Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

Spinel Ferrite-Based Electrodes: Synthesis, Electrochemical Properties, and Emerging Energy Storage Applications

Umeza Mishal
Department of Physics, University of Karachi, Karachi 75270, Pakistan

Bilal Munir
Department of Department of Civil Engineering, NED University of Engineering and Technology, Karachi 75270, Pakistan

Syed Ashad Ali
Department of Science and Humanities, National University of Computer and Emerging Sciences, Karachi 75030, Pakistan

Ishtiaq Ahmed
Department of Science and Humanities, National University of Computer and Emerging Sciences, Karachi 75030, Pakistan

Fazeela Kaneez
CAS Key Laboratory of Standardization and Measurement for Nanotechnology, National Centre for Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, P. R. China

Muhammad Rahim (Corresponding Author)
Department of Science and Humanities, National University of Computer and Emerging Sciences, Karachi 75030, Pakistan
Email:muhammad.rahim@nu.edu.pk

ABSTRACT

Due to its economic benefits and efficient storage capacity, the attention of scientists towards energy storage devices has increased. The novel electroactive materials that can be used to achieve better electrochemical performance have attracted much attention lately. Spinel ferrites having the composition of MFe2O4 (M can be Co, Ni, Zn, Mn, Cu, Mg and other metal elements) have been paid great importance due to various interesting features they offer, including tunable electrical conductivity, multiplicity of redox centres, chemical stability, magnetic property, environment-friendliness, cost-effectiveness and many others. It should be mentioned that the unique crystal structure of spinel ferrites, characterised by a different arrangement of cations, plays an important role in optimising electron transfer and storage. Consequently, due to their unique properties, spinel ferrites can be used as promising candidates in the fabrication of supercapacitors, secondary batteries and sensors, i.e. multifunctional energy storage devices. In this study, structural features,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

preparation techniques, electrode production and electrochemistry of the ferrite-based electrode materials have been discussed comprehensively. Besides, particular emphasis has been put on the applications of ferrites as promising electrode materials in supercapacitors, Li/S batteries and electrochemical sensors. Finally, the important issues, such as lack of sufficient electrical conductivity, volume changes and scaling effect, have also been elaborated in this paper.

Keywords— Spinel ferrites, Electrodes, Supercapacitors, Lithium-ion batteries, Energy storage, Electrochemical sensors

1. Introduction:

The explosion of the world's population, incessant industrialisation, and increased reliance on electronics has created a marked increase in the demand for energy globally. Additionally, the problem of environmental pollution, emission of greenhouse gases, and dwindling fossil fuel resources has further increased the need to look for energy sources that are sustainable and renewable. Energy from sources like the sun, wind, tides, and water holds promise in terms of securing future energy needs. The inherent problems associated with the irregularity of this energy source pose a huge challenge in securing a continuous power supply. The result has been an intense focus worldwide on energy storage technology(Ali et al., 2021; Rahim, Hussain, et al., 2024; Ullah et al., 2021).

Out of different energy storage technologies, electrochemical energy storage devices such as LIBs, SIBs, metal air batteries, and supercapacitors have attracted much attention owing to their high efficiency, fast charging-discharging ability, portability, and ease of integration with existing electronics. The electrochemical energy storage devices find important applications in areas such as portable electronics, electric cars, grid-scale energy storage systems, and hybrid power plants. Despite this, however, the efficiency of these energy storage systems is largely determined by the characteristics of electrode materials. The electrode materials determine the energy density, power density, cycle life, kinetics of electron transfer reactions, and lifetime of the electrochemical energy storage devices (Mishal et al., 2023; Rahim et al., 2025; Rahim, Khan, et al., 2024).

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

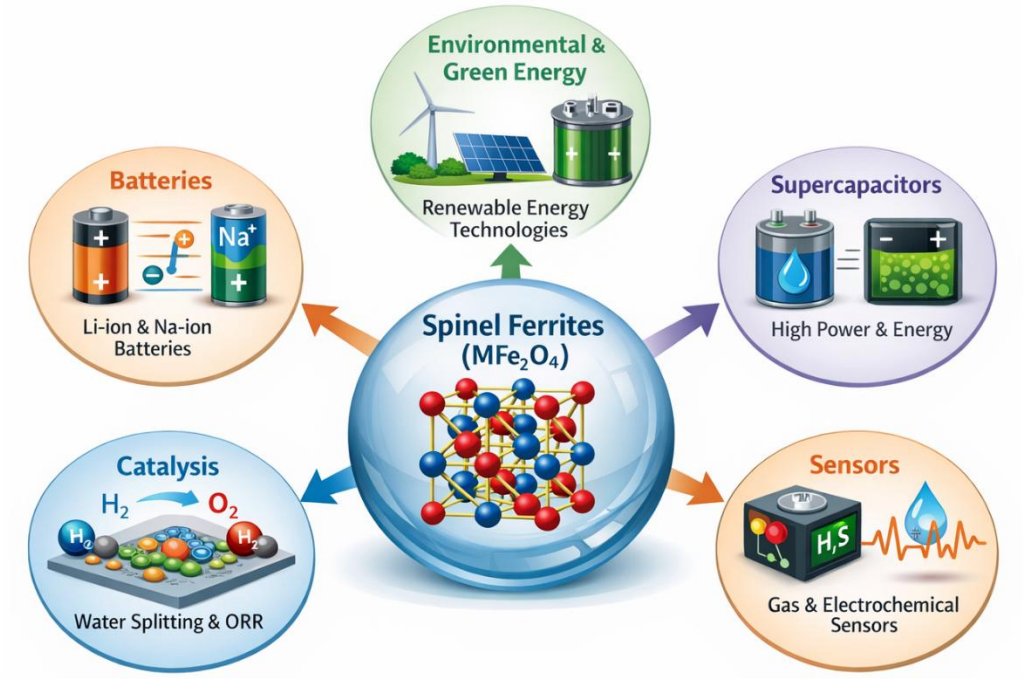


Figure 1. Schematic overview of major applications of spinel ferrite materials in electrochemical energy storage and sensing technologies.

Transition metal oxides are some of the most promising electrodes due to their diverse redox properties, high theoretical capacity, versatility of structures, and chemical stability. Spinel ferrites, a subgroup of transition metal oxides, whose generic formula is MFe_2O_4 (where M = cobalt, nickel, zinc, manganese, copper, magnesium, and other bivalent ions), have attracted increased attention as versatile electroactive materials. Their crystal structure enables flexibility in cation occupancy at the tetrahedral and octahedral lattice sites, influencing such characteristics as conductivity, magnetism, catalysis, and electrochemistry. Moreover, the presence of different oxidation states of iron ions and electron transport among them facilitates better performance in energy storage systems (Hussain et al., 2023; Nazar et al., 2022).

There are a number of advantages that spinel ferrites have when compared to other materials used as electrodes. This includes being cheap, non-toxic, heat-resistant, and durable, among others. They are also relatively easy to synthesise using different techniques of either chemistry or physics. On the other hand, it is relatively easy to optimise the performance of spinel ferrites by manipulating their characteristics, like composition, particle size, shape, and defects, as well as embedding them in conductive media such as carbon nanotubes, graphene, and conducting polymers (Khan et al., 2024; Sharif et al., 2025; Vohra et al., 2025).

The utilisation of spinel ferrites in diverse technological applications ranging from supercapacitors to rechargeable batteries, electrochemical catalysts, sensors, and hybrid energy conversion and storage devices has been gaining significant attention. Although successful results have been achieved, there are a number of challenges that remain unresolved, such as poor electrical conductivity, particle aggregation, structural deterioration after several cycles, and manufacturing at a commercial level (Ahmad et al., 2025).

The purpose of this review is to provide an exhaustive review concerning the topic of

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

spinel ferrite electrodes regarding their crystal structure, methods for their preparation, approaches in designing the electrodes, electrochemical performance, as well as potential application as energy storage materials. Special attention will be paid to the study of relationships between chemical structure and functional behaviour (Salih & Mahmood, 2023).

2. Structural Overview of Spinel Ferrites:

The class of spinel ferrites belongs to mixed-metal oxides and has the general formula MFe_2O_4, where M is a divalent metal ion like Co^{2+}, Ni^{2+}, Zn^{2+}, Mn^{2+}, Cu^{2+}, or Mg^{2+}. These compounds are popular because of the following reasons: they can be readily tuned in terms of their crystal structure and physical/chemical properties; they are chemically stable and exhibit tunable magnetic behaviour and desirable electrochemical characteristics, thus making them ideal for applications related to energy storage and sensing technologies. The distribution of cations in the spinel lattice plays a key role in controlling several other properties (Ndione et al., 2014).

2.1 Spinel Crystal Structure (AB_2O_4):

Spinel ferrites crystallise in a cubic close-packed oxygen lattice that belongs to the Fd3m space group. In this arrangement, oxygen anions form a densely packed framework, while metal cations occupy two types of interstitial positions: tetrahedral (A) sites and octahedral (B) sites. Each unit cell of the spinel structure generally contains eight formula units, offering several cation sites that allow compositional flexibility and property adjustment (Kaur, 2025; Pachpinde, 2018).

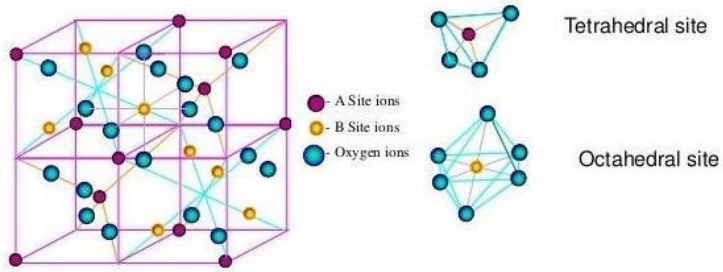


Figure 2. Crystal structure of spinel ferrites illustrating the tetrahedral (A) and octahedral (B) cation sites within the AB_2O_4 lattice.

According to the position of the divalent metal ions and Fe^{3+} ions in these lattice sites, there are usually three types of spinel ferrites, including **Normal spinel,** in which the divalent metal ions are present in the tetrahedral (A) sites, and Fe^{3+} ions are located in the octahedral (B) sites. $ZnFe_2O_4$ is the most common example of normal spinel ferrite, **Inverse spinel,** having Fe^{3+} ions with an equal distribution in both A and B sites, whereas the divalent metal ions are present in the B sites. $NiFe_2O_4$ and $CoFe_2O_4$ are good examples of inverse spinel ferrites, **Mixed spinel,** in which both the divalent metal ions and Fe^{3+} ions are present in the A and B sites. $MnFe_2O_4$ shows a mixed spinel structure (Ahad, 2017; Saha, 2016).

Cation distribution has a great effect on lattice strain, bond length, magnetic interactions, conductivity, and electrochemical performance. The slight difference in the preparation methods can change cation distribution and can drastically change their properties. Optimised cation distribution can improve electron mobility, surface

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197 Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

reactivity, and structural stability under charge-discharge cycles in electrode materials (Cai et al., 2005; Vaccari, 1998).

2.2 Electrical Properties Relevant to Electrodes:

In general, the electrical conductivity in spinel ferrites is controlled by the process of small polaron hopping, where there is movement of electrons between ions with different valence states, mainly $Fe^{2+} \leftrightarrow Fe^{3+}$ at octahedral sites. Hopping could also occur among ions such as Ni^{2+}/Ni^{3+}, Mn^{2+}/Mn^{3+}, or Co^{2+}/Co^{3+}. Such electron hopping is essential for the development of semiconductivity and significantly impacts charge transfer kinetics (Geng et al., 2012; Giannini & Blumberger, 2022; Shuai et al., 2014). Conductivity is an important factor in the case of electrode materials since it plays a crucial role in determining the mobility of electrons in the electrode. Ferrites with high conductivity tend to show high rate capability, reduced internal resistance, increased charge transfer rate, and higher power capacity.

Yet, many of these spinel ferrites have lower conductivities compared with carbons. Hence, enhancing conductivity in ferrites is usually done by doping with other elements or combining them with graphene or CNTs.

2.3 Magnetic Properties and Their Functional Importance:

Spinel ferrites possess ferrimagnetic properties because of the antiparallel alignment of the magnetic moments due to the presence of cations in A and B sites of the crystal structure. The net magnetic moment would be determined by the magnetic moment difference in the two sublattices. While magnetic property is not necessarily a desirable one for electrochemical electrodes, there are many useful applications. Magnetic ferrites could be separated or recycled using an external magnetic field, applied in multifunctional sensors, used in magnetic-electrochemical systems, and useful in catalysis and remediation.

For instance, cobalt ferrite displays high coercive force and mechanical strength, nickel ferrite has moderate magnetic susceptibility and good electrical conductivity, and zinc ferrite could have low magnetism but good electrochemical activity (Priyadharsini et al., 2024).

2.4 Influence of Divalent Metal Cations:

The type of divalent cation (M^{2+}) has a major influence on the structural and electrochemical properties of spinel ferrites such as, **$CoFe_2O_4$**, that possesses high chemical stability, strong magnetic behaviour, and excellent cycling durability, **$NiFe_2O_4$**, having higher electrical conductivity, making it attractive for batteries and supercapacitors, **$ZnFe_2O_4$**, that has high theoretical capacity, particularly suitable for lithium-ion battery applications, **$MnFe_2O_4$**, having multiple oxidation states that promote stronger redox activity, **$CuFe_2O_4$**, which has good catalytic performance with notable pseudocapacitive behaviour, and **$MgFe_2O_4$**, which is chemically stable and environmentally friendly

Choosing the appropriate cation makes it possible to tailor ferrite performance for specific applications, including high-capacity batteries, high-rate supercapacitors, and sensitive electrochemical sensors (Abdulwahab et al., 2024).

2.5 Structure-Property Relationship:

The first benefit of spinel ferrites is the existence of a high correlation between crystal

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

structure and performance characteristics of spinel materials. Parameters like cation distribution, crystallite size, porosity, defects in the crystal lattice, and surface area affect the electrical conductivity, ion mobility, redox reactions, and overall stability during cycling. Thus, the possibility to tune the crystal structure via controlled preparation becomes one of the best strategies to improve the performance of the electrode material based on ferrites.

In general, spinel crystal architecture becomes a highly tunable basis where not only the chemical composition but also the atomic structure can be tailored to get the desired electrochemical characteristics (Dippong et al., 2021).

3. Synthesis Strategies for Electrode-Grade Spinel Ferrites:

Electrochemical performance of spinel ferrites depends heavily on the synthetic technique utilised since the preparation parameters determine particle size, crystalline structure, morphology, porosity, surface imperfections, ion distribution, and purity of phases. The above factors directly affect the conductivity, ion movement mechanisms, active surface area, and cycle stability during the use of ferrites as electrode materials. It is, therefore, crucial to select an appropriate synthesis route when developing highly efficient spinel ferrite electrodes. Traditional and novel methods for making ferrites with specific microstructures have received considerable attention, particularly in the production of spinel ferrites for supercapacitors, batteries, and sensors (M Yaseen et al., 2021; Muhammad Yaseen et al., 2021).

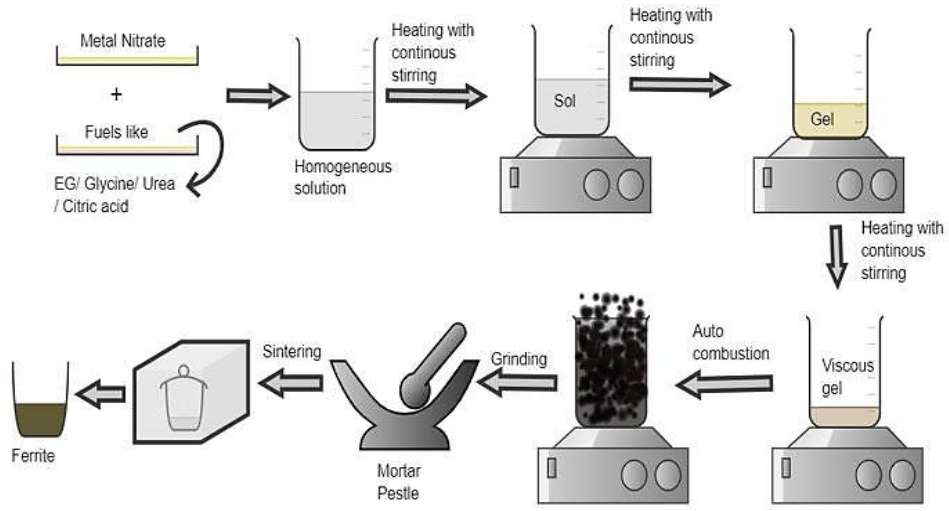


Figure 3. Commonly used synthesis methods for the preparation of spinel ferrite nanostructures.

3.1 Co-precipitation Method

Co-precipitation is one of the most popular wet-chemical methods that is applied for the synthesis of spinel ferrite nanoparticles due to simplicity, low cost and ability to perform reactions at relatively moderate temperatures. This approach involves mixing aqueous solutions of different metal salts, such as nitrates, chlorides and sulfates, in a proper stoichiometric proportion. Further, a precipitation reagent, which can be, for example, sodium or ammonium hydroxide and sodium carbonate, is added to achieve a certain pH and initiate the formation of metal hydroxide precursor compounds.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

Finally, these precursors are separated, dried and annealed to form spinel ferrites (Ati et al., 2025).

The major advantages of this technique can be summarised as excellent controllability of chemical composition, low costs for laboratory equipment and preparation process, high yield of final products, fast process, and possibility of nanoscale particle synthesis.

This technique is well-suited for obtaining $CoFe_2O_4$, $NiFe_2O_4$ and $ZnFe_2O_4$ particles to be utilised as electrode materials for supercapacitors and batteries. If reaction conditions are not properly set, however, there may be a problem with agglomeration of particles, their broad size distribution and incompleteness of crystallisation processes. pH, stirrer rate, reaction and calcination temperatures play a significant role here (Salih & Mahmood, 2023).

3.2 Sol-Gel Auto-Combustion Method

Sol-gel auto-combustion is an excellent example of a highly adaptable chemical technique that is commonly employed for synthesising very homogeneous fine spinel ferrite powders. The process entails dissolution of metal nitrates and their mixing with organic chelating agents like citric acid, glycine, or urea. These substances serve as ligands for complexing with metal ions and contribute to the formation of a homogenous gel network. After heating, drying, and evaporation of the solvent, self-propagation of the combustion process is initiated by the release of heat energy (Hussein & Al-Shakarchi, 2024).

The main benefits of sol-gel auto-combustion include excellent chemical homogeneity, homogeneous and finely dispersed structure, high specific surface area, synthesis at lower temperatures compared to solid-state techniques, and precise control of stoichiometry.

Calcination of the ash-like, porous product of auto-combustion improves its crystalline properties. Due to its ability to yield nanomaterials, which facilitate shorter ion diffusion paths and have a large electrochemically active surface area, sol-gel auto-combustion is particularly useful for synthesising electrode materials. It should be noted, however, that insufficient control of the fuel/oxidiser ratio leads to the presence of carbon in the final product (Bhagwat et al., 2019).

3.3 Hydrothermal and Microwave-Assisted Methods

Hydrothermal synthesis is an advanced solution chemistry approach carried out under high temperatures and pressures in a closed autoclave system. In this way, control of crystal nucleation and growth becomes feasible. It enables the fabrication of spinel ferrites in various morphological forms, including nanorods, nanospheres, nanoflowers, nanosheets, and hollow nanostructures.

The main merits of hydrothermal synthesis include high crystallinity, consistent morphology of the particles, small size distribution, nanostructure-controlled growth, and low defect density.

On the other hand, microwave-assisted synthesis involves microwave irradiation that can heat precursors in solution more quickly and evenly. This technique provides higher reaction rates and reduced synthesis times compared to heating processes.

Similarly, hydrothermal synthesis and microwave-assisted approaches are extremely appealing in electrode manufacturing since controlled nanostructure formation results in improved electrolyte penetration and charge transfer capabilities. However, their

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

application on an industrial scale might be difficult due to the requirements of special equipment and small batch size (Schmidt et al., 2022).

3.4 Solid-State Reaction Method:

The solid-state reaction technique can be considered one of the oldest and most commonly adopted techniques for preparing ferrites. In this process, metallic oxides or carbonates of metals in their required proportions are physically blended and then undergo heating at very high temperatures, typically between 800 °C and 1300 °C. This causes the diffusion of solids to take place, which results in the formation of the spinel structure.

The main advantages of this method include simple processing steps, low-cost raw materials, suitability for large-scale production, and good phase stability.

But due to the practicality and large-scale possibility of this technique, solid-state synthesis is still highly appealing for industrial manufacturing. But unlike other wet-chemical synthesis techniques, solid-state synthesis often leads to bigger particle sizes, reduced surface area, and an inability to control morphology as precisely as in wet-chemical methods (Kumar et al., 2022).

3.5 Green Synthesis Approaches:

Green synthesis has recently attracted significant interest as an environmentally friendly alternative to conventional chemical preparation methods. In these approaches, plant extracts, natural polymers, sugars, microorganisms, or other biomolecules are employed as reducing, stabilising, or templating agents during the synthesis of ferrites. Common examples include the use of leaf extracts, starch, aloe vera, and various bio-waste resources.

The main advantages of green synthesis are reduced dependence on toxic chemicals, lower environmental impact, low-cost and renewable natural precursors, biocompatible surface functionalization, and sustainable processing methods.

The green synthesis approach has recently gained considerable importance as a sustainable method in place of traditional techniques for chemical synthesis. Herein, biological substances such as plant extract, polymers, sugars, microbial cells, etc., are used as reducers, stabilisers, or templates for the synthesis of the ferrite compounds. Examples of these include the use of leaf extract, starch, aloe vera, and even bio-waste materials (Vijayaram et al., 2023).

3.6 Comparative Perspective on Synthesis Methods

Every synthesis technique has its own strengths, which depend on how the product will be utilised. The co-precipitation process and sol–gel method are excellent for nanoparticle formation at low cost, whereas the hydrothermal process is recommended if one wants to have full control over the morphological characteristics of the nanoparticles. Large-scale production would favour solid-state reactions, but greener syntheses are always a better option. In advanced applications, such as electrode materials, it makes sense to use nanosized, porous, crystalline, and homogeneous ferrites (Settambolo, 2009).

3.7 Future Outlook in Ferrite Synthesis

Future research may concentrate on developing scalable synthetic processes at low

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

temperatures, flow synthesis, defect-based synthesis, and hybrid methods incorporating features of more than one technique. The use of artificial intelligence and machine learning in optimising processes may reduce the time required to develop high-performing ferrite electrodes.

Overall, the synthesis method is a critical determinant of spinel ferrite structure and electrochemical properties. Optimised synthesis parameters make it feasible to synthesise advanced ferrite electrodes.

4. Electrode Fabrication Approaches

The actual performance of spinel ferrites in electrochemical applications is determined not only by their intrinsic characteristics but also by their successful incorporation into the electrodes. Even though a ferrite powder may be highly active by itself, an electrode that exhibits poor conductivity, adhesion, electrolyte penetration capability, or mechanical durability throughout multiple cycles will have subpar electrochemical performance even with the presence of such highly active ferrites. In summary, fabricating proper electrodes from ferrite powders is key to obtaining effective supercapacitors, batteries, and sensors. The current approaches in the field involve maximising the active surface area and reducing both resistance and ion transfer limitations (Tan et al., 2017).

4.1 Pure Ferrite Electrodes

The simplest method is by using spinel ferrites as active powder materials in slurry-based coated electrodes. This involves a process of mixing ferrite nanoparticles or microparticles with a binder, including polymer-based binders like PVDF, PTFE, and CMC in combination with the carbon content, including carbon black or graphite. The resulting material would be made into a slurry mixture and coated on metal substrates, including aluminium foil, copper foil, stainless steel, and nickel foam, etc.

The main advantages of pure ferrite electrodes are simple and inexpensive fabrication, easy scalability, suitability for laboratory-scale screening studies, and good compatibility with conventional battery manufacturing methods.

However, their electrochemical performance is often constrained by relatively low intrinsic electrical conductivity, particle agglomeration, weak contact between active particles and the current collector, and lower utilisation of active material at high current densities.

For this reason, pure ferrite electrodes are commonly used as reference systems, while more advanced electrode architectures are developed to achieve better performance (Barrado et al., 1998).

4.2 Composite Electrodes:

To address the conductivity limitations of ferrites, composite electrodes are commonly prepared by integrating spinel ferrites with conductive or mechanically flexible materials. These hybrid systems generate synergistic effects, where ferrites supply redox-active sites, while the additional phase improves electron transport and strengthens structural stability.

Common conductive components include **Graphene,** due to excellent electrical conductivity with a high surface area, **reduced graphene oxide (rGO)** because of defect-rich conductive sheets that provide strong interfacial contact, **Carbon nanotubes (CNTs)** due to one-dimensional pathways for efficient electron transport,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

activated carbon, because of its porous support offering a large electrolyte-accessible surface, and **Conductive polymers** such as polyaniline (PANI), polypyrrole (PPy), and PEDOT.

The main advantages of composite electrodes include faster electron transfer kinetics, higher specific capacitance or capacity, improved cycling durability, lower charge transfer resistance, and greater mechanical flexibility.

For instance, $CoFe_2O_4$/rGO and $NiFe_2O_4$/CNT composites have demonstrated much better supercapacitor and battery performance than pure ferrite electrodes. The interface between ferrite particles and the conductive matrix is particularly important, as strong interfacial coupling helps facilitate efficient charge transport (Barrado et al., 1998).

4.3 Binder-Free Electrodes:

Binder-free electrodes have become an advanced approach for removing inactive materials such as polymer binders and reducing interfacial resistance. In this method, ferrite nanostructures are directly grown or deposited onto conductive substrates, forming self-supported electrodes with strong electrical contact.

Common substrates include Nickel foam, Stainless steel mesh, Carbon cloth, Copper foam and Titanium foil.

Typical fabrication methods include hydrothermal growth, electrodeposition, chemical bath deposition, and solvothermal synthesis.

The main advantages of binder-free electrodes are reduced inactive mass, Higher electrical conductivity, improved electrolyte accessibility, Strong adhesion of the active material, and Better rate performance and long-term cycling stability.

For example, ferrite nanosheets grown on nickel foam are widely studied for supercapacitor applications because the porous metallic framework provides excellent conductivity together with three-dimensional access for the electrolyte (Kang et al., 2020).

4.4 Nanostructured Architectures

Engineering ferrites into nanoscale structures is one of the most effective ways to improve their electrochemical performance. Nanostructuring can shorten ion diffusion distances, increase the surface-to-volume ratio, and expose a larger number of electrochemically active sites. Well-designed morphologies can also help accommodate volume changes that occur during repeated charge–discharge cycles.

Common nanostructured forms include consist of **Nanowires:** Offer direct pathways for electron transport and efficient ion movement, **Nanosheets:** Thin layered structures with a large exposed surface area, **Nanorods:** Provide better structural stability and directional conductivity, **Hollow spheres:** Internal cavities help buffer volume expansion and increase surface area, **Core-shell structures:** Integrate two materials with complementary properties, and **Porous nanoflowers:** Provide high electrolyte accessibility and multiple diffusion channels (Yang et al., 2014).

These nanostructures often deliver higher capacitance, faster reaction kinetics, and longer cycling life compared with bulk ferrite particles.

4.5 Thin Films and Flexible Electrodes:

There is growing interest in thin-film ferrite electrodes for miniaturised electronics and portable energy systems. Thin-film ferrites can be applied on flexible substrates

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

via sputtering, spray pyrolysis, spin-coating, pulsed laser deposition, and a variety of chemical deposition techniques.

Their potential applications are Micro-supercapacitors, Flexible batteries, Self-powered sensors and Portable biomedical electronics. When integrated with conductive polymers or carbon-based textiles, ferrite thin films can enable lightweight, flexible, and bendable energy storage systems (Girtan & Negulescu, 2022).

4.6 Interface Engineering and Surface Modification:

Other than morphological control, surface engineering has emerged as another promising method to boost electrode functionality. Coatings, heterojunctions, and defect-filled interfaces are some ways that can help improve the wettability, conductivity, and kinetics of the reactions at the electrodes. Most common examples are Carbon-coated ferrites, Oxide/ferrite heterostructures, Sulfide-coated ferrites, and Oxygen-vacancy engineered surface. Such modifications can greatly reduce polarisation losses and improve performance at high charge–discharge rates (Souza et al., 2016).

4.7 Comparative Perspective:

Each fabrication method provides specific advantages depending on the targeted application, such as **Pure ferrite electrode** is Low-cost and straightforward to produce; composite **electrodes,** is Highly effective for improving electrical conductivity; binder-free **electrodes** are well-suited for high-power applications; **nanostructured architectures** Offer maximum utilisation of active sites; and **Thin-film/flexible systems** are ideal for portable and wearable electronics. Therefore, selecting an appropriate fabrication strategy is just as important as choosing the ferrite composition itself (Liu et al., 2021).

4.8 Future Outlook:

Future electrode development will be centred around hierarchical three-dimensional structures, additive manufacturing, laser etching for electrodes, flexible substrates, and roll-to-roll processing techniques. The incorporation of spinel ferrites into smart conductive networks, along with advanced interface design, will also expedite the journey of spinel ferrites towards industrial applications.

In general, efficient electrode construction is the process that enables spinel ferrites to transition from potential powder substances into effective electrochemical systems. With proper electrode structure optimisation, improved conductivity, and enhanced robustness, ferrite-based electrodes can effectively cater to the growing needs of energy storage systems (Myllymaa et al., 2012).

5. Electrochemical Performance

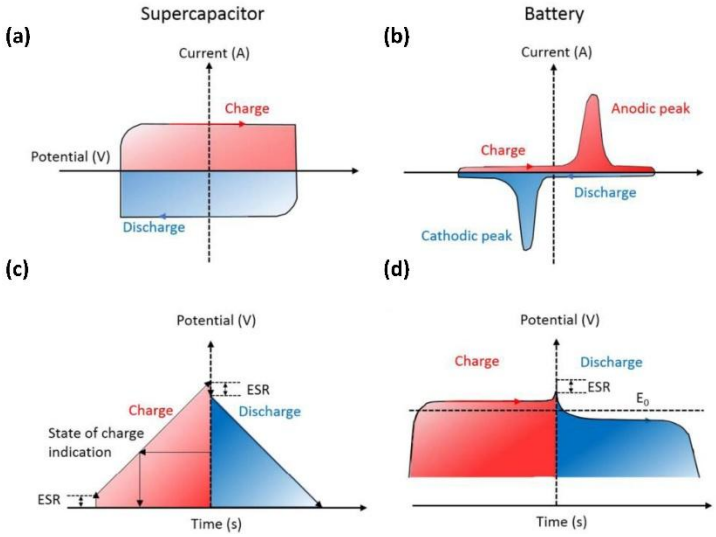
The electrochemical performance of spinel ferrite-based electrodes plays an important role in evaluating the suitability of these materials as candidates for practical energy storage applications such as supercapacitors, lithium-ion batteries, sodium-ion batteries, and hybrid energy storage devices. Electrochemical performance can be assessed based on several important characteristics such as specific capacitance, specific capacity, energy density, power density, rate performance, Coulombic efficiency, and cyclability. These characteristics are strongly associated with many

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

aspects, including the chemical composition, crystalline phase, morphology, electrical conductivity, and design of the electrode. For this reason, electrochemical characterisation plays a key role in the development of spinel ferrite-based electrodes.
Carbon-based materials are typically involved in electric double-layer charging, which means that they do not undergo faradaic redox reactions. Conversely, spinel ferrites are able to carry out reversible faradaic redox reactions in transition metals, enabling high theoretical capacitance or capacity. In addition, the use of nanotechnology techniques and compositional modification can also improve reaction kinetics and cyclability.

5.1 Electrochemical Characterisation Techniques:

Several analytical techniques are commonly used to assess the electrochemical performance of ferrite electrodes. Among them, cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS) are the most frequently applied methods (Bedoya-Lora et al., 2021).



5.1.1 1 Electrochemical Characterisation Techniques (CV):

The cyclic voltammetry analysis technique is widely employed to investigate the redox properties, reaction reversibility, and the mechanism of charging and discharging reactions. This involves the linear variation of the electrode potential between two selected voltage ranges at a specific scanning rate, with concomitant measurement of the corresponding currents.
In the case of spinel ferrites, the cyclic voltammograms usually reveal redox peaks that correspond to oxidation/reduction reactions of metal ions such as Fe2+/Fe3+, Co2+/Co3+, Ni2+/Ni3+, or Mn2+/Mn3+. The appearance of such peaks suggests the occurrence of pseudocapacitance or battery-like charge storage reactions. Key information obtained from CV analysis comprise of Identification of the charge storage mechanism, the reversibility of redox reactions, the kinetic behaviour at different scan rates, the rate capability trends, and the relative contributions of capacitive and diffusion-controlled processes. A larger enclosed CV area usually reflects higher charge storage ability, while preservation of the curve shape at high scan rates suggests favourable electrochemical kinetics.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

5.1.2 Galvanostatic Charge–Discharge (GCD):

Galvanostatic charge–discharge analysis is one of the most practical techniques for evaluating electrode performance. In this method, the electrode is charged and discharged at a constant current, while the change in potential with time is continuously recorded. Several important parameters can be extracted from GCD curves, including Specific capacitance (F g^{-1}), Specific capacity (mAh g^{-1} or C g^{-1}), Coulombic efficiency, Energy density, Power density, and Cycling stability during repeated charge–discharge cycles.

GCD curves for spinel ferrite-based pseudo-capacitor systems may include sections with non-linear shapes or voltage plateaus that result from redox processes. Higher capacitance or capacity values correspond to increased discharge time at constant current. Long cycling experiments prove to be especially useful in evaluating structural integrity (AbdulRaheem, 2024).

5.1.3 Electrochemical Impedance Spectroscopy (EIS):

Electrochemical impedance spectroscopy is an effective method for investigating the charge transport process and surface reactions using a small amplitude signal across a wide range of frequencies. Information that can be obtained by EIS usually consists of **Solution resistance (Rs):** Resistance of the electrolyte and electric contact, **Charge transfer resistance (Rct):** Electron transfer resistance on the electrode or solution interface, **Warburg impedance:** Resistance of ion diffusion, and **Low-frequency capacitive response:** Charge storage ability related. A small semicircle corresponds to lower charge transfer resistance, and a steep line in the low frequency area means good ion diffusion and capacitive response. The combination of ferrite and carbon materials or porous electrodes is always superior compared to pure ferrites (Abdulwahab et al., 2024).

5.1.4 Additional Characterisation Methods:

Other useful electrochemical evaluation methods are **cycling durability tests:** Used to assess stability over thousands of charge-discharge cycles, **Rate capability analysis:** Measures how well performance is maintained at high current densities, **Bode phase analysis:** Provides information on frequency response behaviour, and **In situ / operando techniques:** Monitor structural changes during electrochemical cycling. These approaches offer deeper insight into degradation processes, reaction mechanisms, and long-term electrode behaviour.

5.2 Factors Affecting Electrochemical Performance

There are various parameters that affect the electrochemical behaviour of spinel ferrites. If these parameters are controlled and optimised properly, then the performance of energy storage devices will definitely improve significantly (Ahad, 2017).

5.2.1 Particle Size and Surface Area

Reducing particle size to the nanoscale increases surface area and shortens the pathways for ion and electron transport. This can result in more accessible active sites, Faster electrochemical reaction kinetics, Higher specific capacitance or capacity, Better performance at high charge–discharge rates. However, particles that are too small may become prone to agglomeration or structural instability.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

5.2.2 Cation Substitution and Doping

Substituting cations or introducing dopants is an effective way to tailor the lattice parameters, electronic structure, and redox properties of spinel ferrites. Examples include Zn-doped $CoFe_2O_4$ and Mn-substituted $NiFe_2O_4$. The advantages of doping may include enhanced electrical conductivity, Additional redox-active sites, Improved structural stability, and optimised ion diffusion behaviour

5.2.3 Porous and Hierarchical Morphology

Porous structures improve electrolyte penetration and create a larger contact area between the electrode and electrolyte. Hierarchical architectures with interconnected pores can also help accommodate volume changes during repeated cycling. Their main advantages are Fast ion transport, Higher utilisation of active material, and improved cycling stability.

5.2.4 Carbon Integration

Combining ferrites with conductive carbon materials such as graphene, CNTs, activated carbon, or reduced graphene oxide (rGO) can greatly reduce internal resistance. This leads to Faster electron transport, Lower polarisation losses, Improved power density, and enhanced mechanical stability (Zwiehoff et al., 2022).

5.2.5 Defect Engineering:

The presence of oxygen vacancy, lattice strain, and surface disorder causes the creation of active sites and increases the conductivity of the material. The deliberate incorporation of these defects is emerging as an efficient approach to improve the electrochemical behaviour of ferrites (Zielińska et al., 2009).

5.2.6 Crystallinity and Phase Purity:

Crystalline substances, in general, are more structurally stable than amorphous ones. Amorphous materials or those with low crystallinity are more likely to have low electrical conductivity and catalyse unwanted side reactions. The balance between crystallinity and surface reactivity is desirable in such cases (Zheng, 2009; Zielińska et al., 2009).

5.2.7 Electrolyte Selection:

The type of electrolyte has a major influence on the voltage window, ionic conductivity, and overall compatibility of the electrochemical system. Commonly used electrolytes include **KOH or NaOH:** Widely used in aqueous supercapacitors, **Organic electrolytes:** Preferred when a wider voltage window is required, **Lithium salts:** Commonly employed in lithium-ion batteries (LIBs), and **Sodium salts:** Used in sodium-ion batteries (SIBs).

5.3 Performance Trends in Different Applications:

Criteria used to assess the performance of these materials could be quite different from each other since supercapacitors have requirements like higher capacitance, faster charging, and discharging capability, along with high cyclability, while lithium-ion batteries will need a high specific capacity and structural strength. Sodium-ion batteries should possess stable pathways for diffusion of larger-sized ions (Na^+). Hybrid storage devices will also need a proper balance between energy density and

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

power density. Consequently, there is no specific set of ferrites that can serve the purpose for everything (Zheng & Sanche, 2023).

5.4 Future Outlook:

Future improvements in the electrochemical performance of ferrites are expected to arise from several advanced strategies, consisting of **AI-guided composition optimisation**, **Defect-engineered synthesis methods**, **Multicomponent ferrite systems**, **In situ and operando characterisation techniques**, **Three-dimensional conductive scaffold designs**, and **Compatibility with solid-state electrolytes**.
Overall, spinel ferrites exhibit great promise as electrochemical energy storage materials owing to their redox capability and high degree of structural tunability. Leveraging sophisticated analytical techniques and innovative material synthesis strategies, their efficiency can be enhanced for future energy storage applications (Zhen & Zhu, 2018).

6. Applications:

It is due to their unique features that comprise redox behaviour, structural stability, magnetism, adjustability of conductivity properties, and reasonable pricing that spinel ferrites have gained much popularity in various electrochemical uses. They can be optimised for different purposes thanks to their flexible crystal chemistry. Recently, there have been promising results regarding the use of ferrites with a nanostructure and ferrite composites in supercapacitors, rechargeable batteries, sensors, and combined energy conversion-storage devices. Below, we are going to consider the main application fields of spinel ferrites.

6.1 Supercapacitors:

The supercapacitor is viewed as a promising candidate for electrical energy storage owing to its properties such as fast charging rates, high power density, long cycling stability, and safety. The spinel ferrites, as a material for use in supercapacitors, are very promising electrodes owing to their pseudocapacitance nature, whereby charge storage is made possible via surface or subsurface redox reaction of transition metal ions. Typical redox-active couples include **Fe^{2+} / Fe^{3+}**, **Co^{2+} / Co^{3+}**, **Ni^{2+} / Ni^{3+}**, and **Mn^{2+} / Mn^{3+}**. These faradaic reactions often deliver higher capacitance than conventional electric double-layer carbon electrodes. Common spinel ferrites studied for supercapacitor applications are **$CoFe_2O_4$:** Good stability and multiple accessible redox states, **$NiFe_2O_4$:** Higher conductivity and excellent cycling performance, **$MnFe_2O_4$:** Enhanced redox activity, and **$CuFe_2O_4$:** Strong pseudocapacitive characteristics.
In order to deal with the limitations in conductivity, ferrites have often been used together with conductive substrates like graphene, reduced graphene oxide (rGO), carbon nanotubes, or conductive polymers. Examples of such systems are **$CoFe_2O_4$/rGO** with high specific capacitance and enhanced rate capability, **$NiFe_2O_4$** nanosheets with superior cycle life, and **$MnFe_2O_4$/CNTs** with lower internal resistance. Despite considerable advancements, there is more work to be done to enhance the energy density without sacrificing the impressive power density of supercapacitors (Zhao et al., 2017).

6.2 Lithium-Ion Batteries:

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

Lithium-ion batteries (LIBs) still hold their dominant position in the battery market for portable electronic devices and automobiles. Much attention is being paid to spinel ferrites owing to their higher capacity as compared to graphite anodes.

Charge storage in these materials generally occurs through a conversion reaction:

$$\mathbf{MFe_2O_4 + 8Li^+ + 8e^- \rightarrow M + 2Fe + 4Li_2O}$$

where **M** represents a divalent metal ion such as Co, Ni, Zn, or Mn.

The main advantages of ferrite-based anodes are High theoretical specific capacity, Multiple electron transfer pathways, Good reversibility under optimised conditions, Structural tunability through nanoscale engineering, and Potential compatibility with composite electrode designs. Common spinel ferrites explored as LIB anodes include **$ZnFe_2O_4$:** High capacity and low cost, **$NiFe_2O_4$:** Stable cycling performance and good conductivity, **$CoFe_2O_4$:** Strong structural durability, and **$MnFe_2O_4$:** More environmentally benign composition.

Hollow sphere structures, nanoporous particles, and core-shell systems can be engineered for accommodating volumetric changes that occur during lithium intercalation/de-intercalation cycles, thus extending the cycle life. Moreover, carbon-coated ferrites are especially useful for increasing conductivity and minimising degradation during cycling (Zhang, 2020).

6.3 Sodium-Ion Batteries:

The increasing use of sodium-ion batteries (SIBs) as viable, cheaper substitutes for lithium-ion batteries lies in their abundant availability and cost-effectiveness, considering that the latter batteries rely on expensive, rare elements such as lithium.

Spinel ferrites are being investigated as anode materials for sodium storage because they offer Low raw material cost, Good structural stability, Multi-electron redox activity, and Compatibility with nanostructured electrode designs. However, Na^+ ions are larger than Li^+ ions, which results in slower diffusion kinetics and greater structural stress during cycling. For this reason, ferrite electrodes for SIBs often require Porous architectures, expanded lattice frameworks, Carbon-based composites, and Reduced particle size. Materials such as $ZnFe_2O_4$ and $NiFe_2O_4$ have demonstrated encouraging reversible sodium storage performance when properly engineered (Zahra et al., 2024).

6.4 Electrochemical Sensors:

The electrochemical sensors utilising spinel ferrite have received much attention owing to its catalytically reactive surface, mixed valency, chemical stability, and high active surface area due to their nanocrystalline structure. This permits the effective and specific sensing of various analytes, which are of biological and environmental importance. Ferrite-based sensors have been developed for Glucose monitoring, Heavy metal ions such as Pb^{2+}, Cd^{2+}, and Hg^{2+}, Dopamine detection in biomedical applications, Hydrogen peroxide sensing, and Organic pollutants and pesticides.

The main advantages of ferrite-based sensors include Fast electron transfer kinetics, Low detection limits, Good repeatability, Strong chemical stability, and the possibility of magnetic separation or recovery. For example, $NiFe_2O_4$ and $CoFe_2O_4$ nanostructures have demonstrated excellent electrocatalytic activity for glucose oxidation and neurotransmitter detection (Zahoor et al., 2023).

6.5 Electrocatalysis and Water Splitting:

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

Beyond energy storage applications, many spinel ferrites also function as active electrocatalysts for important renewable energy reactions such as the oxygen evolution reaction (OER), Oxygen reduction reaction (ORR), and Hydrogen evolution reaction (HER). These reactions play a central role in Water electrolysis, Metal-air batteries, and Fuel cells. Metallic ferrites made of Co, Ni, and Mn are very attractive candidates because they can undergo reversible electron transfer via redox-active metallic centres, and their stability stems from an oxide lattice (Yuktha et al., 2022).

6.6 Hybrid Energy Devices:

Spinel ferrites are now being used in multifunctional systems for energy generation, storage, and sensing. Such multifunctional systems include Solar power energy storage systems in which ferrites are charged using solar cells, Hybrid fuel cells with catalytic or energy storage functionalities using ferrites, Energy harvesting self-powered sensors featuring ferrite sensing electrodes, and Photocatalytic energy storage devices that use light energy to store electrochemical energy. The multifunctionality of these systems makes them ideal for remote electronics, wearable technologies, and intelligent sensing (Yousuf et al., 2025).

6.7 Environmental and Biomedical Opportunities:

Spinel ferrites have possible applications in the fields of environment and medicine owing to their characteristic properties of magnetism and stability. Applications include the removal of impurities from wastewater using electrodes, the decomposition of contaminants via catalysts, sensor-based detection systems based on magnets, and medical diagnoses/biosensors. Despite being in the nascent stage of exploration, these applications offer novel areas of utilisation for spinel ferrites, distinct from their current applications in batteries.

6.8 Comparative Perspective:

Various spinel ferrites have their unique properties for particular applications. The $CoFe_2O_4$ ferrite has outstanding stability, magnetism, and supercapacitor uses. The $NiFe_2O_4$ ferrite has great electrical conductivity, hence used in batteries and sensors. The $ZnFe_2O_4$ ferrite is ideal for battery systems with high energy storage capacity. The $MnFe_2O_4$ ferrite is ideal for devices needing strong redox reactions. The $CuFe_2O_4$ ferrite is useful in catalytic and pseudocapacitive devices. It is therefore important to choose the right ferrite for the application.

6.9 Future Outlook:

Further applications of spinel ferrites in the future will be possible due to the development of flexible and wearable electronics, solid-state supercapacitors, high-power sodium-ion batteries, AI-enabled sensor systems, renewable energy microgrids, and smart multifunctional materials. Thus, it can be noted that the potential applications of spinel ferrites are much more diverse than those for which such materials were used in the past. Spinel ferrites can no longer be considered only as magnetic materials; rather, they should be recognised as promising electrochemical materials.

7. Challenges and Future Perspectives:

Though there have been impressive developments with spinel ferrites in applications

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

like supercapacitors, rechargeable batteries, sensors, and electrocatalysts, certain scientific and technological obstacles have yet to be overcome before they can be used widely on a commercial basis. While there have been numerous laboratory experiments that have found spinel ferrites to exhibit excellent electrochemical properties, more work needs to be done in areas such as improving electrical conductivity, stability, manufacturing process, cost-effectiveness, and reproducibility. This is necessary if there is to be any further development in using spinel ferrites in commercial applications.

7.1 Poor Intrinsic Conductivity:

The other main disadvantage that often comes with spinel ferrites is their low electrical conductivity. As compared to the electrical conductivity shown by carbon, metals, and highly conductive polymers, the electrical conductivity of the spinel ferrite materials is low because most of these ferrites display semiconducting characteristics. This commonly results in Lower rate capability at high current densities, Higher polarisation losses, Reduced power density, Incomplete utilisation of active material, and Slower charging and discharging performance.

Some of the approaches that have been studied to counteract this drawback include carbon-containing composites comprising graphene, reduced graphene oxide, carbon nanotubes, and activated carbon; conductive polymers such as polyaniline, polypyrrole, and PEDOT; metal ion doping using nickel (Ni), cobalt (Co), manganese (Mn), copper (Cu), and zinc (Zn) ions as dopants to fine-tune the electronic properties; nanoscale approach, which involves the use of smaller particle sizes in order to reduce electron path length; and coatings like carbon coatings or conductive interfaces. The future direction should emphasise creating conductive paths within ferrites.

7.2 Volume Expansion During Cycling:

Charge storage in battery systems, especially lithium-ion and sodium-ion batteries, occurs mostly by means of conversion reactions in which spinel ferrites act as electrode materials. With multiple cycles of ion intercalation/de-intercalation, such reactions may result in considerable volume changes, and thus may cause particle cracking, pulverisation of the active material, loss of electrical contact, structural collapse, and capacity fading during long-term cycling. This issue is especially critical for high-capacity ferrite anodes.

A variety of useful strategies have been proposed to minimise these impacts, ranging from the use of hollow nanostructures and yolk-shell nanostructures to porous materials with free space inside, flexible carbon nano-materials, core-shell nanostructures, and buffer phases of nanocomposites. Strain-resistant electrode nanostructure design is one of the critical areas that needs attention.

7.3 Particle Agglomeration and Surface Instability:

Ferrite nanoparticles normally possess high surface energy, making them susceptible to agglomeration when synthesised or subjected to repetitive electrochemical cycles. The formation of such aggregates results in decreased surface area and restricted electrolyte access to the active phase.

This problem may lead to several difficulties, including decreased electrochemical reactivity, slow rate of ion migration, uneven current density distribution, and

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

inconsistent experimental outcomes. Moreover, surface passivation phenomena or secondary reactions with the electrolyte could negatively impact the material's performance characteristics progressively.

7.4 Scalability and Industrial Manufacturing:

Although numerous synthesis methods are capable of producing high-quality spinel ferrite materials at the laboratory scale, translating these approaches to industrial-scale manufacturing remains a significant challenge. Techniques such as hydrothermal, microwave-assisted, and template-assisted synthesis frequently encounter constraints associated with limited batch size, high processing cost, variability between production batches, significant energy consumption, and complex equipment requirements. In addition, preserving nanoscale morphology and phase purity at kilogram- or ton-scale production is particularly difficult.

For successful commercialisation, future efforts should focus on continuous-flow synthesis technologies, scalable low-temperature processing routes, roll-to-roll electrode manufacturing, cost-effective precursor materials, and standardised quality control procedures. In many cases, scalable manufacturing remains the main barrier separating academic progress from real market adoption.

7.5 Limited Understanding of Mechanisms:

Although many studies have reported strong electrochemical performance, the exact charge-storage and degradation mechanisms in numerous ferrite systems remain poorly understood. In some cases, the relative roles of surface capacitance, diffusion-controlled storage, interfacial pseudocapacitance, and conversion reactions remain under discussion.

To clarify these processes, advanced characterisation techniques are required, including in situ XRD, operando TEM, XPS during cycling, Raman spectroscopy, and electrochemical kinetic modelling. A deeper mechanistic understanding will support rational material design and reduce dependence on trial-and-error optimisation.

7.6 Electrolyte Compatibility and Interface Issues:

The interface between the electrode and electrolyte plays a crucial role in determining the performance of ferrite-based materials. Undesired side reactions, unstable solid-electrolyte interphase (SEI) layers, corrosion, and poor wettability can all shorten cycle life and lower overall efficiency.

Future progress may be achieved through tailored electrolyte formulations, additives that promote stable SEI formation, solid-state electrolytes, and protective surface coatings for interface stabilisation. As ferrite-based technologies continue to advance, interface engineering is expected to become an increasingly important strategy for next-generation electrochemical devices.

7.7 Future Directions:

Despite the existing challenges, spinel ferrites continue to be highly promising materials because of their tunable structure and multifunctional properties. Several advanced research directions are expected to support further progress in this field.

7.7.1 Multi-Metallic Ferrites:

Introducing two or more divalent metal ions into the spinel lattice can create

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197
Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

synergistic effects that enhance overall material performance. Examples include Ni-Co ferrites, Zn-Mn ferrites, and Cu-Ni ferrites. Potential advantages of these multicomponent systems include enhanced electrical conductivity, multiple redox-active centres, improved structural stability, and tunable electrochemical properties.

7.7.2 Defect Engineering:
The controlled introduction of structural defects, such as oxygen vacancies, lattice strain, surface disorder, and cation vacancies, can significantly enhance electrical conductivity, catalytic activity, and ion adsorption behaviour. As a result, defect engineering is emerging as a highly effective strategy for improving the electrochemical performance of spinel ferrites.

7.7.3 Heterostructure Electrodes:
The formation of interfaces between spinel ferrite materials and other materials may produce an interface structure that facilitates quicker electron migration and ion movement, thereby enhancing the performance of electrochemical systems. Examples include ferrite/carbon heterostructures, ferrite/sulfide composites, ferrite/MXene hybrids, and ferrite/metal oxide junctions. Such hybrid systems frequently exhibit better performance than single-component electrodes.

7.7.4 AI-Guided Materials Discovery:
Artificial intelligence and machine learning have the potential to greatly accelerate materials discovery by enabling the prediction of optimal material compositions, suitable synthesis parameters, electrochemical performance trends, and long-term stability behaviour. Data-driven screening approaches can significantly reduce the need for time-consuming experimental trial-and-error methods.

7.7.5 Green and Scalable Synthesis:
Sustainable methodologies that use plant extracts, low-temperature reactions, waste products as precursors, and efficient manufacturing pathways will be crucial for developing practical and environmentally sustainable applications.

7.7.6 Flexible and Wearable Devices:
With the continued growth of portable electronics, ferrite-based electrodes are expected to see broader application in flexible supercapacitors, textile-integrated energy devices, stretchable sensors, and lightweight hybrid energy storage systems. This emerging area holds considerable promise for future commercial applications.

7.8 Outlook:
It is anticipated that the next phase of spinel ferrite research will move beyond conventional powder synthesis toward more intelligent electrode design, deeper insight into reaction mechanisms, and scalable manufacturing strategies. Realising this advancement will require the integrated efforts of materials chemistry, electrochemistry, nanotechnology, and data science.
In conclusion, despite persistent challenges such as limited electrical conductivity, structural degradation, and large-scale production constraints, the future outlook for spinel ferrites remains highly promising. Continued progress in composition engineering, interface optimisation, and sustainable processing may establish these

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Online ISSN 3007-3197 Print ISSN 3007-3189
Volume 4, Issue 2 (2026)
http://amresearchreview.com/index.php/Journal/about

materials as key components in next-generation energy storage systems and multifunctional electrochemical technologies.

8. Conclusion:

The latest invention of spinel ferrite as a class of materials with multiple functionalities for the latest electrochemical technology is attributable to the tunability of the crystal system, the presence of mixed valence states, chemical stability, magnetic nature, and affordability over other materials. The basic structure formula, that is, MFe2O4, gives way to the substitution of the divalent metal cations over Fe2+ ions, giving control over the electrical conductivity, redox ability, electrocatalytic activity, and mechanical stability. Therefore, spinel ferrites have been receiving more attention as materials for advanced energy storage devices such as supercapacitors, Li-ion, Na-ion batteries, and electrochemical sensors and catalysts.

From the above review, it is clearly evident that the properties of spinel ferrites play an important role in determining the electrochemical capacities of these compounds, which include factors like cation distribution, particle size, morphological aspects, porosity, crystalline properties, defects, and surface chemistry. Control over these parameters becomes crucial during electrode synthesis.

Improved electrochemical performance can be achieved through the use of nanotechnology, porous structures, binder-free electrodes, and composite materials based on graphene, carbon nanotubes, and conducting polymers. These approaches help enhance electrical conductivity, increase the active surface area, reduce damage caused by volume changes, and improve long-term stability. However, challenges such as low intrinsic conductivity, particle agglomeration, structural instability, and difficulties in large-scale manufacturing remain.

To summarise, there is a bright prospect for future research and development of spinel ferrite materials in electrochemical applications. Several approaches, such as multimetal doping, defect engineering, heterostructure design, machine learning-assisted design, green synthetic strategies, and flexible device architecture, will be considered.

References

AbdulRaheem, Y. (2024). Statistical significance versus clinical relevance: key considerations in interpretation medical research data. *Indian Journal of Community Medicine*, *49*(6), 791-795.

Abdulwahab, K. O., Khan, M. M., & Jennings, J. R. (2024). Ferrites and ferrite-based composites for energy conversion and storage applications. *Critical Reviews in Solid State and Materials Sciences*, *49*(5), 807-855.

Ahad, A. (2017). Analysis of grain growth, densification and functional properties of manganese substituted NiCuZn nanocrystalline ferrites.

Ahmad, W., Akhtar, N., Choi, A., Ateeq, M., Shah, N. S., Khan, J. A., Al-Anazi, A., & Han, C. (2025). Hydrothermally engineered TiO2/CdS nanocomposite for efficient photocatalytic degradation of carbamazepine, hydrogen evolution and antibacterial applications. *Separation and Purification Technology*, 136131.

Ali, S., Rahim, M., Fazil, P., Ahmad, M. S., Ullah, A., Shah, M. R., Rukh, G., Ateeq, M., Khattak, R., & Khan, M. S. (2021). Synthesis and photonics applications of afzelechin conjugated silver nanoparticles. *Coatings*, *11*(11), 1295.

Ati, A. A., Abdalsalam, A. H., Alardhi, S. M., Dabagh, S., Salim, A., Ramadhan, A.

A., Abdulkareem, M. H., & Taki, M. M. (2025). Structural, morphology, magnetic, and electrochemical characterization of pure and magnesium-substituted cobalt ferrite nanoparticles. *Journal of Materials Science: Materials in Electronics*, *36*(4), 252.

Barrado, E., Montequi, J., Medina, J., Pardo, R., & Prieto, F. (1998). Electrochemical study of iron ferrite sludge obtained under the conditions proposed for the purification of waste water at a carbon paste electrode. *Journal of Electroanalytical Chemistry*, *441*(1-2), 227-235.

Bedoya-Lora, F. E., Holmes-Gentle, I., & Hankin, A. (2021). Electrochemical techniques for photoelectrode characterisation. *Current Opinion in Green and Sustainable Chemistry*, *29*, 100463.

Bhagwat, V., Humbe, A. V., More, S., & Jadhav, K. (2019). Sol-gel auto combustion synthesis and characterizations of cobalt ferrite nanoparticles: Different fuels approach. *Materials Science and Engineering: B*, *248*, 114388.

Cai, J., Laubernds, K., Galasso, F. S., Suib, S. L., Liu, J., Shen, X. F., Begge, E., Kunz, H. R., & Fenton, J. M. (2005). Preparation method and cation dopant effects on the particle size and properties of BaCeO3 perovskites. *Journal of the American Ceramic Society*, *88*(10), 2729-2735.

Dippong, T., Levei, E. A., & Cadar, O. (2021). Recent advances in synthesis and applications of MFe2O4 (M= Co, Cu, Mn, Ni, Zn) nanoparticles. *Nanomaterials*, *11*(6), 1560.

Geng, H., Peng, Q., Wang, L., Li, H., Liao, Y., Ma, Z., & Shuai, Z. (2012). Toward quantitative prediction of charge mobility in organic semiconductors: tunneling enabled hopping model. *Advanced Materials*, *24*(26), 3568-3572.

Giannini, S., & Blumberger, J. (2022). Charge transport in organic semiconductors: the perspective from nonadiabatic molecular dynamics. *Accounts of Chemical Research*, *55*(6), 819-830.

Girtan, M., & Negulescu, B. (2022). A review on oxide/metal/oxide thin films on flexible substrates as electrodes for organic and perovskite solar cells. *Optical Materials: X*, *13*, 100122.

Hussain, M. A., Rahim, M., Idrees, M. A., Quaser, S., Faisal, M., & Abbas, N. (2023). The Energy Models for Pakistan: Energy Models for Pakistan. *AL-KHWARIZIMI JOURNAL OF SCIENCES & HUMANITIES*, *2*(1).

Hussein, S. S., & Al-Shakarchi, E. K. (2024). Sol gel auto combustion method to prepare nanostructures LiZnCu ferrite. *Ceramics international*, *50*(10), 17913-17923.

Kang, Y., Deng, C., Chen, Y., Liu, X., Liang, Z., Li, T., Hu, Q., & Zhao, Y. (2020). Binder-free electrodes and their application for Li-ion batteries. *Nanoscale research letters*, *15*(1), 112.

Kaur, K. (2025). Introduction to Spinel and Inverse Spinel Ferrites. In *Spinel and Inverse Spinel Ferrites* (pp. 1-15). Chapman and Hall/CRC.

Khan, I., Liu, W., Zada, A., Raziq, F., Ali, S., Shah, M. I. A., Ateeq, M., Khan, M., Alei, D., & Fazil, P. (2024). Recent progress in emerging materials and hybrid nanocomposites for peroxymonosulfate and peroxydisulfate activation towards solar light-driven photocatalytic degradation of emerging pollutants. *Coordination Chemistry Reviews*, *499*, 215466.

Kumar, A., Dutta, S., Kim, S., Kwon, T., Patil, S. S., Kumari, N., Jeevanandham, S., & Lee, I. S. (2022). Solid-state reaction synthesis of nanoscale materials:

strategies and applications. *Chemical reviews*, *122*(15), 12748-12863.

Liu, Z., Tian, B., Zhang, B., Liu, J., Zhang, Z., Wang, S., Luo, Y., Zhao, L., Shi, P., & Lin, Q. (2021). A thin-film temperature sensor based on a flexible electrode and substrate. *Microsystems & nanoengineering*, *7*(1), 42.

Mishal, U., Rahim, M., Ateeq, M., Abbas, N., Khalid, M., Fazil, P., & Hussain, M. A. (2023). Optical study of Desmodium elegan mediated silver nanoparticles using Tauc's equation. *International Journal of Nanoelectronics and Materials (IJNeaM)*, *16*(4), 923-932.

Myllymaa, S., Pirinen, S., Myllymaa, K., Suvanto, M., Pakkanen, T. A., Pakkanen, T. T., & Lappalainen, R. (2012). Improving electrochemical performance of flexible thin film electrodes with micropillar array structures. *Measurement Science and Technology*, *23*(12), 125701.

Nazar, M., Mishal, U., Khalid, M., Fazil, P., & Rahim, M. (2022). The effect of magnesium doping concentration on the structural and optical properties of zinc oxide nanoparticles. *JOURNAL OF OVONIC RESEARCH*, *18*(4), 565-578.

Ndione, P. F., Shi, Y., Stevanovic, V., Lany, S., Zakutayev, A., Parilla, P. A., Perkins, J. D., Berry, J. J., Ginley, D. S., & Toney, M. F. (2014). Control of the electrical properties in spinel oxides by manipulating the cation disorder. *Advanced Functional Materials*, *24*(5), 610-618.

Pachpinde, A. M. (2018). *Ferrite Catalysts*. Lulu. com.

Priyadharsini, R., Manoharan, C., Bououdina, M., Sagadevan, S., Venkateshwarlu, M., & Bahadur, S. A. (2024). Impact of nickel substitution on structural, dielectric, magnetic, and electrochemical properties of copper ferrite nanostructures for energy storage devices. *Journal of Colloid and Interface Science*, *653*, 917-929.

Rahim, M., Hussain, F., Khalid, M., Abbas, N., Ateeq, M., Ashiq, M., Younas, M., Yousef, E. S., & Alshahrani, T. (2024). Structural and dielectric properties of cerium doped magnesium-zinc aluminate spinel nano-crystallites for high frequency applications. *Ceramics international*, *50*(7), 11420-11429.

Rahim, M., Hussain, F., Khalid, M., Younas, M., Boukhris, I., Al-Buriahi, M., & Ashiq, M. (2025). La3+ ion doped Mg-Zn Aluminates Spinel Nanoparticles: A Gateway to High-Frequency Dielectric Applications. *Materials Research Bulletin*, 113901.

Rahim, M., Khan, M., Abbas, N., Khalid, M., & Hussain, M. A. (2024). Synthesis, characterization and antimicrobial activity of Cassia fistula mediated Cobalt doped Copper oxide nanoparticle against Salmonella typhi a step toward antibacterial nanomedicine. *International Journal of Nanoelectronics and Materials (IJNeaM)*, *17*(1), 147-152.

Saha, S. K. (2016). Study of magnetic and magnetoelectric properties of some perovskite-spinel composites.

Salih, S. J., & Mahmood, W. M. (2023). Review on magnetic spinel ferrite (MFe2O4) nanoparticles: From synthesis to application. *Heliyon*, *9*(6).

Schmidt, R., Prado-Gonjal, J., & Morán, E. (2022). Microwave assisted hydrothermal synthesis of nanoparticles. *arXiv preprint arXiv:2203.02394*.

Settambolo, R. (2009). TWO SYNTHETIC METHODOLOGIES AT COMPARISON. *Heterocycles*, *79*, 219-228.

Sharif, T., Ateeq, M., Ahmad, S., Ahmad, W., Zada, A., Fazil, P., Shah, N. S., Al-

Anazi, A., Khan, J. A., & Azizi, S. (2025). Degradation of Rosuvastatin by UV/H2O2 and UV/H2O2/Fe2+ processes: Kinetics, mechanism, toxicity and economic assessment. *Brazilian Journal of Chemical Engineering*, 1-14.

Shuai, Z., Geng, H., Xu, W., Liao, Y., & André, J.-M. (2014). From charge transport parameters to charge mobility in organic semiconductors through multiscale simulation. *Chemical Society Reviews*, *43*(8), 2662-2679.

Souza, V., Husmann, S., Neiva, E., Lisboa, F., Lopes, L., Salvatierra, R., & Zarbin, A. (2016). Flexible, transparent and thin films of carbon nanomaterials as electrodes for electrochemical applications. *Electrochimica Acta*, *197*, 200-209.

Tan, R. K. L., Reeves, S. P., Hashemi, N., Thomas, D. G., Kavak, E., Montazami, R., & Hashemi, N. N. (2017). Graphene as a flexible electrode: review of fabrication approaches. *Journal of Materials Chemistry A*, *5*(34), 17777-17803.

Ullah, A., Fazil, P., Rukh, G., Muhammad, M. T., Rahim, M., Ateeq, M., Khattak, R., Khan, M. S., Abu Ali, O. A., & Saleh, D. I. (2021). A novel colorimetric chemosensor based on ferene-s-conjugated silver nanoparticles for selective recognition of Fe2+. *Coatings*, *11*(11), 1293.

Vaccari, A. (1998). Preparation and catalytic properties of cationic and anionic clays. *Catalysis today*, *41*(1-3), 53-71.

Vijayaram, S., Razafindralambo, H., Sun, Y.-Z., Vasantharaj, S., Ghafarifarsani, H., Hoseinifar, S. H., & Raeeszadeh, M. (2023). Applications of green synthesized metal nanoparticles—a review. *Biological trace element research*, 1.

Vohra, M. I., Alasiri, A., Ateeq, M., Sakr, R. Y., Krzywiecki, M., Shehzad, K., Azizi, S., & Zada, A. (2025). Coordination between semiconductor defects and their role in charge separation and light absorption for exceptional solar light driven photocatalysis. *Coordination Chemistry Reviews*, *545*, 217017.

Yang, H., Liao, S., Huang, C., Du, L., Chen, P., Huang, P., Fu, Z., & Li, Y. (2014). Facile one-pot approach to the synthesis of spherical mesoporous silica nanoflowers with hierarchical pore structure. *Applied surface science*, *314*, 7-14.

Yaseen, M., Khattak, M., Humayun, M., Usman, M., Shah, S., Bibi, S., Hasnain, B., Ahmad, S., Khan, A., & Shah, N. (2021). A review of supercapacitors: materials design, modification, and applications. Energies 2021, 14, 7779. In: s Note: MDPI stays neutral with regard to jurisdictional claims in published ….

Yaseen, M., Khattak, M. A. K., Humayun, M., Usman, M., Shah, S. S., Bibi, S., Hasnain, B. S. U., Ahmad, S. M., Khan, A., & Shah, N. (2021). A review of supercapacitors: materials design, modification, and applications. *Energies*, *14*(22), 7779.

Yousuf, J., Ullah, W., Khalid, M., Younus, M., Ashiq, M., Boukhris, I., Gondal, M., Mehwish, M., Almutawah, Z. S., & Dildar, M. (2025). Structural, morphological, dielectric and magnetic properties of (ZnFe2O4) 1-x (MWCNTs) x nanocomposites. *The European Physical Journal Plus*, *140*(3), 196.

Yuktha, H., Kulkarni, G. S., Shetty, A., & Paarakh, P. M. (2022). Nanoparticles in Pharmaceutical Science. *Journal of Community Pharmacy Practice (JCPP)*, 2799-1199.

Zahoor, S., Sheraz, S., Shams, D. F., Rehman, G., Nayab, S., Shah, M. I. A., Ateeq, M., Shah, S. K., Ahmad, T., & Shams, S. (2023). Biosynthesis and Anti-inflammatory Activity of Zinc Oxide Nanoparticles Using Leaf Extract of

Senecio chrysanthemoides. *BioMed research international*, *2023*(1), 3280708.

Zahra, N., Sabahat, S., Saira, F., Saleem, R. S. Z., Rahim, A., Khan, Z. U. H., & Nazir, F. (2024). Fabrication of nickel ferrite@ MWCNTs for super-capacitor applications. *Journal of Applied Electrochemistry*, *54*(9), 1969-1981.

Zhang, L. (2020). Applications, Challenges and Development of Nanomaterials and Nanotechnology. *Journal of the Chemical Society of Pakistan*, *42*(5).

Zhao, Q., Yan, Z., Chen, C., & Chen, J. (2017). Spinels: controlled preparation, oxygen reduction/evolution reaction application, and beyond. *Chemical reviews*, *117*(15), 10121-10211.

Zhen, Z., & Zhu, H. (2018). Structure and properties of graphene. In *Graphene* (pp. 1-12). Elsevier.

Zheng, Y., & Sanche, L. (2023). Mechanisms of nanoscale radiation enhancement by metal nanoparticles: Role of low energy electrons. *International Journal of Molecular Sciences*, *24*(5), 4697.

Zheng, Z. (2009). *Synthesis and modifications of metal oxide nanostructures and their applications* Queensland University of Technology].

Zielińska, A., Skwarek, E., Zaleska, A., Gazda, M., & Hupka, J. (2009). Preparation of silver nanoparticles with controlled particle size. *Procedia chemistry*, *1*(2), 1560-1566.

Zwiehoff, S., Johny, J., Behrends, C., Landmann, A., Mentzel, F., Bäumer, C., Kröninger, K., Rehbock, C., Timmermann, B., & Barcikowski, S. (2022). Enhancement of proton therapy efficiency by noble metal nanoparticles is driven by the number and chemical activity of surface atoms. *Small*, *18*(9), 2106383.