http://www.jourmag.org/index.php/jma

Journal of Magnetism and Its Applications

Received March17th 2026 received in revised May 6th 2026 accepted June14th 2026

Research articles

Design and Characterization of Nanostructured Magnetic Materials for Advanced Energy Storage Applications

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Article info
Keywords:
magnetic nanomaterials,
spinel ferrites,
energy storage,
supercapacitors,
lithium-ion batteries,
electrochemical characterization,
nanostructured electrodes,
iron oxide composites

Abstract
The rapid expansion of renewable-energy systems, portable electronics, electric transportation, and smart-grid infrastructure has intensified the demand for energy-storage materials that combine high energy density, rapid charge transport, long cycle life, operational safety, and environmental sustainability. Nanostructured magnetic materials, particularly iron oxides, spinel ferrites, magnetic transition-metal oxides, and their carbon-based hybrids, have emerged as promising electrode candidates for lithium-ion batteries, sodium-ion batteries, potassium-ion batteries, hybrid capacitors, and electrochemical supercapacitors. Their technological importance originates from tunable oxidation states, reversible redox reactions, high theoretical charge-storage capacity, magnetic functionality, compositional flexibility, and the possibility of controlling particle size, porosity, morphology, surface chemistry, and electronic structure at the nanoscale. This review discusses the rational design, synthesis, characterization, electrochemical mechanisms, performance limitations, and future development of nanostructured magnetic materials for advanced energy storage. Particular emphasis is placed on magnetite, hematite, nickel ferrite, cobalt ferrite, manganese ferrite, zinc ferrite, and multicomponent spinel systems. Structural characterization through X-ray diffraction, electron microscopy, Raman spectroscopy, Fourier-transform infrared spectroscopy, X-ray photoelectron spectroscopy, surface-area analysis, and magnetic measurements is examined in relation to electrochemical behavior. The review also evaluates how carbon coating, graphene integration, heteroatom doping, hollow architectures, porous nanofibers, nanosheets, and core–shell structures improve conductivity, ion accessibility, mechanical stability, and cycling performance. Although nanostructuring can substantially enhance reaction kinetics and active-surface utilization, challenges involving agglomeration, low tap density, excessive surface reactions, complicated synthesis, and inconsistent testing procedures continue to restrict commercial implementation. Future progress will depend on scalable synthesis, standardized device-level evaluation, operando characterization, computational materials design, and environmentally responsible processing.

Introduction

The transition from fossil-fuel-based energy systems toward renewable electricity requires storage technologies capable of balancing intermittent energy generation with variable consumer demand. Lithium-ion batteries remain dominant in portable electronics and electric vehicles, while supercapacitors are widely investigated for applications requiring rapid charging, high power delivery, and exceptional cycling stability. However, conventional electrode materials frequently experience limited capacity, slow ion transport, structural degradation, poor electrical conductivity, or insufficient energy density. The performance of an electrochemical energy-storage device is therefore closely connected to the composition, dimensions, porosity, surface chemistry, crystal structure, and interface characteristics of its electrode materials.

Nanostructuring provides several important advantages. Reduced particle dimensions shorten solid-state ion-diffusion pathways, expose additional electrochemically active sites, improve contact between the electrode and electrolyte, and allow mechanical strain to be distributed across smaller structural units. Nanomaterials can also enable reaction pathways that are kinetically inaccessible in conventional bulk materials. Nevertheless, their large surface area may increase electrolyte decomposition, solid–electrolyte interphase formation, irreversible first-cycle losses, and manufacturing cost. Low packing density can also reduce volumetric energy density, meaning that the highest gravimetric performance does not necessarily produce the most practical commercial electrode. netic transition-metal oxides and ferrites constitute a particularly versatile group of electrode materials. Magnetite, Fe_3O_4, contains Fe^{2+} and Fe^{3+} ions and can participate in conversion-type electrochemical reactions. Spinel ferrites generally possess the formula MFe_2O_4, where M may include Ni, Co, Mn, Zn, Mg, Cu, or mixed-metal combinations. Their electrochemical behavior can be modified by controlling cation distribution between tetrahedral and octahedral lattice sites, introducing dopants, forming oxygen vacancies, or combining the magnetic phase with conductive carbon networks. These strategies influence electrical conductivity, magnetic ordering, redox activity, diffusion kinetics, and structural stability. The present review is organized around five major areas: rational design and synthesis, structural and magnetic characterization, electrochemical charge-storage mechanisms, applications in batteries and supercapacitors, and the remaining barriers to commercialization.

Rational Design and Synthesis of Nanostructured Magnetic Materials

The design of an effective magnetic electrode begins with the selection of chemical composition and nanoscale architecture. Iron oxides are attractive because of their comparatively low cost, natural abundance, environmental acceptability, and high theoretical lithium-storage capacity. Ferrites offer additional flexibility because the divalent metal ion can be changed or partially substituted to control redox activity, electrical conductivity, magnetic response, and lattice stability. Mixed-metal compositions such as $Mg_{0.5}Ni_{0.5}Fe_2O_4$ can provide more available oxidation states than a single-metal ferrite, thereby increasing faradaic charge-storage activity. Particle morphology strongly influences electrochemical performance. Zero-dimensional nanoparticles provide high surface area but tend to agglomerate because of surface energy and magnetic dipole interactions. One-dimensional nanorods, nanotubes, belts, and fibers establish continuous pathways for electron movement and can tolerate mechanical deformation. Two-dimensional nanosheets reduce ion-diffusion distances and expose a large fraction of surface metal sites. Three-dimensional porous networks, hollow microspheres, and hierarchical structures combine high electrolyte accessibility with interconnected electron-transport channels. Chemical co-precipitation is one of the simplest approaches for producing ferrite nanoparticles. It generally involves the controlled precipitation of metal ions in an alkaline medium followed by washing, drying, and thermal treatment. The technique is inexpensive and scalable, but particle-size distribution and agglomeration may be difficult to control. Sol–gel and auto-combustion methods produce homogeneous precursor mixing at the molecular level and are particularly useful for multicomponent ferrites. However, residual

organics and high-temperature calcination may influence phase purity and particle growth. Hydrothermal and solvothermal synthesis enable control over crystallinity, shape, and porosity by adjusting temperature, pressure, mineralizing agent, reaction time, solvent composition, and precursor concentration. Hydrothermally prepared nickel and zinc ferrites have demonstrated porous structures and measurable supercapacitor performance. In one recent study, zinc ferrite produced higher capacitance and energy density than nickel ferrite under the reported symmetric-device conditions, illustrating the influence of cation chemistry and surface characteristics. ctrospinning is especially valuable for producing one-dimensional magnetic nanofibers. A polymer solution containing metal salts is subjected to a high electric field, generating precursor fibers that are subsequently calcined to form porous oxide networks. Electrospun $Mg_{0·5}Ni_{0·5}Fe_2O_4$ fibers achieved substantially greater specific capacitance than separately prepared $MgFe_2O_4$ nanobelts and $NiFe_2O_4$ nanotubes. The improvement was attributed to multivalent redox centers, porous morphology, accessible grain boundaries, and reduced charge-transfer resistance. ect growth on conductive substrates is another effective design strategy. Magnetic nanosheets, nanoflowers, or nanofeathers can be deposited on nickel foam, stainless steel, carbon cloth, or metal foil. Binder-free electrodes eliminate insulating polymer binders and reduce interfacial resistance between the active material and current collector. Precursor chemistry can also determine final morphology. Nickel ferrite films prepared from different nickel salts have formed distinct nanosheet, nanoflower, and nanofeather structures, demonstrating that coordination chemistry and anion effects can direct nucleation and growth. bon hybridization addresses the poor intrinsic electrical conductivity of many ferrites. Reduced graphene oxide, carbon nanotubes, porous carbon, carbon nanofibers, and conductive polymers create electron-conduction pathways and prevent magnetic nanoparticles from forming dense aggregates. Carbon shells can also act as mechanical buffers during repeated conversion reactions. Hierarchical CdS–$CoFe_2O_4$/reduced-graphene-oxide structures have achieved high reported capacitance because of synergistic interactions among the conductive carbon network, ferrite nanospheres, and redox-active semiconductor component. arch2 Doping provides an additional level of structural control. Aliovalent dopants modify lattice parameters, electronic conductivity, defect concentration, and cation distribution. Titanium-doped Fe_3O_4, for example, has shown stable lithium-storage capacity over repeated cycling, with the improvement associated with electronic and structural stabilization. sequently, advanced electrode design should not focus only on reducing particle size. A more practical strategy is to create micron-scale secondary particles or continuous films containing nanoscale pores, grains, interfaces, and conductive pathways. Such hierarchical architectures can preserve the kinetic advantages of nanomaterials while improving packing density, electrode handling, and volumetric performance.

Structural, Surface, Magnetic, and Morphological Characterization

Comprehensive characterization is required to establish a reliable relationship between synthesis conditions, nanoscale structure, magnetic behavior, and electrochemical performance. No single analytical technique can fully describe a nanostructured electrode; complementary measurements are therefore essential. ay diffraction is used to identify crystalline phases, determine lattice parameters, detect impurity phases, and estimate average crystallite dimensions. Cubic spinel ferrites typically display reflections associated with the (220), (311), (400), (422), (511), and (440) planes. The (311) reflection is often the most intense. Crystallite size may be estimated through the Scherrer equation:

$$D = K\lambda/(\beta \cos \theta)$$

where D is the average coherent crystallite size, K is the shape factor, λ is the X-ray wavelength, β is the corrected full width at half maximum, and θ is the Bragg angle. Because peak broadening may also arise from lattice strain and structural defects, Williamson–Hall analysis can provide a more informative separation of size-related and strain-related contributions. Scanning electron microscopy reveals particle aggregation, surface texture, pore distribution, film coverage, fiber diameter, and electrode thickness. Transmission electron microscopy provides higher-resolution information about particle dimensions, shell thickness, internal cavities, lattice fringes, crystal defects, and heterointerfaces. Selected-area electron diffraction can support phase identification, while energy-dispersive X-ray mapping evaluates elemental composition and spatial uniformity. Brunauer–Emmett–Teller surface-area analysis provides information about specific surface area, pore volume, and pore-size distribution. Mesopores facilitate electrolyte penetration and ion transport, while micropores can increase charge-storage area when their dimensions are compatible with solvated or partially desolvated ions. Excessively small pores may remain inaccessible, whereas very large pores contribute limited surface area. A hierarchical combination of micro-, meso-, and macroporosity is therefore often preferred. Fourier-transform infrared spectroscopy is commonly used to confirm metal–oxygen vibrations associated with tetrahedral and octahedral sites in ferrite lattices. Raman spectroscopy provides complementary information about spinel symmetry, local disorder, phase transformation, and metal–oxygen bonding. Raman analysis is particularly important for distinguishing magnetite, maghemite, and hematite phases that may display related elemental compositions but different electrochemical and magnetic properties. X-ray photoelectron spectroscopy identifies surface oxidation states and chemical environments. For Fe-containing materials, the Fe 2p region helps distinguish Fe^{2+} and Fe^{3+} contributions. Satellite peaks and binding-energy shifts can indicate changes caused by doping, oxygen vacancies, carbon bonding, or interfacial charge transfer. Because electrochemical reactions occur at or near the electrode surface, XPS data may be more directly relevant to initial reaction behavior than bulk compositional measurements. Magnetic properties are normally examined using vibrating-sample magnetometry or superconducting quantum-interference-device magnetometry. The magnetization–field curve provides saturation magnetization, coercivity, remanent magnetization, and magnetic hysteresis information. Particle size, surface disorder, cation distribution, crystal anisotropy, and dopant concentration can substantially alter these parameters. Magnetic characterization is scientifically valuable even when the electrode is not operated under an external magnetic field. Variations in saturation magnetization may indicate changes in cation occupancy, crystallinity, surface spin disorder, or composition. These same structural factors can influence electrical conductivity and redox activity. Magnetic measurements can therefore serve as an additional indicator of changes in the atomic-scale structure of ferrite electrodes. Electrochemical characterization normally includes cyclic voltammetry, galvanostatic charge–discharge testing, electrochemical impedance spectroscopy, rate-capability measurements, and long-term cycling. Cyclic voltammetry identifies reversible redox processes, polarization, and capacitive behavior. Galvanostatic testing provides specific capacity or capacitance under controlled current. Electrochemical impedance spectroscopy separates solution resistance, charge-transfer resistance, interfacial capacitance, and diffusion-related impedance.

For a supercapacitor electrode, gravimetric specific capacitance from a galvanostatic discharge curve is commonly calculated as:

$$Csp = I\Delta t/(m\Delta V)$$

where I is discharge current, Δt is discharge time, m is active-material mass, and ΔV is the effective voltage interval after excluding the initial voltage drop.

Energy density and power density may be estimated as:

$$E = Csp(\Delta V)^2/7.2$$

$$P = 3600E/\Delta t$$

where E is expressed in Wh kg^{-1} when Csp is in F g^{-1}, and P is expressed in W kg^{-1}. Device-level calculations should use the total active mass of both electrodes rather than only the mass of the better-performing electrode.

Electrochemical Charge-Storage Mechanisms and Performance Enhancement

Magnetic oxides store charge through different mechanisms depending on crystal structure, oxidation state, electrolyte, voltage range, and device type. In lithium-ion batteries, many transition-metal oxides undergo a conversion reaction represented in simplified form as:

$$MxOy + 2yLi^+ + 2ye^- \rightleftharpoons xM + yLi_2O$$

This mechanism can provide capacities greater than those of conventional graphite because several electrons participate per formula unit. Early studies of nanosized transition-metal oxides demonstrated that materials containing Fe, Co, Ni, or Cu could reversibly store substantial lithium through conversion-type chemistry. ing the first lithiation, the oxide lattice is reduced, metallic nanoparticles are produced, and Li_2O forms. On delithiation, partial or extensive reoxidation occurs. The reversibility of this process depends on particle dimensions, electronic conductivity, catalytic activity, electrode–electrolyte interfaces, and the stability of the nanoscale metal/Li_2O matrix. Fe_3O_4 is especially attractive because it is inexpensive and possesses mixed Fe^{2+}/Fe^{3+} chemistry. However, it suffers from volume variation, particle aggregation, conductivity limitations, and unstable interfacial layers. Nanostructuring shortens lithium-diffusion distances, while carbon coating or graphene integration maintains

electrical contact when the oxide expands and contracts. Doped magnetite represents another pathway for improving conversion reactions. Titanium incorporation can alter electron density near iron sites, stabilize the crystal framework, and improve transport. A Ti-doped Fe_3O_4 anode was reported to maintain approximately 450 mAh g^{-1} at 0.1 C for at least 100 cycles under the investigated conditions. supercapacitors, ferrite electrodes typically display pseudocapacitive or battery-type faradaic behavior. Surface or near-surface metal ions undergo reversible oxidation-state changes in alkaline or neutral electrolytes. Because these reactions depend on electrolyte penetration and electron transfer, highly porous structures with open channels generally outperform dense particles. The electrochemical response of a ferrite may involve redox transitions among Fe^{2+}/Fe^{3+}, Ni^{2+}/Ni^{3+}, Co^{2+}/Co^{3+}, and Mn^{2+}/Mn^{3+} states. Mixed-metal ferrites can therefore provide multiple reaction centers. In $Mg_{0.5}Ni_{0.5}Fe_2O_4$, nickel incorporation increased redox activity and lowered charge-transfer resistance relative to magnesium ferrite. The porous fibers delivered 647 F g^{-1} at 1 A g^{-1}, retained approximately 91% capacitance after 3,000 cycles at 10 A g^{-1}, and produced an asymmetric device with a reported energy density of 83 Wh kg^{-1} at 700 W kg^{-1}. kel ferrite nanosheet films have exhibited high capacitance because their open morphology increases contact between active material and electrolyte. Under the conditions reported by Bandgar and co-workers, the best-performing $NiFe_2O_4$ morphology reached approximately 1,139 F g^{-1}. However, performance differences among studies must be interpreted cautiously because values may be calculated from different voltage windows, current densities, mass loadings, electrolytes, and electrode configurations. bon-supported ferrites frequently show improved rate capability. Reduced graphene oxide provides a two-dimensional electron-conduction framework, while ferrite nanoparticles prevent complete restacking of graphene sheets. A CdS–$CoFe_2O_4$/rGO nanohybrid delivered a reported capacitance of 1,487 F g^{-1} at 5 A g^{-1} and retained 78% of its initial capacitance after 5,000 cycles. Its performance was attributed to high surface area, accessible ion pathways, rapid electron transport, and synergistic redox activity. arch2 Microwave-assisted synthesis can reduce reaction time and improve nanoparticle distribution on conductive supports. A $MnFe_2O_4$/rGO composite produced through a one-step microwave-assisted hydrothermal method achieved 196.6 F g^{-1} at 0.5 A g^{-1} and maintained approximately 90.22% capacitance after 6,000 cycles at 10 A g^{-1}. c ferrite contains electrochemically active iron centers while Zn^{2+} influences structural arrangement and conductivity. Hydrothermally produced $ZnFe_2O_4$ symmetric electrodes delivered approximately 243.3 F g^{-1} at 0.9 A g^{-1}. An asymmetric $NiFe_2O_4$//$ZnFe_2O_4$ device demonstrated higher capacitance and energy density than either symmetric arrangement under the reported experimental conditions. large variation in published performance illustrates that composition alone cannot predict electrode quality. Morphology, current collector, binder fraction, conductive additive, active mass, electrolyte concentration, potential window, and device architecture must all be considered. Three-electrode measurements are valuable for screening materials but commonly produce higher values than practical two-electrode devices. Commercial relevance therefore requires complete-cell testing at realistic mass loading and thickness.

Applications in Batteries, Supercapacitors, and Hybrid Storage Systems

In lithium-ion batteries, nanostructured magnetic oxides are mainly investigated as high-capacity negative electrodes. Their conversion chemistry can exceed the 372 mAh g^{-1} theoretical capacity of graphite. Fe_3O_4, Fe_2O_3, Co_3O_4, $NiFe_2O_4$, $CoFe_2O_4$, $MnFe_2O_4$, $CuFe_2O_4$, and $ZnFe_2O_4$ have all been evaluated. Nevertheless, conversion reactions usually occur at relatively low voltage and may exhibit significant voltage hysteresis, reducing round-trip energy efficiency. Carbon encapsulation is particularly important for battery electrodes. Carbon shells and nanotube networks accommodate volume change, improve conductivity, limit direct exposure to electrolyte, and prevent active nanoparticles from losing electrical contact. The effectiveness of these structures depends on balancing oxide loading with carbon content. Excess carbon lowers overall theoretical capacity, while inadequate carbon coverage fails to stabilize the oxide. Magnetic ferrites are also under investigation for sodium-ion and potassium-ion batteries. The larger ionic radii of Na^+ and K^+ create more severe diffusion and mechanical challenges than lithium. Hollow structures, defect-rich interfaces, ultrathin sheets, and carbon-supported nanoparticles are therefore especially relevant. However, sodium and potassium systems generally require further improvement in initial Coulombic efficiency, reaction reversibility, and long-term structural stability. In supercapacitors, ferrites are most frequently used as positive electrodes in aqueous alkaline electrolytes. Their faradaic reaction provides higher capacitance than purely electrostatic carbon electrodes, but their operating potential range may be narrower. Pairing a ferrite positive electrode with activated carbon, graphene, or another negative material can extend the complete-cell voltage and create an asymmetric supercapacitor. The energy density of a capacitor varies with the square of its voltage window. Consequently, constructing stable asymmetric devices is often more effective than maximizing electrode capacitance alone. Proper charge balancing is essential and may be represented as:

$$m^+C^+\Delta V^+ = m^-C^-\Delta V^-$$

where m is electrode mass, C is specific capacitance, and ΔV is the stable potential range of the positive or negative electrode. Magnetic materials may provide additional multifunctionality. Their magnetic behavior can support magnetic separation during recycling, remote positioning of particles during fabrication, magnetic-field-responsive transport studies, electromagnetic interference shielding, or integration with sensors. Nevertheless, these functions must not compromise electrochemical capacity, conductivity, stability, or safety. Flexible and wearable energy-storage systems represent another potential application. Ferrite nanosheets grown directly on carbon cloth or metal mesh can produce bendable binder-free electrodes. Composite formation with conducting polymers may further improve mechanical flexibility. Long-term bending, twisting, humidity exposure, and temperature variation should be evaluated alongside electrochemical cycling to establish suitability for wearable electronics. Grid-scale storage requires inexpensive materials, high safety, minimal toxicity, and long service life. Iron-rich ferrites could be advantageous because iron is abundant and comparatively inexpensive. However, cobalt- and nickel-containing compositions raise concerns regarding cost, supply-chain security, mining impacts, and recycling. Future grid-oriented materials should prioritize Fe-, Mn-, Zn-, and Mg-rich systems wherever performance permits.

Challenges, Sustainability, and Future Research Directions

Despite encouraging laboratory performance, several obstacles prevent the widespread commercial adoption of nanostructured magnetic electrodes. The first major challenge is agglomeration. Magnetic dipolar interactions and high surface energy cause nanoparticles to cluster, reducing active area and blocking ion pathways. Surface functionalization, carbon scaffolds, polymer-assisted synthesis, and direct growth on current collectors can reduce aggregation, but each additional processing step increases complexity and cost. The second challenge is low volumetric energy density. A highly porous electrode may exhibit excellent gravimetric capacitance while containing little active material per unit volume. Commercial cells require sufficient tap density, areal capacity, and electrode thickness. Researchers should therefore report volumetric capacitance, areal capacity, active-mass loading, electrode density, and complete-device performance in addition to gravimetric values. The third challenge is irreversible interfacial chemistry. High-surface-area battery electrodes consume electrolyte during initial solid–electrolyte interphase formation, lowering first-cycle Coulombic efficiency. Surface coatings, electrolyte additives, prelithiation, controlled porosity, and artificial interphase engineering may reduce these losses. The fourth challenge is structural instability. Conversion reactions involve extensive bond breaking, metal nanoparticle formation, and volume variation. Hollow particles, yolk–shell structures, flexible carbon matrices, and self-supporting networks can accommodate strain. However, these architectures must retain mechanical integrity during thousands of cycles and under practical electrode pressure. The fifth challenge is inconsistent electrochemical reporting. Capacitance may be calculated using different mass definitions, and some studies report values from only one electrode in a three-electrode cell. Energy density may be overstated when the mass of the counter electrode, separator, current collectors, or packaging is ignored. Standardized protocols are needed for mass loading, potential-window selection, cycle number, current density, temperature, and device-level calculations. Scalable manufacturing remains another concern. Hydrothermal processing, template removal, freeze-drying, vacuum treatment, and multistep carbon coating may be effective at laboratory scale but expensive at industrial scale. Co-precipitation, spray drying, flame synthesis, continuous hydrothermal processing, electrodeposition, and roll-to-roll coating are more promising for large-volume production. Environmental sustainability should be incorporated at the earliest design stage. Water-based synthesis, low-temperature processing, biomass-derived carbon, non-toxic solvents, and recovery of metals from industrial waste can reduce environmental impacts. Life-cycle assessment should examine precursor extraction, energy consumption, solvent recovery, electrode fabrication, device lifetime, and end-of-life recycling. Operando and in situ characterization will be essential for understanding how magnetic electrodes transform during cycling. Operando X-ray diffraction can follow phase changes, Raman spectroscopy can monitor bond evolution, transmission electron microscopy can visualize structural degradation, and X-ray absorption

spectroscopy can identify oxidation-state changes. These techniques should be combined with electrochemical impedance analysis and magnetic measurements. Computational methods can accelerate material discovery. Density-functional theory can predict electronic structure, ion adsorption, diffusion barriers, defect formation, and dopant stability. Machine-learning models can connect synthesis parameters with morphology and performance. However, models require carefully curated experimental datasets with standardized measurements.
Future magnetic electrode design should emphasize the following principles:

- Development of hierarchical micro–nano structures that preserve fast kinetics while improving packing density.
- Replacement of expensive cobalt-rich compositions with abundant Fe-, Mn-, Zn-, and Mg-based systems.
- Direct growth of active materials on lightweight, conductive, corrosion-resistant current collectors.
- Engineering of stable electrode–electrolyte interfaces through coatings and electrolyte additives.
- Evaluation in full cells with commercially relevant mass loading, electrolyte quantity, and electrode thickness.
- Integration of computational screening with automated synthesis and high-throughput characterization.
- Development of recycling approaches that exploit the magnetic separability of active materials.
- Transparent reporting of negative results, degradation mechanisms, and device-level limitations.

Qazi and Sohail studied the factors that affect investors' intention to take part in socially responsible investing. Their research focused on attitude, subjective norms, and perceived behavioral control among Pakistan Stock Exchange investors. The authors highlighted that attitude has a strong role in encouraging socially responsible investment intention.

Mousumi (2026) examined how service quality affects customer engagement and loyalty in Malaysian telecom services. The study showed that improved service quality can increase customer engagement and support long-term customer loyalty. Dr. Nadia Sohail is listed as the supervisor of this study.

Summary

Nanostructured magnetic materials provide a highly adaptable platform for advanced electrochemical energy storage. Iron oxides and spinel ferrites combine multivalent redox chemistry, compositional tunability, structural diversity, and magnetic functionality. By engineering nanoparticles, nanosheets, nanotubes, porous fibers, hollow structures, thin films, and carbon-supported hybrids, researchers can shorten ion-diffusion pathways, increase active-surface utilization, improve electron transport, and accommodate mechanical stress. Structural and electrochemical performance are strongly interconnected. Crystal phase, cation occupancy, oxidation state, surface area, pore dimensions, magnetic ordering, and electrode–electrolyte interfaces must therefore be evaluated through complementary characterization techniques. XRD, SEM, TEM, XPS, Raman spectroscopy, FTIR, BET analysis, VSM, cyclic voltammetry, galvanostatic testing, and impedance spectroscopy collectively provide the information required to understand material behavior. Published studies demonstrate that magnetic nanostructures can deliver high specific capacitance and promising battery capacity. Nevertheless, reported values cannot be directly compared unless testing conditions, active mass, electrolyte, current density, and device configuration are equivalent. The most important future objective is not simply to achieve a record gravimetric value, but to develop electrodes that simultaneously provide high areal and volumetric performance, long life, low cost, safe operation, and scalable production. Commercially relevant progress will require hierarchical electrode architectures, abundant raw materials, sustainable synthesis, standardized testing, operando analysis, and complete-cell validation. With these developments, nanostructured magnetic materials may contribute meaningfully to next-generation batteries, asymmetric supercapacitors, hybrid storage systems, flexible electronics, and renewable-energy infrastructure.

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