of a variety of materials, including carbon-based compounds, conductive polymers (CPs), oxides, sulfides, carbides, nitrides, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), transition metal dichalcogenides (TMDs), and MXenes [60–78]. Electrode performance is primarily governed by capacitance, equivalent series resistance (ESR), and operating voltage, all of which influence ED and PD, while cycle stability is determined by both electrode and electrolyte characteristics [70–73]. Layered materials, such as MXenes and transition metal carbides/nitrides, have a large surface area, rapid ion diffusion, and redox-active sites, which enhance charge transport and SC efficiency [74,75]. Ceramics are appealing despite their small surface area because of their thermal insulation, lightweight nature, huge surface area, and stress resistance [79–82]. Recent advances, including Jiang's all-ceramic V_2O_3/MnO_2 hybrid electrodes [83], Liu's $CuO/La_{1-x}Sr_xCoO_{3-\delta}$ 3D-printed electrodes [84,85], and Chang's hard $B_4C@C$ core-shell ceramics for flexible all-solid-state SCs (SSCs) [86], demonstrate improved electron transport, ion diffusion, and overall device performance. Overall, the combination of improved ceramics, high-specific-surface-area(HSSA)materials, and novel electrode designs is propelling the development of flexible, high-performance, and long-lasting SCs and SSBs, meeting the critical demand for sustainable energy storage solutions.

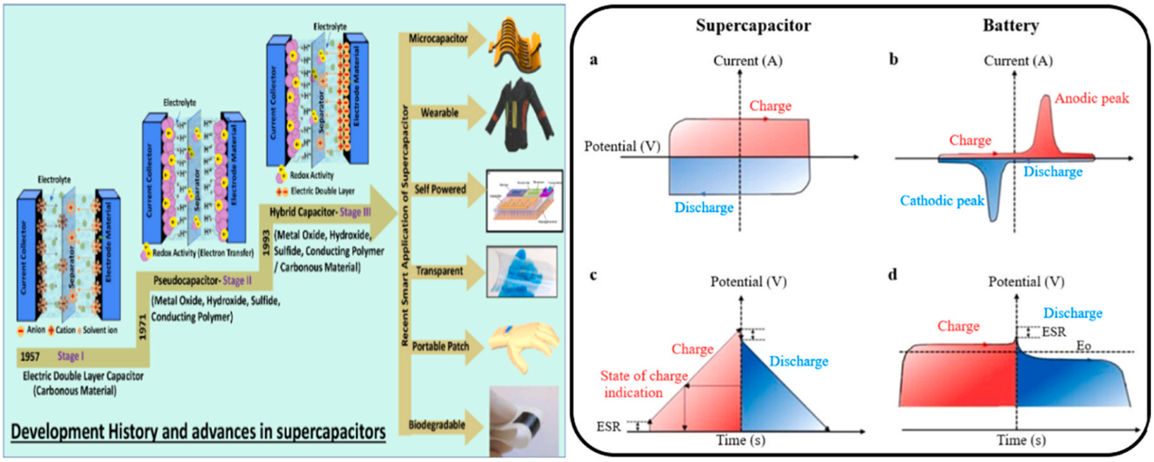
This study summarizes recent improvements in ceramic-based SCs. It investigates a wide range of ceramic electrodes, such as MOs, multielemental oxides, hydroxides, sulfides, carbides, nitrides, carbon-based ceramics, and hybrid or membrane structures, focusing on their composition, structural design, and electrochemical performance. The paper also examines advancements in manufacturing techniques, applications, and industrial potential, as well as important problems, including reaching high ED, extended cycling stability, and high PD. Finally, it discusses further research directions to enhance ceramic materials for next-generation SCs.

2. Mechanisms

2.1. Charge storage mechanisms

2.1.1. Distinguishing between pseudocapacitive and double-layer behaviors in ceramics

The primary distinction is that double-layer capacitance retains charge electrostatically without electron transfer (non-faradaic). In contrast, pseudocapacitance uses quick, reversible surface or near-surface redox processes, electrosorption, or ion intercalation (faradaic). Fig. 2a illustrates the ED and PD of different energy storage systems using the Ragone plot. Traditional and EDLC-based SCs exceed all batteries in terms of PD, but not ED. The EDLC is a device with a high PD due to the rapid adsorption and desorption of electrolyte ions, which



(A) (B)

Fig. 1. (A)Types of SCs with their diverse electrode materials and sophisticated uses [41]. (B-a,b) CV curves and (B-c,d) GCD curves of SCs and batteries [51].

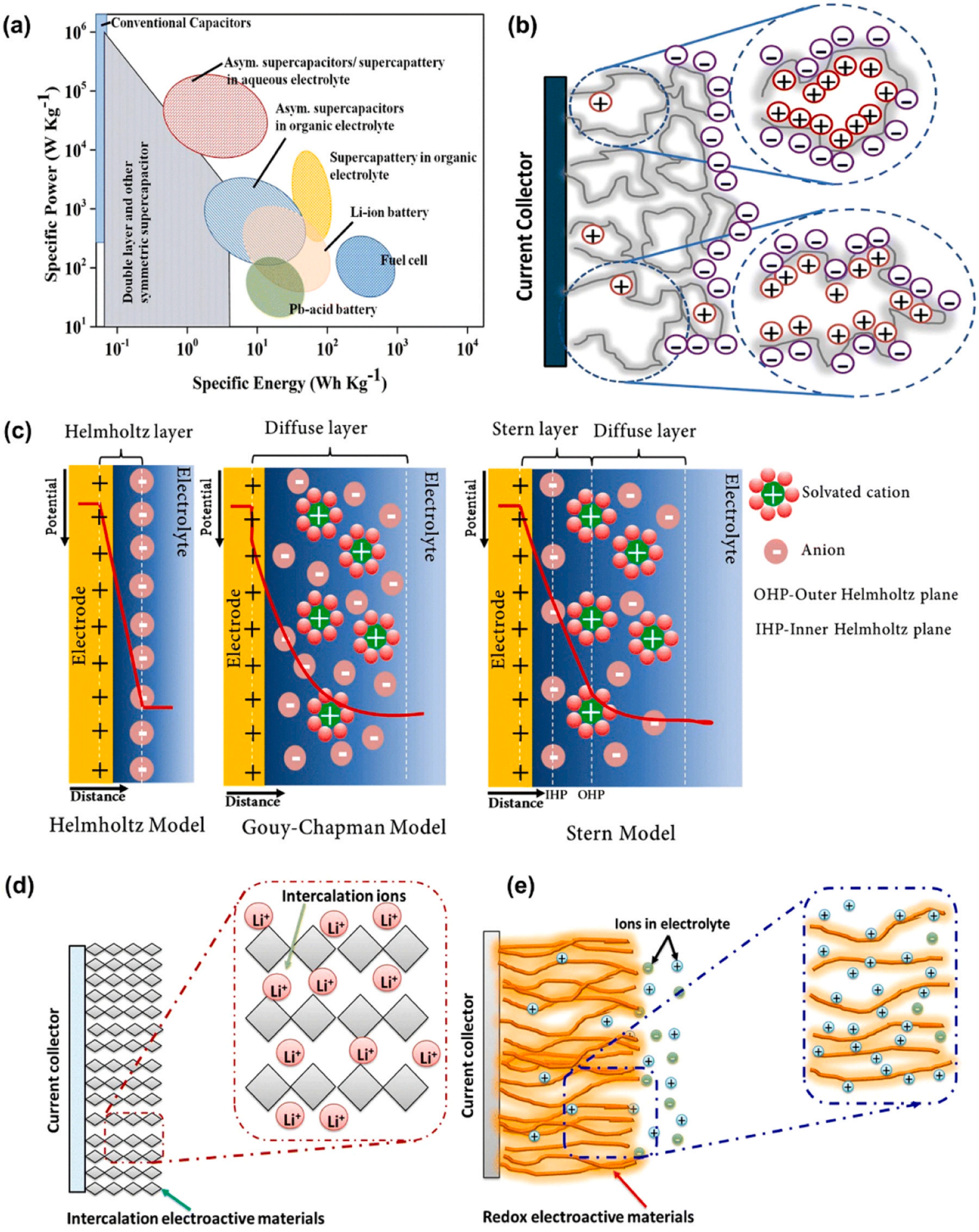


Fig. 2. (a) Ragone graphic comparing various electrochemical energy conversion and storage systems, (b) a schematic representation of an EDL capacitor's charge storage mechanism, (c) representations of EDLC structures, charge storage methods in pseudocapacitors, (d) intercalation (bulk redox), and (e) surface redox.

form an electric double layer (EDL) during charging and discharging (Fig. 2b) [87].

Helmholtz described the electric double layer (EDL) in 1853 as an electrostatically generated layer with no charge transfer (Fig. 2c). Gouy-Chapman established a diffuse layer because of ion mobility, and Stern later split the compact layer into inner and outer Helmholtz planes, inner Helmholtz plane (IHP), and outer Helmholtz plane (OHP) in EDLCs [88]. Ceramic electrodes for SCs are designed with a high surface area, large pores, and efficient ion transport, resulting in a thin IHP and a larger OHP that extends into a diffuse layer and produces a potential difference that influences charge storage [89].

In PCs, reversible Faradaic surface redox processes involving ion intercalation at the electrode/electrolyte interface produce better capacitance and ED than EDLCs, as well as faster energy delivery than batteries [90]. Intercalation occurs when ions tunnel through layers or intercalate inside ceramic electrode materials during Faradaic transfer without changing their crystal structure or phase [91]. This intercalation-based redox method is frequently employed in battery materials [92]. The charge-storing mechanism of a PC is schematically depicted in Fig. 2d,e. Fig. 2 shows a complete description of the various charge storage methods in SC [93]. PCs have higher energy storage properties due to chemical interactions within the bulk material. TMOs and conductive polymers are pseudocapacitive materials, with charge storage methods classified as capacitive non-Faradaic (EDLC), capacitive Faradaic (pseudocapacitive), and non-capacitive Faradaic (battery).

2.1.2. Redox activity in layered ceramics and its impact on energy density

Redox activity in multilayer ceramics increases ED by allowing for many oxidation states; nevertheless, excessive activity may create structural instability. Balancing redox activities with structural stability is critical for improving performance. Material selection and grain boundary engineering to manage porosity and density are particularly important. The addition of soda lime glass or zinc oxide to a well-known ceramic[$(Ba_{1-x}Sr_x)TiO_3$] increased densification, GB strength, and breakdown field while lowering the spark plasma sintering (SPS) temperature [94]. Lanthium doping of another ceramic ($Pb(Zr_xSn_yTi_{1-x-y})O_3$) resulted in a pore-free and uniform fine-grain structure with optimal SPS characteristics. Researchers also investigated relaxor ferroelectrics ($Pb(Zn_{1/3}Nb_{2/3})O_3$-$BaTiO_3$) for high ED storage [95]. Researchers have created a microstructural model for a reverse boundary layer capacitor (RBLC), which exhibits higher electrical conductivity than the grain due to glass additives [96]. Simulations reveal that layered ceramics have higher ED than traditional glass-phase composites, making them interesting for advanced storage devices like hybrid electric vehicles (HEVs) and medical electronics. Ideal materials should have high ED and PD, extended cycle life, stability, and efficiency, as well as cost-effectiveness, sustainability, and tunability for practical use. The molecular structure of various ceramics is given in Table 1[97]. Complex phase diagrams in ceramics cannot be fully investigated due to compositional modifications and differences in expected properties. Modeling approaches like ab initio, atomistic ansatz, molecular dynamics, and discrete element modeling are used.

2.2. Ion transport and structural stability

Ceramic nanoparticles can dramatically improve ion conductivity and thermal stability by forming amorphous patches inside the polymer matrix [98]. This results in a more porous structure, which enhances electrochemical and mechanical properties. Alvarez-Sanchez and his team found that polymer-ceramic-based separators outperformed traditional separators in mechanical and electrochemical performance [99]. This idea has been validated for solid-state electrodes (SSEs) in lithium-sulfur batteries and is predicted to apply to structural SCs. Ceramic separators are utilized in high-temperature solid-state batteries (SSBs) [100]. They are not suitable for regular liquid electrolytes due to their low boiling temperatures [101]. Ceramic separators offer excellent thermal, physical, and electrochemical properties for SCs. However, current ceramic separators in SSCs have inadequate tensile strength, highlighting the need for improved mechanical properties [102]. Zhao and colleagues designed a functional separator for lithium-ion batteries by integrating uneven ceramic fibers into a matrix [103]. The use of irregular ceramic fibers improves the separator's thermal stability and mechanical strength while also enhancing electrolyte wettability, potentially leading to safer and more efficient lithium-ion batteries (LIBs). These fibers have superior mechanical capabilities, with tensile strengths of up to 6 GPa and Young's modulus of up to 420 GPa [104]. Yamamoto and team also developed a method for growing aligned CNTs on ceramic fibers, increasing bonding and porosity, and boosting ionic conductivity [105]. Ceramic materials are created and optimized using solid-state chemistry principles, considering structural stability, atomic size ratio, and point defects. However, performance and stability often trade off, with multicomponent ceramics offering higher stability, creating complex compositions for temperature-resistant materials and catalysts.

3. Ceramics materials

Ceramic is a versatile material noted for its high mechanical strength, outstanding thermal and chemical durability, and substantial electrical, optical, and magnetic capabilities. It also contains no harmful ingredients. Recent research on advanced ceramics highlights the incorporation of organic components to enhance functionality [106]. Organic-inorganic hybrid materials [107,108] are gaining attention for their ability to combine the benefits of both types. Scientists are developing organized hybrid materials [109] through modifications to the classic sol-gel method [110].

Advanced ceramics are used in flexible and wearable energy storage devices like batteries and SCs [111], enabling multifunctional systems [112]. Future research should focus on increasing environmental sustainability [113] and addressing compatibility and stability issues [114]. Optimizing the interface between ceramic electrolytes and electrodes is crucial for reducing resistance and maximizing ion transport in SSBs [115]. Ceramic materials are becoming increasingly important in energy applications as long-term alternatives to fossil-based technology. Their resilience to corrosion, heat, radiation, and stress makes them ideal electrode choices for SCs. Research is focusing on modifying their size, structure, and morphology to increase performance.

3.1. Ceramic-based carbon materials

Carbon and hybrid materials have been popular in energy storage over the last two decades. Wood-derived carbon-based composites, while promising, usually have poor electrochemical performance due to their small surface areas [116]. Wang et al. [117] coated wood-derived monoliths with Ag nanoparticles and $NiCo_2O_4$, resulting in an outstanding areal capacitance of 6.09 F cm^{-2} electrode with 84.5 % stability after 10,000 cycles, as well as exceptional rate capability at 50 mA cm^{-2}. This was made possible by improved electron transport and lower OH^- adsorption energy. Polyamide-derived carbons also perform better when combined with nanomaterials, with dense aromatic polyimides promising as precursors due to their ease of synthesis and high chemical and thermal stability [118]. Li et al. [119] developed hierarchical porous cellulose/polyimide carbon (CPC)-Fe/Zn electrodes with high capacitance and retention, which are appropriate for energy storage applications. The hierarchical porosity structure, combined with Fe/Zn inclusion, creates an abundance of active sites and stable pathways in SCs, leading to high capacitance and durability. Similarly, nitrogen-doped porous carbon nanoparticles [120] and zinc salt-treated carbon materials from flax fiber [121] displayed remarkable SC performance, with the latter obtaining 292 F/g and 102 % retention after 10,000 cycles. Nitrogen doping and zinc salt treatment improve carbon materials' conductivity and surface reactivity, resulting in the stated capacitance and cycling stability. Overall, the performance of most MOs in PCs is restricted, prompting the creation of hybrid electrodes that mix MOs with high-surface-area carbon, such as activated carbon(AC), CNTs, and carbon aerogels(CAs). Table 2 highlights the various MO/carbon composite electrodes utilized in SCs [116–136].

Nanostructures confront difficulties in real-time applications due to scale constraints for accurate size control [137]. Ceramic nanostructures have rapidly advanced, resulting in high-performance electrodes. Tiwari et al. [138] created MnS/CNT and MnO/CNT core-shell heterostructures with high areal capacitances (0.41 and 0.6 Fcm^{-2}, respectively), using asymmetric designs and work function discrepancies. Hu et al. [139] combined $NiCoO_2$ nanosheets with CNTs to create self-supporting 3D electrodes with excellent conductivity, efficient ion transport, and fast Faradaic reactions, improving stability and capacitance. Guo et al. [140] created carbon aerogel-Ni cubic carbon networks for lignin polymerization in hypersaline conditions, whereas Zhou et al. [141] created 3D carbon aerogels with MnOx nanoparticles using radish as a low-cost catalyst. CNTs enhance ion transport, achieving gravimetric capacitances of up to 557 F g^{-1} at 1 A g^{-1} . Kumar et al. [142] discovered that

Table 1
Molecular structure of various ceramics [97].

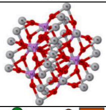
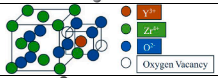
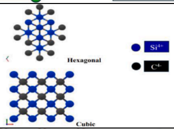
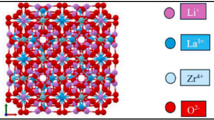
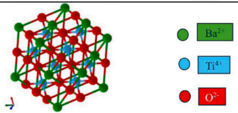
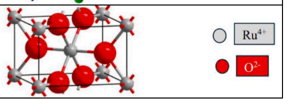
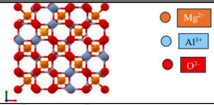
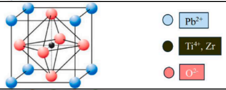
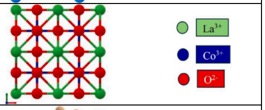
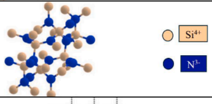
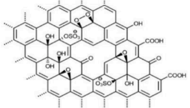
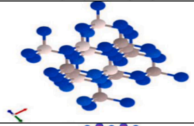
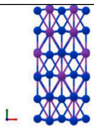
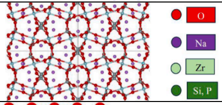
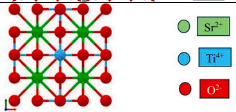
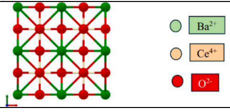
Materials	Various ceramics
Lithium Titanate (Li4Ti5O12)	
Yttria-Stabilized Zirconia (YSZ)	
Silicon Carbide (SiC)	
Lithium Ceramic Garnet (Li7La3Zr2O12)	
Barium Titanate (BaTiO3)	
Ruthenium Oxide (RuO2)	
Magnesium Aluminum Spinel (MgAl2O4)	
Lead Zirconate Titanate (PZT)	
Lanthanum Cobaltite (LaCoO3)	
Silicon Nitride (Si3N4)	
Graphene Oxide (GO)	
Aluminum Nitride (AlN)	
Titanate Ceramics (Potassium Sodium Niobate (KNN))	
Sodium Superionic Conductor (NASICON) Ceramics	
Strontium Titanate (SrTiO3)	
Perovskite -Based Proton Conductors (BaZrO3, BaCeO3)	

Table 2
An overview of the various metal oxide/carbon composite electrodes utilized in SCs.

Material	Potential Window/V	Electrolyte	C_{sp}/ F g^{-1} (Scan Rate or Current Density)	Retention/% (Cycles)	areal mass loading (m) (mg cm^{-2})	ED (Wh kg^{-1})	PD (kW $kg)^{-1}$	Reference
ZrO_2 carbon nanofibers	0–1	6 M KOH	140 (1 A g^{-1})	82.6 (10,000)	> 1.0	56.1	0.349	[116]
$RuNiO_2$ /rGO composites	0–1	0.5 M Na_2SO_4	792(1 A g^{-1})	93 (10,000)	6.9	3.93	—	[117]
NiO/activated carbon composites	0–0.4	2 M KOH	568.7 (0.5 A g)	90.6 (5000)	—	22.6	0.8	[118]
$NiCo_{0.25}$ oxide/carbon nanofibers	−1–0	6 M KOH	431.2 (1 A g^{-1})	94 (2000)	2.0	35.5	1.0	[119]
MnO/Fe_2O_3/carbon nanofibers	0–1	6 M KOH	437 (1 A g^{-1})	94 (800)	–	7.9	0.12	[120]
ZnO/MnO/ carbon nanofibers	0–1.6	6 M KOH	1080 (1 A g^{-1})	96 (800)	–	–	–	[121]
Au-Mn_3O_4 /GO nanocomposites	−0.2–1	0.5 M H2SO4	475 (1 A g^{-1})	94 (10,000)	–	4.86	0.250	[122]
Bi_2O_3 /MWCNT composites	−1.2–0.2	6 M KOH	437 (1 A g^{-1})	88.7 (3000)	2.0	110	0.500	[123]
NiO/MnO_2 /MWCNT composites	0–0.55	2 M KOH	1320(1 A g^{-1})	93.5 (3000)	4.0	52.4	0.800	[124]
Carbon nanosheets/MnO_2/$NiCo_2O_4$ composites	0–1	1 M KOH	1254 (1 A g^{-1})	81.9 (5000)	–	–	–	[125]
ZrO_2/C nanocomposites	0–1	1 M H_2SO_4	214(1.5Ag^{-1})	97 (2000)	–	6.5	0.125	[126]
NiO/porous amorphous carbon nanostructure	0–1.6	6 M KOH	508 (1 A g^{-1})	78 (3000)	–	–	–	[127]
Defective mesoporous Carbon/MnO_2 nanocomposites	−0.8–0.8	1 M Na_2SO_4	292 (0.5 A g^{-1})	78 (2000)	~1.1–1.2	55.8	4.5	[128]
Activated carbon/MWCNT/$ZnFe_2O_4$ composites	−0.1–0.6	3 M KOH	609 (1 A g^{-1})	91 (10,000)	–	–	–	[129]
NiO/C@CNF composites	−0.1–0.5	3 M KOH	742.2 (1 A g^{-1})	88 (5000)	–	–	–	[130]
N-doped carbon quantum dots/Co_3O_4 nanocomposites	–0.4–0.6	6 M KOH	1867 (1 A g^{-1})	96 (500)	–	22.2	0.7279	[131]
Mn_3O_4 /Fe_3O_4@Carbon composites	–0.4–1.2	1 M NaCl	178 (1 A g^{-1})	95 (1000)	1.0	29	1.5	[132]
rGO/CNTs/MnO2composites//	0–1.8	1 M Na SO_4	332.5 (0.5 A g^{-1})	89.2 (10,000)	–	7	0.586	[133]
(HPC)/polyaniline (PANI) nanowire	0–1.8	1 M H SO_4	1080 (1 A g^{-1})	91.6 (5000)	3.0	34	0.1	[134]
Cyclodextrin polymer functionalized polyaniline (CDP)//porous carbon composites (PC)	−0.2–0.8	6 M KOH	437 (0.1 A g^{-1})	81 (5000)	1.0	–	–	[135]
MnO_2 /Graphene Oxide/Polyaniline composites	0–1	1 M Na SO_4	512 (0.25 A g^{-1})	97 (5100)	2.68	58.43	1947	[136]

RGO/Co composites may be prepared in less than 90 s to improve SC electrode performance. Overall, integrating carbon-based and pseudocapacitive materials with high-surface-area carbon aerogels improves capacitance, discharge efficiency, and stability.

Ceramic composites that include reinforcing components in a ceramic matrix can be utilized to reduce the brittleness and low fracture toughness of conventional ceramics. Reinforcements can include:

- Ceramic particles (e.g., silicon carbide (SiC) and silicon nitride (Si_3N_4)) enhance toughness and wear resistance.
- CNTs improve hardness, electrical, and thermal conductivity.
- Graphene nanoplatelets increase fracture toughness by crack deflection and bridging.
- Hybrid reinforcements, including CNTs and graphene or nano/microsecond-phase particles, offer both strength and versatility.

The matrix-reinforcement interface plays a key role in performance. A weak interphase enables crack deflection along the interface, which increases toughness, whereas an overly strong interphase causes cracks to penetrate reinforcements, resulting in brittleness like monolithic ceramics. Thus, by carefully selecting reinforcement types and optimizing interfacial interactions, ceramic composites can attain exceptional mechanical characteristics, making them appropriate for demanding high-performance applications.

3.2. *Metal oxide ceramics for supercapacitors*

Metal-based materials, particularly MOs, are extensively explored for electrochemical energy storage due to their high theoretical capacities and abundance; however, low conductivity and cycle stability limit performance [143–149]. Compositing, element doping, and producing oxygen vacancies (V_o) can improve conductivity and electrochemical behavior. Multi-component MOs and composites, such as $FeCo_2O_4$@NiCo-LDH [143] and $NiCo_2O_4/MnO_2$ [144], exhibit high *C*, ED, and PD due to synergistic effects and abundant active sites. Combining hydroxides with metal quantum dots or organic compounds enhances performance [145]. Nanostructure and microstructure engineering are important for enhancing surface area, ion transport, and electrolyte wettability. For example, 1D $NiCo_2O_4$ nanowire-coated reduced graphene oxide (RGO) achieves 1248 F g^{-1} [146], whereas 2D $MnMo_4 \cdot H_2O$@MnO_2 nanosheets achieve 3560.2 F g^{-1} and an ED of 45.6 Wh kg^{-1} [147]. Using metal-organic frameworks (MOFs) as precursors enables tailored MO microstructures, albeit research is currently limited to a few prominent MOFs. Low electroconductivity is still a challenge [148], but it can be overcome by combining with highly conductive materials such as MXenes, a family of 2D transition metal carbides and nitrides [149].

Transition metal oxides (TMOs) have aroused broad interest due to their low cost and eco-friendliness. Ruthenium dioxide (RuO_2) is suitable for pseudocapacitive electrodes due to its high theoretical capacitance (2000 F g^{-1}), rapid Faradaic redox processes, superior electrical conductivity, chemical and thermal stability, and wide operating voltage range [150]. However, its high cost limits large-scale usage; thus, composite synthesis has been employed to reduce costs while maintaining electrochemical performance [151]. TMO ceramics (MnO_2, Mn_3O_4, Co_3O_4, NiO, ZrO_2, V_2O_5), Al_2O_3, and SnO_2 have been extensively studied as SC electrodes (Table 3 [152–170]). TMO ceramics provide high energy density through fast redox reactions. Lang et al. [152] created a MnO_2 electrode with a nanoporous V_2O_3 skeleton, resulting in electrical outputs up to 422 W cm^{-3} and better pseudocapacitance due to improved charge transfer at the MnO_2/V_2O_3 interface. Electrospinning has been utilized to fabricate ultrathin Co_3O_4 nanowires [161] and NiO nanowires [163], resulting in high capacitance, low resistance, and excellent cycling stability. Additionally, MnO_2 films produced via electrospinning exhibit favorable pseudocapacitive behavior [153]. SCs might potentially benefit from Al_2O_3 and SnO_2 ceramics. Some results were obtained, as illustrated in Fig. 3A [171]. Li et al. [169] provided an easy and fast approach for creating planar micro-SCs using alumina ceramic plates (Fig. 3A-a). The plates were subjected to selective laser etching, yielding SH and SHL patterns (Fig. 3A-b). Graphene ink was then introduced to cover the patterned interdigital electrode region based on the etched surface's wettability difference (Fig. 3A-c). The interdigital electrode area was electrolyte-applied with polyvinyl alcohol-sulfuric acid (PVA-H_2SO_4) gel (Fig. 3A-d), resulting in an SC with a C of 5.5 $mFcm^{-2}$ (Fig. 3A-e). SnO_2, with its unique optical and electrical properties and strong chemical stability, provides SnO_2-based materials with distinct qualities [172]. Barium stannate ($BaSnO_3$) is a potential material for thermally stable capacitors due to its dielectric properties [173]. The performance of ceramics and MOs is determined by microstructure, grain size, density, flaws, and conductivity. Designing MOs with improved microstructures and higher conductivity is critical for enhancing SC performance.

3.3. Multi-element oxide ceramics for supercapacitors

3.3.1. Spinel oxide ceramics

Spinel oxide ceramics are made up of two metals with a more complex redox chemistry than single-component oxides [174]. Spinel oxides are often produced by solid-phase, liquid-phase, or vapor-phase processes. The solid-phase approach is straightforward and exothermic, requiring grinding and heat treatment to ensure phase purity. Liquid-phase processes are more adaptable, allowing for large-scale manufacturing while controlling particle size, shape, and morphology. In contrast, vapor-phase procedures rely on precursor vaporization and condensation, providing accurate deposition but necessitating complicated equipment. Spinel ferrites (MFe_2O_4) are used in SC electrodes due to their superior electrical conductivity and electrochemical activity compared to single-component oxides. The study investigated $NiFe_2O_4$ ceramic powders produced through combustion synthesis, polyol-mediated, and sol-gel procedures **(**Fig. 3**B-a)**[175]. The shape of the EDLCs seen in this $NiFe_2O_4$ ceramic powder regulated the behavior of the EDLCs. The $NiFe_2O_4$ ceramic produced using the sol-gel technique achieved the highest C of 97.5 Fg^{-1} due to its well-balanced micro and mesoporosity (Fig. 3B-b). The electrochemical performance remains unchanged even after 100 CV cycles. Rani and associates developed a safer co-precipitation method for creating a cobalt-doped zinc-ferrite ceramic, $Co_xZn_{0.04\text{-}x}Fe_2O_4$ ($x = 0$, 0.01, 0.02) [176], which consists of large clusters and nanoparticles (Fig. 3B-c). The electrode C was increased by approximately 377 Fg^{-1} through cobalt substitution at a scan rate of 10 mVs^{-1} (Fig. 3B-d). Anandhan and colleagues developed mesoporous spinel zinc $ZnMn_2O_4$(ZMO) for potential use in electric devices like SCs, using sol-gel-assisted electrospinning and calcination procedures [177]. The study by Kovalenko and his team found that ceramic nanofibers containing hexagonal $ZnMnO_3$ and MnO phases have a large SSA (79.51 m^2g^{-1}) and four band gaps after calcination, making them a potential electrode material [178]. Researchers have discovered that $NiCo_2O_4$, a nanocrystalline material with 25–30 % open

Table 3
A description of some metal oxide ceramics used in SCs.

Materials	Shapes	Methods	Capacitance	areal mass loading (m) (mg cm^{-2})	ED (Wh kg^{-1})	PD (kW $kg)^{-1}$	Reference
MnO_2	Film	Electrophoretic deposition	0.34 F/cm^2 at 2 mV/s	–	–	–	[152]
MnO_2	Film	Electrophoretic deposition	–	–	–	–	[153]
$K_xMnO_{2+y}(H_20)z$	Film	Electrodeposition	353 F/g at 2 mV/s	0.045	–	–	[154]
MnOx	Cellular foam	Hydrothermal and mild templating route	–	–	–	–	[155]
MnO_2-MWCNT	Nanocomposites	Liquid-liquid extraction method	5.7 F/cm^2 at 2 mV/s	36	–	–	[156]
Mn_3O_4-MWCNT	Nanocomposites	Liquid-liquid extraction method	3.1 F/cm^2 at 2 mV/s	36	–	–	[156]
MnO_2-foamed nickel	Film	Spray Pyrolysis	45 F/g	–	–	–	[157]
Mn_3O_4-CNT	Flakes	Chemical precipitation and electrostatic hetero coagulation	5.04 F/cm^2 at 2 mV/s	36	–	–	[158]
(Fe, Zn)OOH-PNT	Composite	Chemical precipitation	4 F/cm^2 at 2 mV/s	36	–	–	[158]
V_2O_3/MnO_2	Corundum-type crystalline	Pulsed electrodeposition	1172 F/cm^3 at 10 mV/s	36	–	–	[159]
Co_3O_4	Urchin-like particles	Hydrothermal	–	–	–	–	[160]
Co_3O_4	Urchin-like Nanowires	Electrospinning	1110 F/g at 1 A/g	2.0–2.5	~47.6	~1.400	[161]
$CuOeCo_3O_4$	Nanowires	Electrospinning	1277 F/g at 2 A/g	–	52.6	~15	[162]
NiO	Nanowires	Electrospinning	670 F/g at 5 A/g	–	–	–	[163]
NiO	Nanoplatelet	Chemical precipitation	1000 F/g at 2 A/g	≈ 1	17.4	1085	[164]
NiO/Ni	Core-Shell nanoparticles	Colloidal processing	755 F/g at 2 A/g	1	–	–	[165]
$NiOZrO_2$	Membranes	Template method	342 F/g at 2 A/g	200–250	–	–	[166]
$(ZrO_2)_{0.6}(In_2O_3)_{0.4}$	Nanocrystalline power	Citrate sol-gel method	–	–	–	–	[167]
V_2O_5	Scaffold's lamellar structure	Sol-gel method and freezing	–	–	–	–	[168]
Al_2O_3	Micropillars	Selective laser etching	5.5 mF/cm^2 at 5 mV/s	–	–	–	[169]
$SnO_2/CaSnO_3$-Ba (shell)/Dye	Core-shell	Spray pyrolysis	–	–	–	–	[170]

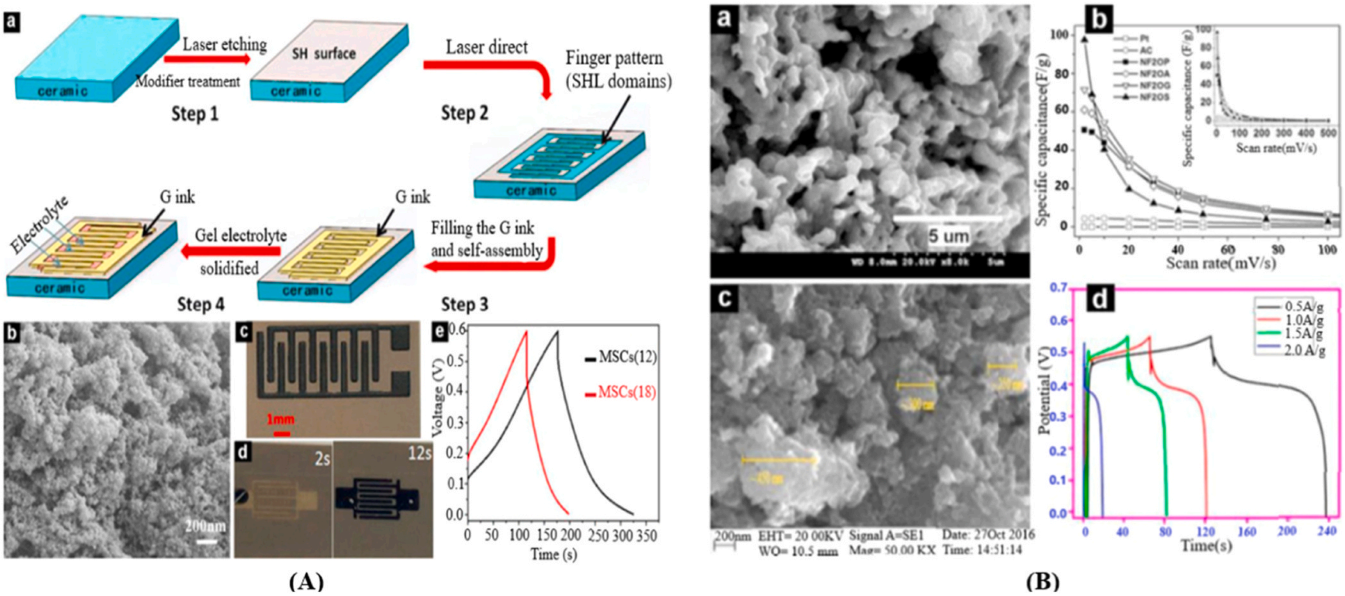


Fig. 3. (A-a) Production of graphene-based planar MSCs on an alumina ceramic plate. (A-b) SEM photographs of laser-etched ceramic surfaces, (A-c) optical representations of graphene-based MSCs, and (A-d) self-assembly graphene ink photos with interdigital patterns lasting 2–12 s. (A-e) Galvanostatic charge-discharge curves of graphene-based MSCs. (A-f) Graphene-based MSC-GCD curves [151]. (B-a) SEM picture of $NiFe_2O_4$ ceramic powder made via sol-gel technique, (B-b) Specific capacitance values for $NiFe_2O_4$ generated using various methods, (B-c) SEM picture, and (d) galvanostatic charge-discharge curve of $Co_{0.02}Zn_{0.02}Fe_2O_4$ ceramic calcined at 800°C [151].

porosity, can be created by combining nitrate crystallization with heat and ultrasonic treatment [178]. Combining crystallization with ultrasonic treatment results in porous $NiCo_2O_4$ with a high surface area, enhancing ion transport and electrochemical activity. Exploring novel synthesis processes will broaden the scope of potential applications for these materials.

3.3.2. Barium titanate ceramics

Polymers have been separated using various alkaline earth metal titanites. The combination of polyvinylidene fluoride (PVDF), polypropylene (PPG), and lithium chloride resulted in the formation of a sponge-shaped polymer called barium titanate ($BaTiO_3$), which was phase-inverted through solvent precipitation and heating [179]. Lithium chloride enhances porosity for faster charge transfer, while $BaTiO_3$ ceramics increase the dielectric constant of the polymer $BaTiO_3$ film (PCC/BTA), making it a suitable separator electrode material with an electrochemical resistance of 42.5 Ω and a C of 305.6 Fg^{-1}. Gu and his team utilized roll coating and heat curing to create $BaTiO_3$/polymer/Al (BPA) composite films [180]. The size of $BaTiO_3$ particles (D_{90}=0.83μm) affects their dielectric characteristics and electrochemical performance. $BaTiO_3$ ceramics were developed to enhance nanocomposite material, creating high aspect ratio $BaTiO_3$ nanowires in a polymer matrix [181]. The synthesized material showed an ED of 10.48 J/cc at 300 MV m^{-1} and a core-shell structure with a low volume percentage of 17.5 % $BaTiO_3$. Chung and colleagues identified a secondary phase of $Ba_2TiSi_2O_8$, a ferroelectric material having electrochemical properties, near the core-shell boundary (fressnoite) [182]. $BaTiO_3$ particles (300–500 nm in diameter) were sintered using the Stober process and covered with a silica shell. Advanced sintering methods like spark plasma sintering created a bulk composite with low dielectric loss and temperature stability [183]. This material demonstrated strong SC performance due to Ti^{4+} reduction, space charge relaxation, internal grain conductivity, and silica barriers. The structure helped build large dielectric properties in ferroelectric cores, exceeding ferroelectric constraints under high electrical stress [183]. Chung and team used a silica shell to improve conductivity and reduce dielectric losses [184], identifying $BaTiO_3@Si_5$ as a good SC electrode material. Although $BaTiO_3$ ceramics are commonly employed in SCs due to their high dielectric constant and low dielectric loss, their poor energy storage density limits their employment in high-energy devices. Ion doping has developed as a viable approach for modifying electronic structures, increasing conductivity, and improving overall performance.

3.3.3. Multi-elemental Oxide Ceramics

Doping ceramics with rare-earth elements (such as TiO_2 and NiO) improves dielectric characteristics [185]. Transition metals in $CaCu_3Ti_4O_{12}$ (CCTO) enhance conductivity, reduce activation energy, and boost C [186]. The high dielectric permittivity is attributed to the electron-pinned defect-dipole (EPDD) or Maxwell-Wagner (M-W) polarization mechanism, which enables the use of multi-elemental oxide ceramics in superconductors and SCs. Table 4 [187–211] highlights commonly used ceramics in SCs. Shiri et al. [187] developed polypyrrole (PPy)/ yttrium aluminum garnet (YAG) thin-film electrodes with 254 F g^{-1} at 25 mV s^{-1} . YAG nanoparticles enhanced capacitance and cycling stability. Yttria has also been employed in separators, where YSZ-NiO-graphite composites produce porous, low-resistance membranes [190]. Maity et al. [197] developed CCTO nanocubes with 1185 mF cm^{-2} at 10 mV s^{-1} , while CCTO/PANI composites achieved a C of 610 Fg^{-1} at 0.5 A g^{-1} . A symmetric SC with 5 % CCTO-PANI obtained 30 Wh kg^{-1} ED, 20 kW kg^{-1} PD, and 80 % capacitance retention (CR) after 2000 cycles using $Li_{0.33}La_{0.56}TiO_3$ electrodes [202]. Li^+ caused ionic migration and lattice modifications, resulting in pure capacitive behavior at 2 V. Overall, these examples show how compositional tweaking, defect engineering, and composite synthesis in oxide ceramics affect dielectric characteristics, ion transport, and electrochemical performance of SCs.

Liu et al. [203] used CuO nanoparticles on a ceramic substrate called $La_{1-x}Sr_xCoO_{3-d}$ (LSC; $0 \leq x \leq 0.8$) (Fig. 4A-a). The material's porous shape, good conductivity (Fig. 4A-b), and evenly scattered CuO nanoparticles make it ideal for energy storage devices. Its high C (545 Fg^{-1}) and 74.1 % CR after 3000 cycles at 20 mA cm^{-2} make it a reliable choice (Fig. 4A-c, A-d). This material created a quasi-solid-state asymmetric SC with a PVA/KOH gel electrolyte and a carbon fiber anode. At 1 mA cm^{-2}, the SC device exhibited a capacitance of 1.26 F cm^{-2}. $La_{0.7}Sr_{0.3}CoO_{3-d}$ (LSC) electrodes were synthesized using a solid-state method, with Sr^{2+} substitution increasing electrical conductivity

Table 4
A summary of the most used multi-elemental oxide ceramics in SCs.

Materials	Shapes	Methods	Capacitance	Reference
$PPy/Al_5Y_3O_{12}$	Nanoparticles	Electro-polymerization	254 F/g at 25 mV/s	[187]
$Ba_2TiSi_2O_8$	Particles	Ball-milling	–	[188]
$(ZrO_2)_{0.6}(In_2O_3)_{0.4}$	Membrane	Sol-gel method	–	[189]
NiO/YSZ	Membrane	Mixing and calcination	272 F/g at 1 A/g	[190]
Carbon-$SiO_2/TiO_2/YZrO_2/Al_2O_3$	Monoliths	Sintering and decomposition	–	[191]
$Li_7La_3Zr_2O_{12}$	Rounded lines/columns	3D-print and sinter	–	[192]
$(Nb_{0.5}Ga_{0.5})_x(Ti_{0.9}Zr_{0.1})_{1-x}O_2$	Octahedron	Solid-state reaction	–	[193]
$CaCu_3Ti_4O_{12}$	Grains	Ball-milling and calcination	–	[194]
$CaCu_3Ti_4O_{12}$	Spherical particles	Solid-state reaction	4 F/cm^2 at 2 mV/s	[195]
$CaCu_3Ti_4O_{12}$	Nanocubes	Molten salt method	1185 mF/cm^2 at 10 mV/s	[186]
$Ce_{0.9}Cd_{0.05}O_{1.975}/Ti/Al$	Films	Femtosecond laser micro-process	–	[196]
$PANI/CaCu_3Ti_4Co_3O_{12}$	Nanofiber	Chemical oxidative polymerization	610 C/g at 0.5 A/g	[197]
$Ba_{0.6}Sr_{0.4}TiO_3/PVDF$	Nanoparticles	Tape casting method	–	[198]
$Na_{0.5}Bi_{0.5}TiO_3$	Nanoparticles and Films	Solid-state reaction	–	[199]
$Li_{0.5}La_{0.5}TiO_3$	Tetragonal	Solid-state reaction	–	[200]
$Li_{3x}La_{2/3-x}TiO_3$	Cubic	Solid-state chemistry	–	[201]
$Li_{3x}La_{2/3-x}TiO_3$	Cubic	Solid-state reaction	0.28 mF/g at 10 mV/s	[202]
$CuO–La_{1-x}Sr_xCoO_{3-d}$	Porous substrate	Solid-state reaction	545 F/g at 1 mA/cm^2	[203]
$NiO/La_{0.7}Sr_{0.3}CoO_{3-d}$	Porous substrate	Solid-state reaction	1064.1 F/g at 20 mA/cm^2	[204]
$Ca_8H_2(PO_4)_6.5H_2O$	Plate-like	Solution precipitation	6 mA h/g	[205]
$Li_3V_2(PO_4)_3$	Nanoparticles	Heat treatment	116.4 F/g at 0.5 A/g	[206]
$Li_{1.3}Al_{0.3}Ti_{1.7}P_3O_{12}$	Bulk	Solid-state reaction	0.13 F/cm at 2 mV/s	[207]
$Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$	Pellets	Sol-gel method	55 μF/g at 50 mV/s	[208]
$Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ –SWCNT	Nanoparticles	Sol-gel method	3.16 mF/g at 5 mV/s	[209]
$Li_{1+x}Al_xTi_{2-x}(PO_4)_3$	Bulk	Heat treatment	–	[210]
$LiM_2(PO_4)_3$ (M=Ti/Ge)	Bulk	Heat treatment	–	[211]

[204]. NiO nanoparticles were loaded onto LSC, improving electrode-specific capacity. Phosphates have been used as SC electrode materials with glass-ceramic electrodes [205–211], containing $Li_3V_2(PO_4)_3$[206], exhibiting a remarkable *C* of 116.4Fg^{-1} at 0.5Ag^{-1}, and ceramic ($Li_{1.3}Al_{0.3}Ti_{1.7}P_3O_{12}$)(LATP) used as an electrolyte [207]. Liao and colleagues [208] utilized single-walled CNTs (SWCNTs) with LATP ceramic electrolytes to enhance the contact area, achieve a *C* of 0.13 Fcm^{-1} at 2 mVs^{-1}, and reduce total resistance. Multi-elemental oxide ceramics are promising SC electrode materials due to the synergistic effects of multiple metal elements and richer redox chemistry, which improve *C*, conductivity, and stability via mechanisms such as the cocktail effect and higher oxygen vacancy concentration.

3.4. Metal hydroxide ceramics for supercapacitors

Metal hydroxides can create SCs with high capacity and mechanical strength, such as the $Cu(OH)_2$ lattice electrode [212]. A ceramic lattice substrate was fabricated using 3D printing, electroless copper plating, and electro-oxidation (Fig. 4B-a, B-b). The 3D-printed CLS maintained its size after sintering (Fig. 4B-c), while the $Cu(OH)_2$ had an urchin-like structure (Fig. 4B-d). The $Cu(OH)_2/Cu/CLS$ composite exhibited a coulombic efficiency of about 98.1 % and excellent redox reversibility (Fig. 4B-e). The $Cu(OH)_2/Cu/CLS$-based solid-state SC demonstrated great coulombic efficiency and outstanding redox reversibility, with high volumetric capacitance and CR of around 60 % at 200 Acm^{-3} (Fig. 4B-f)[212]. The SC achieved 24.3 Wh kg^{-1}ED and 314.4 Wkg^{-1} PD, comparable to previously published SCs (Fig. 4B-g). The 3D spatial framework architecture and hierarchical ion transport pathway were responsible for the remarkable performance. Gonzalez and colleagues [213] used NiO films for SC electrodes, while Zhitomirsky and colleagues discovered octyl gallate as a good extractor for FeOOH ceramic particles [156]. This led to FeOOH-MWCNT electrodes with a 2.4 Fcm^{-2} *C* at 2 mVs^{-1}. Metal hydroxide ceramics, particularly bimetallic and ternary systems, have high capacitance, good redox activity, and are low in cost, with nanostructuring, binder-free electrodes, and new synthesis processes improving performance even further. MOs and hydroxides can acquire charge in either the positive or negative regions of the potential window. As a result, different MOs and hydroxides with enhanced redox kinetics can be combined in positive and negative electrodes to give high charge storage capacity, excellent responsiveness, and long-term stability. These asymmetric combinations can considerably boost the ED of SC cells while maintaining a suitable power response in aqueous electrolytes. It is worth noting that asymmetric systems with battery-like responsive electrodes will be known as hybrid SCs.

Controlling the intrinsic properties of MOs and hydroxide electrodes is an important way to increase electrochemical performance. However, intrinsic limitations such as the low electronic conductivity of oxides and hydroxides, as well as the structural instability of hydroxides, make it difficult to overcome merely by intrinsic materials engineering. As a result, extrinsic engineering and functionalization techniques, such as cation or anion doping and composites with other materials, have emerged as effective options for enhancing charge storage performance. Hybrid electrodes, for example, provide a higher storage capacity because of greater electron conductivity and surface area. Similarly, composites of metal oxides and hydroxides with conductive metals or carbon-based nanomaterials comprise a popular research route focused on improving electrode performance.

3.5. Metal Sulfide Ceramics for Supercapacitors

Metal sulfides (MSs) are crucial for energy storage due to their large surface area and diverse oxidation states [214]. EDL and

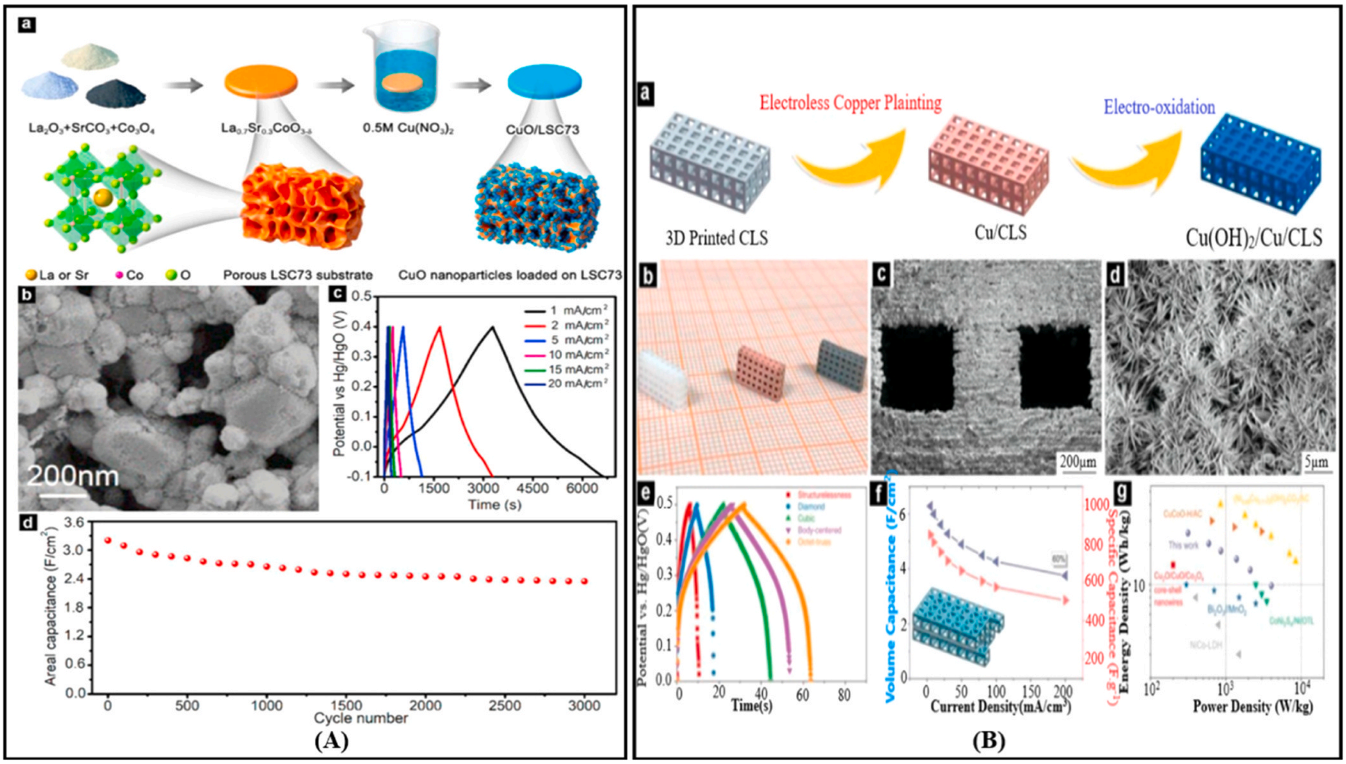


Fig. 4. (A-a) Schematic diagram for CuO/La$_{0.7}$Sr$_{0.3}$CoO$_{3-\delta}$ electrode fabrication, (A-b) SEM picture, (A-c) GCD curve, and (A-d) cycle stability of CuO/La$_{0.7}$Sr$_{0.3}$CoO$_{3-\delta}$ [151]. (B-a) The construction of a Cu(OH)$_2$/Cu/CLS-based SC, (B-b) SEM images of the 3D-printed electrode, (B-c) CLS, and (B-d) Cu(OH)$_2$/Cu/CLS, (B-e) an electrode's GCD curve, (B-f) volumetric and *C*-curves vs current density, and (B-g) Ragone plots for samples [151].

pseudo-capacitive charge storage technologies enable them to store high energy [215]. Ultrathin nanosheets with a vast surface area and multiple oxidation states store charges electrostatically, resulting in high C and ED [216]. MSs with anisotropic crystal structures offer high reactivity for effective electrochemical processes [217]. However, low conductivity and re-stacking hinder their potential as advanced SC electrodes [218]. 2D-MSs with a wide surface area and active edge sites enhance catalytic activity and substrate compatibility. Manganese cobalt sulfide (MnCoS$_5$) nanospheres allow electrodes to expand and compress during charge-discharge cycles [219]. MnCoS$_5$ nanospheres possess a mixed-phase, porous structure and HSSA, enabling them to perform various redox processes [220]. The SCs demonstrated high electronic

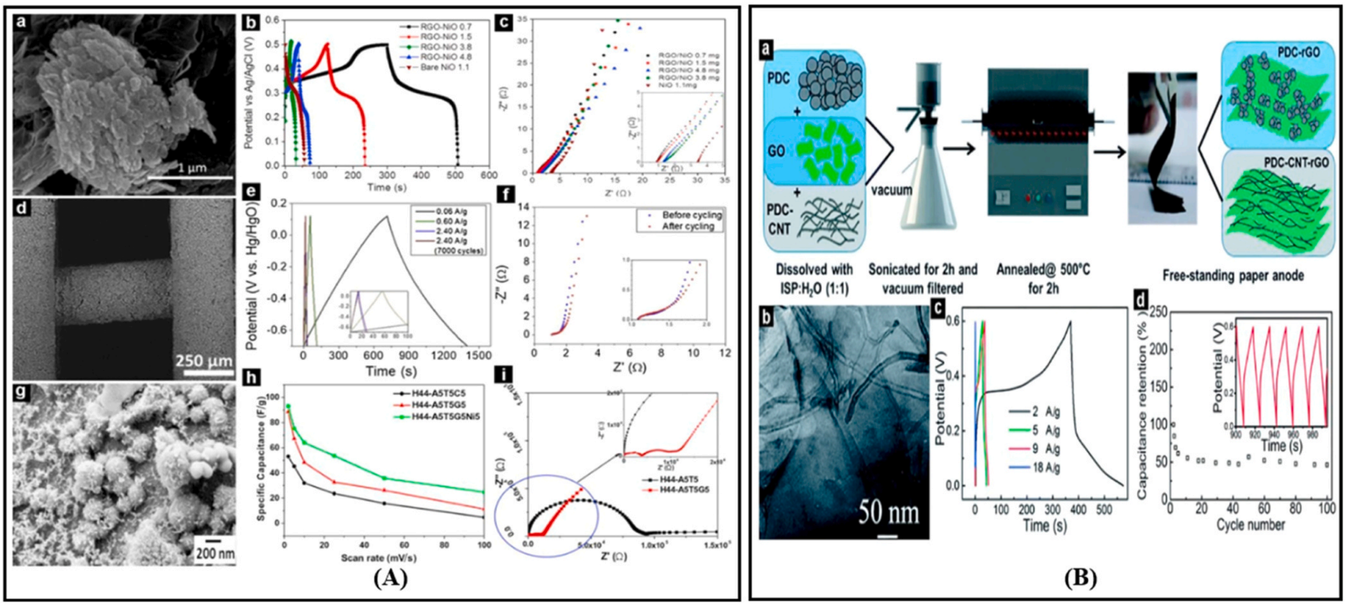


Fig. 5. (A-a) SEM picture, (A-b) GCD data, and (A-c) EIS data for RGO/NiO electrodes. (A-d) SEM picture, (A-e) GCD data, and (A-f) Nyquist diagram of the RGOF/SiCN electrode. (A-g) SEM picture, (A-h) Capacitance, and (A-i) EIS data for hybrid poly (methylphenyl silsesquioxane) APTES-TEOS-MWCNT Ceramic [151]. (B-a) A diagram of the fabrication of free-standing Si(B)CN-CNT paper. (B-b) A TEM image of the Si(B)CN-CNT composite. (B-c) GCD data; (B-d) cyclic stability of Si(B)CN-CNT-RGO composites [151].

conductivity and achieved a *C* of 992 Fg^{-1}, retaining 102 % after 5500 cycles at 10 Ag^{-1}. Liu and colleagues electrochemically coated carbon fibers with polypyrrole (PPy) [221], creating a PPy/Cu_9S_8@C-CC nanocomposite with a *C* of 270 Fg^{-1} and 80 % CR after 3000 cycles. MSs and mixed MSs, which have high redox activity, have higher conductivity and flexibility than MOs and carbon materials because the presence of sulfur improves electron transfer, whereas MO- and carbon-based electrodes suffer from low volumetric capacitance, agglomeration, and fabrication issues.

3.6. Carbon-based ceramics for supercapacitors

Carbon-based materials, such as graphene oxide (GO) and graphene, show promise for energy devices due to their high strength, electrical conductivity, flexibility, and vast surface area [222]. CNTs also have great tensile strength, conductivity, and a large surface area, making them ideal for transistors and SCs [223]. Carbon-based ceramics, such as RGO, CNTs, and AC, are extensively researched as SC electrodes because of their rapid charge transfer [224]. 2D-GO is widely used in energy storage and conversion [225], whereas graphene-ceramic composites have been produced as SSEs [226]. RGO was electrostatically intercalated into NiO nanoplatelets, resulting in a core-shell structure (Fig. 5A-a), and then electrophoretically deposited on Ni foam collectors while maintaining structural integrity with ceramic necks. The composite exhibits a C of 940 F g^{-1} at 2 A g^{-1} due to its low charge transfer resistance (Figs. 5A-b, 5A-c) [226]. GO was also employed to fabricate RGO foam (RGOF)/SiCN electrodes via a preceramic polymer method, in which ink-written GO scaffolds were infiltrated with a polysilazane precursor to replicate the 3D structure (Fig. 5A-d). After heat treatment, the amorphous SiCN matrix embedded with GO achieved 39 F g^{-1} at 0.6 A g^{-1} and showed excellent cycle stability (Figs. 5A-e, 5A-f) [227]. In addition, a monolithic material composed of polysiloxane microspheres, graphene, multi-walled CNTs (MWCNTs), and metal nanoparticles was synthesised (Fig. 5A-g), exhibiting a SSA of 540 m^2 g^{-1} , hierarchical porosity, and 93 F g^{-1} at 2 mV s^{-1} (Fig. 5A-h), with enhanced ion mass transfer (Fig. 5A-i) [228]. Carbon-based ceramic materials for SCs can be optimized by enhancing SSA and pore volume through controlled manufacturing, creating hierarchical porous structures, and integrating metal oxide nanoparticles to combine pseudocapacitance with EDLC. Other improvements include heteroatom doping (for example, nitrogen) to boost capacitance and the use of asymmetric or hybrid designs to increase ED.

1D-CNT hybrid ceramics offer high conductivity and large surface area, enhancing charge transfer and energy storage [229]. Singh et al. [230] developed low-frequency plasmonic AlN–SWCNT composites, where dense composites with low SWCNT content showed increased negative permittivity due to inductive loops formed by high-aspect-ratio SWCNTs, improving thermal conductivity. David et al. [231] fabricated lightweight, porous, self-supporting Si(B)CN–CNT–RGO composite paper (Fig. 5B-a) sandwiched between graphene sheets (Fig. 5B-b), functioning as a SC electrode with a C of 269.52 F g^{-1} at 5 A g^{-1} and excellent cycle stability (Figs. 5B-c, 5B-d). Boron-doped SiCN enhances conductivity, while CNTs and RGO improve porosity and electron conduction. Lee et al. [232] combined polypyrrole with CNTs on ceramic fabric, achieving 152.78 F g^{-1} at 1 mA cm^{-2} through improved CNT adhesion and interconnected networks. Carbide-derived carbon has also been used as an SC electrode [233], and PVA–ceramic nanoparticle (Al_2O_3, SiO_2, TiO_2) separator films [234] enhance ion conductivity by forming amorphous regions in the polymer matrix. Carbon-ceramic composites are being investigated for SCs because they combine the large surface area and conductivity of carbon materials (e.g., AC, CNTs, graphene) with the electrochemical activity of ceramic materials (such as MOs, hydroxides, and carbides). This synergy enhances ED and PD, leading to higher capacitance, stability, and overall energy storage performance in advanced SC systems.

3.7. Carbide and nitride-based ceramics

Carbide and nitride ceramics are increasingly used in demanding applications due to their low density, high-temperature strength, thermal stability, corrosion resistance, and outstanding electrical properties [235]. Chang and co-workers [86] developed B_4C@C core-shell ceramic nanoparticles as electrodes, highlighting their potential in SC electrode materials as shown in Fig. 6a, b, and c. The carbon shell enhanced the B_4C ceramic's electrical conductivity, enhancing stability during charging and discharging while combining graphene with B_4C@C nanoparticles, creating flexible all-solid-state micro-SCs (Fig. 6d). SC electrode materials have been developed using carbide and nitride ceramics, with metal carbide ceramics being commonly utilized. Carbide and nitride ceramics provide good conductivity and stability, which makes metal carbides particularly appealing as SC electrode materials. A new type of lattice SCs has been created using a ceramic matrix. These SCs exhibited a *C* of 7.33 mF cm^{-2} at a scan rate of 1 mV/s and worked effectively across a wide temperature range (-25–75°C)(Fig. 6e). The ceramic matrix-based lattice SCs show consistent capacitance and wide temperature operation, indicating their promise for practical energy storage applications. The authors emphasized the mechanical flexibility of the B_4C@C-MSCs devices (Fig. 6f), which maintain 99.4 % of their initial capacity even after 1200 cycles of deformation (Fig. 6g). B_4C@C-MSCs have great mechanical flexibility and high CR under repeated deformation, indicating their potential as flexible energy storage devices. They also highlight their use of SiOC-based polymer--derived ceramics as SC electrodes. SiOC-based polymer-derived ceramics were employed as SC electrodes, and SiOC fiber mats formed by electrospinning and pre-ceramic polymers such as H44, MK, and RSN [236]. SiOC-based polymer-derived ceramics, particularly fiber mats generated by electrospinning, have adjustable structures and stability, making them interesting candidates for SC electrodes. Similarly, Kaskel and colleagues advocated using SiOC-derived carbon (SiOCDC) in SCs [237]. SiOCDC electrodes produced at 1000°C have a *C* of 86 Fg^{-1} at 30 Ag^{-1}. In addition, a SiOC nanostructured material with lamella-like characteristics was developed and used as an SC electrode [238]. SiOC-derived carbons, particularly SiOCDC and nanostructured lamella-like forms, exhibit good capacitance and structural properties, highlighting their potential as effective SC electrodes.

SiC ceramics are extremely strong, flexible, and thermally/chemically stable [239]. SiC@$Ni(OH)_2$ nanowires grown on flexible carbon fabrics supplied 1724 F g^{-1} at 2 A g^{-1} and 72.4 Wh kg^{-1} ED [240], whereas SiC-N-MnO_2 nanoneedles were deployed in asymmetric SCs, achieving 59.9 F g^{-1} and 113.92 W kg^{-1} PD [241,242]. After 3000 cycles, the porous SiC nanofiber membranes maintained 189 F g^{-1} and 91.7 % retention [243]. SiC-based composites combine mechanical toughness with good electrochemical performance, providing superior capacitance, energy density, and long-term cycling stability for advanced SC applications. Nitride ceramics, with their high strength, low thermal expansion, and resistance to wear, corrosion, and thermal shock, are perfect for aerospace applications [244]. Xia et al. [245] successfully reached 403 mAh g^{-1} by adding Co particles into an amorphous Si_3N_4 matrix. Wei et al. [246] developed a core-shell framework using Si@Si_3N_4 nanoparticles coated on carbon nanofibers to create flexible 3D electrodes for SCs [247]. Nitride ceramics not only give structural and thermal benefits, but when paired with metals or carbon nanostructures, they enable high capacity and flexible topologies appropriate for improved SC electrodes. Carbide and nitride-based ceramics are attractive SC electrodes due to their excellent conductivity, stability, and structural strength. MXenes and other transition metal carbides/nitrides provide metallic conductivity and many redox-active sites, while SiC and transition metal nitrides (TMNs) are also being investigated. Mechanical stability, adhesion to current collectors, scalable manufacture, and surface activation are all ongoing concerns. In practice, carbides enable quick charge transfer but have low capacitance, whereas nitrides exhibit high conductivity and moderate redox

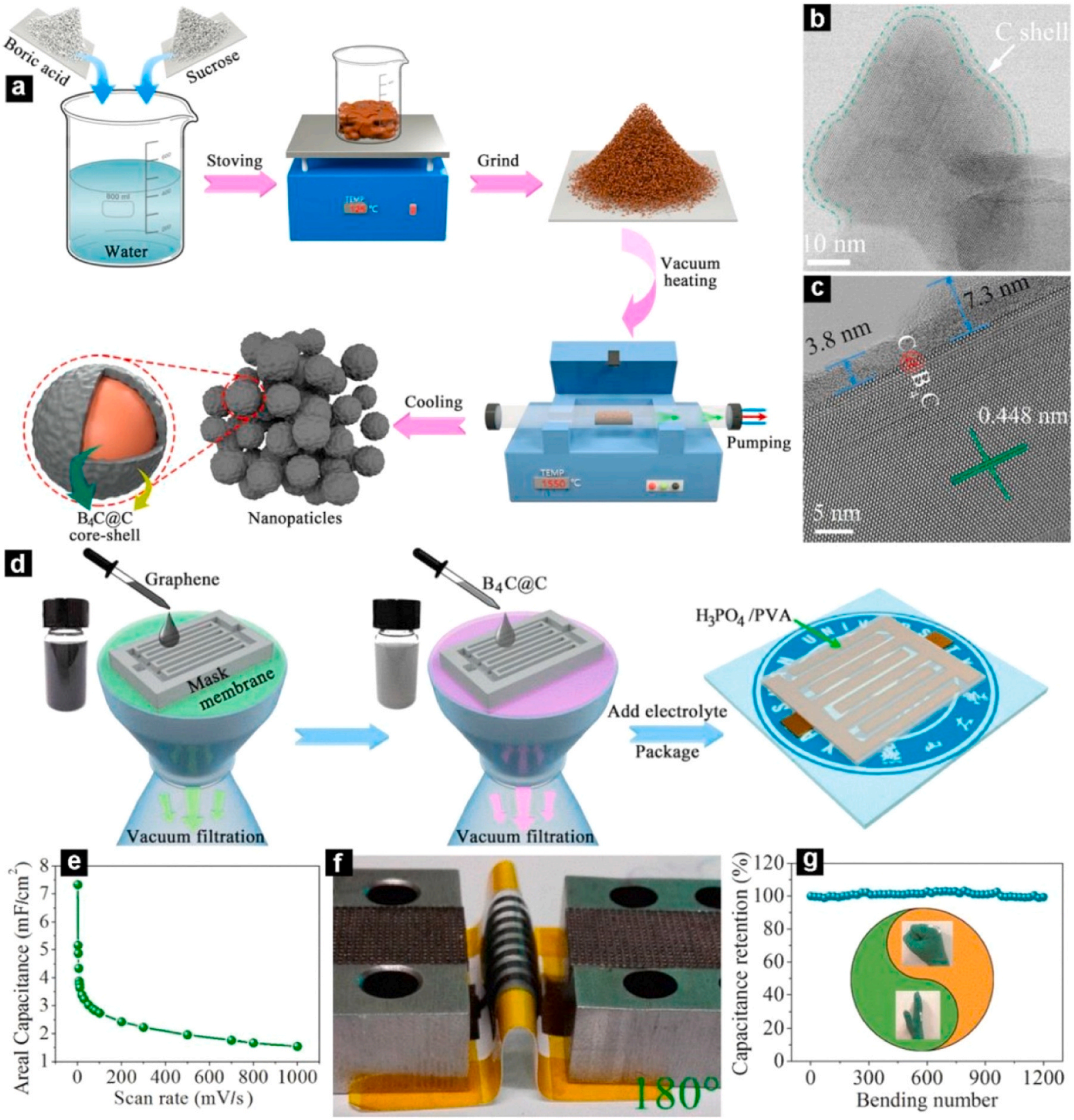


Fig. 6. (a) Procedure for producing $B_4C@C$ ceramic nanoparticles. (b) TEM and HRTEM pictures of $B_4C@C$ core-shell nanoparticles. (d) Production of the $B_4C@C$-MSCs device. (e) Areal capacitance, (f) optical image, and (g) CR for the $B_4C@C$-MSC device [151].

activity, but are prone to surface oxidation. As a result, they operate best when used in composites or as conductive support, rather than as primary active materials.

3.8. Additional unique ceramics for supercapacitors

Innovative ceramics and nanostructures, such as $(Sm_{0.02}Ag_{0.94})(Nb_{0.9}Ta_{0.1})O_3$ ceramics [248], $Li_2SeP_2S_5$ glass-ceramic electrolyte [249], and MXene ceramic [250], may provide remarkable energy storage and conversion performance. MXene is a highly conductive, layered substance commonly utilized as an electrode for SCs [251]. Gogotsi and his team demonstrated that 2D MXene outperforms EDLCs at faster rates and has higher volumetric and areal capacitance than carbon, polymers, or TMOs [252]. They found that using the macroporous $Ti_3C_2T_x$ film on the MXene design demonstrated a *C* of 210 Fg^{-1} at 10 Vs^{-1}, outperforming the best carbon-based SCs. Furthermore, RuO_2 particles were combined with $Ti_3C_2T_x$ and MXene to create an asymmetric SC [253]. MXene-based materials have excellent rate capability and capacitance. Combining them with RuO_2 improves performance, making them a promising material for next-generation SCs. MXene was identified as an ideal material for PC electrodes due to its surface redox reaction capability. Other developing ceramic-based SC materials include high-entropy oxides, ceramic-ceramic nanocomposites, and carbons formed from MOFs, all of which have higher ED, *C*, and stability. High-entropy oxides use multi-elemental compositions to obtain superior electrochemical characteristics, whereas ceramic-ceramic nanocomposites combine conductive ceramics and MOs to boost charge storage efficiency. Meanwhile, MOF-derived carbons have well-ordered macro-microporous structures that enable efficient ion transport and electron diffusion, hence improving SC performance.

3.9. Nanoceramic materials

Nanoceramics are made up of structural units smaller than 100 nm, such as nanocrystals, nanowires, nanofilms, and bulk materials with nanocrystalline phases. MO nanoceramics (Co_3O_4, NiO, and CeO_2) are attractive pseudocapacitive electrodes for SCs due to their huge surface area, plentiful active sites, quick ion diffusion, and structural flexibility, enhancing ED and PD. Nonetheless, difficulties such as low intrinsic conductivity and limited cycling stability persist, necessitating solutions via improved nanostructuring and composite design.

Nanoceramics, nanoparticles, and nanocomposites exhibit high strength, hardness, and fatigue resistance, making them ideal for energy storage applications. They improve performance by boosting mechanical strength, surface area, and changing electrical or thermal properties. However, processing remains a considerable challenge, especially when manufacturing bulk nanoceramics. The control of particle size, contamination, and agglomeration during nanocrystalline powder manufacture is critical, and numerous chemical techniques are being investigated to achieve uniform composition and mixing.

Nanoceramic coatings are rapidly gaining popularity for their hardness, wear resistance, and thermal stability, providing long-lasting and environmentally beneficial corrosion protection in industries such as automotive. Nanoceramic composites show considerable potential in medicinal, wastewater, and energy applications due to their strength, porosity, and huge surface area. These properties make nanoscale ceramics appealing for SC electrodes because they have outstanding conductivity and durability; yet their restricted surface area and activity pose problems. Continued optimization and advanced research are required to enhance charge storage and electron transport capacities.

4. Performance

4.1. Novel ceramic materials

4.1.1. Latest developments in TMOs

Electrode materials in SCs play a crucial role in determining optimal voltage ranges. Oxidation-reduction reactions correlate with molecular orbital work function, and materials with significant work function variations can increase the voltage in asymmetrical SCs [254]. Carbon-based electrodes provide chemical stability and a high PD [255], but graphene is chosen for its superior structural stability and electrical conductivity in electrochemical processes. Graphene's single-layer Sp^2 hybrid carbon architecture hinders its widespread use in industrial applications due to its low PD [256]. Combining conductive polymer-based PCs with graphene has become a viable approach to address challenges [257]. The use of TMOs like vanadium (V_2O_5), manganese (MnO_2 and Mn_3O_4), cobalt (CoO and Co_3O_4), nickel (NiO and Ni_2O_3), copper (Cu_2O and CuO), and zinc (ZnO) as active electrode materials offer a cost-effective alternative to RuO_2, with binary/ternary forms that improve redox activity and conductivity, making them adaptable and useful electrode materials for SCs. The electrochemical characteristics of these oxides can be enhanced by binary and ternary MOs, which introduce additional redox states and enhance electrical conductivity. Various electrode materials were widely used in SC applications, including NiO, V_2O_5, Fe_3O_4, Co_3O_4, MnO_2, and CuO [258]. Nanostructured TMOs are of significant interest for SC electrodes due to their excellent structural and electrical properties. They offer higher capacitance than carbon-based electrodes because of their greater redox activity. Research on TMOs' capacitive properties has progressed consistently. Nanowire-assembled Co_3O_4@$NiCo_2O_4$ structures on Ni foam substrate exhibited exceptional pseudocapacitive performance, with electrodes exhibiting specific capacitance and good flexibility, with symmetric and asymmetric devices exhibiting the highest areal capacitance [259]. Wei et al. synthesized Co_3O_4 nanowires and nanosheets, demonstrating a *C* of $2053.1 Fg^{-1}$ and outstanding cyclic stability [89]. Liu et al. [260] fabricated CuO nanorods, achieving a CR of 96.45 % even after 4000 cycles. Nanostructured Co_3O_4 and CuO electrodes show high capacitance and outstanding cyclic stability, underscoring the importance of morphology control for improving SC performance. Efficiency comparisons of a few TMO electrode materials are shown in Table 5 [261–266]. Recent advances in TMOs for SCs have focused on developing high-performance materials using composite architectures, including TMOs mixed with carbon materials and ternary MOs, to boost conductivity and surface area. Hydrothermal synthesis and core-shell architecture design have been key developments in improving stability and capacitance. Researchers are also looking into ternary oxides such as Ni-Co-Mn and MOFs to get high *C* and EDs.

4.1.2. Emerging mixed-metal oxides and perovskite oxides

SCs are symmetric and asymmetric, depending on the electrodes used for charge storage [267]. Key compatibility factors are high SSA, pore size dispersion, cost, environmental friendliness, and increased electronic and ionic conductivity. Considerations include single metal oxides (e.g., MnO, Fe_2O_3, RuO_2), bimetallic oxides (MNO_4, M, and N are Ni, Co, Zn, Mn), intercalation types, and metal heterostructures [268]. ABO_3 perovskite oxides show promise due to their deformed structures, high tap densities, and oxygen vacancies. Recent advances in modified forms, such as A-site doped ($A_{1\text{-}x}A'BO_3$) and B-site doped ($AB1\text{-}xB'O_3$) perovskites, improve long-term stability [269]. MO-based composites improve material characteristics by creating nanostructures, lowering diffusion distances for electroactive species, and boosting charge storage performance. Recent research investigates the charge storage properties of perovskite derivatives, such as Ruddlesden-Popper(RP) phases and quaternary perovskite oxides [270]. The structural durability of perovskites concerning oxygen vacancies is crucial for their electrochemical properties, warranting further research. Table 6 shows a variety of uses for smart and advanced ceramic materials. Although the presented material does not cover all members of the Perovskite family, their

Table 6
Smart and advanced ceramic materials have several applications.

s	Functional ceramics
Bioceramics	Piezoceramics
Automotive ceramics	Magnetoceramics
Nuclear ceramics	Package ceramics
Ceramics used in cutting tools	Optical ceramics
Tribological ceramics	Conductive ceramics

Table 5
Comparison of several TMO electrode materials.

TMOs	Cyclic stability (no. of cycles)	Capacitance (current density/scan rate)	Electrolyte used	Potential	Reference
$MgCo_2O_4$	99.06 % (5000 cycles)	626.5 F/g (1 A/g)	2 M KOH	0–0.58 V	[261]
IrO_2@Mn_3O_4 nanocomposite	91 % (10,000 cycles)	1027 F/g (1 mA cm^{-2})	1 M Na_2SO_4	−1.0–1.0 V	[262]
NiO	90.1 % (800 cycles)	1000 F/g (0.5 A/g)	1 M KOH	0–0.55 V	[263]
$NiCo_2O_4$ NPs	82 % (1500 cycles)	1073 F/g	2 M KOH	0–0.5 V	[264]
MnO2-rGO	88 % (3500 cycles)	759 F/g (2 A/g)	1 M Na2SO4	0–0.9 V	[265]
Co_3O_4/CNF	74 % (2000 cycles)	586 F/g	6 M KOH	−0.05–0.45 V	[266]

existence and contribution to the energy storage field are unavoidable (Fig. 7A).

Perovskite oxide materials possess high entropy and can be fine-tuned, promoting dual ion intercalation. The RP structure ($A_{n+1}B_nO_{3n+1}$), consisting of alternating rock salt and ABO_3 layers, regulates diffusion rates and enhances charge storage in the bulk [270]. Quaternary perovskite oxides with mixed metal cations further improve pseudo-capacitive charge storage [271]. Thus, producing RP perovskites with higher n values is essential for efficient SC electrodes [272]. Ruddlesden–Popper perovskite oxides, especially quaternary compositions with higher n values, enable tunable structures and dual-ion intercalation, enhancing diffusion and pseudo-capacitive charge storage for SC electrodes.

Emerging mixed-MOs and perovskite oxides are gaining popularity for SC applications due to their structural plasticity, abundance of oxygen vacancies, high *C*, and attractive electrochemical characteristics. Perovskite oxides (ABO_3) have tunable crystal frameworks and compositions that can be engineered to optimize charge storage performance. Mixed-MOs have strong redox activity and good conductivity, especially when integrated with complementary nanomaterials like MXenes or transition metal selenides (TMSes). Together, these materials have great potential for producing SCs with higher ED, power capability, and long-term cycling stability.

4.2. Hybrid ceramic materials

4.2.1. Ceramic-polymer and ceramic-carbon composites

PCC separators combine polymer strength with ceramics' high dielectric constant, ionic conductivity, and thermal stability [273]. PCCs such as PVDF, polypropylene, and titanates improve porosity, decrease resistance, and raise dielectric constant [274]. Heat treatment improves strength (71 % increase in Young's modulus) but decreases capacitance due to pore closure [275]. The schematic of ion transport in SCs (Fig. 7B-a) demonstrates that pore size and distribution have a major impact on separator performance. A p-n gate membrane was used as a diode-like separator (Fig. 7B-b), whereas PVA-ceramic composites (Al_2O_3, SiO_2, TiO_2) improved conductivity and stability without considerable deterioration [234]. PVA-TiO_2 enhanced capacitance by 68.6 % (Fig. 7B-c) and maintained capacitance retention (CR) for 5000 cycles (Fig. 7B-d). A $BaTiO_3$/PEDOT: PSS-PVA separator in a graphene SC lowered resistance (42 Ω) [276,277], giving C of 195 Fg^{-1} . Liu et al. [278] created low-cost Al_2O_3 nanowire/polyvinyl butyral membranes with high porosity, strength, and ionic conductivity, outperforming commercial separators (Fig. 7B-e). High-temperature SCs use solid organic electrolytes, ionic liquids, and ceramic composites [279,280]. NiO-ZrO_2 ceramic separators with carbon electrodes and KOH-glycerine electrolyte achieved excellent capacitance at 140 °C with 30 % graphite, but higher loadings reduced stability [281]. Porous Al_2O_3-based membranes and NiO-ZrO_2 ceramic separators offer improved ionic conductivity and thermal stability, making them ideal for high-temperature SC applications.

Ceramic-based separators promise scalable SCs in wearable electronics due to their compactness, flexibility, and high energy storage capacity. Planar asymmetric SCs with MnO_2/PEDOT: PSS, boron nanoride separators, and graphene nanosheet electrodes retained 99 % capacitance after 180°C bending and 92 % after 5000 cycles, with a volumetric power density of 8.6 mW cm^{-3} [275,282]. Separators for energy storage require mechanical strength. Vertically aligned carbon nanotubes (VACNTs)-derived Al_2O_3 structural separators improved tensile strength by 47 % and stiffness by 131 %, while interlaminar voids reduced strength by 6 % [283–285]. Multipurpose devices that combine energy storage and structural load-bearing capabilities are recommended for reducing system weight [284]. TMOs, including TiO_2, ZnO, Fe_2O_3, CuO, MnO_2, RuO_2, NiO, V_2O_5, and Co_3O_4, have various nanostructures (nanoparticles, rods, fibers, platelets, flowers) and are extensively studied for their pseudocapacitive properties [285–287]. Hydrothermal synthesis creates graphene/GO composites with increased surface area and stability. TiO_2 and TiO_2/RGO or TiO_2 nanowire/RGO hybrids provide excellent capacitance and little agglomeration for SCs [288,289], while other MO-graphene hybrids improve ED and cycling stability [290,291]. Qi et al. [291] reported a MnO_2@G-CNF hybrid SC with 612 F g^{-1} at 2 mV s^{-1} and ~100 % CR after 5000 cycles [292]. The MnO_2@G-CNF hybrid SC exhibits high capacitance and great cycling stability, demonstrating the potential of hybrid nanostructures for long-lasting energy storage. Fig. 8a–c illustrate the device architecture, SEM images, and performance at varied MnO_2 loadings. Advances in 3D printing and graphene-based inclusions have improved the electrical, thermal, and surface properties of ceramic composites for biomedical implants and wearable electronics [293,294]. Ceramic-polymer composites, which are mostly used as separators, improve ionic conductivity and safety, whereas ceramic-carbon composites, which have a conductive carbon backbone, serve as

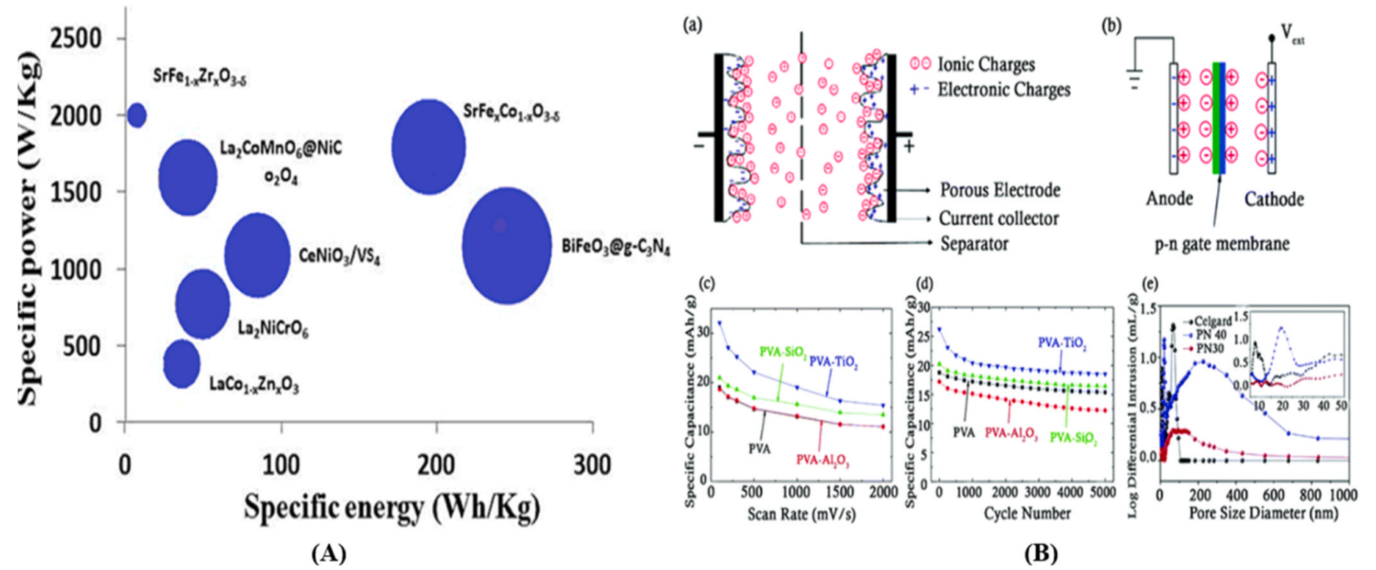


Fig. 7. (A) Performance metrics for a new perovskite oxide-SC material. (B-a) representation of a SC. (B-b) Diode-like gate structure in the middle of the cell. (B-c) *C*-varies with scan rate at a potential range of 0–1.5 V, and (B-d) Separator cycle life. (B-e) A plot showing the distribution of porosity [275].

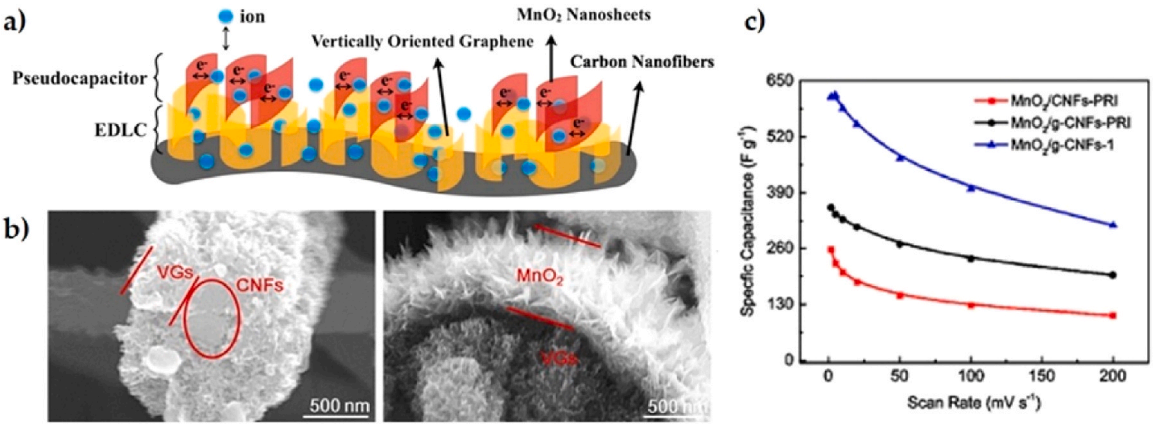


Fig. 8. (a) MnO_2@G-CNF hybrid SC architecture schematic; (b) SEM micrographs of the material. The electrostatic double-layer consists of a carbon nanofiber substrate and vertically oriented graphene sheets (VG). MnO nanosheets are formed on VG to form the PC. (c) Sample performance under varied treatments and MnO_2 concentrations [292].

high-performance electrodes. Filler composition and structure, as dictated by their kind and volume percentage, influence their specific applications. Table 7 compares ceramic-polymer and ceramic-carbon composites for SC applications.

4.2.2. *Functionalized ceramics for improved electrical conductivity and capacitance*

Electrical conductivity is a material's capacity to conduct electricity, and ceramics often have substantially lower values than metals because most are dielectric. Conductivity in ceramics is frequency and temperature dependent, as thermal energy provides the activation energy required for charge migration, which may be calculated using the Arrhenius relation and a.c. conductivity analysis. Capacitors require large surface areas and thin dielectric layers to provide high capacitance. Porous carbon electrodes, nanometer-scale dielectrics, and electrolyte-filled structures are used in SCs, which are commonly made by layering aluminum foils of regulated thickness and contact terminals. Ceramic-based SCs have a longer charge-discharge cycle life than other technologies. Ceramic materials have high ionic and electronic conductivity, making them suitable for electrochemical applications [295]. They can be created with a variety of substitution and doping strategies to improve stability in multicomponent ceramics, yielding complex compositions for temperature-resistant materials, LIBs, and catalysts [296].

Table 7
Comparison of ceramic–polymer and ceramic–carbon composites for SC applications.

Aspect	Ceramic–Polymer Composites	Ceramic–Carbon Composites
Key Components	Ceramics (e.g., MOs, nitrides) + polymers (e.g., PANI, PEDOT, PVDF)	Ceramics (e.g., MOs, carbides, nitrides) + carbon materials (e.g., AC, CNTs, graphene)
Conductivity	Enhanced with conductive polymers, although often lower than carbon composites	High because of the conductive carbon matrix and ceramics with redox activity
Mechanical Properties	Excellent flexibility, lightweight, and processability	High structural rigidity, yet less flexible
Electrochemical Properties	Polymers provide pseudocapacitance, while ceramics promote stability	Ceramics increase pseudocapacitance, but carbon has a large surface area and fast electron transport
Capacitance	Moderate to high, based on polymer conductivity and ceramic loading	High due to the synergistic effects of the huge surface area and the redox activity
Energy Density	Polymer pseudocapacitance improves performance, but conductivity limits it	Higher, due to the combination of surface and faradic storage processes
Cycle Stability	Frequently limited by polymer breakdown when cycling	Superior, as the carbon matrix improves stability and conductivity
Scalability	Easy processing with polymer matrices	More difficult synthesis, but scalable with an appropriate design
Typical Applications	Flexible and wearable energy storage technologies	High-power and high-energy supercapacitors for grid, automotive, and industrial applications

5. Fabrication

5.1. *Innovative synthesis methods*

5.1.1. *Sol-gel method*

The sol-gel technique involves dissolving ceramic precursors in a solvent to form a sol that gels into a solid. The gel is then dried and calcined to eliminate the solvent, yielding the finished ceramic product [297]. This process includes hydrolysis and condensation of metal alkoxides or salts, resulting in a gel with colloidal particles (Fig. 9a). The sol-gel technique is a method used to create thin ceramic films, coatings, and nanoparticles for energy storage devices like batteries and capacitors. It achieves high purity and uniformity at low temperatures, enabling fine microstructure development [298]. However, the procedure is time-consuming and necessitates exact conditions to ensure reproducibility. Drying and calcination can induce cracking and shrinkage, which could compromise the final material's integrity and performance. Sol-gel processing uses metal-organic compounds, primarily metal alkoxides, as precursors. High pH hydrolysis forms oxide particles, while low pH results in a gel. The alkoxides dissolve in a nonaqueous solution, which gels when water is added. The gel is transformed into powder through annealing. The hydrolysis reaction of an alcoholic alkoxide solution can be represented by the following Eq. (1):

$$M(OR)_n + nH_20 \rightarrow (OH)_n + nROH \tag{1}$$

$M(OH)_n$ molecules undergo condensation and polymerization reactions to form colloidal polymers, with properties influenced by water content, pH, and temperature. This method offers advantages in rheological characteristics, allowing for complex shapes, substrate deposition, or spraying, and enhancing chemical homogeneity through molecular-level mixing.

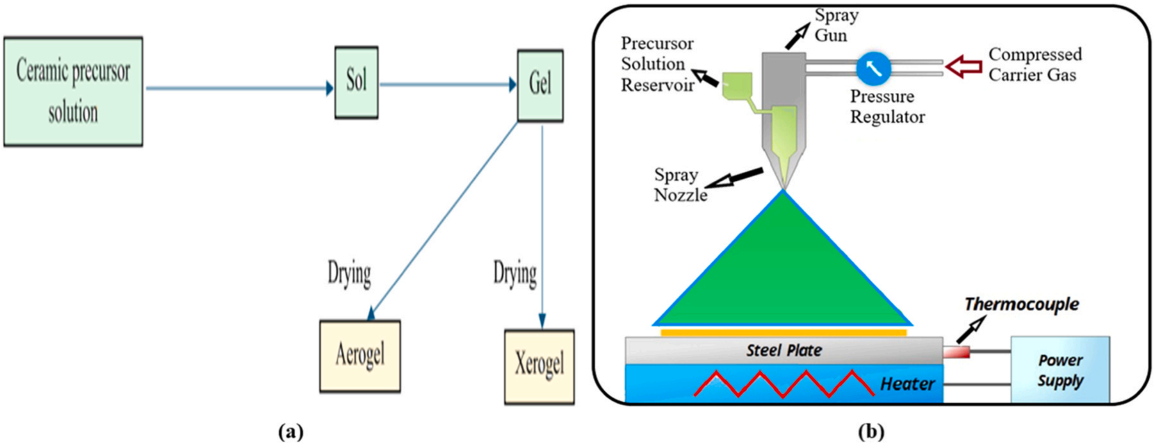


Fig. 9. (a) Sol-gel method. (b) Scheme of spray pyrolysis technology.

5.1.2. *Hydrothermal technique*

Hydrothermal synthesis is the process of reacting precursors in an aqueous solution at high temperatures and pressure. The precursors are dissolved in water and heated in a sealed autoclave reactor, producing crystalline ceramic materials that are then rinsed, dried, and optionally annealed [299]. This technology is commonly used to generate ceramic nanoparticles and nanocrystals with exact control of size, shape, and crystallinity for energy storage applications such as batteries and capacitors. It offers advantages such as creating highly crystalline materials at low temperatures and maintaining control over particle morphology while using water as a solvent. However, the necessity for high-pressure containers, long reaction times, and the possibility of undesirable secondary phases or contaminants can reduce throughput and raise production costs.

5.1.3. *Spray pyrolysis method*

Spray pyrolysis (SP) has long been a popular process for depositing thin films of numerous materials, including metals, semiconductors, and oxides. Although most of the SP process is recognized, several aspects of the deposition process are still unclear [300]. Many researchers claim that the deposition process is like chemical vapor deposition (CVD). CVD is a chemical procedure in which gaseous precursor molecules deposit ceramic thin coatings on substrates [301]. SP is a low-cost, easy, and adaptable process for producing high-purity, homogenous ceramic powders with consistent sizes and spherical morphology [302]. It is used for producing submicron and spherical luminous materials [303], multicomponent oxides, chlorosilicates, metals, catalysts, and nanopowders [304]. SP is a four-step process for material production. The process begins with the precursor forming droplets, which diminish following evaporation. The precursors react to form oxides, which solidify. Chamberlin and Sharman invented the SP method in 1966 as a modified version of chemical bath deposition methods for developing CdS thin films for solar cell applications (Fig. 9b). Pawar et al. [305] employed SP to manufacture vanadium oxide (V_2O_5) electrodes with high C, demonstrating that this technique is useful for manufacturing ceramic SC electrodes with superior electrochemical characteristics. Joshi et al. [306] employed SP to produce sodium-doped CuO thin films, proving that doping can enhance SC performance by adjusting ceramic properties. SP allows for easy control of film characteristics by adjusting parameters like substrate temperature, airflow pressure, and precursor concentration [307]. This technology operates at moderate temperatures (100–500°C), making it possible to produce films on low-quality substrates. The chemical spray technique typically requires an atomizer and a heated substrate, but it can also be conducted using a single-fluid nozzle that atomizes liquid under pressure. To address hollowness and porosity issues in large-scale SP products, enhanced procedures employ artificial colloidal solutions, which allow greater control over the final material's composition and morphology.

5.1.4. *High-entropy ceramics for enhanced structural complexity*

High-entropy ceramics (HECs) are a novel family of materials distinguished by their extraordinary hardness and superior thermal, electrical, mechanical, and oxidative capabilities when compared to standard ceramics. HECs, which are made up of many elements in similar atomic amounts, have a very disordered crystal structure. They typically contain five or more different cations or anions, such as $(Zr_{0.2}Ta_{0.2}Hf_{0.2}Nb_{0.2}Ti_{0.2})C$ for high-entropy carbides and $(Zr_{0.2}Hf_{0.2}Ta_{0.2}Nb_{0.2}Ti_{0.2})B_2$ for high-entropy borides. HECs can also form compounds with nitrogen, carbon, boron, and oxygen, resulting in materials like high-entropy oxides and nitrides. Overall, HECs offer superior properties compared to standard ceramics. They are uniphase with a simple lattice structure, with atomic diameters determining uniform element mixing. Entropic stabilization increases with increased element concentration [308]. HECs typically have rock salt structures, but six additional structures have been observed, as shown in Fig. 10a [309].

HECs can outperform traditional ceramics in mechanical properties, while high-entropy nitrides are valued for their excellent thermal properties and durability. Their unpredictable nature and the synergistic effects of their components result in outstanding functional properties, making HECs ideal for energy storage and conversion [310]. Ceramic materials are potential SC electrodes, but their performance is hindered by low SSA and poor surface activity [311]. $(FeCoCrMnZn)_3O_4$ and $(CoCrFeMnMg)_3O_4$ have shown exceptional performance, with C of 340.3 Fg^{-1} and 193.7 Fg^{-1}, respectively, demonstrating their potential for SC applications [312]. Understanding the structure-property relationship of HECs is critical for improving their applications in energy storage and thermal management. More research on phase stability, microstructural evolution, and multi-element effects is required to fully realize their potential. With their distinct electrochemical properties, HECs hold potential for next-generation systems such as enhanced thermal barrier coatings and composite materials that improve strength and durability.

5.2. *Scalable fabrication*

5.2.1. *3D printing and roll-to-roll processes for mass production*

Additive manufacturing, or 3D printing, creates three-dimensional structures through the layer-by-layer deposition of ceramic powders. Techniques like stereolithography, selective laser sintering, and binder jetting produce complex parts from digital models, which are then debonded and sintered. Recent research has shown that scalable fabrication approaches, such as on-chip printing of ceramic frameworks that can operate at 300 °C [313], are critical for obtaining consistent

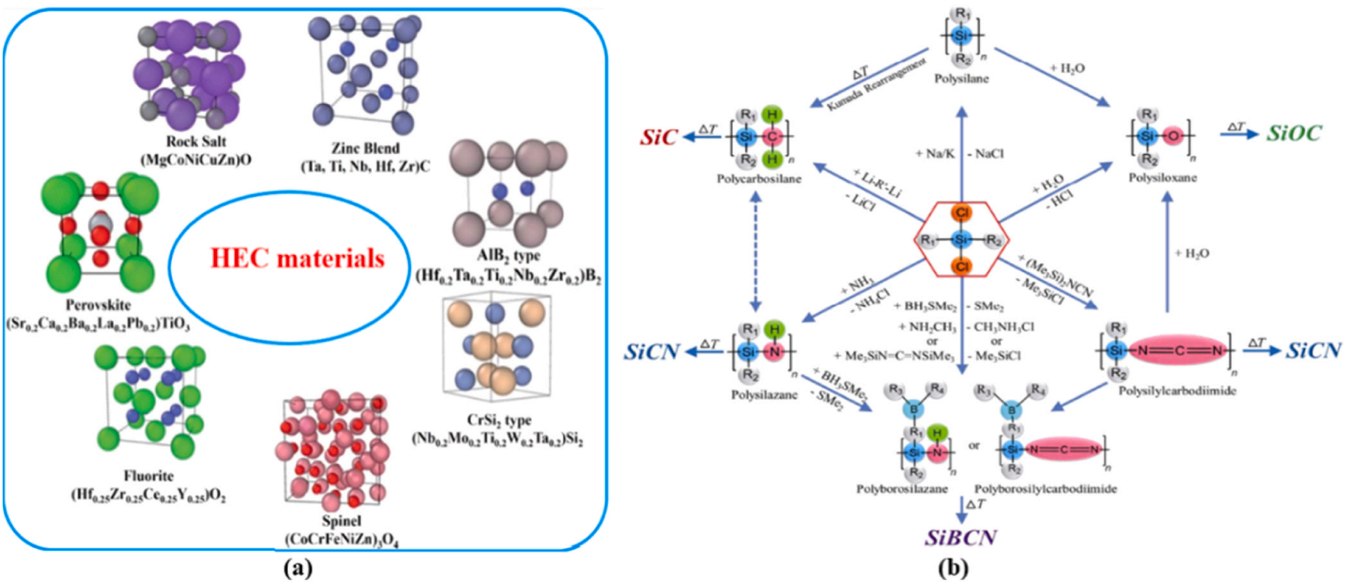


Fig. 10. (a)Various structural forms of HECs (the smaller spheres represent cations while the larger spheres represent anions), adapted from [309], MDPI, 2024. (b) The synthetic methods for typical Si-based polymers and ceramics derived from organochlorosilanes. R1–R4 denote organic groups or hydrogen linked to the silicon of the polymer backbone [327].

performance, high throughput, and practical implementation of ceramic-based SCs. It also decreases material waste and manufacturing lead times, allowing for faster modifications and optimizations. 3D printing offers the ability to create complex parts with unique geometries, but it faces challenges in high-density, defect-free products due to layer-by-layer deposition, post-processing requirements, and high-temperature sintering. Current 3D printing technologies may not be sufficient for high-volume ceramic component production, posing scalability issues.

5.2.2. Effective cost-reduction techniques

Roll-to-roll (RTR) manufacturing is a continuous process that involves unrolling flexible substrates and processing them using material deposition, cleaning, or patterning. It finds widespread use in batteries, flexible electronics, photovoltaics, fuel cells, multilayer capacitors, sensors, textiles, and paper products. This cost-effective technology allows the deposition of water-based compounds using methods such as gravure, offset printing, or flexography, with the substrate being rewound for further treatments following film deposition. Recent research highlights the advantages of RTR manufacturing in producing ceramic materials for SCs [314]. The method enables scalable, cost-effective, and efficient fabrication techniques, facilitating the development of high-performance SC for industrial applications [315]. RTR manufacturing has emerged as a transformational technology in the manufacture of ceramic materials for SCs, providing various benefits that improve performance and scalability.

TMSs have unique properties such as low band gaps and shallow valence bands, that distinguish them from MOs. Recent breakthroughs have resulted in the development of complex morphologies such as nanoparticles, nanowires, nanoribbons, nanosheets, nanorods, nanocages, nanoflowers, honeycomb structures, and nanospheres [316], which allow them to use the full solar spectrum. Hydrothermal/solvothermal and co-precipitation methods are widely used due to ease of control, low cost, and repeatability. Template methods prepare high-performance hollow nanostructures, while electrodeposition methods are used for binder-free or flexible electrodes. Table 8 [316] shows the benefits and drawbacks of several techniques for TMS synthesis.

Table 8
Advantages and disadvantages of various approaches for TMS synthesis [316].

Synthetic approach	Advantages	disadvantages	Samples
Hydrothermal/ solvothermal method	Suitable for laboratory studies, different nanostructures, easy control, broad application, and low cost	Low output, long reaction time	$NiCo_2S_4$ Cu_2S/ NiS/ Ni_3S_4
Template method	Fabricating hollow nanostructures with high activity and rate capabilities	Templates are complicated and involve numerous processes	$Zn_xCd_{1-x}S$ hollow sphere
Electrodeposition method	Suitable for creating free-standing electrodes	Requiring electrochemical equipment	CuMnS $NiCo_2S_4$/ MoS_x
Sol-gel method	Suitable for creating nanoparticles; high controllability	Complex synthesis process, volatile organic solvents, and toxicity	Ce-doped ZnS Ni-doped CdS
Co-precipitation method	Suitable for preparing nanoparticles; easy, high efficiency	Free-standing electrodes are difficult to prepare due to their complicated shape	Cu-doped ZnS Fe/Ni-doped ZnS
Exfoliation/ intercalation method	Creating single or multi-layer nanosheets	Complex process, volatile organic solvent, and toxicity	1 T-MoS_2 WS_2
Solid state method	Simple operations, large-scale production	High temperature and gas protection	CoS_2/NC Various NiS

6. Challenges and obstacles

6.1. Intrinsic limitations

6.1.1. Trade-offs between conductivity, mechanical strength, and electrochemical stability

Ceramics are commonly employed in nuclear reactors as moderators, barriers, neutron control materials, and fuels because of their thermal stability, chemical resistance, and durability. MO-based ceramics mixed with conductive ceramics result in high-performance electrodes [317], whereas ionically conducting ceramics act as excellent catalyst supports throughout a wide temperature range, enabling electrochemical catalysis for energy storage. Advances in nanotechnology have resulted in ceramic-ceramic nanocomposites with superior supercapacitor characteristics [318]. MO-based ceramics have a high capacitance, but ionically conductive ceramics allow for quicker ion movement, resulting in improved SC performance.

However, obstacles remain, such as maintaining nanoscale morphology, improving composite composition, and addressing interface compatibility issues [319,320]. Interlayers or surface modification are critical interface engineering solutions for overcoming thermal, ionic, and mechanical mismatches [321]. Furthermore, balancing high energy density with fracture toughness necessitates novel design and processing to improve durability [322], while the inherent poor ionic and electrical conductivities of some ceramics continue to limit charge-discharge efficiency [323].

Ceramic-ceramic nanocomposites have potential in high-power applications, but ion transport capacities must be improved while maintaining material stability [324]. Zirconia-toughened alumina nanocomposites can be used to construct implants with extended life spans. Recent experimental methods have revealed the atomic structures of ceramic-ceramic surfaces, with Al_2O_3 and SiC creating an important interface for various applications, including matrix-nanoparticle composites [325] and high-power electrical devices [326]. Maintaining chemical homogeneity in electroceramics is challenging due to the presence of minor reactants. Solid-state reactions often result in aggregated powders, which are undesirable for high-strength components. Volatile compounds like lead oxide can be removed through evaporation at high temperatures, like 1373 K. Conventional nonoxide synthesis involves carbothermic reduction of carbon-oxide combinations to metal, which is then nitrided to produce silicon nitride (Si_3N_4) as shown in Eq. (2).

$$3SiO_2 + 6\,C + 2N_2 \rightarrow Si_3N_4 + 6CO \tag{2}$$

Mechanical grinding of oxide ceramics introduces impurities and residual oxygen, which negatively impact the mechanical behavior of fabricated components.

Organochlorosilanes are utilized as starting materials to produce various silicon-based polymers, including polycarbosilanes, polysiloxanes, and polysilazanes, as depicted in Fig. 10**b**[327]. Organochlorosilanes and bis(trimethylsilyl)carbodiimide react to produce poly (silylcarbodiimides). SiBCN ceramics can be made in two ways: monomers or by chemically modifying polysilazanes or poly(silylcarbodiimides) to make preceramic polymers like polyborosilazane or polyborosilylcarbodiimide. Chemical modification relies on hydroboration and dehydrocoupling reactions.

6.1.2. Degradation mechanisms and long-term cycling performance

ESSs degrade for a variety of reasons, including mechanical, electrical, and design flaws. Mechanical and thermal stresses, chemical attacks, environmental exposure, microstructural changes, wear, and radiation damage are all major degradation issues in ceramics. These can result in fractures, fissures, surface degradation, and diminished mechanical properties over time. Understanding these mechanisms is critical for improving device durability and extending its lifespan. Advanced ceramics, with their chemical stability and resistance to harsh environments, maintain structural integrity and performance in SCs, batteries, and thermal storage systems, making them excellent for long-term energy applications. Ceramic SCs suffer from performance degradation primarily due to electrolyte decomposition, structural and chemical changes in the electrodes (e.g., volume expansion, fragmentation, and dissolution), current collector corrosion, and interphase instability, all of which contribute to reduced capacitance and cycling stability.

6.2. Scalability and environmental concerns

6.2.1. High-demand synthesis techniques and sustainable alternatives

Advanced processing techniques enable the modification of highly porous ceramics to nano-scale characteristics, making them crucial for various technical applications in medicine, environmental science, transportation, energy, aerospace, and military use. Ceramic foams are macroporous ceramics known for their low efficiency in collecting minute dust particles, although they are widely used in solid-liquid contact processes. Recent advancements include the in-situ growth of nanowires on these porous ceramics using a cost-effective method. Porous ceramics are essential in energy generation and storage, functioning as catalyst supports, adsorbers, membranes, and thermal protection components. Innovative processing methods enable the creation of large, lightweight parts with high mechanical strength. These review the current developments in porous ceramics across key technological fields. Advanced ceramics are eco-friendly materials, sourced from natural resources and processed efficiently, reducing environmental impact in energy storage technologies [327]. Their integration into energy storage systems promotes sustainable solutions in line with environmental goals.

6.2.2. Challenges associated with the integration of ceramics and flexible wearable devices

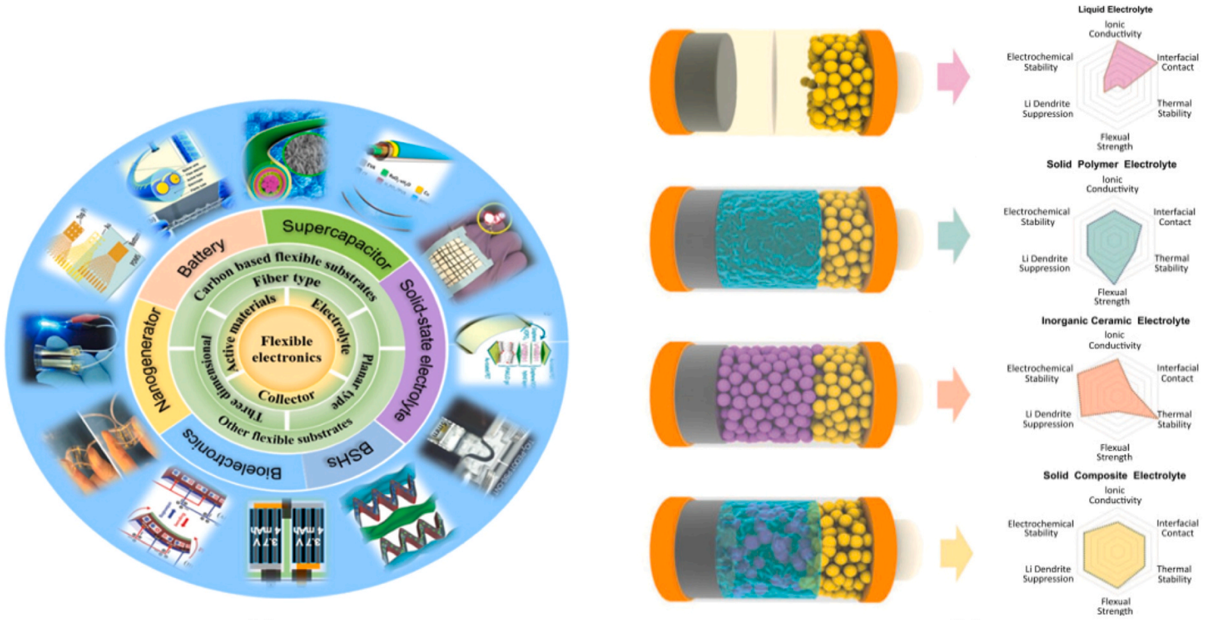
Integrating ceramics with flexible wearable devices remains difficult due to their brittleness, limited stretchability, and interface compatibility difficulties. Recent advancements in ceramic fiber materials position them as a robust platform for the energy industry and electrical devices. Their inherent stability and porosity make them suitable for electrodes and battery separators in LIBs and solid-state capacitors [328]. Furthermore, their substantial surface area, permeability, microstructure, and adaptable composition enable their use in various electrical devices [329]. Hybrid electrolytes, combining polymer and inorganic ceramic electrolytes, enhance all-solid-state batteries [330] by offering high ionic conductivity, mechanical strength, and good electrode contact. Materials known as "ceramic in polymer" (CIP) or "polymer in ceramic" (PIC) integrate these electrolytes to achieve both high ionic conductivity and mechanical strength, resulting in impressive electrochemical performance and mechanical stability in applications such as flexible rechargeable batteries, SCs, nanogenerators, and bioelectronics. Despite challenges in developing flexible ceramic devices, ongoing research focuses on creating flexible and stretchable materials with superior electrochemical properties, as illustrated in Fig. 11a [331]. Flexible batteries require flexible components, and advancements in printing and surface functionalization are driving the development of sensors for flexible, wearable, and 3D electronics. Advanced ceramics, with their high mechanical strength and thermal stability, are crucial for developing smaller, lighter energy storage components for wearables, medical implants, and Internet of Things(IoT) devices [332], potentially forming multifunctional systems to enhance device performance.

7. Opportunities and emerging trends

7.1. Integration with novel technologies

7.1.1. Ceramic materials for hybrid supercapacitor-battery systems

Advanced ceramics have the potential to transform solid-state batteries by improving safety, ED, and cycle life over ordinary LIBs. Ceramic electrolytes with greater ionic conductivity and stability are being investigated for lithium metal anodes, as well as applications in Na-ion, K-ion, and Mg-ion batteries, flexible SCs, and energy-harvesting systems [333]. Their thermal stability makes them ideal for thermal energy storage. Ceramics are versatile for hybrid energy storage, including pseudocapacitive ceramic electrodes in capacitors, ceramic membranes in redox flow batteries, and ceramic electrolytes in SC batteries. They combine the fast kinetics of EDLCs with the higher capacity



(a) (b)

Fig. 11. (a) Flexible energy storage devices and electrodes in their manufacture [331]. (b) The key properties of liquid electrolyte(LE), polymer electrolyte (PE), ceramic electrolyte(CE), and ceramic-polymer electrolyte(CPE) [359].

of pseudocapacitive and battery electrodes. Sustainable development is aided by additive manufacturing, environmentally friendly synthesis, and recycling, whereas nanostructured ceramics and tailored interfaces promote charge transfer, ion diffusion, and stability in hybrid SC-battery systems [334,335].

Furthermore, ceramics are being studied for usage with renewable energy sources in hybrid systems, microgrids, and off-grid applications, as well as for smart and self-healing designs that improve longevity and reliability [336]. Their usefulness for space exploration is also under investigation, as they must endure harsh circumstances such as radiation, low gravity, and temperature variations [337]. Long-term monitoring, rapid testing, and precise characterization are essential to achieve these milestones, while system-level issues influence the development of next-generation ceramic-based energy storage systems.

7.1.2. Ceramics in renewable energy systems

Advanced ceramics serve as ’invisible heroes’ in renewable energy and environmental technologies by improving the efficiency and durability of photovoltaic, wind, and hydropower generation. Ceramics are used in raw glass production, wear-resistant bearings, thermal decoupling, wire rolling, heat sinks, substrates, and plasma chambers in solar systems, as well as ceramic substrates and heat sinks in wind turbines to extend service life and reduce maintenance costs.

Ceramics have a variety of applications outside of energy, including aircraft, cars, optical devices [338], and medical sectors like dentistry and orthopedics [339]. They help with water purification [340], CO_2 adsorption [341], alternative batteries, and thermal energy storage in solar plants [342]. Additionally, they enhance thermal recovery in turbines and enable low-carbon solutions through nickel replacement and CO_2 capture [343]. Advanced ceramics are predicted to enhance energy production, distribution, storage, and conversion systems, necessitating strong, cost-effective integration [344]. Although the ceramics industry is energy-intensive [345], ceramic-based hybrids are becoming increasingly important for energy harvesting, including hydrogen synthesis by water splitting [346]. Ceramics’ adaptability, stability, and flexibility allow them to be converted into hybrids and scaled for nuclear and hydrogen energy applications, demonstrating their outstanding breadth and usefulness in a sustainable future.

7.2. Focus on sustainability

7.2.1. Development of bio-derived or recycled ceramics

Ceramics production often involves significant biological costs, including resource consumption, energy use, and greenhouse gas emissions. To reduce these costs, eco-friendly ceramic materials are being explored. One approach is using reused or waste-based raw materials, such as tiles and flatware, to reduce waste and conserve natural resources [347]. Advancements in material-handling technologies can enhance the use of secondary raw materials without compromising the quality or performance of ceramic products [348]. Another strategy is to use renewable sources for binders and additives, such as bio-based binders from starch, cellulose, and lignin [349]. These bio-based materials can reduce carbon emissions and improve the economic qualities of ceramic materials. Microwave sintering, plasma sintering, and 3D printing technologies provide opportunities for waste reduction and improved energy efficiency [350]. Sustainable ceramics enhance environmental performance and resource efficiency, contributing to the circular economy.

7.2.2. Lifecycle assessments for environmental compliance

Life cycle assessment (LCA) evaluates the environmental, social, and economic impacts of a product across its entire lifespan. Lifecycle sustainability assessment (LCSA) is a newer framework that combines environmental LCA, social LCA, and life cycle costing [351]. For ceramics, mining poses one of the most significant environmental challenges, as surface extraction heavily disrupts landscapes. After extraction, raw materials undergo processing to remove impurities and improve mixing and forming. LCA assesses the environmental implications of ceramics from manufacturing to disposal or recycling, with a focus on identifying critical supply chain ’hotspots’ rather than just measuring impacts. Traditional E-LCAs are limited because they lack location-specific qualitative data. LCA considers both endpoint consequences, such as human health, resource depletion, and ecosystem quality, and midpoint impacts, which include climate change, land and water consumption, toxicity, and pollution. LCA enables product comparisons and promotes the production of ceramic materials with smaller environmental footprints by combining technical and economic concerns [352].

Lifecycle energy efficiency is an important parameter for assessing storage devices, influenced by characteristics such as self-discharge rate, round-trip efficiency, and lifespan. Higher round-trip efficiency decreases adoption barriers and reduces emissions, and longer lifespans increase total usable energy over time. Recyclability is also important, since it affects material recovery, end-of-life recycling rates, technological feasibility, and material value. Considering these issues helps limit resource use and environmental effect, thereby enhancing the overall efficiency and sustainability of storage solutions.

7.3. Innovations in electrolyte compatibility

7.3.1. Exploration of ionic liquids, solid-state electrolytes, and gel electrolytes

Liquid electrolytes (LEs) containing combustible organic solvents provide a leakage and fire risk during overcharging or misuse, prompting the adoption of all-solid-state electrolytes in lithium batteries [353]. Solid-state electrolytes are divided into three types: solid polymer electrolytes (SPEs), inorganic ceramic electrolytes (ICEs), and solid composite electrolytes (SCEs). Electrochemical devices for energy storage have used LEs for decades due to their volatility and flammability [354]. These substances can release flammable gases and pose fire hazards at extreme temperatures. Thermal decomposition in batteries and SCs is primarily dependent on the electrolyte, which is crucial for high-temperature applications. Solid electrolytes (SEs), such as polymer electrolytes (PEs) [355], ceramic electrolytes (CEs) [356], and ceramic-polymer electrolytes (CPEs) [357], are excellent choices for controlling the thermal runaway (TR) of electrochemical devices. SEs have superior ionic conductivity and voltage safety windows at high temperatures compared to LEs [358]. Fig. 11b demonstrates that CPE surpasses LE, PE, and CE in terms of flexibility, thermal stability, mechanical durability, electrochemical performance, ionic conductivity, interfacial contact, and Li dendrite suppression properties [359].

Despite their popularity, oxide, sulphide, and SPEs have electrode interface issues, chemical instability, and low ionic conductivity [360]. Gel polymer electrolytes (GPEs) are a potential option due to their superior conductivity, processability, and stability [361]. They display features like LEs and SPEs, and their ion conduction mechanism is generally consistent with LEs. However, interactions between the polymer and charge carriers have a considerable influence on ionic conductivity. Addressing these difficulties demands extensive investigation.

7.3.2. Tailoring ceramic surfaces for enhanced electrolyte interaction

Hybrid electrolytes (HEs) are electrolytes with various components that enhance the ionic conductivity and mechanical robustness of solid SPEs by offering an alternative to regular electrolytes [362]. Active and passive electrolytes are distinguished by their fillers, including lithium-ion ceramic fillers, like Li_3N or $LiNbO_3$, as well as ceramic fillers like SiO_2 or TiO_2. Active HEs offer better ion conduction due to an extra ion conduction pathway through the fillers [363]. Passive HEs with ceramic fillers like SiO_2, TiO_2, Al_2O_3, ZrO_2, ZnO, and clays exhibit interesting structural properties. The grain boundary effect [364] improves ionic conductivity due to inorganic species at the polymer chain interface. Lewis's acid/base interactions promote ion dissociation and preferred conduction paths at ceramic nanoparticle limits [365]. The development of HEs based on ceramic materials with outstanding mechanical characteristics and ionic conductivity is critical to the advancement of smart mobility.

8. Performance metrics and comparative analysis

8.1. Latest benchmarks for energy density, power density, and cycling stability

Parameters such as ED, PD, and cyclic stability are all critical factors in energy storage system performance. The energy storage capacity and cycle stability of a device are crucial factors to consider for optimal performance, along with *C*, output voltage, conductivity, surface area, and voltage window. Ceramic SCs offer advantages, although they are still in the development stage. SCs have poor ED compared to batteries, as they store less energy [366] and have a decrease in voltage output as they discharge. To address this issue, new ceramic electrode materials can be explored to efficiently store more charges. The ceramic electrode structure should have a large surface area and suitable morphologies for more ceramic electrolyte ions, enhancing device performance. Surface engineering and selecting electrolytes with a wide working potential range can also improve performance.

Self-discharge refers to the rapid voltage drop and energy loss of SCs, which can be detrimental to their performance [367]. This can be caused by factors like impurities on the ceramic electrode surface, ohmic leakage, and charge redistribution. To ensure long-term energy storage, additives, ceramic electrode modifications, an ion exchange membrane, and proper sealing can be used to suppress self-discharge in SCs. 3D ceramic electrode materials can overcome ion diffusion by exposing active sites to electrolytes. However, high production costs and complex synthesis processes limit practical applications. New synthesis techniques and easier preparation could address this issue.

8.2. Comparative analysis of ceramics with other material systems in supercapacitors

Research has demonstrated the superior mechanical and electrical properties of 3D graphene foam, achieved through CVD synthesis on nickel foam and hydrothermal deposition of MnO_2 MnO_2 [368] and $CoMoO_4$ [369]. Graphene is a versatile material for flexible and stretchy composites due to its strong conductivity and mechanical support. Researchers have developed graphene nanocomposites using Co_3O_4 and Mn_3O, starting with Hummer's method [370,371], resulting in *C* of 144 and 439.7 Fg^{-1}, respectively, and PD values of 44 and 900 Wkg^{-1}. The precursor solution was mixed with GO, and Mn_3O_4/Co_3O_4 was deposited on RGO surfaces via assisted treatment.

Nanostructured carbon-based electrode materials are widely used in electrochemical applications due to their low cost, outstanding electrical properties, thermal and chemical stability, and reversible redox reactions. They lack knowledge and have a predictable life cycle. Li et al. investigated α-MnO_2 on carbon fibers and the redox transitions between Mn^{3+} and Mn^{4+} during charge/discharge [372]. The researchers developed a CNT-modified carbon fiber/α-MnO_2 composite electrode for flexible SCs, resulting in high rate capability and extended working voltage. The α-MnO_2/carbon fiber system has reversible Mn^{3+}/Mn^{4+} redox transitions, which improve pseudocapacitance and electrochemical performance. Researchers developed a flexible CFF/MnO_2 electrode material for SC applications by functionalizing CFF with a coral-like MnO_2 nanostructure, enhancing its pseudo-capacitive capabilities [373]. CFF was chosen for its great corrosion resistance, low cost, ease of manufacture, one-dimensional structure, and good electrical conductivity. The CFF/MnO_2 electrode exhibits dynamic electrochemical activity during cycling, demonstrating substantial interaction between the carbon framework and MnO_2, contributing to increased stability and capacitance. The electrode's unique shape allowed for rapid ion diffusion, resulting in a *C* of 467 Fg^{-1} and 100 % initial maintenance after 5000 cycles. The device also exhibited an ED of 20 Wh kg^{-1} and faster charge and discharge rates. The device demonstrated a strong interaction between CFF and MnO_2, with an ED of 20 Wh g^{-1} and a PD of 0.175 kW kg^{-1}. Carbon nanoparticles are attractive for energy storage devices because of their high conductivity, huge surface area, and mechanical characteristics. MOs with 3D support, such as graphene foam, RGO, carbon nanopaper, and electrospun CNF, are recommended for high-performance SCs. However, these materials have low values of PD compared to LIBs. Tunable 3D graphene networks are preferred for efficient ion/charge pathways and large interstitial surface area, while hybrid carbon nanometal oxide-based materials are emerging as a novel approach for SC electrodes.

Polymer-derived ceramics (PDCs) are advanced ceramics formed by the thermal treatment of preceramic polymers, which range from amorphous to crystalline. PDC technology is a novel chemical approach for producing near-net-shaped products [374]. PDCs are divided into binary systems (SiC, Si_3N_4, AlN, BN), ternary systems (SiOC, SiCN, BCN), and quaternary systems (SiCON, SiBCN, SiBCO, SiAlCN, SiAlCO). A pentanary PDC system has been described [375] for high-temperature applications because it is resistant to creeping, oxidation, crystallization, phase separation, and chemical reactions. Its nanoscale structure has broadened its potential uses, including high-temperature-resistant materials, hard materials, chemical engineering materials, and functional materials. SiC compound materials are extensively employed because of their high lithium-ion intercalation capacity and cyclic stability, and the in-situ synthesis approach improves anode material electrochemical performance [376]. The SiC compound material is a novel type of high-capacity negative material that will be the next lithium-ion battery advancement trend.

9. Applications and market potential

9.1. Real-world applications

Energy storage, power electronics, and thermal management are all examples of EV components that use advanced ceramics [377]. Ceramics are broadly classified into classic types, glassware, abrasives, insulators, refractories, enamels, and advanced ceramics, as shown in Fig. 12 [378]. Ceramics created by tape casting and screen printing improve electrical insulation, thermal conductivity, and mechanical strength in EV power electronics, hence boosting the efficiency of high-power semiconductor systems [379]. Housings and casings made with additive manufacturing, such as 3D printing, improve reliability and endurance by resisting environmental pressures, mechanical stresses, and temperature cycling.

Hot isostatic pressing and powder metallurgy are used to create ceramic bearings and insulators for EV motors, resulting in high-strength, wear-resistant components that reduce friction and improve dependability [380]. Sintering and hot pressing allow the production of sophisticated magnets like samarium cobalt and neodymium iron boron, which improve EV efficiency and PD. Thermal barrier coatings (TBCs) sprayed using physical vapor deposition (PVD) and plasma spraying help to safeguard battery casings and power electronics modules by minimizing heat transfer and regulating operational temperatures. EV heat exchangers use high thermal conductivity ceramics such as SiC, whilst ceramic electrolytes support solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs), enhancing fuel cell performance. Advanced ceramics, such as YSZ and perovskite oxides, are critical for hydrogen energy production, storage, transport, and utilization [381], with applications including electrolysis cells, thermochemical reactors, membranes, and metal hydride storage systems. Special and engineering ceramics are the next generation of complex, multifunctional materials designed for these uses.

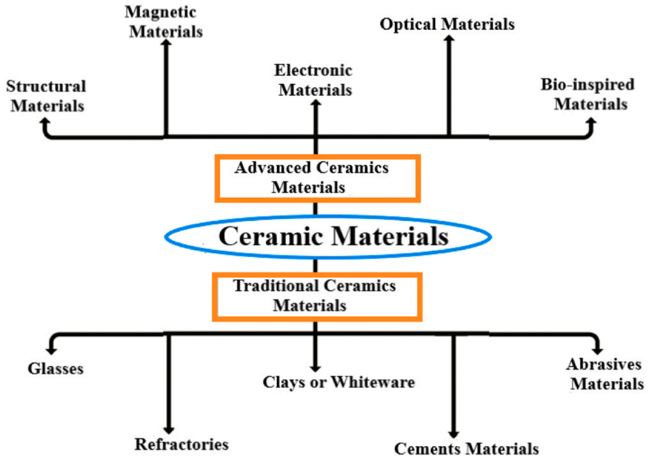


Fig. 12. Classification of Ceramic Materials [379].

Ceramics have a major role in hydrogen compression, storage, and distribution systems due to their conductivity, stability, and mechanical durability [382]. They are also used in hydrogen fuel cells, backup power systems, and portable electronics to improve structural integrity and efficiency while also functioning as proton-conducting membranes or separators for purification and separation [383]. Ceramics are also utilized as hydrogen sensors and detectors in factories, gas stations, and hydrogen-powered cars [384]. These devices, which use metal oxides, perovskites, and nanocomposites, have fast response times, low power consumption, and can tolerate extreme conditions [385]. Ceramic combustion chambers also help by detecting hydrogen leaks in real time, ensuring safety, allowing for stable combustion, and promoting hydrogen-rich fuel applications.

Advanced ceramics are being explored for flexible and wearable energy storage technologies, including batteries and solar cells, and for thermal energy storage in industrial processes [386]. Their lightweight, radiation-resistant, and thermally stable properties make them suitable for energy storage in space exploration and extraterrestrial habitation [387], such as in spacecraft and lunar or Mars bases. Future research may aim to develop energy storage devices capable of operating in extreme conditions.

9.2. Economic and industrial perspectives

The development of tougher and mechanically resistant ceramics is essential for energy storage systems, necessitating innovative design for industrial-scale production. These materials find applications across sectors like aerospace, electronics, biomedical, and optics. Engineered ceramics, including glass and tiles, are hard and brittle yet versatile, proving superior to metals in cost-effectiveness and weight, particularly in healthcare. Advanced ceramics are vital for medical devices such as endoscopy tools and implants, with their complex geometric capabilities and resistance to heat and chemicals driving market growth.

The ceramic nanomaterials market has the potential to grow significantly as production processes improve, and production time and cost are reduced. Ceramic materials like SiC are highly favored in supercapacitors because of their durability, thermal stability, and long cycle life, which offer clear industrial benefits by reducing maintenance and enhancing reliability in challenging conditions. Recent research emphasizes scalable production approaches that can offset higher raw material prices, making ceramics economically viable for large-scale deployment [388]. Newer microelectronic advancements, including quantum computing and nanocomposite transistors, are expected to revolutionize the capabilities and device designs of the advanced ceramics sector. The Japan Fine Ceramics Association (JFCA) was founded in 1986 to foster collaboration between manufacturers, users, universities, research institutes, and other sectors of the fine ceramics industry [389]. They developed the FC Roadmap 2050 in 2021 to reflect market changes over five years. Fig. 13a displays the global output share of the fine ceramics sector [389]. The fine ceramics sector, valued at over US $70 billion in 2018, is dominated by Japan, accounting for over 40 % of global manufacturing, and the United States, at 30 %. Fig. 13b displays the most recent global sales market predictions [389]. The global sales market, primarily driven by China and the US, is expected to grow at an

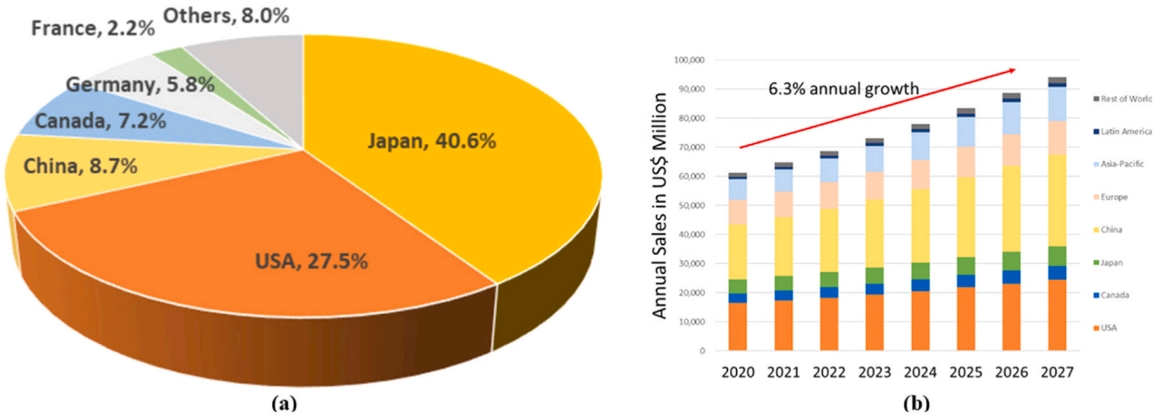


Fig. 13. (a) The contribution of the fine ceramic industry to global production. (b)Global sales market share and projections for annual sales [389].

average annual rate of 6.3 % between 2020 and 2027, with Japan accounting for around 8 % of its output.

10. Future Directions and Open Research Questions

10.1. Strategies for overcoming current ceramic limits

Ceramic membranes have long-standing problems, such as expensive raw material costs, brittleness, and fouling, which hinder widespread industrial use. These problems can be solved by optimizing sintering conditions, incorporating additives, and developing powder synthesis and finishing techniques, whereas emerging manufacturing methods such as 3D printing and multi-material fabrication improve mechanical reliability and open new application domains [390]. Structural engineering techniques, such as nanostructuring, porous electrode topologies, and hybrid electrode designs, have greatly enhanced capacitance, operating voltage, and overall performance in ceramic SCs [391]. Interfacial engineering is also important, as evidenced by NASICON-polymer composite electrolytes, which showed that interface modification with thin solvent layers increased capacitance, ED/PD, and cycling stability [392]. Composition adjustment and defect management also address low ionic conductivity and structural instabilities; for example, Na-excess ceramics processed at high sintering temperatures reduced glassy phases and increased ionic transport [393]. Furthermore, hybrid and composite membrane techniques, such as mixing clay with room-temperature ionic liquids (RTILs), provide mechanical and thermal stability while maintaining adequate ionic conductivity, allowing for dependable operation at high temperatures and voltages [394]. These tactics highlight the significance of combining compositional tuning, defect control, structural engineering, and hybrid material design, as well as advances in electrolytes and scalable production, to realize the full promise of ceramic-based SCs.

10.2. Identification of unexplored ceramic compositions

Advanced ceramics, divided into oxides, non-oxides, and composites [395], are designed for high-performance applications. Oxide ceramics, such as Al_2O_3, ZrO_2, and TiO_2, are highly thermally stable, chemically resistant, and wear-resistant. Non-oxides such as SiC, BN, and Si_3N_4 have excellent mechanical strength and hardness, making them suitable for high-temperature and wear-intensive applications [396]. Advanced ceramics exceed ordinary ceramics and metals in terms of abrasion, corrosion resistance, and high-speed machining efficiency. To achieve densification and improved properties, they go through several phases of processing with high-purity powders and burning at high temperatures [397]. To decrease reactivity at high temperatures in non-oxide ceramics, powder preparation, chemical synthesis, and controlled sintering are critical. Ceramic-based composites can contain oxides, non-oxides, metals, or polymers, with production processes chosen based on reinforcement type, geometry, and operating conditions. Slip casting, powder metallurgy, polymer infiltration, and reaction bonding are among the most common processes [398].

10.3. Artificial intelligence and machine learning

Artificial intelligence (AI) can speed up ceramic design by assisting with material selection, shape, and process optimization. Additive manufacturing (AM) is an ideal platform for AI integration due to its automation and sensitivity to many process parameters [399]. Future ceramic production innovations may rely on AI-powered tools for process optimization, feedstock design, and real-time fault correction. While Fig. 14a demonstrates AI's vast promise in AM, present challenges include high computer costs, limited datasets, and inadequate automation of ceramic AM. Near-term progress is predicted in priority areas such as process optimization, fault detection, and feedstock development.

Machine learning (ML), a type of AI, allows for data-driven process control and predictive design. Closed-loop automation and autonomous experimentation are especially important for ceramic AM [400]. However, these systems necessitate a significant investment in workflow design, equipment, and software, as well as interdisciplinary skills. Balancing development costs and practical benefits will remain a significant barrier for integrating AI/ML technologies into ceramics research and manufacture.

10.4. Development of multifunctional supercapacitors

SCs, which were originally conceived as energy storage devices, are increasingly being investigated for multifunctional applications. Future systems are planned to incorporate mechanical deformability, self-healing, self-charging, color tunability, sensing, and actuation for enhanced electronics (Fig. 14b). Self-healing shape memory SCs (SHSMCs) are being developed to address device degradation caused by repetitive mechanical deformation [401]. Self-healing polymers (SHPs) are being studied as electrode components, using methodologies such as Leibler's method [402].

The goal is to incorporate multifunctionality while preserving electrochemical performance. Electrode materials, electrolytes, substrates, and current collectors must be customized to each application [403]. Ceramic-based electrodes, electrolytes, and collectors can improve stability, but their heavier weight and volume reduce gravimetric and volumetric capacitance. Similarly, heavy SHPs, shape memory alloys, and inflexible substrates (for example, ITO/FTO glass in electrochromic SCs) limit their usefulness for lightweight applications [404]. Series and parallel connections of ceramic SCs may assist in meeting energy and power requirements, but efficiency and durability must be enhanced,

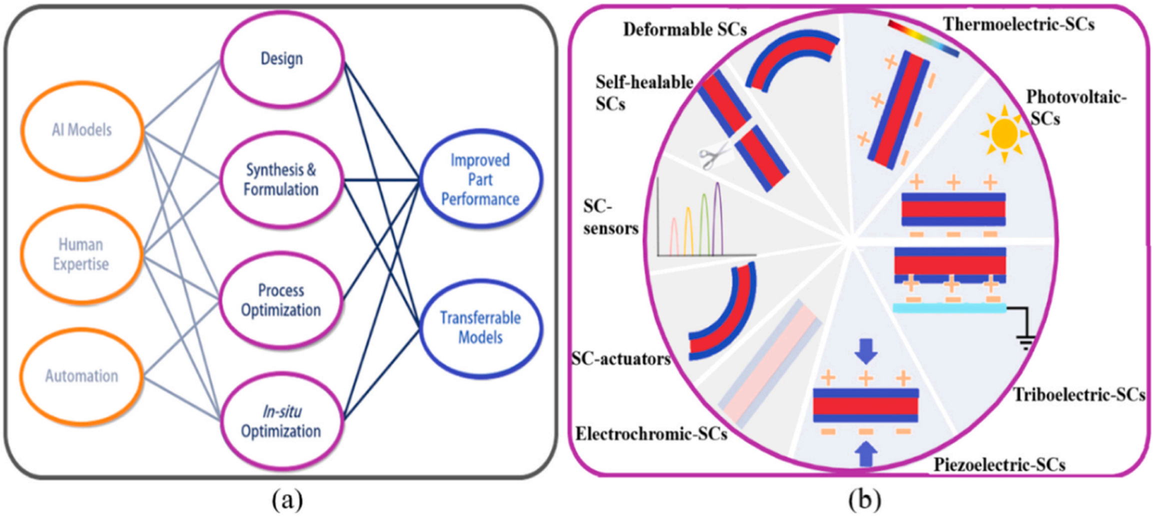


Fig. 14. (a) The potential of AI in AM. AI models, human expertise, and automation (left column) collaborate to optimize the entire process from design to production (middle column), yielding improved part performance and transferable AI models (right column). (b) Illustration diagram of multifunctional SCs, which include mechanically deformable, self-healable SCs, SC sensors, SC actuators, electrochromic SCs, and self-chargeable SCs (piezoelectric, triboelectric, solar, and thermoelectric SCs).

especially for implantable devices that require biodegradable materials.

Lightweight, efficient, multifunctional ceramic SCs, together with a greater understanding of electrochemical phenomena, represent a feasible route for future research. Progress is contingent on overcoming specific difficulties such as lowering ceramic nanoparticle production costs, improving device adhesion and flexibility, and minimizing electrolyte instability.

11. Perspectives

Ceramic materials show promise as SC electrodes, but their low SSA and limited surface activity limit their efficacy. SCs remain appealing energy storage devices due to their high PD, C, ED, long cycle life, and lack of memory effects. However, obstacles persist, particularly in selecting appropriate electrolytes and improving ED. Future flexible electronics will require SCs with deformability, packaging stability, and

Fig. 15. Key problems in the production of ceramic nanoparticles.

consistent electrochemical performance [405]. Nanomaterials have been intensively studied for low-cost, stable electrodes, with ceramics being one of the most promising types. To be effective, ceramic electrodes must have increased electrical conductivity and better electron transport routes. MOs, multi-elemental oxides, hydroxides, MSs, carbides, nitrides, carbon-based hybrids, and MXenes are among the most recent advancements.

Ceramic-based SCs are ideal for applications needing fast charging, high cycle stability, and extended operating lives, although their ED is lower than that of rechargeable batteries. Progress is dependent on a better knowledge of the electrode-electrolyte interface, where interfacial processes have a significant impact on capacity and stability. Advanced nanoceramics and hybrid materials must be designed to balance ED, conductivity, and mechanical strength. The ED of SCs is lower than that of batteries due to the limited *C* and low solubility of electrolytes in organic solvents. Optimizing electrode materials and electrolytes can improve SC performance, leading to high-performance devices (Fig. 15). Emerging ceramic electrode research emphasizes the importance of composition and microstructural design in influencing performance, cost effectiveness, and industrial scalability. Device degradation from repeated use necessitates careful investigation.

The production of ceramic nanoparticles remains one of the most crucial obstacles.

1. Particle size and morphology must be accurately controlled for optimal functionality.
2. High surface energy causes agglomeration, which reduces dispersion and efficiency. However, sintering can remove nanoscale characteristics.
3. Reproducibility is limited due to changes in reaction conditions, precursors, and reaction periods that affect size, shape, and surface properties.
4. To protect health and the environment, manufacturing, handling, and disposal must be strictly regulated.
5. Variations between batches constrain scalability and hinder large production.
6. High costs hinder wider adoption, requiring cost-effective synthesis methods.
7. Reaction temperature and duration considerably impact nanoparticle development, size, and behavior.
8. Impurities from precursors or processing equipment can lower performance.
9. Solution chemistry (pH, ionic strength, reagent concentration) affects nucleation, growth, and surface states.

Overall, ceramic nanoparticle synthesis necessitates precise control over nucleation and growth, as these processes determine final morphology, structure, and functioning [406–410].

Densification of nanocrystalline ceramics has been investigated to utilize nanoscale mechanical capabilities; however, maintaining grain sizes < 100 nm is challenging due to coarsening during sintering [411]. Precise control of sintering settings is required to avoid contamination or undesired growth. Advances in nanopowder synthesis and sintering processes (such as two-step or pressure-assisted sintering) have permitted the production of fully dense nanoceramics with higher toughness, strength, and fatigue resistance. Sol-gel [412], hydrothermal, and solvothermal procedures provide tighter control of particle size, phase, and morphology, enabling the rational design of functional nanoceramics.

SCs are increasingly used in remote power and smart devices, but cost is a major issue. Advances in nanotechnology aim to enhance electrochemical performance while reducing expenses. Key improvements for longer device lifetimes include minimizing self-discharge and optimizing electrode and electrolyte designs, as well as utilizing ceramic electrodes for their strength against corrosion and heat [413]. However, energy density remains lower than that of batteries due to issues like low capacitance and electrolyte solubility. Future focus areas include optimizing ceramic-polymer electrolytes to reduce ESR, enhancing ceramic electrode flexibility, and developing scalable nanoceramic manufacturing methods. Additionally, nanoceramic electrodes from TMOs may facilitate rapid, reversible reactions, potentially closing the gap with batteries by increasing capacitance. Selecting suitable materials will be essential for the development of competitive PCs.

Ceramic SCs with simple compositions and low sintering temperatures are being explored for military, aerospace, electric cars, pulsed laser, fusion systems, power grids, and radar applications. Grain size engineering, interface design, and lattice/strain modulation are all fabrication processes that can help increase dielectric and storage properties. Ceramic-based thin films, which have a higher breakdown strength and energy storage density than bulk ceramics, are another viable method; however, the film thickness limits absolute energy storage. Layered structures, scroll geometries, and automated high-throughput processing could all help to overcome these limits, increasing scalability and cost-effectiveness. To progress ceramic SCs, future research should concentrate on integrating mechanism-based understanding of pseudocapacitance, creating comparative benchmarks with batteries and EDLCs, and solving unique technical challenges such as nanoparticle production costs, scalability, adhesion, and flexibility. Ceramic SCs could become cost-effective, dependable, and multifunctional devices for next-generation energy storage by combining structural design, improved synthesis, and optimal interfaces.

12. Conclusion and outlook

Ceramic-based SCs have considerable potential for future applications in flexible, wearable, and high-temperature energy storage. Ceramic SCs can transition from laboratory-scale studies to viable, commercial solutions that bridge the gap between batteries and traditional capacitors by combining advances in material design, scalable production, and device-level engineering. Ceramic-based SCs are a rapidly evolving type of energy storage technology that offers excellent stability, safety, and customizable electrochemical performance. This paper summarizes current advances in ceramic electrodes, separators, and composites, with a special emphasis on TMOs, carbides, nitrides, MXenes, and polymer-ceramic hybrids. Surface area, porosity, conductivity, and mechanical integrity are important factors in influencing capacitance, ED, and cycling stability. Collectively, these developments demonstrate ceramics' versatility in meeting a wide range of energy storage applications, from high-power delivery to functioning in severe situations.

However, significant obstacles persist. Low electrical conductivity, structural brittleness, and limitations in scalable, low-cost production continue to impede widespread adoption. To overcome these limitations, approaches such as hybridization with carbon nanostructures, doping and defect engineering, conductive surface coatings, and 3D-printed porous architectures are being researched. Furthermore, electrolyte optimization and multifunctional separator design will be essential for creating high-performance, long-lasting devices.

Looking ahead, ceramic SCs have great promise for next-generation applications in flexible, wearable, and high-temperature energy storage. Future research that combines materials innovation, scalable manufacturing, and device-level engineering will speed up the transition of ceramic SCs from laboratory prototypes to practical technologies, bridging the gap between traditional capacitors and batteries.

CRediT authorship contribution statement

Theodore Azemtsop Manfo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hannu Laaksonen:** Writing – review & editing, Supervision, Methodology.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I would like to express my heartfelt gratitude to the School of Technology and Innovations and the University of Vaasa for their ongoing encouragement and support. Their advice and research atmosphere have been critical in facilitating the study's progress and successful completion.

Data availability

No data was used for the research described in the article.

References

[1] X. Li, S. Aftab, A. Abbas, S. Hussain, M. Aslam, F. Kabir, H.S. Abd-Rabboh, H. Hegazy, F. Xu, M. Ansari, Advances in mixed 2D and 3D perovskite heterostructure solar cells: a comprehensive review, Nano Energy 118 (2023) 108979, https://doi.org/10.1016/j.nanoen.2023.108979.

[2] H. Yu, D. Chen, X. Ni, P. Qing, C. Yan, W. Wei, J. Ma, X. Ji, Y. Chen, L. Chen, Reversible adsorption with oriented arrangement of a zwitterionic additive stabilizes electrodes for ultralong-life Zn-ion batteries, Energy Environ. Sci. 16 (2023) 2684–2695, https://doi.org/10.1039/D3EE00982C.

[3] D. Wang, X.-X. Wang, M.L. Jin, P. He, S. Zhang, Molecular level manipulation of charge density for solid-liquid TENG system by proton irradiation, Nano Energy 103 (2022), https://doi.org/10.1016/j.nanoen.2022.107819.

[4] A.M. Theodore, A.A. Abbas, P.S. Dhapola, Effect of layered, spinel, and Olivine-Based positive electrode materials on rechargeable Lithium-Ion batteries: a review, JCMPS 6 (2023) 38–57, https://doi.org/10.46253/jcmps.v6i4.a4.

[5] A.M. Theodore, Progress into lithium-ion battery research, 17475198231183349, J. Chem. Res. 47 (2023), https://doi.org/10.1177/174751982311833.

[6] S. Konwar, P.K. Singh, R.M. Mehra, Y. Kumar, M. Gupta, PEO+ NaSCN and ionic liquid-based polymer electrolyte for supercapacitor, mater. Today 34 (2021) 802–812, https://doi.org/10.1016/j.matpr.2020.05.340.

[7] T.A. Manfo, M.E. Şahin, Intercalation reaction in lithium-ion battery: effect on cell characteristics, TIJMET 6 (2023) 70–78.

[8] T.A. Manfo, H. Laaksonen, A review of carbon-based hybrid materials for supercapacitors, Carbon 235 (2025) 120043, https://doi.org/10.1016/j.carbon.2025.120043.

[9] T.A. Manfo, H. Laaksonen, A review of carbon-based hybrid materials for supercapacitors, N. Carbon Mater. 40 (2025) 81–110, https://doi.org/10.1016/S1872-5805(25)60943-7.

[10] A. Noori, M.F. El-Kady, M.S. Rahmanifar, R.B. Kaner, M.F. Mousavi, Towards establishing standard performance metrics for batteries, supercapacitors and beyond, Chem. Soc. Rev. 48 (2019) 1272–1341, https://doi.org/10.1039/C8CS00581H.

[11] A.M. Theodore, M. Srivastava, S. Kumar, M.Z.A. Yahya, T. Yadav, S.N.F. Yusuf, Ionic liquid mixed polymer electrolyte for supercapacitor, Macromol. Symp. 414 (2025) 1–18, https://doi.org/10.1002/masy.202400153.

[12] T.M. Azemtsop, Optical, vibrational, electrical, and electrochemical studies of new plasticized methylcellulose-based solid polymer electrolytes for supercapacitor application, Electrochem. Sci. Adv. 4 (2024) 1–15, https://doi.org/10.1002/elsa.202300018.

[13] M.G. Tadesse, E. Kasaw, J.F. Lübben, Valorization of banana peel using carbonization: potential use in the sustainable manufacturing of flexible supercapacitors, Micromachines 14 (2023) 330, https://doi.org/10.3390/mi14020330.

[14] M.G. Tadesse, E. Kasaw, B. Fentahun, E. Loghin, J.F. Lübben, Banana peel and conductive Polymers-Based flexible supercapacitors for energy harvesting and storage, Energies 15 (2022) 2471, https://doi.org/10.3390/en15072471.

[15] A.A. Simegnaw, B. Malengier, G. Rotich, M.G. Tadesse, L. Van Langenhove, Study the electrical properties of surface mount device integrated silver coated vectran yarn, Materials 15 (2022) 272, https://doi.org/10.3390/ma15010272.

[16] R.T. Yadlapalli, R.R. Alla, R. Kandipati, A. Kotapati, Super capacitors for energy storage: progress, applications and challenges, J. Energy Storage 49 (2022) 104194, https://doi.org/10.1016/j.est.2022.104194.

[17] Z. Végvári, Supercapacitors and their military applicability, Honv. édségi Szle 147 (2020) 38–49, https://doi.org/10.35926/HDR.2019.1-2.3.

[18] S. Chakraborty, N.L. Mary, Review—An overview on supercapacitors and its applications, J. Electrochem. Soc. 169 (2022) 020552 https://doi.org/1945-7111/ac5306.

[19] F. Bu, W. Zhou, Y. Xu, Y. Du, C. Guan, W. Huang, Recent developments of advanced micro-supercapacitors: design, fabrication, and applications, npj Flex. Electron 4 (2020) (2020) 31, https://doi.org/10.1038/s41528-020-00093-6.

[20] G. Sriram, G. Hegde, K. Dhanabalan, Y. Kalegowda, D. Mouraliraman, R. S. Vishwanath, M. Kurkuri, T.H. Oh, Recent trends in hierarchical electrode materials in supercapacitor: synthesis, electrochemical measurements, performance, and their charge-storage mechanism, J. Energy Storage 94 (2024) 112454, https://doi.org/10.1016/j.est.2024.112454.

[21] M. Winter, R.J. Brodd, R.J. What are batteries, fuel cells, and supercapacitors? Chem. Rev. 104 (2004) 4245–4270, https://doi.org/10.1021/cr020730k.

[22] Z. Song, J. Hou, H. Hofmann, J. Li, M. Ouyang, Sliding-mode and lyapunov function-based control for battery/supercapacitor hybrid energy storage system used in electric vehicles, Energy 122 (2017) 601–612, https://doi.org/10.1016/j.energy.2017.01.098.

[23] M.G. Carignano, R. Costa-Castelló, V. Roda, N.M. Nigro, S. Junco, D. Feroldi, Energy management strategy for fuel cell-supercapacitor hybrid vehicles based on prediction of energy demand, J. Power Sources 360 (2017) 419–433, https://doi.org/10.1016/j.jpowsour.2017.06.016.

[24] S.B. Aziz, M.A. Brza, M.M. Nofal, R.T. Abdulwahid, S.A. Hussen, A.M. Hussein, W. O. Karim, A comprehensive review on optical properties of polymer electrolytes and composites, Materials 13 (2020) 3675, https://doi.org/10.3390/ma13173675.

[25] T.A. Manfo, Materials and components used for supercapacitors. in Advanced Ceramic Coatings for Energy Applications, Elsevier, Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands, 125 London Wall, London EC2Y 5AS, United Kingdom 50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States, 2024, pp. 39–56, https://doi.org/10.1016/B978-0-323-99620-4.00003-8.

[26] A.M. Theodore, Development and characterization of a new solid polymer electrolyte for supercapacitor device, Int. J. Electrochem 2023 (2023) 4825624, https://doi.org/10.1155/2023/4825624.

[27] S. Dhanasekar, A.T. Ganesan, T.L. Rani, V.K. Vinjamuri, M. Nageswara Rao, E. Shankar, Dharamvir, P.S. Kumar, W. Misganaw Golie, A comprehensive study of ceramic matrix composites for space applications, Adv. Mater. Sci. 2022 (2022) 6160591, https://doi.org/10.1155/2022/6160591.

[28] L. Yao, J. He, L. Yao, J. He, Recent progress in antireflection and self-cleaning technology –From surface engineering to functional surfaces, Prog. Mater. Sci. 61 (2014) 94–143, https://doi.org/10.1016/j.pmatsci.2013.12.003.

[29] V.F. Rajan, R. Pachaiappan, L. Cornejo-Ponce, A. Geetha, Nano-based technologies for antibacterial, antifungal, and antiviral coatings. in Antiviral and Antimicrobial Smart Coatings, Elsevier, 2023, pp. 357–412, https://doi.org/10.1016/B978-0-323-99291-6.00001-3.

[30] A. Dey, D. Rangappa, C.D. Madhusoodana, A. KD Mukhopadhyay. Advanced Ceramic and Nanomaterials for Sustainable Development, Ceram. Int. 45(18), 24955–24956 https://doi.org/10.1016/j.ceramint.2019.09.253.

[31] Y. Cheng, X. Xiao, K. Pan, H. Pang, Development and application of self-healing materials in smart batteries and supercapacitors, Chem. Eng. J. 380 (2020) 122565, https://doi.org/10.1016/j.cej.2019.122565.

[32] S.B. Ulaeto, J.K. Pancrecious, T.P.D. Rajan, B.C. Pai, Smart coatings. in: Noble Metal-Metal Oxide Hybrid Nanoparticles, Woodhead Publishing, 2019, pp. 341–372, https://doi.org/10.1016/B978-0-12-814134-2.00017-6.

[33] Y. Li, Y. He, Ceramic-based smart thin films. in Advanced Ceramic Coatings for Energy Applications, Elsevier, Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands, 125 London Wall, London EC2Y 5AS, United Kingdom 50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States, 2024, pp. 85–115, https://doi.org/10.1016/B978-0-323-99620-4.00006-3.

[34] N. Shehata, M.A. Abdelkareem, E.T. Sayed, D.E. Egirani, A.W. Opukumo, Smart materials: the next generation. in: Encyclopedia of Smart Materials, Elsevier, Oxford, 2022, pp. 288–299, https://doi.org/10.1016/B978-0-12-815732-9.00062-0.

[35] S.S. Chai, L. Zhang, W.B. Zhang, X. Bao, Y.W. Guo, X.W. Han, X.J. Ma, Acid etching halloysite-loaded cobalt boride material for supercapacitor electrode application, Appl. Clay Sci. 218 (2022) 106426, https://doi.org/10.1016/j.clay.2022.106426.

[36] Z. Sun, Y. Zhao, C. Sun, Q. Ni, C. Wang, H. Jin, High entropy spinel-structure oxide for electrochemical application, Chem. Eng. J. 431 (2022) 133448, https://doi.org/10.1016/j.cej.2021.133448.

[37] S. Naeem, Electrodeposited cobalt hydroxide thin films: a comprehensive investigation from synthesis to advanced electrochemical behavior for high-performance energy storage, Trans. Electr. Electron. Mater. 25 (2024) 589–599, https://doi.org/10.1007/s42341-024-00542-3.

[38] S. Naeem, A.V. Shaikh, A. Rasool, D. Husain, M.T. Alam, A.V. Patil, Enhancing supercapacitor performance through electrodeposition of cobalt hydroxide thin film: structural analysis, morphological characterization, and investigation of electrochemical properties, Ionics 30 (2024) 399–405, https://doi.org/10.1007/s11581-023-05293-4.

[39] O.M. Pardeshi, S. Naeem, A.V. Patil, Synthesis of FeVO4 nanoparticles using sol-gel auto-combustion method and their application in supercapacitors, Energy Storage 6 (2024) e683, https://doi.org/10.1002/est2.683.

[40] S. Chen, Y. Ding, H. Mu, W. Tian, X. Deng, R. Gao, W. Cai, C. Fu, Research progress on multilayer ceramic capacitors for energy storage: review, J. Mater. Sci Mater. Electron 36 (2025) 77, https://doi.org/10.1007/s10854-024-14004-2.

[41] N. Kumar, S.B. Kim, S.Y. Lee, S.J. Park, Recent advanced supercapacitor: a review of storage mechanisms, electrode materials, modification, and perspectives, Nanomater 12 (2022) 3708, https://doi.org/10.3390/nano12203708.

[42] Y.J. Heo, J.H. Lee, S.H. Kim, S.J. Mun, S.Y. Lee, S.J. Park, Derived millimeter-thick yarn supercapacitors enabling high volumetric energy density, ACS Appl. Mater. Interfaces 14 (2022) 42671–42682, https://doi.org/10.1021/acsami.2c10746.

[43] A. Tundwal, H. Kumar, B.J. Binoj, R. Sharma, G. Kumar, R. Kumari, A. Dhayal, A. Yadav, D. Singh, P. Kumar, Developments in conducting polymer-, metal oxide-, and carbon nanotube-based composite electrode materials for supercapacitors: a review, RSC Adv. 14 (2024) 9406–9439, https://doi.org/10.1039/D3RA08312H.

[44] A. Afif, S.M. Rahman, A.T. Azad, J. Zaini, M.A. Islan, A.K. Azad, Advanced materials and technologies for hybrid supercapacitors for energy storage – a review, J. Energy Storage 25 (2019) 100852, https://doi.org/10.1016/j.est.2019.100852.

[45] B. Pal, S. Yang, S. Ramesh, V. Thangadurai, R. Jose, Electrolyte selection for supercapacitive devices: a critical review, Nanoscale Adv. 1 (2019) 3807–3835, https://doi.org/10.1039/C9NA00374F.

[46] L. Yu, G.Z. Chen, Redox electrode materials for supercapatteries, J. Power Sources 326 (2016) 604–612, https://doi.org/10.1016/j.jpowsour.2016.04.095.

[47] D.P. Dubal, N.R. Chodankar, D.H. Kim, P. Gomez-Romero, Towards flexible solid-state supercapacitors for smart and wearable electronics, Chem. Soc. Rev. 47 (2018) 2065–2129, https://doi.org/10.1039/C7CS00505A.

[48] J. Park, J.C. Hwang, G.G.J.U. Kim, Flexible electronics based on one-dimensional and two-dimensional hybrid nanomaterials, InfoMat 2 (2020) 33–56, https://doi.org/10.1002/inf2.12047.

[49] Y. Lin, Y. Gao, Z. Fan, Printable fabrication of nanocoral-structured electrodes for high-performance flexible and planar supercapacitor with artistic design, Adv. Mater. 29 (2017) 1701736, https://doi.org/10.1002/adma.201701736.

[50] C. Tan, J. Chen, X.J. Wu, H. Zhang, Epitaxial growth of hybrid nanostructures, Nat. Rev. Mater. 3 (2018) 1–13, https://doi.org/10.1038/natrevmats.2017.89.

[51] Y. Shao, M.F. El-Kady, J. Sun, Y. Li, Q. Zhang, M. Zhu, H. Wang, B. Dunn, R. B. Kaner, Design and mechanisms of asymmetric supercapacitors, Chem. Rev. 118 (2018) 9233–9280, https://doi.org/10.1021/acs.chemrev.8b00252.

[52] C. Wang, K. Fu, S.P. Kammampata, D.W. McOwen, A.J. Samson, L. Zhang, G. T. Hitz, A.M. Nolan, E.D. Wachsman, Y. Mo, V. Thangadurai, Garnet-type solid-state electrolytes: materials, interfaces, and batteries, Chem. Rev. 120 (2020) 4257–4300, https://doi.org/10.1021/acs.chemrev.9b00427.

[53] Z. Hao, Q. Zhao, J. Tang, Q. Zhang, J. Liu, Y. Jin, H. Wang, Functional separators towards the suppression of lithium dendrites for rechargeable high-energy batteries, Mater. Horiz. 8 (2021) 12–32, https://doi.org/10.1039/D0MH01167C.

[54] M.A. Kebede, N. Palaniyandy, Metal Oxide-Based anode materials for Lithium-Ion battery. in Electrochemical Devices for Energy Storage Applications (1st ed), CRC Press, 2019, https://doi.org/10.1201/9780367855116.

[55] C.C. Parhi, A.B. Thirumalasetty, A.R. James, M. Wuppulluri, Relative investigation on Microwave-Assisted Zr-Modified $PbTiO_3$ and $BaTiO_3$ ferroelectric ceramics for energy storage application, ACS Omega 8 (2023) 37752–37768, https://doi.org/10.1021/acsomega.2c06764.

[56] R.G. Adli, Y. Su, M.G. Hosseini, A. Hajalilou, Metal oxides for supercapacitors. Handbook of Supercapacitor Materials: Synthesis, Characterization, and Applications, Wiley-VCH, Weinheim, Germany, 2021, https://doi.org/10.1002/9783527824779.ch9.

[57] W. Ding, Y. Shi, M. Braun, F. Kessel, M. Frieß, A. Bonk, T. Bauer, Compatibility of 3D-printed oxide ceramics with molten chloride salts for high-temperature thermal energy storage in next-generation csp plants, Energies 14 (2021) 2599, https://doi.org/10.3390/en14092599.

[58] C. Yang, K. Fu, Y. Zhang, E. Hitz, L. Hu, Protected lithium-metal anodes in batteries: from liquid to solid, Adv. Mater. 29 (2017) 1701169, https://doi.org/10.1002/adma.201701169.

[59] H. Jeong, J. Jang, C. Jo, A review on current collector coating methods for next-generation batteries, J. Chem. Eng. 446 (2022) 136860, https://doi.org/10.1016/j.cej.2022.136860.

[60] E.E. Miller, Y. Hua, F.H. Tezel, Materials for energy storage: review of electrode materials and methods of increasing capacitance for supercapacitors, J. Energy Storage 20 (2018) 30–40, https://doi.org/10.1016/j.est.2018.08.009.

[61] S. Najib, E. Erdem, Current progress achieved in novel materials for supercapacitor electrodes: mini review, Nanoscale Adv. 1 (2019) 2817–2827, https://doi.org/10.1039/C9NA00345B.

[62] M.A.A.M. Abdah, N.H.N. Azman, S. Kulandaivalu, Y. Sulaiman, Review of the use of transition-metal-oxide and conducting polymer-based fibres for high-performance supercapacitors, Mater. Des. 186 (2020) 108199, https://doi.org/10.1016/j.matdes.2019.108199.

[63] J.M. Gonçalves, M.I. da Silva, H.E. Toma, L. Angnes, P.R. Martins, K. Araki, Trimetallic oxides/hydroxides as hybrid supercapacitor electrode materials: a review, J. Mater. Chem. A. 8 (2020) 10534–10570, https://doi.org/10.1039/D0TA02939D.

[64] Y. Zhao, Z. Shi, T. Lin, L. Suo, C. Wang, J. Luo, Z. Ruan, C.A. Wang, J. Li, Brownian-snowball-mechanism-induced hierarchical cobalt sulfide for supercapacitors, J. Power Sources 412 (2019) 32–330, https://doi.org/10.1016/j.jpowsour.2018.11.055.

[65] Y. Zhao, Z. Shi, H. Li, C.A. Wang, Designing pinecone-like and hierarchical manganese cobalt sulfides for advanced supercapacitor electrodes, J. Mater. Chem. A. 6 (2018) 12782–12793, https://doi.org/10.1039/C8TA02438C.

[66] T. Chen, M. Li, S. Song, P. Kim, J. Bae, Biotemplate preparation of multilayered TiC nanoflakes for high-performance symmetric supercapacitor, Nano Energy 71 (2020) 104549, https://doi.org/10.1016/j.nanoen.2020.104549.

[67] Y. Liu, Q. Wu, L. Liu, P. Manasa, L. Kang, F. Ran, Vanadium nitride for aqueous supercapacitors: a topic review, J. Mater. Chem. A. 8 (2020) 8218–8233, https://doi.org/10.1039/D0TA01490G.

[68] H. Wang, J. Li, K. Li, Y. Lin, J. Chen, L. Gao, V. Nicolosi, X. Xiao, J.M. Lee, Transition metal nitrides for electrochemical energy applications, Chem. Soc. Rev. 50 (2021) 1354–1390, https://doi.org/10.1039/D0CS00415D.

[69] Q. Li, Z. Dai, J. Wu, W. Liu, T. Di, R. Jiang, X. Zheng, W. Wang, X. Ji, P. Li, Z. Xu, Fabrication of ordered macro-microporous single-crystalline MOF and its derivative carbon material for supercapacitor, Adv. Energy Mater. 10 (2020) 1903750, https://doi.org/10.1002/aenm.201903750.

[70] S. Ali, M.A.F. Qaisar, M.S. Javed, K. Umer, S.S. Alarfaji, M. Mateen, M. Chhattal, S. Ali, A. Parkash, T.L. Tamang, J. Qi, Two-dimensional MXene-based innovative electrode materials for supercapacitors: recent advances and prospects, Fuel 377 (2024) 132783, https://doi.org/10.1016/j.fuel.2024.132783;
M. Hu, H. Zhang, T. Hu, B. Fan, X. Wang, Z. Li, Chem. Soc. Rev. 49 (2020) 6666–6693, https://doi.org/10.1039/D0CS00175A.

[71] A. Allagui, T.J. Freeborn, A.S. Elwakil, M.E. Fouda, B.J. Maundy, A.G. Radwan, Z. Said, M.A. Abdelkareem, Review of fractional-order electrical characterization of supercapacitors, J. Power Sources 400 (2018) 457–467, https://doi.org/10.1016/j.jpowsour.2018.08.047.

[72] A. Mohanty, D. Jaihindh, Y.P. Fu, S.P. Senanayak, L.S. Mende, A. Ramadoss, An extensive review on three architectural Metal-Organic frameworks towards supercapacitor application, J. Power Sources 488 (2021) 229444, https://doi.org/10.1016/j.jpowsour.2020.229444.

[73] A. González, E. Goikolea, J.A. Barrena, R. Mysyk, Review on supercapacitors: technologies and materials, Renew. Sustain. Energy Rev. 58 (2016) 1189–1206, https://doi.org/10.1016/j.rser.2015.12.249.

[74] S. Ali, S.S. Ahmad Shah, M. Sufyan Javed, T. Najam, A. Parkash, S. Khan, M. A. Bajaber, S.M. Eldin, R.A. Tayeb, M.M. Rahman, J. Qi, Recent advances of transition metal dichalcogenides-based materials for energy storage devices, in view of monovalent to divalent ions, Chem. Rec. 24 (2024) e202300145, https://doi.org/10.1002/tcr.202300145.

[75] S. Ali, A. Ahmad, I. Hussain, S.S.A. Shah, S. Ali, A. Ali, M.S. Javed, Experimental and theoretical aspects of MXene-based energy storage and energy conversion devices, J. Chem. Environ. 2 (2023) 54–81, https://doi.org/10.56946/jce.v2i2.214.

[76] Y.Z. Zhang, Y. Wang, T. Cheng, L.Q. Yao, X. Li, W.Y. Lai, W. Huang, Printed supercapacitors: materials, printing and applications, Chem. Soc. Rev. 48 (2019) 3229–3264, https://doi.org/10.1039/C7CS00819H.

[77] J. Zhou, B. Wang, Emerging crystalline porous materials as a multifunctional platform for electrochemical energy storage, Chem. Soc. Rev. 46 (2017) 6927–6945, https://doi.org/10.1039/C7CS00283A.

[78] N. Choudhary, C. Li, J. Moore, N. Nagaiah, L. Zhai, Y. Jung, J. Thomas, Asymmetric supercapacitor electrodes and devices, Adv. Mater. 29 (2017) 1605336, https://doi.org/10.1002/adma.201605336.

[79] T.A. Otitoju, P.U. Okoye, G. Chen, Y. Li, M.O. Okoye, S. Li, Advanced ceramic components: materials, fabrication, and applications, J. Ind. Eng. Chem. 8 (2020) 34–65, https://doi.org/10.1016/j.jiec.2020.02.002.

[80] Z.Y. Shen, Y. Wang, Y. Tang, Y. Yu, W.Q. Luo, X. Wang, Y. Li, Z. Wang, F. Song, Glass modified barium strontium titanate ceramics for energy storage capacitor at elevated temperatures, J. Mater. 5 (2019) 641–648, https://doi.org/10.1016/j.jmat.2019.06.003.

[81] P. Colombo, Conventional and novel processing methods for cellular ceramics, Philos. Trans. A Math. Phys. Eng. Sci. 364 (2006) 109–124, https://doi.org/10.1098/rsta.2005.1683.

[82] A.R. Studart, U.T. Gonzenbach, E. Tervoort, L.J. Gauckler, Processing routes to macroporous ceramics: a review, J. Am. Ceram. Soc. 89 (2006) 1771–1789, https://doi.org/10.1111/j.1551-2916.2006.01044.x.

[83] X.Y. Lang, B.T. Liu, X.M. Shi, Y.Q. Li, Z. Wen, Q. Jiang, Ultrahigh-power pseudocapacitors based on ordered porous heterostructures of electron-correlated oxides, Adv. Sci. 3 (2016) 1500319, https://doi.org/10.1002/advs.201500319.

[84] P. Liu, X. Weng, Z. Liu, Y. Zhang, Q. Qiu, W. Wang, M. Zhou, W. Cai, M. Ni, M. Liu, J. Liu, High-Performance Quasi-Solid-State supercapacitor based on CuO nanoparticles with Commercial-Level mass loading on ceramic material $La_{1-x}Sr_xCoO_{3-\delta}$ as cathode, ACS Appl. Energy Mater. 2 (2019) 1480–1488, https://doi.org/10.1021/acsaem.8b02046.

[85] P. Chang, H. Mei, Y. Zhao, W. Huang, S. Zhou, L. Cheng, 3D structural strengthening urchin-like $Cu(OH)_2$-based symmetric supercapacitors with adjustable capacitance, Adv. Funct. Mater. 29 (2019) 1903588, https://doi.org/10.1002/adfm.201903588.

[86] Y. Chang, X. Sun, M. Ma, C. Mu, P. Li, L. Li, M. Li, A. Nie, J. Xiang, Z. Zhao, J. He, Application of hard ceramic materials B_4C in energy storage: design $B_4C@C$ core-shell nanoparticles as electrodes for flexible all-solid-state micro-supercapacitors with ultrahigh cyclability, Nano Energy 75 (2020) 104947, https://doi.org/10.1016/j.nanoen.2020.104947.

[87] S. Iqbal, H. Khatoon, P.A. Hussain, S. Ahmad, Recent development of carbon-based materials for energy storage devices, Mater. Sci. Energy Technol. 2 (2019) 417–428, https://doi.org/10.1016/j.mset.2019.04.006.

[88] Y. Wang, Y. Song, Y. Xia, Electrochemical capacitors: mechanism, materials, systems, characterization, and applications, Chem. Soc. Rev. 45 (2016) 5925–5950, https://doi.org/10.1039/C5CS00580A.

[89] J. Varghese, H. Wang, L. Pilon, Simulating electric double layer capacitance of mesoporous electrodes with cylindrical pores, J. Electrochem. Soc. 158 (2011) A1106, https://doi.org/10.1149/1.3622342.

[90] Y. Jiang, J. Liu, Definitions of pseudocapacitive materials: a brief review, Energy Environ. Mater. 2 (1) (2019) 30–37, https://doi.org/10.1002/eem2.12028.

[91] A. Djire, P. Pande, A. Deb, J.B. Siegel, O.T. Ajenifujah, L. He, A.E. Sleightholme, P.G. Rasmussen, L.T. Thompson, Unveiling the pseudocapacitive charge storage mechanisms of nanostructured vanadium nitrides using in situ analyses, Nano Energy 60 (2019) 72–81, https://doi.org/10.1016/j.nanoen.2019.03.003.

[92] J.H. Chae, K.C. Ng, G.Z. Chen, Nanostructured materials for the construction of asymmetrical supercapacitors, Proc. Inst. Mech. Eng. Part A J. Power Energy 224 (2010) 479–503, https://doi.org/10.1243/09576509JPE861.

[93] S. Balasubramaniam, A. Mohanty, S.K. Balasingam, S.J. Kim, A. Ramadoss, Comprehensive insight into the mechanism, material selection, and performance evaluation of supercapatteries, NanoMicro Lett. 12 (2020) 1–46, https://doi.org/10.1007/s40820-020-0413-7.

[94] G. Viola, H. Ning, X. Wei, M. Deluca, A. Adomkevicius, J. Khaliq, M. John Reece, H. Yan, Dielectric relaxation, lattice dynamics, and polarization mechanisms in $Bi_{0.5}Na_{0.5}TiO_3$-based lead-free ceramics, J. Appl. Phys. 114 (2013) 014107, https://doi.org/10.1063/1.4812383.

[95] H. Ning, H. Yan, Z. Gao, X. Wei, M.J. Reece, M.J., effect of donor dopants cerium and tungsten on the dielectric and electrical properties of high curie point ferroelectric strontium niobate, Ceram. Int. 39 (2013) 7669–7675, https://doi.org/10.1016/j.ceramint.2013.03.019.

[96] X. Wei, Y. Haixue, W. Tong, H. Qingyuan, G. Viola, G. Salvatore, J. Qinghui, J. Li, X. Zhuo, J.R. Michael, Reverse boundary layer capacitor model in glass/ceramic composites for energy storage applications, J. Appl. Phys. 11 (2013) 024103, https://doi.org/10.1063/1.4775493.

[97] K.S. Randhawa, Advanced ceramics in energy storage applications: batteries to hydrogen energy, J. Energy Storage 98 (2024) 113122, https://doi.org/10.1016/j.est.2024.113122.

[98] A. Freitag, U. Langklotz, A. Rost, M. Stamm, L. Ionov, Ionically conductive Polymer/Ceramic separator for Lithium-Sulfur batteries, Energy Storage Mater. 9 (2017) 105–111, https://doi.org/10.1016/j.ensm.2017.05.014.

[99] C.O. Alvarez-Sanchez, J.A. Lasalde-Ramírez, E.O. Ortiz-Quiles, R. Massó-Ferret, E. Nicolau, Polymer-$MTiO_3$ (M = Ca, Sr, Ba) composites as facile and scalable supercapacitor separators, Energy Sci. Eng. 7 (2019) 730–740, https://doi.org/10.1002/ese3.299.

[100] H.W. Cheong, S.H. Ha, Y. Choi, Surface modified ceramic fiber separators for thermal batteries, J. Ceram. Process. Res. 3 (2012) 308–311.

[101] Z. Pang, J. Duan, Y. Zhao, Q. Tang, B. He, L.A. Yu, Ceramic NiO/ZrO_2 separator for High-Temperature supercapacitor up to 140°C, J. Power Sources 400 (2018) 126–134, https://doi.org/10.1016/j.jpowsour.2018.08.008.

[102] W. Zschiebsch, Y. Sturm, M. Kucher, D.P. Hedayati, T. Behnisch, N. Modler, R. Böhm, Multifunctionality analysis of structural Supercapacitors—a review, Materials 17 (2024) 739, https://doi.org/10.3390/ma17030739.

[103] X. Zhao, Z. Zhang, S. Yang, G. Liang, Inorganic ceramic fiber separator for electrochemical and safety performance improvement of Lithium-Ion batteries, Ceram. Int. 43 (2017) 14775–14783, https://doi.org/10.1016/j.ceramint.2017.07.219.

[104] M.Ö. Seydibeyoglu, A. Mohanty, M. Misra, Fiber technology for Fiber-Reinforced composites; woodhead publishing series in composites science and engineering (Ed.), Elsevier, Duxford, UK, 2017.

[105] N. Yamamoto, H.A. John, E.J. Garcia, S.S. Wicks, H.M. Duong, A.H. Slocum, B. L. Wardle, High-Yield growth and morphology control of aligned carbon nanotubes on ceramic fibers for multifunctional enhancement of structural composites, Carbon 47 (2009) 551–560, https://doi.org/10.1016/j.carbon.2008.10.030.

[106] R. Zhao, G. Shao, Y. Cao, L. An, C. Xu, Temperature sensor made of polymer-derived ceramics for high-temperature applications, Sens. Actuators A Phys. 219 (2014) 58–64, https://doi.org/10.1016/j.sna.2014.08.012.

[107] L. Fang, C. Wang, M. Dai, G. Huang, J. Sun, Q. Fang, New organic–inorganic hybrid materials: high refractive index polymers based on cyclotriphosphazene with high thermostability and transparency, Mater. Chem. Front 5 (2021) 5826–5832, https://doi.org/10.1039/D1QM00635E.

[108] S. Atri, R. Tomar, A review on the synthesis and modification of functional Inorganic-Organic-Hybrid materials via Microwave-Assisted method, ChemistrySelect 6 (2021) 9351–9362, https://doi.org/10.1002/slct.202102030.

[109] A.P. Alivisatos, Semiconductor clusters, nanocrystals, and quantum dots, Science 271 (1996) 933–937, https://doi.org/10.1126/science.271.5251.933.

[110] M. Adachi, Y. Murata, J. Takao, J. Jiu, M. Sakamoto, F. Wang, Highly efficient Dye-Sensitized solar cells with a titania Thin-Film electrode composed of a network structure of Single-Crystal-like TiO_2 nanowires made by the "Oriented Attachment" mechanism, J. Am. Chem. Soc. 126 (2004) 14943–14949, https://doi.org/10.1021/ja048068s.

[111] Y. Yang, A mini-review: emerging all-solid-state energy storage electrode materials for flexible devices, Nanoscale 12 (2020) 3560–3573, https://doi.org/10.1039/C9NR08722B.

[112] Y. Huang, M. Zhu, Y. Huang, Z. Pei, H. Li, Z. Wang, Q. Xue, C. Zhi, Multifunctional energy storage and conversion devices, J. Adv. Mater. 28 (2016) 8344–8364, https://doi.org/10.1002/adma.201601928.

[113] X. Yu, A. Manthira, Sustainable battery materials for next generation electrical energy storage, Adv. Energy Sust. Res 2 (2021) 2000102, https://doi.org/0.1002/aesr.202000102.

[114] Q. Yuan, M. Chen, S. Zhan, Y. Li, Y. Lin, H. Yang, Q. Yuan, M. Chen, S. Zhan, Y. Li, Y. Lin, H. Yang, Ceramic-based dielectrics for electrostatic energy storage applications: fundamental aspects, recent progress, and remaining challenges, J. Chem. Eng. 446 (2022) 136315, https://doi.org/10.1016/j.cej.2022.136315.

[115] N. Boaretto, I. Garbayo, S. Valiyaveettil-SobhanRaj, A. Quintela, C. Li, M. Casas-Cabanas, F. Aguesse, Lithium solid-state batteries: State-of-the-art and challenges for materials, interfaces and processing, J. Power Sources 502 (2021) 229919, https://doi.org/10.1016/j.jpowsour.2021.229919.

[116] J. Yang, H. Li, S. He, H. Du, K. Liu, C. Zhang, S. Jiang, Facile electrodeposition of $NiCo_2O_4$ nanosheets on porous carbonized wood for Wood-Derived asymmetric supercapacitors, Polymers 14 (2022) 2521, https://doi.org/10.3390/polym14132521.

[117] F. Wang, X. Liu, G. Duan, H. Yang, J.Y. Cheong, J. Lee, J. Ahn, Q. Zhang, S. He, J. Han, Y. Zhao, Wood-Derived conductivity and hierarchical pore integrated thick electrode enabling high Areal/Volumetric energy density for hybrid capacitors, Small 17 (2021) 2102532, https://doi.org/10.1002/smll.202102532.

[118] H. Li, L. Cao, H. Zhang, Z. Tian, Q. Zhang, F. Yang, H. Yang, S. He, S. Jiang, Intertwined carbon networks derived from Polyimide/Cellulose composite as porous electrode for symmetrical supercapacitor, J. Colloid Interface Sci. 609 (2022) 179–187, https://doi.org/10.1016/j.jcis.2021.11.188.

[119] H. Li, Y.L. Liu, H. Jin, L. Cao, H. Yang, S. Jiang, S. He, S. Li, K. Liu, G. Duan, Bimetallic salts template-assisted strategy towards the preparation of hierarchical porous polyimide-derived carbon electrode for supercapacitor, Diam. Relat. Mater. 128 (2022) 109283, https://doi.org/10.1016/j.diamond.2022.109283.

[120] S. Zheng, J. Zhang, H. Deng, Y. Du, X. Shi, Chitin-derived nitrogen-doped porous carbons with ultrahigh specific surface area and tailored hierarchical porosity for high-performance supercapacitors, Bioresour. Bioprod. 6 (2021) 142–151, https://doi.org/10.1016/j.jobab.2021.02.002.

[121] G. Duan, L. Zhao, C. Zhang, L. Chen, Q. Zhang, K. Liu, F. Wang, Pyrolysis of zinc salt-treated flax fiber: hierarchically porous carbon electrode for supercapacitor, Diam. Relat. Mater. 129 (2022) 109339, https://doi.org/10.1016/j.diamond.2022.109339.

[122] H. Aydın, U. Kurtan, M. Demir, S. Karakuş, Synthesis and application of a self-standing zirconia-based carbon nanofiber in a supercapacitor, Energy Fuels 36 (2022) 2212–2219, https://doi.org/10.1021/acs.energyfuels.1c04208.

[123] S. Bera, M. Miah, T.K. Mondal, A. Debnath, S.K. Saha, Synthesis of new mixed metal oxide $RuNi_2O_4$ phase decorated on reduced graphene oxide for supercapacitor applications, Electrochim. Acta 424 (2022) 140666, https://doi.org/10.1016/j.electacta.2022.140666.

[124] R. Vinodh, R.S. Babu, R. Atchudan, H.J. Kim, M. Yi, L.M. Samyn, A.L.F. de Barros, Fabrication of High-Performance asymmetric supercapacitor consists of nickel oxide and activated carbon (NiO//AC), Catalyst 12 (2022) 375, https://doi.org/10.3390/catal12040375.

[125] A. Mohammadpour-Haratbar, P. Kiaeerad, S. Mazinani, A.M. Bazargan, F. Sharif, Bimetallic nickel–cobalt oxide nanoparticle/electrospun carbon nanofiber composites: preparation and application for supercapacitor electrode, Ceram. Int. 48 (2022) 10015–10023, https://doi.org/10.1016/j.ceramint.2021.12.210.

[126] E. Samuel, A. Aldalbahi, M. El-Newehy, H. El-Hamshary, S.S. Yoon, Flexible and freestanding manganese/iron oxide carbon nanofibers for supercapacitor electrodes, Ceram. Int. 48 (2022) 18374–18383, https://doi.org/10.1016/j.ceramint.2022.03.106.

[127] B. Joshi, E. Samuel, Y. Kim, T. Kim, M. El-Newehy, A. Aldalbahi, S.S. Yoon, Electrospun zinc-manganese bimetallic oxide carbon nanofibers as freestanding supercapacitor electrodes, Int. J. Energy Res. 46 (2022) 22100–22112, https://doi.org/10.1002/er.7719.

[128] S. Rudra, N. Deka, A.K. Nayak, M. Pradhan, G.K. Dutta, Facile hydrothermal synthesis of Au-Mn_3O_4 decorated graphene oxide nanocomposites for solid-state supercapacitor, J. Energy Storage 50 (2022) 104615, https://doi.org/10.1016/j.est.2022.104615.

[129] D. Zhang, Q. Xiang, Electrophoretic co-deposition of Bi_2O_3–multiwalled carbon nanotubes coating as supercapacitor electrode, J. Am. Ceram. Soc. 105 (2022) 5638–5648, https://doi.org/10.1111/jace.18556.

[130] H. Peçenek, F.K. Dokan, M.S. Onses, E. Yılmaz, Outstanding supercapacitor performance with intertwined flower-like NiO/MnO_2/CNT electrodes, Mater. Res. Bull. 149 (2022) 111745, https://doi.org/10.1016/j.materresbull.2022.111745.

[131] X. Hong, C. Deng, X. Wang, W. Dong, B. Liang, Carbon nanosheets/MnO2/NiCo2O4 ternary composite for supercapacitor electrodes, J. Energy Storage 53 (2022) 105086, https://doi.org/10.1016/j.est.2022.105086.

[132] V. Shrivastav, S. Sundriyal, U.K. Tiwari, K.-H. Kim, A. Deep, Metal-organic framework derived zirconium oxide/carbon composite as an improved supercapacitor electrode, Energy 135 (2021) 121351, https://doi.org/10.1016/j.energy.2021.121351.

[133] R.A. Geioushy, S.Y. Attia, S.G. Mohamed, H. Li, O.A. Fouad, High-performance electrode materials for supercapacitor applications using Ni-catalyzed carbon nanostructures derived from biomass waste materials, J. Energy Storage 48 (2022) 104034, https://doi.org/10.1016/j.est.2022.104034.

[134] N. Mohammadi, K. Pourreza, N.B. Adeh, M. Omidvar, Defective mesoporous carbon/MnO_2 nanocomposite as an advanced electrode material for supercapacitor application, J. Alloy. Compd. 883 (2021) 160874, https://doi.org/10.1016/j.jallcom.2021.160874.

[135] M. Mandal, S. Subudhi, I. Alam, B.V.R.S. Subramanyam, S. Patra, J. Raiguru, S. Das, P. Mahanandia, Facile synthesis of new hybrid electrode material based on activated carbon/multiwalled carbon nanotubes@ $ZnFe_2O_4$ for supercapacitor applications, Inorg. Chem. Commun. 123 (2021) 108332, https://doi.org/10.1016/j.inoche.2020.108332.

[136] S. Shin, M.W. Shin, Nickel metal–organic framework (Ni-MOF) derived NiO/C@CNF composite for the application of high-performance self-standing

supercapacitor electrode, Appl. Surf. Sci. 540 (2021) 148295, https://doi.org/10.1016/j.apsusc.2020.148295.

[137] R. Ramaseshan, S. Sundarrajan, R. Jose, S. Ramakrishna, Nanostructured ceramics by electrospinning, J. Appl. Phys. 102 (2007) 111101, https://doi.org/10.1063/1.2815499.

[138] P. Tiwari, D. Janas, R. Chandra, Self-standing MoS_2/CNT and MnO_2/CNT one-dimensional core-shell heterostructures for asymmetric supercapacitor application, Carbon 177 (2021) 291–303, https://doi.org/10.1016/j.carbon.2021.02.080.

[139] C. Hu, L. Miao, Q. Yang, X. Yu, L. Song, Y. Zheng, C. Wang, L. Li, L. Zhu, X. Cao, H. Niu, Self-assembly of CNTs on ni foam for enhanced performance of $NiCoO_2$@ CNT@ NF supercapacitor electrode, J. Chem. Eng. 410 (2021) 128317, https://doi.org/10.1016/j.cej.2020.128317.

[140] S. Guo, H. Li, X. Zhang, H. Nawaz, S. Chen, X. Zhang, F. Xu, Lignin carbon aerogel/nickel binary network for cubic supercapacitor electrodes with ultra-high areal capacitance, Carbon 174 (2021) 500–508, https://doi.org/10.1016/j.carbon.2020.12.051.

[141] H. Zhou, Y. Zhan, F. Guo, S. Du, B. Tian, Y. Dong, L. Qian, Synthesis of biomass-derived carbon aerogel/MnOx composite as electrode material for high-performance supercapacitors, Electrochim. Acta 390 (2021) 138817, https://doi.org/10.1016/j.electacta.2021.138817.

[142] R. Kumar, S. Sahoo, W.K. Tan, G. Kawamura, A. Matsuda, K.K. Kar, Microwave-assisted thin reduced graphene oxide-cobalt oxide nanoparticles as hybrids for electrode materials in supercapacitor, J. Energy Storage 40 (2021) 102724, https://doi.org/10.1016/j.est.2021.102724.

[143] X. He, R. Li, J. Liu, Q. Liu, R. Chen, D. Song, J. Wang, Hierarchical FeCo2O4@ NiCo layered double hydroxide core/shell nanowires for high-performance flexible all-solid-state asymmetric supercapacitors, Chem. Eng. J. 334 (2018) 1573–1583, https://doi.org/10.1016/j.cej.2017.11.089.

[144] S. Zhang, B. Yin, C. Liu, Z. Wang, D. Gu, Self-assembling hierarchical NiCo2O4/MnO2 nanosheets and MoO_3/PPy core-shell heterostructured nanobelts for supercapacitor, Chem. Eng. J. 312 (2017) 296–305, https://doi.org/10.1016/j.cej.2016.11.144.

[145] J. Ding, W. Hu, E. Paek, D. Mitlin, Review of hybrid ion capacitors: from aqueous to lithium to sodium, Chem. Rev. 118 (2018) 6457–6498, https://doi.org/10.1021/acs.chemrev.8b00116.

[146] C. Zhang, C.L. Lei, C. Cen, S.L. Tang, M.S. Deng, Y.L. Li, Y.W. Du, Interface polarization matters: enhancing supercapacitor performance of spinel NiCo2O4 nanowires by reduced graphene oxide coating, Electrochim. Acta 260 (2018) 814–822, https://doi.org/10.1016/j.electacta.2017.12.044.

[147] J.S. Xu, Y.D. Sun, M.J. Lu, L. Wang, J. Zhang, J.H. Qian, X.Y. Liu, Fabrication of hierarchical $MnMoO_4{\cdot}H_2O$@ MnO_2 core-shell nanosheet arrays on nickel foam as an advanced electrode for asymmetric supercapacitors, Chem. Eng. J. 334 (2018) 1466–1476, https://doi.org/10.1016/j.cej.2017.11.085.

[148] H. Osgood, S.V. Devaguptapu, H. Xu, J. Cho, G. Wu, Transition metal (Fe, Co, Ni, and Mn) oxides for oxygen reduction and evolution bifunctional catalysts in alkaline media, Nano Today 11 (2016) 601–625, https://doi.org/10.1016/j.nantod.2016.09.001.

[149] M. Ates, M. Yildirim, The synthesis of rGO/RuO_2, rGO/PANI, RuO_2/PANI and rGO/RuO_2/PANI nanocomposites and their supercapacitors, Polym. Bull. 77 (2020) 2285–2307, https://doi.org/10.1007/s00289-019-02850-8.

[150] F. Yu, L. Pang, H.-X. Wang, Preparation of Mulberry-like RuO_2 electrode material for supercapacitors, Rare Met 40 (2021) 440–447, https://doi.org/10.1007/s12598-020-01561-8.

[151] X. Zeng, H. Song, Z.Y. Shen, Z.Y, M. Moskovits, Progress and challenges of ceramics for supercapacitors, J. Mater. 7 (2021) 1198–1224, https://doi.org/10.1016/j.jmat.2021.03.001.

[152] Y. Liu, M.S. Ata, K. Shi, G.Z. Zhu, G.A. Botton, I. Zhitomirsky, Surface modification and cathodic electrophoretic deposition of ceramic materials and composites using celestine blue dye, RSC Adv. 4 (2014) 29652, https://doi.org/10.1039/C4RA03938F.

[153] M.S. Ata, I. Zhitomirsky, Electrophoretic nanotechnology of ceramic films, Adv. Appl. Ceram. 111 (2012) 345–350, https://doi.org/10.1179/1743676111Y.0000000070.

[154] J. Wei, N. Nagarajan, I. Zhitomirsky, Manganese oxide films for electrochemical supercapacitors, J. Mater. Process. Technol. 186 (2007) 356–361, https://doi.org/10.1016/j.jmatprotec.2007.01.003.

[155] Y. Xing, X. Guo, D. Wu, Z. Liu, S. Fang, S.L. Suib, Construction of macroscopic 3D foams of metastable manganese oxides via a mild templating route: effects of atmosphere and calcination, J. Alloy. Compd. 719 (2017) 22–29, https://doi.org/10.1016/j.jallcom.2017.05.128.

[156] J. Milne, R.M. Silva, I. Zhitomirsky, Surface modification and dispersion of ceramic particles using liquid-liquid extraction method for application in supercapacitor electrodes, J. Eur. Ceram. 39 (2019) 3450–3455, https://doi.org/10.1016/j.jeurceramsoc.2018.12.023.

[157] O.A. Shilova, V.N. Antipov, P.A. Tikhonov, I.Y. Kruchinina, M.Y. Arsent'ev, T. I. Panova, L.V. Morozova, V.V. Moskovskaya, M.V. Kalinina, I.N. Tsvetkova, Ceramic nanocomposites based on oxides of transition metals for ionistors, Glass Phys. Chem. 39 (2013) 570–578, https://doi.org/10.1134/S1087659613050179.

[158] R. Poon, W. Liang, I. Zhitomirsky, I. Mn_3O_4 And (ZnFe)OOH composites for supercapacitors with high active mass, Met. Mater. Trans. A 51 (2020) 855–862, https://doi.org/10.1007/s11661-019-05561-x.

[159] X.Y. Lang, B.T. Liu, X.M. Shi, Y.Q. Li, Z. Wen, Q. Jiang, Ultrahigh-power pseudocapacitors based on ordered porous heterostructures of electron-correlated oxides, Adv. Sci. 3 (2016) 1500319, https://doi.org/10.1002/advs.201500319.

[160] S.F. Shen, M.L. Xu, D.B. Lin, and H.B. Pan, The growth of urchin-like Co3O4 directly on sensor substrate and its gas sensing properties, Appl. Surf. Sci. 396 (201), 327–332. https://doi.org/10.1016/j.apsusc.2016.10.147.

[161] B. Vidyadharan, R.Abd Aziz, I.I. Misnon, G.M.A. Kumar, J. Ismail, M.M. Yusoff, R. Jose, High-energy and power density asymmetric supercapacitors using electrospun cobalt oxide nanowire anode, J. Power Sources 270 (2014) 526–535, https://doi.org/10.1016/j.jpowsour.2014.07.134.

[162] R. Jose, S.G. Krishnan, B. Vidyadharan, I.I. Misnon, M. Harilal, R.A. Aziz, J. Ismail, M.M. Yusoff, Supercapacitor electrodes delivering high energy and power densities, Mater. Today 3 (2016) S48–S56, https://doi.org/10.1016/j.matpr.2016.01.007.

[163] B. Vidhyadharan, N.K.M. Zain, I.I. Misnon, R.Abd Aziz, R. Ismail, J. Yusoff, M.M. R. Jose, High-performance supercapacitor electrodes from electrospun nickel oxide nanowires, J. Alloy. Compd. 610 (2014) 143–150, https://doi.org/10.1016/j.jallcom.2014.04.211.

[164] J. Yus, B. Ferrari, A.J. Sanchez-Herencia, Z. Gonzalez, Understanding the effects of different microstructural contributions in the electrochemical response of Nickel-based semiconductor electrodes with 3D hierarchical network shapes, Electrochim. Acta 335 (2020) 135629, https://doi.org/10.1016/j.electacta.2020.135629.

[165] J. Yus, B. Ferrari, A.J. Sanchez-Herencia, A. Caballero, J. Morales, Z. Gonzalez, In situ synthesis and electrophoretic deposition of NiO/Ni core-shell nanoparticles and its application as pseudocapacitor, Coat 7 (2017) 193, https://doi.org/10.3390/coatings7110193.

[166] Z. Pang, J. Duan, Y. Zhao, Q. Tang, B. He, L. Yu, A ceramic ni O/ZrO2 separator for high-temperature supercapacitor up to 140 °C, J. Power Sources 400 (2018) 126–134, https://doi.org/10.1016/j.jpowsour.2018.08.008.

[167] M.V. Kalinina, L.V. Morozova, T.L. Egorova, M.Y. Arsent'ev, I.A. Drozdova, O. A. Shilova, The dual role of SiO2 as a pore former and sintering aid in the preparation of the porous ceramic in ZrO_2-In_2O_3 system, Glass Phys. Chem. 41 (2015) 431–436, https://doi.org/10.1134/S1087659615040082.

[168] A. Knöller, S. Kilper, A.M. Diem, M. Widenmeyer, T. Runčevski, R.E. Dinnebier, J. Bill, Z. Burghard, Ultrahigh damping capacities in lightweight structural materials, Nano Lett. 18 (2018) 2519–2524, https://doi.org/10.1021/acs.nanolett.8b00194.

[169] T. Li, Y. Cao, W. Xue, B. Sun, D. Zhu, Self-assembly of graphene-based planar micro-supercapacitor with selective laser etching-induced superhydrophobic/superhydrophilic pattern, SN Appl. Sci. 2 (2020) 1–9, https://doi.org/10.1007/s42452-020-2000-4.

[170] K. Tennakone, G.L.M.P. Apsonsu, Y.P.Y.P. Ariyasinghe, R.C. Buchanan, V.P. S. Perera, H. Tennakone, T.R.C.K. Wijayarathna, Dye-sensitized solar cells based on nanostructured semiconductor oxide ceramics with ultra-thin barrier layers, Integr. Ferroelectr. 115 (2010) 120–131, https://doi.org/10.1080/10584587.2010.488561.

[171] S. Balasubramaniam, A. Mohanty, S.K. Balasingam, S.J. Kim, A. Ramadoss, Comprehensive insight into the mechanism, material selection, and performance evaluation of supercapatteries, Nanomicro Lett. 12 (2020) 85, https://doi.org/10.1007/s40820-020-0413-7.

[172] S. Mihaiu, O. Scarlat, G. Aldica, M. Zaharescu. SnO_2 electroceramics with various additives, 2001, pp. 1801–1804, vol. (21)10.1016/S0955-2219(01)00119-4.

[173] M.A. Janifer, S. Anand, C.J. Prabagar, S. Pauline, Structural and optical properties of $BaSnO_3$ ceramics by solid state reaction method, Mater. Today 47 (2021) 2067–2070, https://doi.org/10.1016/j.matpr.2021.04.429.

[174] Y. Zhang, Z. Guo, Z. Han, X. Xiao, Y. Zhang, Z. Guo, Z. Han, X. Xiao, Effect of rare earth oxides doping on $MgAl_2O_4$ spinel obtained by sintering of secondary aluminum dross, J. Alloy. Compd. 735 (2018) 2597–2603, https://doi.org/10.1016/j.jallcom.2017.11.356.

[175] S. Anwar, K.S. Muthu, V. Ganesh, N. Lakshminarasimhan, A comparative study of electrochemical capacitive behavior of NiFe2O4 synthesized by different routes, JES 158 (2011) A976, https://doi.org/10.1149/1.3601863.

[176] B.J. Rani, G. Ravi, R. Yuvakkumar, V. Ganesh, S. Ravichandran, M. Thambidurai, A.P. Rajalakshmi, A. Sakunthala, Pure and cobalt-substituted zinc-ferrite magnetic ceramics for supercapacitor applications, Appl. Phys. A. 124 (2018) 1–12, https://doi.org/10.1007/s00339-018-1936-3.

[177] C. Shamitha, T. Senthil, L. Wu, B.S. Kumar, S. Anandhan, Sol–gel electrospun mesoporous $ZnMn_2O_4$ nanofibers with superior specific surface area, J. Mater. Sci. Mater. Electron 28 (2017) 15846–15860, https://doi.org/10.1007/s10854-017-7479-0.

[178] A.S. Kovalenko, O.A. Shilova, L.V. Morozova, M.V. Kalinina, I.A. Drozdova, M. Y. Arsent'ev, Features of the synthesis and the study of nanocrystalline cobalt-nickel spinel, Glass Phys. Chem. 40 (2014) 106–113, https://doi.org/10.1134/S1087659614010131.

[179] C.O. Alvarez-Sanchez, J.A. Lasalde-Ramírez, E.O. Ortiz-Quiles, R. Massó-Ferret, E. Nicolau, Polymer-$MTiO_3$ (M = Ca, Sr, Ba) composites as facile and scalable supercapacitor separators, Energy Sci. Eng. 7 (2019) 730–740, https://doi.org/10.1002/ese3.299.

[180] L. Gu, T. Li, Y. Xu, C. Sun, Z. Yang, D. Zhu, D. Chen, Effects of the particle size of $BaTiO_3$ fillers on fabrication and dielectric properties of $BaTiO_3$/Polymer/Al films for capacitor Energy-Storage application, Mater 12 (2019) 439, https://doi.org/10.3390/ma12030439.

[181] H.X. Tang, Y.R. Lin, H.A. Sodano, Synthesis of high aspect ratio $BaTiO_3$ nanowires for high energy density nanocomposite capacitors, Adv. Energy Mater. 3 (2014) 451–456, https://doi.org/10.1002/aenm.201200808.

[182] U.C. Chung, C. Elissalde, F. Mompiou, J. Majimel, S. Gomez, C. Estournès, S. Marinel, A. Klein, F. Weill, D. Michau, S. Mornet, Interface investigation in

nanostructured $BaTiO_3$/Silica composite ceramics, JACerS 93 (2010) 865–874, https://doi.org/10.1111/j.1551-2916.2009.03474.x.

[183] C. M. Maglione, Elissalde y U-C. Chung, interface control in $BaTiO_3$-based supercapacitors. Proc. SPIE 7603 OxideBased Mater. Devices 76030U, 2010, 10.1117/12.846563.

[184] U.C. Chung, C. Elissalde, S. Mornet, M. Maglione, C. Estournès, Controlling internal barrier in low-loss $BaTiO_3$ supercapacitors, Appl. Phys. Lett. 94 (2009) 072903, https://doi.org/10.1063/1.3076125.

[185] D. Bhattacharya, D. Ghoshal, D. Mondal, B.K. Paul, J. Pal, B. Gupta, N. Bose, P. Nandy, M. Basu, S. Das, Delafossite-type $CuCo_{0.5}Ti_{0.5}O_2$ composite structure: a futuristic ceramic for supercapacitor and EMI shielding application, Ceram. Int. 47 (2021) 9907–9922, https://doi.org/10.1016/j.ceramint.2020.12.135.

[186] S. Maity, M. Samanta, A. Sen, K.K. Chattopadhyay, Investigation of electrochemical performances of ceramic oxide $CaCu_3Ti_4O_{12}$ nanostructures, J. Solid State Chem. 269 (2019) 600–607, https://doi.org/10.1016/j.jssc.2018.10.016.

[187] H.M. Shiri, A. Ehsani, J.S. Shayeh, Synthesis and highly efficient supercapacitor behavior of a novel poly pyrrole/ceramic oxide nanocomposite film, RSC Adv. 5 (2015) 91062–91068, https://doi.org/10.1039/C5RA19863A.

[188] C. Xu, Z. Zhang, J. Zhang, L. Lei, D. Zhang, Z. Fu, A new route to fabricate barium titanate with high permittivity, Ceram. Inter 40 (2014) 10927–10931, https://doi.org/10.1016/j.ceramint.2014.03.090.

[189] L.V. Morozova, T.I. Panova, V.P. Popov, I.N. Tsvetkova, O.A. Shilova, Synthesis and study of oxide and phosphor-silicate nanocomposites for the creation of new-generation supercapacitors, Glass Phys. Chem. 38 (2012) 332–338, https://doi.org/10.1134/S1087659612030121.

[190] X. Zhang, B. He, Y. Zhao, Q. Tang, A porous ceramic membrane-tailored high-temperature supercapacitor, J. Power Sources 379 (2018) 60–67, https://doi.org/10.1016/j.jpowsour.2018.01.033.

[191] M. Kosmulski, J. Skubiszewska-Zięba, R. Leboda, K. Marczewska-Boczkowska, P. Próchniak, New ceramic–carbon composites for electrodes for electrochemical capacitors, J. Colloid Interface Sci. 309 (2007) 160–168, https://doi.org/10.1016/j.jcis.2006.12.078.

[192] D.W. McOwen, S. Xu, S, Y. Gong, Y. Wen, G.L. Godbey, J.E. Gritton, T.R. Hamann, J. Dai, G.T. Hitz, L. Hu, E.D. Wachsman, 3D-printing electrolytes for solid-state batteries, Adv. Mater. 30 (2018) 1707132, https://doi.org/10.1002/adma.201707132.

[193] W. Xia, Y. Liu, G. Wang, J. Li, C. Cao, Q. Hu, Y. Chen, Z. Lu, D. Wang, Frequency and temperature independent $(Nb_{0.5}Ga_{0.5})x(Ti_{0.9}Zr_{0.1})_{1\text{-}x}O_2$ ceramics with giant dielectric permittivity and low loss, Ceram. Int. 46 (2020) 2954–2959, https://doi.org/10.1016/j.ceramint.2019.09.292.

[194] J.W. Lee, J.H. Koh, Grain size effects on the dielectric properties of $CaCu_3Ti_4O_{12}$ ceramics for supercapacitor applications, Ceram. Int. 41 (2015) 10442–10447, https://doi.org/10.1016/j.ceramint.2015.04.109.

[195] S.F. Shao, J.L. Zhang, P. Zheng, W.L. Zhong, C.L. Wang, Microstructure and electrical properties of $CaCu_3Ti_4O_{12}$ ceramics, J. Appl. Phys. 99 (2006) 084106, https://doi.org/10.1063/1.2191447.

[196] E. Mishuk, J. Shklovsky, Y. Berg, N. Vengerovsky, T. Paul, Z. Kotler, Y. Tsur, Y. Shacham-Diamand, S. Krylov, I. Lubomirsky, Femtosecond laser processing of ceria-based microactuators, Microelectron. Eng. 217 (2019) 111126, https://doi.org/10.1016/j.mee.2019.111126.

[197] M. Padmini, P. Elumalai, P. Thomas, Symmetric supercapacitor performances of $CaCu_3Ti_4O_{12}$ decorated polyaniline nanocomposite, Electrochim. Acta 292 (2018) 558–567, https://doi.org/10.1016/j.electacta.2018.09.179.

[198] L. Wang, F. Gao, J. Xu, K. Zhang, M. Wang, M. Qin, Fabrication, characterization, and dielectric properties of KH550 modified BST/PVDF nanocomposites with high dielectric strength, High. Volt. 1 (2016) 158–165, https://doi.org/10.1049/hve.2016.0065.

[199] A. Lahmar, J. Belhadi, M. El Marssi, M. Zannen, H. Khemakhem, N. Al-Dahoudi, Energy storage property of Lead-free Na0.5Bi0.5TiO3 ceramic and thin film. 2017 International Conference in Energy and Sustainability in Small Developing Economies (ES2DE), Funchal, Portugal, 2017, pp. 1–4, 10.1109/ES2DE.2017.8015355.

[200] R. Gu, K. Yu, L. Wu, R. Ma, H. Sun, L. Jin, Y. Xu, Z. Xu, X. Wei, Dielectric properties and IV characteristics of $Li_{0.5}La_{0.5}TiO_3$ solid electrolyte for ceramic supercapacitors, Ceram. Int. 45 (2019) 8243–8247, https://doi.org/10.1016/j.ceramint.2019.01.128.

[201] O. Bohnke, The fast lithium-ion conducting oxides $Li_xLa_{2/3-x}TiO_3$ from fundamentals to application, Solid State Ion.. 179 (2008) 9–15, https://doi.org/10.1016/j.ssi.2007.12.022.

[202] D.L. Lu, R.R. Zhao, J.L. Wu, J.M. Ma, M.L. Huang, Y.B. Yao, T. Tao, B. Liang, J. W. Zhai, S.G. Lu, Investigations on the properties of $Li_{3x}La_{2/3-x}TiO_3$ based all-solid-state supercapacitor: relationships between the capacitance, ionic conductivity, and temperature, J. Eur. Ceram. 40 (2020) 2396–2403, https://doi.org/10.1016/j.jeurceramsoc.2020.02.006.

[203] P. Liu, X. Weng, Z. Liu, Y. Zhang, Q. Qiu, W. Wang, M. Zhou, W. Cai, M. Ni, M. Liu, J. Liu, High-Performance Quasi-Solid-State supercapacitor based on CuO nanoparticles with Commercial-Level mass loading on ceramic material $La_{1\text{-}x}Sr_xCoO_{3\text{-}\delta}$ as cathode, ACS Appl. Energy Mater. 2 (2019) 1480–1488, https://doi.org/10.1021/acsaem.8b02046.

[204] P. Liu, Z. Liu, P. Wu, X. Ou, Y. Zhang, W. Cai, F. Yu, M. Ni, S. Cheng, M. Liu, J. Liu, Enhanced capacitive performance of nickel oxide on porous $La_{0.7}Sr_{0.3}CoO_{3\text{-}\delta}$ ceramic substrate for electrochemical capacitors, Int. J. Hydrog. Energy 43 (2018) 19589–19599, https://doi.org/10.1016/j.ijhydene.2018.09.023.

[205] M. Tuncer, F. Bakan, H. Gocmez, E. Erdem, Capacitive behaviour of nanocrystalline octacalcium phosphate (OCP)$(Ca_8H_2(PO_4)_{6.5}H_2O)$ as an electrode material for supercapacitors: biosupercaps, Nanoscale 11 (2019) 18375–18381, https://doi.org/10.1039/C9NR07108C.

[206] M.M. El-Desoky, A.M. Al-Syadi, H.M. Al-Assiri, H.M. Hassan, G. El Enany, Electrochemical performance of novel $Li_3V_2(PO_4)_3$ glass-ceramic nanocomposites as electrodes for energy storage devices, JES 20 (2016) 2663–2671, https://doi.org/10.1007/s10008-016-3267-7.

[207] X. Hu, Y. Chen, Z. Hu, Y. Li, Z.Y. Ling, All-solid-state supercapacitors based on a carbon-filled porous/dense/porous layered ceramic electrolyte, JES 165 (2018) A1269, https://doi.org/10.1149/2.0481807jes.

[208] G. Liao, S. Geier, T. Mahrholz, P. Wierach, M. Wiedemann, $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ used as solid electrolyte for structural supercapacitors, in: In: Smart Materials, Adaptive Structures and Intelligent Systems, 57298, American Society of Mechanical Engineers, 2015, https://doi.org/10.1115/SMASIS2015-8915.

[209] G.Y. Liao, S. Geier, T. Mahrholz, P. Wierach, M. Wiedemann, $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ used as a solid electrolyte for structural supercapacitors, in: In Smart Materials, Adaptive Structures and Intelligent Systems, 58257, American Society of Mechanical Engineers, Colorado Springs, Colorado, USA, September 2017, https://doi.org/10.1115/SMASIS2015-8915.

[210] J. Fu, Superionic conductivity of glass-ceramics in the system $Li_2O\text{-}Al_2O_3\text{-}TiO_2\text{-}P_2O_5$, Solid State Ion.. 96 (1997) 195–200, https://doi.org/10.1016/S0167-2738(97)00018-0.

[211] B.V.R. Chowdari, G.S. Rao, G.Y.H. Lee, XPS and ionic conductivity studies on $Li_2O–Al_2O_3–(TiO_2$ or $GeO_2)–P_2O_5$ glass–ceramics, Solid State Ion.. 136 (2000) 1067–1075, https://doi.org/10.1016/S0167-2738(00)00500-2.

[212] P. Chang, H. Mei, Y. Zhao, W. Huang, S. Zhou, L. Cheng, 3D structural strengthening Urchin-Like $Cu(OH)_2$-Based symmetric supercapacitors with adjustable capacitance, Adv. Funct. Mater. 29 (2019) 1903588, https://doi.org/10.1002/adfm.201903588.

[213] Z. Gonzalez, B. Ferrari, A.J. Sanchez-Herencia, A. Caballero, J. Morales, Use of polyelectrolytes for the fabrication of porous NiO films by electrophoretic deposition for supercapacitor electrodes, Electrochem. Acta 211 (2016) 110–118, https://doi.org/10.1016/j.electacta.2016.06.014.

[214] H. Li, Y. Zhao, C.A. Wang, MoS_2/CoS_2 composites composed of CoS_2 octahedrons and MoS_2 nano-flowers for supercapacitor electrode materials, Front. Mater. Sci. 12 (2018) 354–360, https://doi.org/10.1007/s11706-018-0437-9.

[215] Y. Zhao, Z. Shi, T. Lin, L. Suo, C. Wang, J. Luo, Z. Ruan, C.A. Wang, J. Li, Brownian-snowball-mechanism-induced hierarchical cobalt sulfide for supercapacitors, J. Power Sources 412 (2019) 321–330, https://doi.org/10.1016/j.jpowsour.2018.11.055.

[216] W. Choi, N. Choudhary, G.H. Han, J. Park, D. Akinwande, Y.H. Lee, Recent development of two-dimensional transition metal dichalcogenides and their applications, Mater. Today 20 (2017) 116–130, https://doi.org/10.1016/j.mattod.2016.10.002.

[217] Y. Yang, H. Fei, G. Ruan, C. Xiang, J.M. Tour, Edge-Oriented MoS_2 nanoporous films as flexible electrodes for hydrogen evolution reactions and supercapacitor devices, Adv. Mater. 26 (2014) 8163–8168, https://doi.org/10.1002/adma.201402847.

[218] Y. Tian, X. Song, J. Liu, L. Zhao, P. Zhang, L. Gao, Generation of monolayer MoS_2 with 1T phase by Spatial-Confinement-Induced ultrathin PPy anchoring for High-Performance supercapacitor, Adv. Mater. Interfaces 6 (2019) 1900162, https://doi.org/10.1002/admi.201900162.

[219] Y. Zhao, Z. Shi, H. Li, C.A. Wang, Designing pinecone-like and hierarchical manganese cobalt sulfides for advanced supercapacitor electrodes, J. Mater. Chem. A 6 (2018) 12782–12793, https://doi.org/10.1039/C8TA02438C.

[220] X.Y. Yu, X.W. Lou, Mixed metal sulfides for electrochemical energy storage and conversion, Adv. Energy Mater. 8 (2018) 1701592, https://doi.org/10.1002/aenm.201701592.

[221] Y.P. Liu, X.H. Qi, L. Li, S.H. Zhang, T. Bi, MOF-derived PPy/carbon-coated copper sulfide ceramic nanocomposite as high-performance electrode for supercapacitor, Ceram. Int. 45 (2019) 17216–17223, https://doi.org/10.1016/j.ceramint.2019.05.277.

[222] K. Kim, T. Lee, Y. Kwon, Y. Seo, J. Song, J.K. Park, H. Lee, J.Y. Park, H. Ihee, S. J. Cho, R. Ryoo, Lanthanum-catalysed synthesis of microporous 3D graphene-like carbons in a zeolite template, Nature 535 (2016) 131–135, https://doi.org/10.1016/j.ceramint.2019.05.277.

[223] R. Xiang, T. Inoue, Y. Zheng, A. Kumamoto, Y. Qian, Y. Sato, M. Liu, D. Tang, D. Gokhale, J. Guo, K. Hisama, One-dimensional van der waals heterostructures, Science 367 (2020) 537–542, https://doi.org/10.1126/science.aaz2570.

[224] X. He, X. Xie, J. Wang, X. Ma, Y. Xie, J. Gu, N. Xiao, J. Qiu, From fluorene molecules to ultrathin carbon nanonets with an enhanced charge transfer capability for supercapacitors, Nanoscale 11 (2019) 6610–6619, https://doi.org/10.1039/C9NR00068B.

[225] X. He, X. Xie, J. Wang, X. Ma, Y. Xie, J. Gu, N. Xiao, J. Qiu, From fluorene molecules to ultrathin carbon nanonets with an enhanced charge transfer capability for supercapacitors, Nanoscale 11 (2019) 6610–6619, https://doi.org/10.1039/C9NR00068B.

[226] J. Yus, Y. Bravo, A.J. Sanchez-Herencia, B. Ferrari, Z. Gonzalez, Electrophoretic deposition of RGO-NiO core-shell nanostructures driven by hetero coagulation method with high electrochemical performance, Electro Acta 308 (2019) 363–372, https://doi.org/10.1016/j.electacta.2019.04.053.

[227] J.J. Moyano, J. Mosa, M. Aparicio, D. Pérez-Coll, M. Belmonte, P. Miranzo, Strong and light cellular silicon carbonitride–Reduced graphene oxide material with enhanced electrical conductivity and capacitive response, M.I, Addit. Manuf. 10 (2019) 100849, https://doi.org/10.1016/j.addma.2019.100849.

[228] P. Moni, W.F. Chaves, M. Wilhelm, K. Rezwan, Polysiloxane microspheres encapsulated in carbon allotropes: a promising material for supercapacitor and

carbon dioxide capture, J. Colloid Interface Sci. 542 (2019) 91–101, https://doi.org/10.1016/j.jcis.2019.01.087.

[229] M.S. Lal, R. Sundara, High entropy oxides—a cost-effective catalyst for the growth of high-yield carbon nanotubes and their energy applications, ACS Appl. Mater. Interfaces 11 (2019) 30846–30857, https://doi.org/10.1021/acsami.9b08794.

[230] R. Singh, A. Chakravarty, S. Mishra, R.C. Prajapati, J. Dutta, I.K. Bhat, U. Pandel, S.K. Biswas, K. Muraleedharan, AlN–SWCNT metacomposites having tunable negative permittivity in radio and microwave frequencies, ACS Appl. Mater. Interfaces 11 (2019) 48212–48220, https://doi.org/10.1021/acsami.9b15909.

[231] L. David, K.M. Shareef, M.A. Abass, G. Singh, Three-dimensional polymer-derived ceramic/graphene paper as a Li-ion battery and supercapacitor electrode, RSC Adv. 6 (2016) 53894–53902, https://doi.org/10.1016/j.electacta.2011.06.113.

[232] H. Lee, H. Kim, M.S. Cho, J. Choi, Y. Lee, Fabrication of polypyrrole (PPy)/carbon nanotube (CNT) composite electrode on ceramic fabric for supercapacitor applications, Electrochim. Acta 56 (2011) 7460–7466, https://doi.org/10.1016/j.electacta.2011.06.113.

[233] M. Oschatz, E. Kockrick, M. Rose, L. Borchardt, N. Klein, I. Senkovska, T. Freudenberg, Y. Korenblit, G. Yushin, S. Kaskel, A cubic ordered, mesoporous carbide-derived carbon for gas and energy storage applications, Carbon 48 (2010) 3987–3992, https://doi.org/10.1016/j.carbon.2010.06.058.

[234] C.Y. Bon, L. Mohammed, S. Kim, M. Manasi, P. Isheunesu, K.S. Lee, J.M. Ko, Flexible poly (vinyl alcohol)-ceramic composite separators for supercapacitor applications, J. Ind. Eng. Chem. 68 (2018) 173–179, https://doi.org/10.1016/j.jiec.2018.07.043.

[235] S. Chabi, V.G. Rocha, E. García-Tuñón, C. Ferraro, E. Saiz, Y. Xia, Y. Zhu, Ultralight, strong, three-dimensional SiC structures, ACS Nano 10 (2016) 1871–1876, https://doi.org/10.1021/acsnano.5b05533.

[236] S.B. Mujib, R. Cuccato, S. Mukherjee, G. Franchin, P. Colombo, G. Singh, Electrospun SiOC ceramic fiber mats as freestanding electrodes for electrochemical energy storage applications, Ceram. Int. 46 (2020) 3565–3573, https://doi.org/10.1016/j.ceramint.2019.10.074.

[237] A. Meier, M. Weinberger, K. Pinkert, M. Oschatz, S. Paasch, L. Giebeler, H. Althues, E. Brunner, J. Eckert, S. Kaskel, Silicon oxycarbide-derived carbons from a polyphenyl silsesquioxane precursor for supercapacitor applications, Microporous Mesoporous Mater. 188 (2014) 140–148, https://doi.org/10.1016/j.micromeso.2013.12.022.

[238] P. Pazhamalai, K. Krishnamoorthy, S. Sahoo, V.K. Mariappan, S.J. Kim, J. Chem. Eng. 387 (2020) 123886, https://doi.org/10.1016/j.micromeso.2013.12.022.

[239] H. Wang, X. Zhang, N. Wang, Y. Li, X. Feng, Y. Huang, C. Zhao, Z. Liu, M. Fang, G. Ou, H. Gao, Ultralight, scalable, and high-temperature–resilient ceramic nanofiber sponges, Sci. Adv. 3 (2017) e1603170, https://doi.org/10.1126/sciadv.1603170.

[240] L. Gu, Y. Wang, R. Lu, W. Wang, X. Peng, J. Sha, Silicon carbide nanowires@ ni (OH) 2 core-shell structures on carbon fabric for supercapacitor electrodes with excellent rate capability, J. Power Sources 273 (2015) 479–485, https://doi.org/10.1016/j.jpowsour.2014.09.113.

[241] M. Kim, J. Kim, Development of high power and energy density microsphere silicon carbide–MnO_2 nanoneedles and thermally oxidized activated carbon asymmetric electrochemical supercapacitors, Phys. Chem. Chem. Phys. 16 (2014) 11323–11336, https://doi.org/10.1039/C4CP01141D.

[242] L. Gu, Y. Wang, Y. Fang, R. Lu, J. Sha, Performance characteristics of supercapacitor electrodes made of silicon carbide nanowires grown on carbon fabric, J. Power Sources 243 (2013) 648–653, https://doi.org/10.1016/j.jpowsour.2013.06.050.

[243] Y. Zhao, W. Kang, L. Li, G. Yan, X. Wang, X. Zhuang, B. Cheng, Solution-blown silicon carbide porous nanofiber membrane as electrode materials for supercapacitors, Electrochim. Acta 207 (2016) 257–265, https://doi.org/10.1016/j.electacta.2016.05.003.

[244] Y. Wang, Z.W. Yang, L.X. Zhang, D.P. Wang, J.C. Feng, Carbon-based nanomaterials in sensors for food safety, J. Mater. 2 (2016) 66–74, https://doi.org/10.3390/nano9091330.

[245] S.M. Yao, K. Xi, G.R. Li, X.P. Gao, Preparation and electrochemical properties of Co–Si3N4 nanocomposites, J. Power Sources 184 (2008) 657–662, https://doi.org/10.1016/j.jpowsour.2008.01.077.

[246] Z. Xiao, C. Lei, C. Yu, X. Chen, Z. Zhu, H. Jiang, F. Wei, Si@ Si_3N_4@ c composite with egg-like structure as high-performance anode material for lithium-ion batteries, Energy Storage Mater. 24 (2020) 565–573, https://doi.org/10.1016/j.ensm.2019.06.031.

[247] S.J. Kim, M.C. Kim, S.B. Han, G.H. Lee, H.S. Choe, D.H. Kwak, S.Y. Choi, B.G. Son, M.S. Shin, K.W. Park, 3D flexible Si-based-composite (Si@ Si_3N_4)/CNF electrode with enhanced cyclability and high-rate capability for lithium-ion batteries, Nano Energy 17 (2016) 545–553, https://doi.org/10.1016/j.nanoen.2016.08.012.

[248] K. Han, N. Luo, S. Mao, F. Zhuo, L. Liu, B. Peng, X. Chen, C. Hu, H. Zhou, Y. Wei, Ultrahigh energy-storage density in A-/B-site co-doped $AgNbO_3$ lead-free antiferroelectric ceramics: insight into the origin of antiferroelectricity, J. Mater. Chem. A. 7 (2019) 26293–26301, https://doi.org/10.1039/C9TA06457E.

[249] B.E. Francisco, C.M. Jones, S.H. Lee, C.R. Stoldt, Nanostructured all-solid-state supercapacitor based on Li2S-P2S5 glass-ceramic electrolyte, Appl. Phys. Lett. 100 (2012) 103902, https://doi.org/10.1063/1.3693521.

[250] M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi, M.W. Barsoum, Two-dimensional nanocrystals produced by exfoliation of Ti_3AlC_2. In MXenes, Jenny Stanford Publishing, 2011, pp. 15–29.

[251] P. He, X.X. Wang, Y.Z. Cai, J.C. Shu, Q.L. Zhao, J. Yuan, M.S. Cao, Tailoring Ti_3C_2Tx nanosheets to tune local conductive network as an environmentally friendly material for highly efficient electromagnetic interference shielding, Nanoscale 11 (2019) 6080–6088, https://doi.org/10.1039/C8NR10489A.

[252] M.R. Lukatskaya, S. Kota, Z. Lin, M.Q. Zhao, N. Shpigel, M.D. Levi, J. Halim, P. L. Taberna, M.W. Barsoum, P. Simon, Y. Gogotsi, Ultra-high rate pseudocapacitive energy storage in two-dimensional transition metal carbides, Nat. Energy 2 (2017) 1–6, https://doi.org/10.1038/nenergy.2017.105.

[253] Q. Jiang, N. Kurra, M. Alhabeb, Y. Gogotsi, H.N. Alshareef, All pseudocapacitive MXene-RuO_2 asymmetric supercapacitors, Adv. Energy Mater. 8 (2018) 703043, https://doi.org/10.1002/aenm.201703043.

[254] J.H. Lee, G. Yang, C.-H. Kim, R.L. Mahajan, S.-Y. Lee, S.-J. Park, Flexible solid-state hybrid supercapacitors for the Internet of everything (IoE), Energy Environ. Sci. 15 (2022) 2233–2258, https://doi.org/10.1039/D1EE03567C.

[255] Q. Ma, M. Liu, F. Cui, J. Zhang, T. Cui, Fabrication of 3D graphene microstructures with uniform metal oxide nanoparticles via molecular self-assembly strategy and their supercapacitor performance, Carbon 204 (2023) 336–345, https://doi.org/10.1016/j.carbon.2022.12.066.

[256] T. Doi, Y. Shimizu, M. Hashinokuchi, M. Inaba, LiBF4-Based concentrated electrolyte solutions for suppression of electrolyte decomposition and rapid lithium-ion transfer at $LiNi_{0.5}Mn_{1.5}O_4$/electrolyte interface, J. Electrochem. Soc. 163 (2016) A2211, https://doi.org/10.1149/2.0331610jes.

[257] Y. Chen, C. Kang, L. Ma, L. Fu, G. Li, Q. Hu, Q. Liu, MOF-derived Fe2O3 decorated with MnO_2 nanosheet arrays as anode for high energy density hybrid supercapacitor, Chem. Eng. J. 417 (2021) 129243, https://doi.org/10.1016/j.cej.2021.129243.

[258] C. Guan, A. Sumboja, H. Wu, W. Ren, X. Liu, H. Zhang, Z. Liu, C. Cheng, S. J. Pennycook, J. Wang, Hollow Co_3O_4 nanosphere embedded in carbon arrays for stable and flexible solid-state zinc-air batteries, Adv. Mater. 29 (2017) 1704117, https://doi.org/10.1002/adma.201704117.

[259] Y. Lu, L. Li, D. Chen, G. Shen, Nanowire-assembled Co_3O_4@$NiCo_2O_4$ architectures for high-performance all-solid-state asymmetric supercapacitors, J. Mater. Chem. A 5 (2017) 24981–24988, https://doi.org/10.1039/C7TA06437C.

[260] Y. Liu, C. Xueying, J. Degang, J. Dedong, J. Jingquan, Hierarchical CuO nanorod arrays in situ generated on three-dimensional copper foam via cyclic voltammetry oxidation for high-performance supercapacitors, J. Mater. Chem. A 6 (2018) 10474–10483, https://doi.org/10.1039/C8TA00945G.

[261] M. Chaudhary, M. Singh, A. Kumar, Y.K. Gautam, A.K. Malik, Y. Kumar, B. P. Singh, Experimental investigation of co and Fe-doped CuO nanostructured electrode material for remarkable electrochemical performance, Ceram. Int. 47 (2021) 2094–2106, https://doi.org/10.1016/j.ceramint.2020.09.042.

[262] D.P. Dubal, G.S. Gund, C.D. Lokhande, R. Holze, CuO cauliflowers for supercapacitor application: novel potentiodynamic deposition, Mater. Res. Bull. 48 (2013) 923–928, https://doi.org/10.1016/j.materresbull.2012.11.081.

[263] Z. Song, W. Liu, N. Sun, W. Wei, Z. Zhang, H. Liu, Z. Zhao, One-step self-assembly fabrication of three-dimensional copper oxide/graphene oxide aerogel composite material for supercapacitors, Solid State Commun. 287 (2019) 27–30, https://doi.org/10.1016/j.ssc.2018.10.007.

[264] Q. Wang, Y. Zhang, J. Xiao, H. Jiang, T. Hu, C. Meng, Copper oxide/cuprous oxide/hierarchical porous biomass-derived carbon hybrid composites for high-performance supercapacitor electrode, J. Alloy. Compd. 782 (2019) 1103–1113, https://doi.org/10.1016/j.jallcom.2018.12.235.

[265] P.S. Kumar, H.H. Kyaw, M.T.Z. Myint, L. Al-Haj, A.A.H. Al-Muhtaseb, M. Al-Abri, V.K. Ponnusamy, Green route synthesis of nanoporous copper oxide for efficient supercapacitor and capacitive deionization performances, Int. J. Energy Res. 44 (2020) 10682–10694, https://doi.org/10.1002/er.5712.

[266] A. Qayyum, M. Okash, F. Ahmad, M. Ahmed, S.M. Ramay, S. Atiq, Performance optimization of Nd-doped $LaNiO_3$ as an electrode material in supercapacitors, Solid State Ion. 395 (2023) 116227, https://doi.org/10.1016/j.ssi.2023.116227.

[267] S.G. Sayyed, M.A. Mahadik, A.V. Shaikh, J.S. Jang, H.M. Pathan, Nano-metal oxide-based supercapacitor via electrochemical deposition, ES Energy Environ. 7 (2019) 25–44, https://doi.org/10.30919/esee8c211.

[268] M. Vangari, T. Pryor, L. Jiang, Supercapacitors: review of materials and fabrication methods, J. Energy Eng. 139 (2013) 72–79, https://doi.org/10.1061/(asce)ey.1943-7897.0000102.

[269] J.T. Mefford, W.G. Hardin, S. Dai, K.P. Johnston, K.J. Stevenson, Anion charge storage through oxygen intercalation in $LaMnO_3$ perovskite pseudocapacitor electrodes, Nat. Mater. 13 (2014) 726–732, https://doi.org/10.1038/nmat4000.

[270] M. Wei, W. Che, H. Li, Z. Wang, F. Yan, Y. Liu, J. Liu, Ruddlesden-Popper type $La_2NiO_{4+\delta}$ oxide coated by ag nanoparticles as an outstanding anion intercalation cathode for hybrid supercapacitors, Appl. Surf. Sci. 484 (2019) 551–559, https://doi.org/10.1016/j.apsusc.2019.04.015.

[271] S. Maity, M. Samanta, A. Sen, K.K. Chattopadhyay, Investigation of electrochemical performances of ceramic oxide $CaCu_3Ti_4O_{12}$ nanostructures, J. Solid State Chem. 269 (2019) 600–607, https://doi.org/10.1016/j.jssc.2018.10.016.

[272] R.P. Forslund, J. Pender, C.T. Alexander, K.P. Johnston, K.J. Stevenson, Comparison of perovskite and perovskite derivatives for use in anion-based pseudo-capacitor applications, J. Mater. Chem. A 7 (2019) 21222–21231, https://doi.org/10.1039/c9ta06094d.

[273] S.H. Ko, J. Chung, H. Pan, C.P. Grigoropoulos, D. Poulikakos, Fabrication of multilayer passive and active electric components on polymer using inkjet printing and low-temperature laser processing, Sens. Actuators A Phys. 134 (2007) 161–168, https://doi.org/10.1016/j.sna.2006.04.036.

[274] C.O. Alvarez-Sanchez, J.A. Lasalde-Ramírez, E.O. Ortiz-Quiles, R. Massó-Ferret, E. Nicolau, Polymer-$MTiO_3$ ($M = Ca$, Sr, Ba) composites as facile and scalable supercapacitor separators, Energy Sci. Eng. 7 (2019) 730–740, https://doi.org/10.1002/ese3.299.

[275] S. Ahankari, D. Lasrado, R. R. Subramaniam, Advances in materials and fabrication of separators in supercapacitors, Mater. Adv. 3 (2022) 1472–1496, https://doi.org/10.1039/D1MA00599E.

[276] G. Behzadi Pour, L. Fekri Aval, M. Mirzaee, Flexible graphene supercapacitor based on the PVA electrolyte and BaTiO3/PEDOT: PSS composite separator, J. Mater. Sci. Mater. Electron 29 (2018) 17432–17437, https://doi.org/10.1007/s10854-018-9842-1.

[277] J.Y. Shieh, S.Y. Tsai, B.Y. Li, H.H. Yu, High-performance flexible supercapacitor based on porous array electrodes, Mater. Chem. Phys. 195 (2017) 114–122, https://doi.org/10.1016/j.matchemphys.2017.04.034.

[278] M. Liu, K. Turcheniuk, W. Fu, Y. Yang, M. Liu, G. Yushin, Scalable, safe, high-rate supercapacitor separators based on the Al_2O_3 nanowire polyvinyl butyral nonwoven membranes, Nano Energy 71 (2020) 104627, https://doi.org/10.1016/j.nanoen.2020.104627.

[279] P. Sivaraman, S.P. Mishra, D.D. Potphode, A.P. Thakur, K. Shashidhara, A. B. Samui, A.R. Bhattacharyya, A supercapacitor based on longitudinal unzipping of multi-walled carbon nanotubes for high-temperature application, RSC Adv. 5 (2015) 83546–83557, https://doi.org/10.1039/C5RA13136G.

[280] R. Na, P. Huo, X. Zhang, S. Zhang, Y. Du, K. Zhu, Y. Lu,M. Zhang, J. Luan, G. Wang, A flexible solid-state supercapacitor based on a poly (aryl ether ketone)–poly (ethylene glycol) copolymer solid polymer electrolyte for high-temperature applications, RSC Adv. 6 (2016) 65186–65195, https://doi.org/10.1039/C6RA11202A.

[281] Z. Pang, J. Duan, Y. Zhao, Q. Tang, B. He, L. Yu, A ceramic NiO/ZrO_2 separator for high-temperature supercapacitor up to 140°C, J. Power Sources 400 (2018) 126–134, https://doi.org/10.1016/j.jpowsour.2018.08.008.

[282] S. Zheng, W. Lei, J. Qin, Z.S. Wu, F. Zhou, S. Wang, X. Shi, C. Sun, Y. Chen, X. Bao, All-solid-state high-energy planar asymmetric supercapacitors based on all-in-one monolithic film using boron nitride nanosheets as separator, Energy Storage Mater. 10 (2018) 24–31, https://doi.org/10.1016/j.ensm.2017.08.002.

[283] L. Lee, M. Yanilmaz, O. Toprakci, K. Fu, X. Zhang, A review of recent developments in membrane separators for rechargeable lithium-ion batteries, Energy Environ. Sci. 7 (2014) 3857–3886, https://doi.org/10.1039/C4EE01432D.

[284] L.H. Acauan, Y. Zhou, E. Kalfon-Cohen, N.K. Fritz, B.L. Wardle, Multifunctional nanocomposite structural separators for energy storage, Nanoscale 11 (2019) 21964–21973, https://doi.org/10.1039/C9NR06954B.

[285] M. Yusuf, M. Kumar, M.A. Khan, M. Sillanpääillanpa, H. Arafat, A review on exfoliation, characterization, environmental and energy applications of graphene and graphene-based composites, Adv. Colloid Interface Sci. 273 (2019) 102036, https://doi.org/10.1016/j.cis.2019.102036.

[286] S.Z. Hussain, M. Ihrar, S.B. Hussain, W.C. Oh, K. Ullah, A review on graphene-based transition metal oxide composites and its application towards supercapacitor electrodes, SN Appl. Sci. 2 (2020) 1–23, https://doi.org/10.1007/s42452-020-2515-8.

[287] S. Yadav, A. Devi, Recent advancements of metal oxides/Nitrogen-doped graphene nanocomposites for supercapacitor electrode materials, J. Energy Storage 30 (2020) 101486, https://doi.org/10.1016/j.est.2020.101486.

[288] A.V. Fulari, M.V.R. Reddy, S.T. Jadhav, G.S. Ghodake, D.Y. Kim, G.M. Lohar, TiO_2/reduced graphene oxide composite-based nano-petals for supercapacitor application: effect of substrate, J. Mater. Sci. Mater. Electron 29 (2018) 10814–10824, https://doi.org/10.1007/s10854-018-9146-5.

[289] H.Y. Yue, E.H. Guan, X. Gao, F. Yao, W.Q. Wang, T. Zhang, Z. Wang, S.S. Song, H. J. Zhang, One-step hydrothermal synthesis of TiO_2 nanowires-reduced graphene oxide nanocomposite for supercapacitor, Ionics 25 (2019) 2411–2418, https://doi.org/10.1007/s11581-018-2678-0.

[290] B. Ding, X. Wu, Transition metal oxides anchored on graphene/carbon nanotubes conductive network as both the negative and positive electrodes for asymmetric supercapacitor, J. Alloy. Compd. 842 (2020) 155838, https://doi.org/10.1016/j.jallcom.2020.155838.

[291] H. Qi, Z. Bo, S. Yang, L. Duan, H. Yang, J. Yan, K. Cen, K.K. Ostrikov, Hierarchical nanocarbon-MnO2 electrodes for enhanced electrochemical capacitor performance, Energy Storage Mater. 16 (2019) 607–618, https://doi.org/10.1016/j.ensm.2018.07.019.

[292] C. Ramírez, M. Belmonte, P. Miranzo, M.I. Osendi, Applications of Ceramic/Graphene composites and hybrids, Materials 14 (2021) 2071, https://doi.org/10.3390/ma14082071.

[293] Y. Wang, W. Zhou, K. Cao, X. Hu, L. Gao, Y. Lu, Architectured graphene and its composites: manufacturing and structural applications, Compos. Part A Appl. Sci. Manuf. 140 (2021) 106177, https://doi.org/10.1016/j.compositesa.2020.106177.

[294] P. Miranzo, M. Belmonte, M.I. Osendi, From bulk to cellular structures: a review on ceramic/graphene filler composites, J. Eur. Ceram. Soc. 37 (2017) 3649–3672, https://doi.org/10.1016/j.jeurceramsoc.2017.03.016.

[295] O. Guillon, Ceramic materials for energy conversion and storage: a perspective, Int J. Ceram. Eng. Sci. 3 (2021) 100–104, https://doi.org/10.1002/ces2.10086.

[296] C. Oses, C. Toher, S. Curtarolo, High-entropy ceramics, Nat. Rev. Mater. 5 (2020) 295–309, https://doi.org/10.1038/s41578-019-0170-8.

[297] A.E. Danks, S.R. Hall, Z.J.M.H. Schnepp, The evolution of 'sol–gel' chemistry as a technique for materials synthesis, Mater. Horiz. 3 (2016) 91–112, https://doi.org/10.1039/C5MH00260E.

[298] K.S. Randhawa, Advanced ceramics in energy storage applications: batteries to hydrogen energy, J. Energy Storage 98 (2024) 113122, https://doi.org/10.1016/j.est.2024.113122.

[299] S.K. Roy, K. Prasad, Hydrothermal nanotechnology: putting the last first. in: Exploring the realms of nature for nanosynthesis, Springer, Cham, 2018, pp. 291–317, https://doi.org/10.1007/978-3-319-99570-0_13.

[300] S.B. Weber, H.L. Lein, T. Grande, M.A. Einarsrud, Deposition mechanisms of thick lanthanum zirconate coatings by spray pyrolysis, J. Am. Ceram. Soc. 94 (2011) 4256–4262, https://doi.org/10.1111/j.1551-2916.2011.04807.x.

[301] M. Sabzi, S.H. Mousavi Anijdan, M. Shamsodin, M. Farzam, A. Hojjati-Najafabadi, P. Feng, U. Lee, A review on sustainable manufacturing of ceramic-based thin films by chemical vapor deposition (CVD): reaction kinetics and the deposition mechanisms, Coatings 13 (2023) 188, https://doi.org/10.3390/coatings13010188.

[302] Olivares, J. Antonio, D. Puyol, J.A. Melero, J. Dufour, Wastewater treatment residues as resources for biorefinery products and biofuels, Elsevier, 2019.

[303] N. Xin, D. Wei, Y. Zhu, M. Yang, S. Ramakrishna, O. Lee, H. Luo, H. Fan, Upconversion nanomaterials: a platform for biosensing, theranostic and photoregulation, Mater. Today Chem. 17 (2020) 100329, https://doi.org/10.1016/j.mtchem.2020.100329.

[304] J. Wang, S. Wu, X.-K. Suo, H. Liao, The processes for fabricating nanopowders, in: B.S. Guan-Jun Yang, Xinkun Suo (Eds.), Micro and Nano Technologies, Advanced Nanomaterials and Coatings by Thermal Spray, Elsevier Amsterdam, 2019, pp. 13–25, https://doi.org/10.1016/B978-0-12-813870-0.00002-4.

[305] P.G. Pawar, A.V. Ghorpade, S.M. Nikam, S.H. Mujawar, S.J. Pawar, Supercapacitor performance of vanadium oxide nanostructures synthesized by spray pyrolysis technique, ES Energy Environ. 28 (2024) (2024) 1343, https://doi.org/10.30919/esee1343.

[306] B. Jos, C.R. Babu, J. Naduvath, A.S. Shanu, S. Shaji, A. Hossain, E.I. Anila, Na+ doped CuO: a new paradigm electrode material for high-performance supercapacitors, Ceram. Int. 50 (2024) 43627–43634, https://doi.org/10.1016/j.ceramint.2024.08.213.

[307] M. Mousavi, A. Kompany, N. Shahtahmasebi, M.M. Bagheri-Mohagheghi, The effect of solution concentration on the physical and electrochemical properties of vanadium oxide films deposited by spray pyrolysis, J. Semicond. 34 (2013) 103001, https://doi.org/10.1088/1674-4926/34/10/103001.

[308] S. Jiang, T. Hu, J. Gild, N. Zhou, J. Nie, M. Qin, T. Harrington, K. Vecchio, J. Luo, A new class of high-entropy perovskite oxides, Scr. Mater. 142 (2018) 116–120, https://doi.org/10.1016/j.scriptamat.2017.08.040.

[309] P.C. Verma, S.K. Tiwari, A. Saurabh, A. Manoj, Recent advances in High-Entropy ceramics: synthesis methods, properties, and emerging applications, Ceramics 7 (2024) 1365–1389, https://doi.org/10.3390/ceramics7040089.

[310] C.M. Rost, E. Sachet, T. Borman, A. Moballegh, E.C. Dickey, D. Hou, J.L. Jones, S. Curtarolo, J.P. Maria, Entropy-stabilized oxides, Nat. Commun. 6 (2015) 8485, https://doi.org/10.1038/ncomms9485.

[311] X. Zeng, H. Song, Z.Y. Shen, M. Moskovits, Progress and challenges of ceramics for supercapacitors, J. Mater. 7 (2021) 1198–1224, https://doi.org/10.1016/j.jmat.2021.03.00.

[312] B. Liang, Y. Ai, Y. Wang, C. Liu, S. Ouyang, M. Liu, Spinel-type $(FeCoCrMnZn)_3O_4$ high-entropy oxide: facile preparation and supercapacitor performance, Materials 13 (2020) 5798, https://doi.org/10.3390/ma13245798.

[313] S. Chen, Z. Li, K. Gola, G. Li, R. Chen, J. Sun, A. Talyzin, J. Li, Liquid-Locked bassanites for scalable fabrication of High-Temperature Micro-Supercapacitors working at 300° c, Adv. Funct. Mater. (2025) e10592, https://doi.org/10.1002/adfm.202510592.

[314] T. Punkari, A. Kattainen, A. Fonseca, J. Pronto, J. Keskinen, M. Mäntysalo, "Monolithic supercapacitors prepared by roll-to-roll screen printing,", 2024 IEEE Int. Conf. Flex. Printable Sens. Syst. (FLEPS) Tamp. Finl. (2024) 1–4, https://doi.org/10.1109/FLEPS61194.2024.10603726.

[315] H. Belay, Y. Guo, M. Liu, Large-scale roll-to-roll manufacturing of flexible, hydrophobic, and fire-resistant mica/SiO_2 nanofiber aerogel paper, Nano Lett. 25 (2025) 1345–1352, https://doi.org/10.1021/acs.nanolett.5c02732.

[316] C. Zhang, J. He, G. Wang, X. Hong, C. Zhao, Recent advances in heteroatom doped transition metal sulfides for high-performance supercapacitors, J. Energy Storage 104 (2024) 114562, https://doi.org/10.1016/j.est.2024.114562.

[317] M. Diantoro, I. Istiqomah, I. Istiqomah, Y.A. Fath, N. Nasikhudin, Y. Alias, W. Meevasana, Potential of MnO_2-based composite and numerous morphological for enhancing supercapacitors performance, Int. J. Appl. Ceram. Technol. 20 (2023) 2077–2098, https://doi.org/10.1111/ijac.14377.

[318] P.H.C. Camargo, K.G. Satyanarayana, F. Wypuch, Nanocomposites: synthesis, structure, properties and new application opportunities, Mater. Res. 12 (2009) 1–39, https://doi.org/10.1590/S1516-14392009000100002.

[319] A. Okada, Physical limitations of the inherent toughness and strength in ceramic-ceramic and ceramic-metal nanocomposite, J. Eur. Ceram. 28 (2008) 1097–1104, https://doi.org/10.1016/j.jeurceramsoc.2007.09.016.

[320] P. Palmero, Structural ceramic nanocomposites: a review of properties and powders' synthesis methods, Nanomaterials 5 (2015) 656–696, https://doi.org/10.3390/nano5020656.

[321] Z. Shen, G. Liu, L. He, R. Mu, L. Wang, Dy-doped $Gd_2Zr_2O_7$ thermal barrier coatings: thermal expansion coefficient, microstructure, and failure mechanism, Appl. Surf. Sci. Adv. 6 (2021) 100174, https://doi.org/10.1016/j.apsadv.2021.100174.

[322] M. Steen, Fractography and fracture mechanics property assessment of advanced structural ceramics, Int. Mater. Rev. 44 (1999) 165–216, https://doi.org/10.1179/095066099101528270.

[323] S. Gandi, V.S.C.S. Vaddadi, S.S.S. Panda, N.K. Goona, S.R. Parne, M. Lakavat, A. Bhaumi, Recent progress in the development of glass and glass-ceramic cathode/solid electrolyte materials for next-generation high capacity all-solid-

state sodium-ion batteries: a review, J. Power Sources 521 (2022) (2022) 230930, https://doi.org/10.1016/j.jpowsour.2021.

[324] S. Xin, Y. You, S. Wang, H.-C. Gao, Y.-X. Xin, Y.-G. Guo, Solid-state lithium metal batteries promoted by nanotechnology: progress and prospects, ACS Energy Lett. 2 (2017) 1385–1394, https://doi.org/10.1021/acsenergylett.7b00175.

[325] L.P. Ferroni, G. Pezzotti, T. Isshiki, H.-J. Kleebe, Determination of amorphous interfacial phases in Al2O3/sic nanocomposites by computer-aided high-resolution electron microscopy, Acta Mater. 49 (2001) 2109–2113, https://doi.org/10.1016/S1359-6454(01)00117-3.

[326] K. Shimamura, F. Shimojo, R.K. Kalia, A. Nakano, P. Vashista, Bonding and structure of ceramic-ceramic interfaces, Phys. Rev. Lett. 111 (2013) 066103, https://doi.org/10.1103/PhysRevLett.111.066103.

[327] a) Q.Wen, F. Qu, Z. Yu, M. Graczyk-Zajac, X. Xiong, R. Riedel, Si-based polymer-derived ceramics for energy conversion and storage, J. Adv. Ceram. 11 (2022) 197–246, https://doi.org/10.1007/s40145-021-0562-2;
b) P. Molaiyan, S. Bhattacharyya, G.S. dos Reis, R. Sliz, A. Paolella, U. Lassi, Towards greener batteries: sustainable components and materials for next-generation batteries, Green. Chem. 26 (2024) 7508–7531, https://doi.org/10.1039/D3GC05027K.

[328] a) S. Liu, Y. Zhao, X. Li, J. Yu, J. Yan, B. Ding, Solid-state lithium metal batteries with extended cycling enabled by dynamic adaptive solid-state interfaces, Adv. Mater. 33 (2021) 2008084, https://doi.org/10.1002/adma.202008084;
b) J.-G. Wang, Y. Yang, Z.-H. Huang, F. Kang, Coaxial carbon nanofibers/MnO2 nanocomposites as freestanding electrodes for high-performance electrochemical capacitors, Electrochim. Acta 56 (2011) 9240–9247, https://doi.org/10.1016/j.electacta.2011.07.140.

[329] P. Schütz, A.K. Alves, C.P. Bergmann, Effect of the in-air heat treatment in the phase formation and morphology of electrospun Cu_2ZnSnS_4 fibers, Ceram. Int. 40 (2014) 11551–11557, https://doi.org/10.1016/j.ceramint.2014.03.103.

[330] M.M.E. Jacob, E. Hackett, E.P. Giannelis, From nanocomposite to nanogel polymer electrolytes, J. Mater. Chem. 13 (2003) 1–5, https://doi.org/10.1039/B204458G.

[331] Q. Zhang, X.W. Gao, X. Liu, J.J. Mu, Q. Gu, Z. Liu, W.B. Luo, Flexible wearable energy storage devices: materials, structures, and applications, Battery Energy 3 (2024) 20230061, https://doi.org/10.1002/bte2.20230061.

[332] J. Kim, R. Kumar, A.J. Bandodkar, J. Wang, Advanced materials for printed wearable electrochemical devices: a review, Adv. Electron. Mater. 3 (2017) 1600260, https://doi.org/10.1002/aelm.201600260.

[333] Y. Yang, A mini-review: emerging all-solid-state energy storage electrode materials for flexible devices, Nanoscale 12 (2020) 3560–3573, https://doi.org/10.1039/C9NR08722B.

[334] Y. Huang, M. Zhu, Y. Huang, Z. Pei, H. Li, Z. Wang, C. Zhi, Multifunctional energy storage and conversion devices, Adv. Mater. 28 (2016) 8344–8364, https://doi.org/10.1002/adma.201601928.

[335] X. Yu, A. Manthiram, Sustainable battery materials for next-generation electrical energy storage, Adv. Energ. Sust. Res 2 (2021) 2000102, https://doi.org/10.1002/aesr.202000102.

[336] R. Narayan, C. Laberty-Robert, J. Pelta, J.M. Tarascon, R. Dominko, Self-healing: an emerging technology for next-generation smart batteries, Adv. Energy Mater. 12 (2022) 2102652, https://doi.org/10.1002/aenm.202102652.

[337] J.C. Ince, M. Peerzada, L.D. Mathews, A.R. Pai, A. Al-Qatatsheh, S. Abbasi, N. V. Salim, Overview of emerging hybrid and composite materials for space applications, Adv. Compos. Hybrid. Mater. 6 (2023) 130, https://doi.org/10.1007/s42114-023-00678-5.

[338] K. Chu, Y. Shi, B. Fang, J. Ding, Ferroelectric phase transition and optical performance of PLZnNZT transparent ceramics, J. Phys. Chem. Sol. 81 (2015) 10–14, https://doi.org/10.1016/j.jpcs.2015.01.011.

[339] L. Koroglu, E. Ayas, A systematic study on solid-state synthesis of monticellite (CaMgSiO4) based ceramic powders obtained from boron derivative waste, Adv. Powder Technol. 29 (2018) 2835–2844, https://doi.org/10.1016/j.apt.2018.08.003.

[340] R. Chihi, I. Blidi, M. Trabelsi-Ayadi, F. Ayari, Elaboration and characterization of a low-cost porous ceramic support from natural Tunisian bentonite clay, C. R. Chim. 22 (2019) 188–197, https://doi.org/10.1016/j.crci.2018.12.002.

[341] L.K.G. Bhatta, S. Subramanyam, M.D. Chengala, S. Olivera, K. Venkatesh, Progress in hydrotalcite-like compounds and metal-based oxides for CO2 capture: a review, J. Clean. Prod. 103 (2015) 171–196, https://doi.org/10.1016/j.jclepro.2014.12.059.

[342] D.C. Stack, D. Curtis, C. Forsberg, Performance of firebrick resistance-heated energy storage for industrial heat applications and round-trip electricity storage, Appl. Energy 242 (2019) 782–796, https://doi.org/10.1016/j.apenergy.2019.03.

[343] B. Stutz, N. Le Pierres, F. Kuznik, K. Johannes, E.P. Del Barrio, J.-P. Bédécarrats, et al., Storage of thermal solar energy stockage thermique de l'énergie solaire, C. R. Phys. 18 (2017) 401–414, https://doi.org/10.1016/j.crhy.2017.09.008.

[344] M. Singh, R. Asthana, K.L. Lin, Integration challenges in alternative and renewable energy systems, Eng. Ceram. Curr. Status Future Prospects (2016) 291–329, https://doi.org/10.1002/9781119100430.ch16.

[345] D.D.F. Del Rio, B.K. Sovacool, A.M. Foley, S. Griffiths, M. Bazilian, J. Kim, D. Rooney, Decarbonizing the ceramics industry: a systematic and critical review of policy options, developments and sociotechnical systems, Renew. Sustain. Energy Rev. 157 (2022) 112081, https://doi.org/10.1016/j.rser.2022.112081.

[346] I. Sadiq, S. Asim, T. Ahmad, Advanced hybrid ceramics for nuclear and hydrogen energy applications, ChemistrySelect 8 (2023) e202300837, https://doi.org/10.1002/slct.202300837.

[347] R.J. Galán-Arboledas, M.T. Cotes-Palomino, C. Martínez-García, J.M. Moreno-Maroto, M. Uceda-Rodríguez, S. Bueno, Ternary diagrams as a tool for developing ceramic materials from waste: relationship between technological properties and microstructure, ESPR 26 (2019) 35574–35587, https://doi.org/10.1007/s11356-019-05343-3.

[348] T. Zanatta, R.A.A.B. Santa, N. Padoin, C. Soares, H.G. Riella, Eco-friendly ceramic tiles: development based on technical and market demands, JMRT 11 (2021) 121–134, https://doi.org/10.1016/j.jmrt.2020.12.081.

[349] U. Parmar, S. Ahmed, R. Vayas, C. Lavanya, M. Manjunatha, N. Singh, H. Kumar, Towards sustainable ceramic forming: techniques, materials, and applications in evolving paradigms. In E3S Web of Conferences 552, EDP Sciences, 2024, p. 01099, https://doi.org/10.1051/e3sconf/202455201099.

[350] L. Yue, M. Jayapal, X. Cheng, T. Zhang, J. Chen, X. Ma, X. Dai, H. Lu, R. Guan, W. Zhang, Highly dispersed ultra-small nano Sn-SnS_b nanoparticles anchored on N-doped graphene sheets as high-performance anode for sodium-ion batteries, Appl. Surf. Sci. 512 (2020) 145686, https://doi.org/10.1016/j.apsusc.2020.145686.

[351] X. Wang, S. Ni, Z. Shi, Uranium distribution in the sediment of the mianyuan river near a phosphate mining region in China and the related uranium speciation in water, Geochemistry 74 (2014) 661–669, https://doi.org/10.1016/j.chemer.2014.03.001.

[352] S.S. Lee, T.W. Hong, Life cycle assessment for proton conducting ceramics synthesized by the Sol-Gel process, Materials 7 (2014) 6677–6685, https://doi.org/10.3390/ma7096677.

[353] J. Janek, W.G. Zeier, A solid future for battery development, Nat. Energy 1 (2016) 1–4, https://doi.org/10.1038/nenergy.2016.141.

[354] L.P. Teo, M.H. Buraidah, A.K. Arof, Development on solid polymer electrolytes for electrochemical devices, Molecules 26 (2021) 6499, https://doi.org/10.3390/molecules26216499.

[355] A. Du, H. Zhang, Z. Zhang, J. Zhao, Z. Cui, Y. Zhao, S. Dong, L. Wang, X. Zhou, G. Cui, A crosslinked polytetrahydrofuran-borate-based polymer electrolyte enabling wide-working-temperature-range rechargeable magnesium batteries, Adv. Mater. 31 (2019) 1805930, https://doi.org/10.1002/adma.201805930.

[356] J.Y. Liang, X.X. Zeng, X.D. Zhang, T.T. Zuo, M. Yan, Y.X. Yin, J.L. Shi, X.W. Wu, Y. G. Guo, L.J. Wan, Engineering janus interfaces of ceramic electrolyte via distinct functional polymers for stable high-voltage Li-metal batteries, J. Am. Chem. Soc. 141 (2019) 9165–9169, https://doi.org/10.1021/jacs.9b03517.

[357] H. Huo, Y. Chen, J. Luo, X. Yang, X. Guo, X. Sun, Rational design of hierarchical "ceramic-in-polymer" and "polymer-in-ceramic" electrolytes for dendrite-free solid-state batteries, Adv. Energy Mater. 9 (2019) 1804004, https://doi.org/10.1002/aenm.201804004.

[358] B. Zhang, R. Tan, L. Yang, J. Zheng, K. Zhang, S. Mo, Z. Lin, F. Pan, Mechanisms and properties of ion-transport in inorganic solid electrolytes, ESM 10 (2018) 139–159, https://doi.org/10.1016/j.ensm.2017.08.015.

[359] V. Kumaravel, J. Bartlett, S.C. Pillai, Solid electrolytes for high-temperature stable batteries and supercapacitors, Adv. Energy Mater. 11 (2021) 2002869, https://doi.org/10.1002/aenm.202002869.

[360] S. Chen, D. Xie, G. Liu, J.P. Mwizerwa, Q. Zhang, Y. Zhao, X. Xu, X. Yao, Sulfide solid electrolytes for all-solid-state lithium batteries: structure, conductivity, stability and application, ESM 14 (2018) 58–74, https://doi.org/10.1016/j.ensm.2018.02.020.

[361] A.M. Stephan, Review on gel polymer electrolytes for lithium batteries, Eur. Polym. J. 42 (2006) 21–42, https://doi.org/10.1016/j.eurpolymj.2005.09.017.

[362] J. Liang, J. Luo, Q. Sun, X. Yang, R. Li, X. Sun, Recent progress on solid-state hybrid electrolytes for solid-state lithium batteries, ESM 21 (2019) 308–334, https://doi.org/10.1016/j.ensm.2019.06.021.

[363] Qingpeng Guo, Yu Han, Hui Wang, Shizhao Xiong, Weiwei Sun, Chunman Zheng, Kai Xie, "Flame-retardant and stable $Li_{1.5}Al_{0.5}Ge_{1.5}$ $(PO_4)_3$-supported ionic liquid gel polymer electrolytes for high safety rechargeable solid-state lithium metal batteries, J. Phys. Chem. C. 122 (2018) 10334–10342, https://doi.org/10.1021/acs.jpcc.8b02693.

[364] S.A. Suthanthiraraj, M. Johnsi, Nanocomposite polymer electrolytes, Ionics 23 (2017) 2531–2542, https://doi.org/10.1007/s11581-016-1924-6.

[365] V. Pryamitsyn, V. Ganesan, Interplay between depletion and electrostatic interactions in polyelectrolyte–nanoparticle systems, Macromol 47 (2014) 6095–6112, https://doi.org/10.1021/ma501014u.

[366] Y. Lu, Q. Zhang, L. Li, Z. Niu, J. Chen, Design strategies toward enhancing the performance of organic electrode materials in metal-ion batteries, Chem 4 (2018) 2786–2813, https://doi.org/10.1016/j.chempr.2018.09.005.

[367] K. Liu, C. Yu, W. Guo, L. Ni, J. Yu, Y. Xie, Z. Wang, Y. Ren, J. Qiu, Recent research advances of self-discharge in supercapacitors: mechanisms and suppressing strategies, J. Energy Chem. 58 (2021) 94–109, https://doi.org/10.1016/j.jechem.2020.09.041.

[368] A. Bello, O.O. Fashedemi, J.N. Lekitima, M. Fabiane, D. Dodoo-Arhin, K. I. Ozoemena, Y. Gogotsi, A.T.C. Johnson, N. Manyala, High-performance symmetric electrochemical capacitor based on graphene foam and nanostructured manganese oxide, AIP Adv. 3 (2013) 082118, https://doi.org/10.1063/1.4819270.

[369] X. Yu, B. Lu, Z. Xu, Super long-life supercapacitors based on the construction of nanohoneycomb-like strongly coupled CoMoO(4)-3D graphene hybrid electrodes, Adv. Mater. 26 (2014) 1044–1051, https://doi.org/10.1002/adma.201304148.

[370] X. Cao, B. Zheng, W. Shi, J. Yang, Z. Fan, Z. Luo, X. Rui, B. Chen, Q. Yan, H. Zhang, Reduced graphene oxide-wrapped MoO3 composites prepared by using metal–organic frameworks as precursor for all-solid-state flexible supercapacitors, Adv. Mater. 27 (2015) 4695–4701, https://doi.org/10.1002/adma.201501310.

[371] L.J. Xie, J.F. Wu, C.M. Chen, C.M. Zhang, L. Wan L, J.-L. Wang, Q.-Q. Kong, C.-X. Lv, K.-X. Li, G.-H. Sun, A novel asymmetric supercapacitor with an activated carbon cathode and a reduced graphene oxide–cobalt oxide nanocomposite

anode, J. Power Sources 242 (2013) 148–156, https://doi.org/10.1016/j.jpowsour.2013.05.081.

[372] M. Li, K. Zhu, H. Zhao, Z. Meng, C. Wang, P.K. Chu, Construction of α-MnO2 on carbon fibers modified with carbon nanotubes for ultrafast flexible supercapacitors in ionic liquid electrolytes with wide voltage Windows, Nanomaterials 12 (2022) 2020, https://doi.org/10.3390/nano12122020.

[373] M. Cakici, R.R. Kakarla, F. Alonso-Marroquin, Advanced electrochemical energy storage supercapacitors based on the flexible carbon fiber fabric-coated with uniform coral-like MnO2 structured electrodes, Chem. Eng. J. 309 (2017) 151–158, https://doi.org/10.1016/j.cej.2016.10.012.

[374] J. Bill, F. Aldinger, Precursor-derived covalent ceramics, Adv. Mater. 7 (1995) 775–787, https://doi.org/10.1002/adma.19950070903.

[375] P. Colombo, C. Mera, R. Riedel, G.D. Sorarù, Polymer-derived ceramics: 40 years of research and innovation in advanced ceramics, J. Am. Ceram. Soc. 93 (2010) 1805–1837, https://doi.org/10.1111/j.1551-2916.2010.03876.x.

[376] W. Tu, Z. Bai, Z. Deng, H. Zhang, H. Tang, In-situ synthesized si@ c materials for the lithium-ion battery: a mini review, Nanomater 9 (2019) 432, https://doi.org/10.3390/nano9030432.

[377] G. Zhao, X. Wang, M. Negnevitsky, Connecting battery technologies for electric vehicles from battery materials to management, Science 25 (2022) 103744, https://doi.org/10.1016/j.isci.2022.103744.

[378] A. Kumar, Advanced Ceramics for Energy and Environmental Applications (ed.), CRC Press, Boca Raton, 2021, ⟨https://lccn.loc.gov/2021016128⟩.

[379] C.L. Cramer, E. Ionescu, M. Graczyk-Zajac, A.T. Nelson, Y. Katoh, J.J. Haslam, M. Minary-Jolandan, Additive manufacturing of ceramic materials for energy applications: road map and opportunities, J. Eur. Ceram. Soc. 42 (2022) 3049–3088, https://doi.org/10.1016/j.jeurceramsoc.2022.01.058.

[380] Q. Diao, Y. Zeng, J. Chen, The applications and latest progress of ceramic 3D printing, Addit. Manuf. Front. 3 (2024) 200113, https://doi.org/10.1016/j.amf.2024.200113.

[381] M.H. Bocanegra-Bernal, Hot isostatic pressing (HIP) technology and its applications to metals and ceramics, J. Mater. Sci. 39 (2004) 6399–6420, https://doi.org/10.1023/B:JMSC.0000044878.11441.90.

[382] O. Faye, J. Szpunar, U. Eduok, A critical review on the current technologies for the generation, storage, and transportation of hydrogen, Int. J. Hydrog. Energy 47 (2022) 13771–13802, https://doi.org/10.1016/j.ijhydene.2022.02.112.

[383] Z. Tao, L. Yan, J. Qiao, B. Wang, L. Zhang, J. Zhang, A review of advanced proton-conducting materials for hydrogen separation, Prog. Mater. Sci. 74 (2015) 1–50, https://doi.org/10.1016/j.pmatsci.2015.04.002.

[384] H. Wang, X. Wang, B. Meng, X. Tan, K.S. Loh, J. Sunarso, S. Liu, Perovskite-based mixed protonic–electronic conducting membranes for hydrogen separation: recent status and advances, J. Ind. Eng. Chem. 60 (2018) 297–306, https://doi.org/10.1016/j.jiec.2017.11.016.

[385] P. Soundarrajan, F. Schweighardt, Hydrogen sensing and detection. Hydrogen Fuel, CRC Press, 2008, pp. 507–546.

[386] N.V. Krishna Prasad, K. Venkata Prasad, S. Ramesh, S.V. Phanidhar, K. Venkata Ratnam, S. Janardhan, K. Srinivas, Ceramic sensors: a mini-review of their applications, Front. Mater. 7 (2020) 593342, https://doi.org/10.3389/fmats.2020.593342.

[387] Y. Yang, A mini-review: emerging all-solid-state energy storage electrode materials for flexible devices, Nanoscale 12 (2020) 3560–3573, https://doi.org/10.1039/C9NR08722B.

[388] J.C. Ince, M. Peerzada, L.D. Mathews, A.R. Pai, A. Al-Qatatsheh, S. Abbasi, N. V. Salim, Overview of emerging hybrid and composite materials for space applications, Adv. Compos. Hybrid. Mater. 6 (4) (2023) 130, https://doi.org/10.1007/s42114-023-00678-5.

[389] Y. Liu, G. Li, L. Huan, S. Cao, Advancements in silicon carbide-based supercapacitors: materials, performance, and emerging applications, Nanoscale 16 (2024) 504–526, https://doi.org/10.1039/D3NR05050E.

[390] H. Takemura, H. Fukushima, Recent trends of advanced ceramics industry and fine ceramics roadmap 2050, Int. J. Appl. Ceram. Technol. 20 (2023) 681–688, https://doi.org/10.1111/ijac.14254.

[391] L. Gao, F. Liu, J. Qi, W. Gao, G. Xu, Recent advances and challenges in hybrid supercapacitors based on metal oxides and carbons, Inorganics 13 (2025) 49, https://doi.org/10.3390/inorganics13020049.

[392] A. Patel, S.K. Patel, R.S. Singh, R.P. Patel, Review on recent advancements in the role of electrolytes and electrode materials on supercapacitor performances, Discov. Nano 19 (2024) 188, https://doi.org/10.1186/s11671-024-04053-1.

[393] A. Dalvi, Achieving high-performance parameters in NASICON-polymer composite electrolyte-based solid-state supercapacitors by interface modification, RSC Adv. 15 (2025) 6518–6530, https://doi.org/10.1039/D4RA08292C.

[394] M. Iordache, A. Oubraham, I. Petreanu, C. Sisu, S. Borta, C. Capris, A. Soare, A. Marinoiu, NASICON membrane with high ionic conductivity synthesized by High-Temperature Solid-State reaction, Materials 17 (2024) 823, https://doi.org/10.3390/ma17040823.

[395] A. Bahaa, A. Alhammadi, K.C. Lethesh, R.A. Susantyoko, M.O. Bamgbopa, Ionic liquid electrolyte selection for high voltage supercapacitors in high-temperature applications, Front. Chem. 12 (2024) 1349864, https://doi.org/10.3389/fchem.2024.1349864.

[396] E.C. Hammel, O.R. Ighodaro, O.I. Okoli, Processing and properties of advanced porous ceramics: an application-based review, Ceram. Int. 40 (2014) 15351–15370, https://doi.org/10.1016/j.ceramint.2014.06.095.

[397] T.A. Otitoju, P.U. Okoye, G. Chen, Y. Li, M.O. Okoye, S. Li, Advanced ceramic components: materials, fabrication, and applications, J. Ind. Eng. Chem. 85 (2020) 34–65, https://doi.org/10.1016/j.jiec.2020.02.002.

[398] T. Do, C. Shin, P. Kwon, J. Yeom, Fully enclosed ceramic micro-burners using fugitive phase and powder-based processing, Sci. Rep. 6 (2016) 31336, https://doi.org/10.1038/srep31336.

[399] M.S. Rayat, S.S. Gill, R. Singh, L. Sharma, Fabrication and machining of ceramic composites—A review on current scenario, Mater. Manuf. Process 32 (2017) 1451–1474, https://doi.org/10.1080/10426914.2017.1279301.

[400] J. Yang, Y. Chen, W. Huang, Y. Li, Survey on artificial intelligence for additive manufacturing. In 23rd International Conference on Automation and Computing (ICAC), IEEE, 2017, pp. 1–6, https://doi.org/10.23919/IConAC.2017.8082053.

[401] L.M. Rueschhoff, L.A. Baldwin, J.O. Hardin, J. Kaufman, Future directions in ceramic additive manufacturing: fiber reinforcements and artificial intelligence, J. Am. Ceram. Soc. 107 (2024) 1505–1522, https://doi.org/10.1111/jace.19408.

[402] Y. Huang, M. Zhong, Y. Huang, M. Zhu, Z. Pei, Z. Wang, Q. Xue, X. Xie, C. Zhi, A self-healable and highly stretchable supercapacitor based on a dual crosslinked polyelectrolyte, Nat. Commun. 6 (2015) 10310, https://doi.org/10.1038/ncomms10310.

[403] W. Wang, J. Yan, J. Liu, D. Ou, Q. Qin, B. Lan, Y. Ning, D. Zhou, Y. Wu, Self-healing polyaniline-graphene oxides-based electrodes with enhanced cycling stability, Electrochim. Acta 282 (2018) 835–844, https://doi.org/10.1016/j.electacta.2018.06.121.

[404] F. Wang, X. Wu, X. Yuan, Z. Liu, Y. Zhang, L. Fu, Y. Zhu, Q. Zhou, Y. Wu, W. Huang, Latest advances in supercapacitors: from new electrode materials to novel device designs, Chem. Soc. Rev. 46 (2017) 6816, https://doi.org/10.1039/C7CS00205J.

[405] J. Chen, P.S. Lee, Electrochemical supercapacitors: from mechanism understanding to multifunctional applications, Adv. Energy Mater. 11 (2021) 2003311, https://doi.org/10.1002/aenm.202003311.

[406] X. Han, G. Xiao, Y. Wang, X. Chen, G. Duan, Y. Wu, X. Gong, H. Wang, Design and fabrication of conductive polymer hydrogels and their applications in flexible supercapacitors, J. Mater. Chem. A. 8 (2020) 23059–23095, https://doi.org/10.1039/D0TA07468C.

[407] J. Polte, Fundamental growth principles of colloidal metal nanoparticles–a new perspective, CrystEngComm 17 (2015) 6809–6830, https://doi.org/10.1039/C5CE01014D.

[408] M. Barberio, P. Antici, In situ study of nucleation and aggregation phases for nanoparticles grown by Laser-Driven methods, Sci. Rep. 7 (2017) 41372, https://doi.org/10.1038/srep41372.

[409] A. Karatutlu, A. Barhoum, A. Sapelkin, Emerging applications of nanoparticles and architecture nanostructures. Elsevier; Amsterdam, the Netherlands: 2018. Liquid-phase synthesis of nanoparticles and nanostructured materials. Copyright ©, Elsevier Inc, 2018 https://doi.org/10.1016/C2016-0-01906-X.

[410] J. McGinty, N. Yazdanpanah, C.J. Price, J. Ter Horst, J. Sefcik, Nucleation and crystal growth in continuous crystallization. The Handbook of Continuous Crystallization, RSC, 2020, pp. 1–50, https://doi.org/10.1039/9781788013581-00001.

[411] S. Prasad, V. Kumar, S. Kirubanandam, A. Barhoum, Engineered nanomaterials: nanofabrication and surface functionalization. Emerging applications of nanoparticles and architectural nanostructures, Elsevier, 2018, pp. 305–340, https://doi.org/10.1016/B978-0-323-51254-1.00011-7.

[412] K.A. Khalil, Advanced sintering of nano-ceramic materials, Ceram. Mater. Prog. Mod. Ceram. (2012) 65–82, https://doi.org/10.5772/38287.

[413] V. Ephraim, S.B. Mishra, A.K. Mishra, B.B. Mamba, Nanoceramics: fundamentals and advanced perspectives. Sol-gel based nanoceramic materials: preparation, properties and applications, Springer International Publishing, Cham, 2016, pp. 1–20, https://doi.org/10.1007/978-3-319-49512-5_1.