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$Ni_{0.4}Cu_{0.6}Mn_2O_4$ SPINEL OXIDES: POTENTIAL FOR HIGH-TEMPERATURE FUEL-CELL APPLICATIONS

POTENCIAL ŠPINELNIH OKSIDOV TIPA $Ni_{0.4}Cu_{0.6}Mn_2O_4$ ZA VISOKO TEMPERATURNE APLIKACIJE GORIVNIH CELIC

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$Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel is investigated as a potential multifunctional material for solid-oxide fuel cell (SOFC) applications due to its structural stability, mixed ionic–electronic conductivity, and catalytic activity. This review examines the crystal structure, methods of synthesis, and electrochemical behaviour of Ni–Cu–Mn spinel, with the emphasis on the relationship between cation distribution, defect chemistry, and performance. The spinel structure enables electron transport through small polaron hopping, although conductivity and catalytic efficiency remain lower than conventional Ni–YSZ and perovskite electrodes. The effects of synthesis parameters, including calcination temperature and mixing time, on phase purity, particle morphology, and catalytic behaviour are critically analysed. In addition, the catalytic properties for the fuel-oxidation and oxygen-reduction reactions are discussed, highlighting the limitations in polarization resistance and reaction kinetics. Stability considerations, including resistance to carbon deposition and chromium poisoning, are evaluated, although the long-term durability data remain limited. Strategies such as doping, composite formation, and microstructure engineering are identified as potential routes for performance enhancement. However, current studies lack standardized electrochemical validation and full-cell testing. Future work should focus on establishing structure–property–performance relationships and long-term evaluation under realistic SOFC operating conditions.

Keywords: $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel; Solid oxide fuel cell; Catalytic properties; Electrode

Avtorji v članku opisujejo pregled raziskav špinela vrste $Ni0{,}4Cu0{,}6Mn_2O_4$ kot potencialnega večnamenskega materiala za uporabo v trdnih oksidnih gorivnih celicah (SOFC; angl.: Solid Oxide Fuel Cells), zaradi svoje strukturne stabilnosti, mešane ionsko-elektronske prevodnosti in katalitične aktivnosti. Avtorji so preučevali kristalno strukturo, metode sinteze in elektrokemijsko obnašanje špinela Ni-Cu-Mn s poudarkom na razmerju med porazdelitvijo kationov, kemijo strukturnih napak in zmogljivostjo. Struktura špinela omogoča transport elektronov z majhnimi polaronskimi skoki, čeprav prevodnost in katalitična učinkovitost ostajata nižji kot sta pri običajnih z nikljem in itrijevim oksidom stabiliziranem cirkonijevem oksidu (Ni-YSZ) in perovskitnih elektrodah. Kritično so analizirali učinke parametrov sinteze, vključno s temperaturo kalcinacije in časom mešanja na fazno čistost, morfologijo delcev in katalitično obnašanje. Poleg tega so ugotavljali kakšne so katalitične lastnosti za reakcije oksidacije goriva in redukcije kisika, pri čemer so poudarjene omejitve v polarizacijski upornosti in reakcijski kinetiki. Ocenili so vidike stabilnosti, vključno z odpornostjo na odlaganje ogljika in neželeno onesnaženje (zastrupitev) s kromom. Dolgotrajna stabilnost materiala pa ostaja še neraziskana. Avtorji so strategije, kot so dopiranje, tvorba kompozitov in mikrostrukturno inženirstvo opredelili kot možne poti za izboljšanje zmogljivosti. Ugotavljajo, da obstoječim študijam manjka standardizirana elektrokemijska validacija in testiranje celotne celice. Avtorji v zaključkih ugotavljajo, da bi se prihodnje raziskave morale osredotočiti na ugotavljanje razmerij med strukturo, lastnostmi in zmogljivostjo ter dolgoročno oceno v realnih obratovalnih pogojih SOFC.

Ključne besede: špinel tipa $Ni0{,}4Cu0{,}6Mn_2O_4$, trdna oksidna gorivna celica, katalitične lastnosti, elektroda

1 INTRODUCTION

1.1 Background on Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells (SOFCs) are a promising technology for high-efficiency and low-emission energy-conversion systems. Unlike combustion-based systems, SOFCs generate electricity through direct electrochemical oxidation, which reduces thermodynamic losses and improves system efficiency. They directly convert chemical energy into electrical energy through electrochemical reactions between a fuel such as hydrogen, methane, or biogas and oxygen. SOFCs are distinguished from other fuel-cell types by the use of a solid ceramic electrolyte, which enables operation at temperatures ranging from 600 °C to 1000 °C.[1] A typical SOFC comprises an anode, a cathode, and an electrolyte. The electrolyte conducts O^{2+} ions, while the electrodes must exhibit mixed ionic–electronic conductivity to sustain charge transfer and reaction kinetics under operating conditions.

One of the most notable benefits of SOFCs is their high efficiency. SOFCs can achieve electrical efficiencies exceeding 60 % when used independently and up to 85 % in combined heat and power (CHP) systems that use waste heat to generate extra energy.[2,3] This performance has been quantitatively validated in several system-level studies, where thermal integration reduces en-

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ergy losses compared with conventional gas-turbine systems. This high efficiency arises from the direct electrochemical conversion of chemical energy without intermediate combustion processes, which reduces energy losses compared with conventional systems.[4] Furthermore, SOFCs operate with a wide range of fuels, including hydrogen, natural gas, and biogas, which increases system flexibility but introduces challenges related to fuel impurities and carbon deposition. Carbon deposition and sulphur poisoning remain limiting factors, particularly for hydrocarbon fuels, requiring improved catalyst tolerance. The environmental benefits are also significant, with low emissions of nitrogen oxides and sulfur oxides, while the main by-products are water and carbon dioxide.[5]

At the anode, nickel-based catalysts accelerate fuel oxidation by breaking down the fuel into smaller molecules, enhancing energy-conversion efficiency.[6] However, quantitative studies report degradation rates associated with Ni coarsening and carbon accumulation, leading to increased polarization resistance during long-term operation. Their stability is a concern, as high temperatures and interactions with cell components can lead to degradation or sintering, impacting long-term performance. One approach to improving anode materials is the development of metal-ceramic composites. For example, Pulse Plasma Sintering (PPS) was used to fabricate Al_2O_3–Cu–Ni composites at 1250 °C, 1300 °C, and 1350 °C.[7] The best density and mechanical properties were achieved at 1300 °C, optimizing the microstructure for applications like SOFC.[8] However, these studies rarely report electrochemical metrics such as conductivity or power density, limiting comparison with conventional Ni-YSZ systems. On the cathode side, catalysts are essential for the oxygen reduction reaction (ORR), where oxygen is converted into oxygen ions.[9]

This reaction is typically slow, so high-performance perovskite-based materials are employed to boost reaction kinetics due to their catalytic activity and stability in the harsh operating conditions of SOFCs.[10–12] Recent literature reports $La_{0.6}Sr_{0.4}CoO_{3-\delta}$ cathodes exhibit polarization resistance values below 0.1 $\Omega \cdot cm^2$ at 800 °C under air, indicating fast oxygen-reduction kinetics and high catalytic activity compared with conventional electrode materials.[13] However, cobalt-based perovskites such as LSC and LSCF exhibit degradation under chromium poisoning during extended operation, where $SrCrO_4$ formation and surface segregation reduce the oxygen-exchange kinetics and increase the polarization resistance. Reported degradation rates reach several $\Omega \cdot cm^2$ per 1000 h, accompanied by time-dependent declines in oxygen surface-exchange coefficients and progressive impedance growth under chromium exposure.[14–17] Similar degradation trends have been reported in perovskite cathodes under long-term operation, where surface segregation and chromium interaction lead to performance decay.[18] These devices utilize a solid ceramic electrolyte to facilitate the electrochemical reaction between a fuel and oxygen at high operating temperatures. Key components include the anode, where nickel-based cermet catalysts facilitate fuel oxidation, and the cathode, where perovskite-based materials enable the oxygen reduction reaction due to their mixed ionic–electronic conductivity and high catalytic activity.[19–22] Despite these advances, degradation mechanisms such as chromium poisoning and thermal mismatch continue to limit durability.

The performance of SOFC catalysts affects their longevity and stability, with research focusing on addressing catalyst degradation, poisoning, and phase shifts that can reduce the SOFC's efficiency and operational lifetime.[23] Recent studies emphasise the need for materials that exhibit balanced ionic and electronic conductivity while maintaining structural stability during redox cycling, as these factors govern electrochemical performance and long-term durability.[24–27] While spinel oxides exhibit high thermal stability and chemical compatibility, several studies report low ionic conductivity in undoped systems, often of the order of 10^{-4} $S \cdot cm^{-1}$, which restricts their use as stand-alone electrodes and necessitates composite or hybrid electrode design.[28,29] Recent studies emphasise the need for alternative materials that combine thermal stability with balanced ionic and electronic conductivity. In this context, spinel oxides such as $Ni_{0.4}Cu_{0.6}Mn_2O_4$ have attracted attention. Compared with conventional Ni-YSZ anodes and cobalt-based cathodes, spinel systems offer improved resistance to carbon deposition and lower material costs, although reported performance varies across studies. However, existing literature largely reports qualitative improvements without sufficient quantitative comparison to established materials. For example, the reported electrical conductivity of Ni–Cu–Mn spinels ranges from 10^{-2} $S \cdot cm^{-1}$ to 10^2 $S \cdot cm^{-1}$ depending on the method of synthesis, whereas conventional Ni–YSZ anodes typically exhibit higher and more stable conductivity under similar conditions, indicating that spinel systems remain less competitive without further optimization. This highlights the need for systematic evaluations of the conductivity, catalytic activity, and long-term stability using standardized electrochemical metrics. **Figure 1** summarizes the key advantages of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ for SOFC applications.

1.2 Importance of Spinel Structures in SOFCs

Spinel oxides are a type of ceramic substance with a distinct crystal structure, represented by the general formula AB_2O_4.[30] This structure has been widely investigated in SOFC research due to its tuneable cation distribution and its influence on electrochemical behaviour. In this arrangement, A- and B-site cations occupy specific positions within a face-centred-cubic lattice, where 'A' and 'B' denote metal cations located in tetrahedral and octahedral sites, respectively. A divalent metal cation, such as magnesium or zinc, typically occupies the A-site, while trivalent or tetravalent cations, such as aluminium,

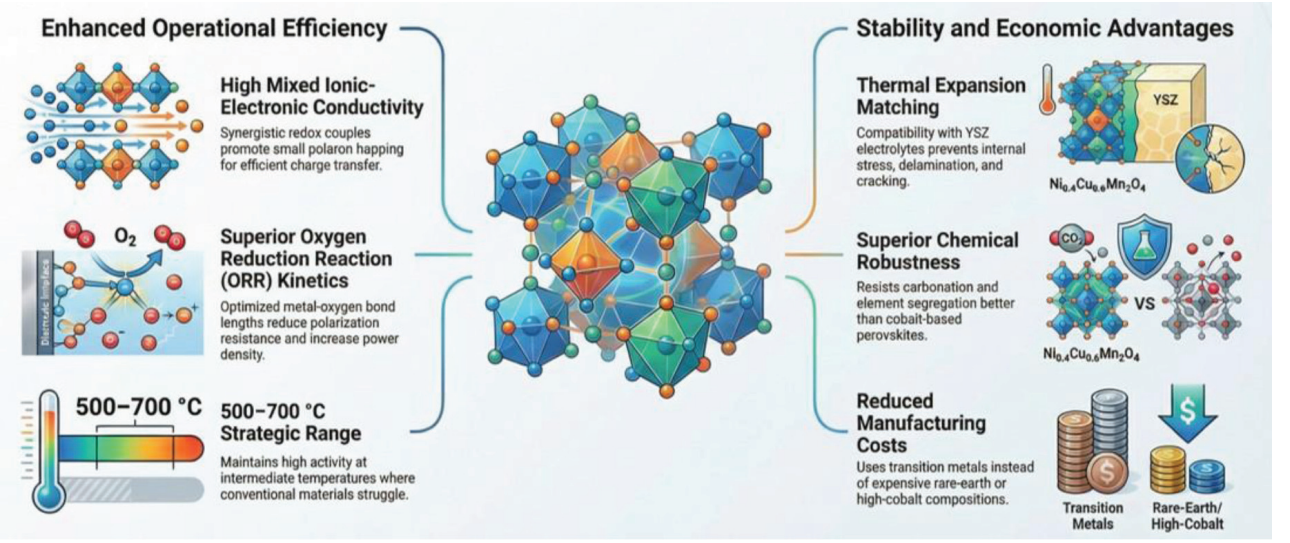

Figure 1: Advantages of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ material

chromium, or iron, occupy the B-site. However, many reported systems exhibit partial inversion, where cations exchange lattice sites, which modifies electronic conductivity and catalytic activity.[31] This cation disorder is rarely quantified but has been shown to affect charge-transport mechanisms.

As shown in **Figure 2**, oxygen ions form a close-packed-cubic structure, creating interstitial tetrahedral and octahedral sites for cation occupation. This arrangement defines the oxygen-ion migration pathways and electron hopping between transition-metal ions, which directly influence the conductivity and the SOFC's performance.[32] For example, small polaron hopping between Mn^{3+}/Mn^{4+} or Cu^{+}/Cu^{2+} couples contributes to electronic conductivity, typically reported in the range 10^{-3} S·cm^{-1} to 10^{1} S·cm^{-1} depending on the composition.[33] This structure contributes to high structural stability, moderate ionic conductivity, and mixed electronic conductivity in spinel oxides. In comparison, yttria-stabilised zirconia exhibits a higher ionic conductivity at elevated temperatures, while cobalt-based perovskites demonstrate superior oxygen-reduction kinetics, indicating that spinel oxides occupy an intermediate performance position rather than outperforming established materials. However, ionic conductivity remains lower than 10^{-2} S·cm^{-1} in most cases, limiting their stand-alone electrolyte application.[34–36]

Spinel oxides are widely studied for SOFC applications due to their functional properties. Their ionic conductivity supports oxygen-ion transport, which is essential for electrode reactions.[38] However, some alternative materials exceed yttria-stabilized zirconia in ionic conductivity but are limited by electronic leakage and stability issues.[39–41] Comparative studies indicate that yttria-stabilised zirconia exhibits limited ionic conductivity at intermediate temperatures (800 °C), which constrains

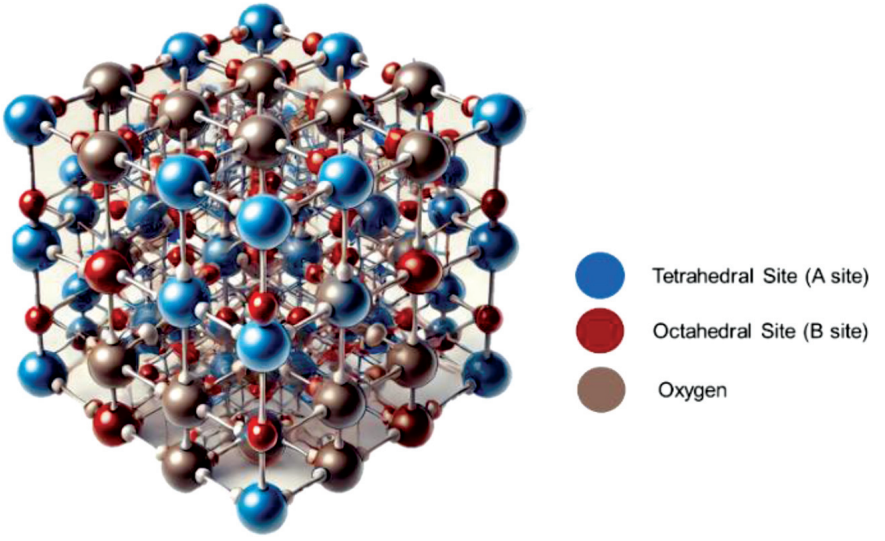

Figure 2: Spinel structure in SOFC. Adapted from[37]

the SOFC's performance.[41,42] Spinel structures also exhibit strong thermal stability, allowing them to operate under high-temperature conditions without significant structural degradation. Thermal expansion coefficients of spinel oxides (typically 8–12 × 10^{-6} K^{-1}) are generally compatible with SOFC components when properly matched, reducing mechanical stresses during operation.[43,44] This stability reduces mechanical failures during thermal cycling but does not fully eliminate phase-transformation risks during prolonged operation.

In addition, spinel oxides demonstrate catalytic activity for both the fuel-oxidation and oxygen-reduction reactions. However, quantitative comparisons show that their oxygen-reduction activity is generally lower than that of cobalt-based perovskites, which often achieve a polarization resistance below 0.1 Ω·cm^2 at intermediate temperatures.[45] Despite this, their catalytic performance often remains inferior to advanced perovskite materials, particularly in oxygen-reduction kinetics. Spinel materials offer advantages in chemical stability, especially under reducing and carbon-rich environments, where perovskites may degrade.[46] These combined properties make spinel oxides suitable for use in SOFC components such as anodes, cathodes, and protective coatings. Nevertheless, performance strongly depends on the synthesis method, cation distribution, and microstructural control, which are often not systematically compared in existing studies.

1.3 $Ni_{0.4}Cu_{0.6}Mn_2O_4$ Spinel as a Promising Catalyst Material

$Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel has been identified as a potential material for SOFC applications.[47] Conventional Ni-YSZ and cobalt-based perovskites exhibit compositional limitations and higher material costs.[48,49] Therefore, $Ni_{0.4}Cu_{0.6}Mn_2O_4$ is considered as a potential alternative for SOFC applications. This composition benefits from the synergistic effects of its constituent metals, where each element contributes to catalytic performance. Nickel provides strong catalytic activity for hydrogen and hydrocarbon oxidation at the anode.[50] However, Ni-based systems are prone to carbon deposition and sintering, which limits long-term stability.[51] Copper contributes to catalytic stability and may reduce carbon deposition under certain operating conditions.[52] Experimental studies report reduced carbon deposition rates in Cu-containing systems compared with pure Ni catalysts under methane-fuel conditions. Manganese supports the oxygen-reduction reaction (ORR) at the cathode through redox activity.[53] Despite these contributions, reported ORR activity remains lower than perovskite electrodes, indicating slower surface-exchange kinetics.

The XRD analysis provides evidence of phase formation and structural evolution rather than directly confirming catalytic performance. Therefore, an interpretation of **Figure 3** must be limited to crystallographic and microstructural changes rather than performance claims. **Figure 3** presents the XRD patterns of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ and CuMnO showing phase evolution and crystallinity changes with mixing time. The peak sharpening observed with increased mixing time indicates improved crystallinity, which is associated with enhanced structural stability but may reduce the active surface area due to grain growth. This trade-off between crystallinity and surface area is rarely quantified but directly influences catalytic activity. The regions labelled A and B further illustrate structural variation, where Region A shows gradual phase evolution and Region B indicates improved crystallite development through peak narrowing and intensity increase. No secondary impurity peaks are evident at longer mixing times, suggesting improved phase purity.

$Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel exhibits mixed ionic–electronic conductivity.[47] The incorporation of Ni and Cu enhances the overall conductivity by promoting oxygen-vacancy formation, which increases charge transport through enhanced hopping mechanisms within the spinel structure.[55] Electron transport is commonly associated

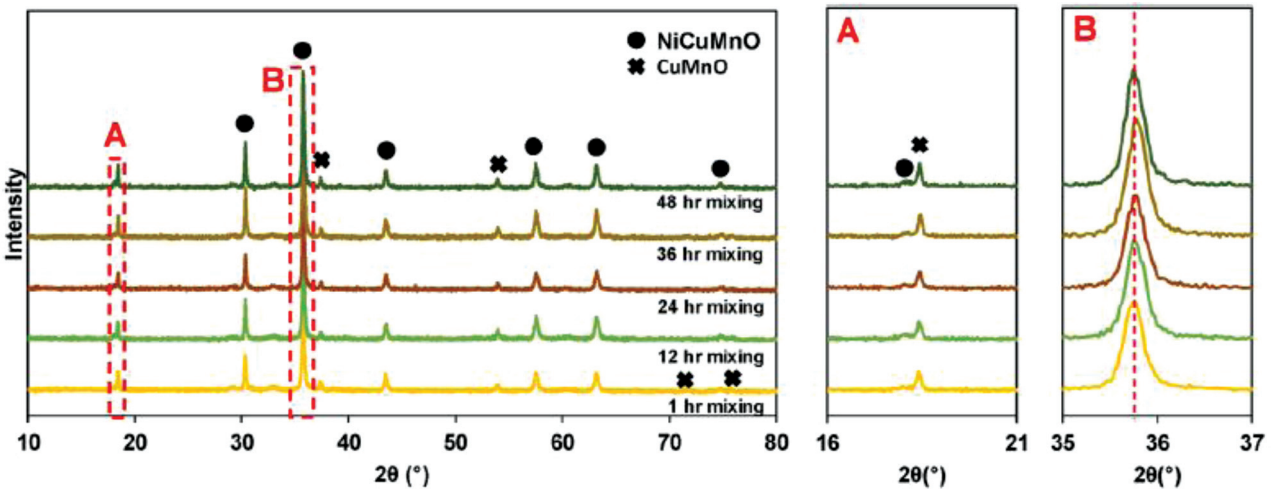

Figure 3: XRD pattern of $Ni_{0.4}Cu_{0.6}Mn_2O_4$.[54]

Table 1: Comparison of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel with conventional SOFC electrode materials

Material	Conductivity ($S \cdot cm^{-1}$)	Polarization Resistance ($\Omega \cdot cm^2$)	Key Limitation
$Ni_{0.4}Cu_{0.6}Mn_2O_4$	Reported 10^{-2}–10^2	Limited data	Limited electrochemical validation; slower ORR kinetics inferred
LSCF (perovskite)	$\approx 10^2$	<0.1	Chromium poisoning (interconnect-derived degradation)
Ni–YSZ	High, stable	Low	Carbon deposition under hydrocarbon fuels

with small polaron hopping between mixed valence states such as Mn^{3+}/Mn^{4+} and Cu^{+}/Cu^{2+}.[56,57] Reported conductivity values span a wide range (10^{-2}–10^2 S/cm) depending on the temperature and the composition, with optimized Ni–Cu–Mn spinels reaching 70–90 S/cm at 600–800 °C, reflecting a strong dependence on the cation stoichiometry and synthesis conditions.[58,59] As summarized in **Table 1**, available data indicate that cobalt-based perovskites generally achieve higher and more consistent conductivity at intermediate temperatures, while Ni–YSZ systems provide more stable electrochemical performance, indicating that $Ni_{0.4}Cu_{0.6}Mn_2O_4$ requires further optimization to reach comparable performance levels.

For comparison, cobalt-based perovskites exhibit a high electronic conductivity at intermediate temperatures (600–800 °C), contributing to enhanced charge transport, although reported values vary significantly across compositions and operating conditions.[60–62] Similar conductivity limitations in spinel systems compared with perovskites have been widely reported, where electron transport is governed by small polaron hopping rather than band conduction.[63] This suggests that although the material provides a balanced conductivity, further optimization is required. Defect engineering, including oxygen vacancy tuning and cation substitution, has been proposed but lacks systematic validation across studies.

This comparison highlights that, although $Ni_{0.4}Cu_{0.6}Mn_2O_4$ exhibits moderate conductivity and catalytic activity, its electrochemical performance remains lower than that of conventional electrode materials, particularly in oxygen-reduction kinetics. The material also exhibits thermal and chemical stability under SOFC conditions. The spinel lattice resists structural degradation during thermal cycling. Thermal expansion coefficients for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ are compatible with common electrolytes such as SDC or YSZ, reducing interfacial stresses. However, long-term stability data under realistic operating conditions remain limited. Chemical stability in both reducing and oxidizing environments supports its application potential. Nevertheless, many laboratory-scale studies report stability over relatively short durations compared with the long-term operational requirements of SOFC systems, limiting a direct comparison with benchmark electrode performance.

Another important feature of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel is its compositional flexibility. Adjusting Ni, Cu, and Mn ratios modifies the cation distribution, oxygen-vacancy concentration, and electronic structure, which directly affect the catalytic performance. This enables targeted optimization for specific applications. For example, increasing Cu content can enhance electrical conductivity and influence redox behaviour, while Mn contributes to redox activity through variable oxidation states, with overall performance strongly dependent on composition and cation interactions.[64–66] However, uncontrolled variation in composition may lead to secondary-phase formation and inconsistent properties. Reports of CuO or Mn_2O_3 secondary phases indicate a strong sensitivity to the synthesis conditions, particularly temperature, and may arise from phase decomposition or kinetic limitations during spinel formation.[67–69] Therefore, precise synthesis control is required to achieve reproducible performance and maintain phase stability across different operating conditions.

In summary, $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel shows potential as a multifunctional material due to its structural stability, mixed conductivity, and catalytic activity. However, its electrochemical performance remains lower than that of conventional SOFC electrode materials. Current studies rarely report key performance metrics such as power density ($mW \cdot cm^{-2}$) or polarization resistance ($\Omega \cdot cm^2$), limiting an objective comparison. An evaluation based on quantitative metrics such as power density and polarization resistance is required to establish practical relevance. Future work should integrate half-cell and full-cell testing to correlate the material properties with device-level performance. Further work should focus on controlled synthesis, performance validation, and integration into full SOFC systems.

2 FUNDAMENTALS OF $Ni_{0.4}Cu_{0.6}Mn_2O_4$ SPINEL STRUCTURE

2.1 Crystal Structure and Phase Composition

$Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel is a mixed-metal oxide with a complex crystal structure belonging to the spinel oxide family, represented by the general formula AB_2O_4.[47] This structure is widely studied due to its ability to accommodate multiple oxidation states, which directly affects the electrochemical functionality in SOFC systems. In this structure, divalent cations occupy the A-site, while trivalent cations occupy the B-site. In practice, this ideal distribution is often altered by partial inversion and cation

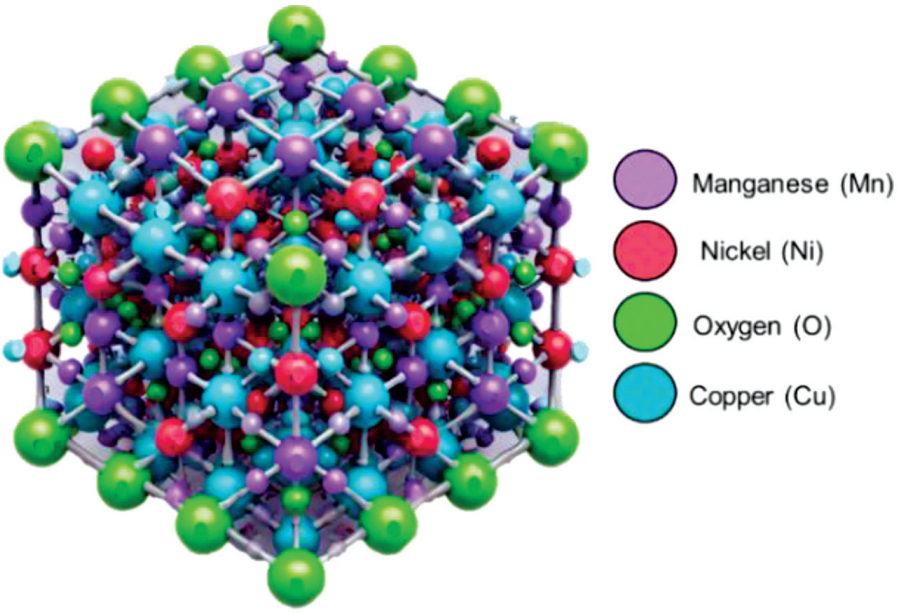

Figure 4: Spinel structure illustration of $Ni_{0.4}Cu_{0.6}Mn_2O_4$.[54]

disorder, which significantly influence material properties. The spinel structure is characterized by a cubic close-packed arrangement of oxygen anions, with cations located in interstitial sites. These structural features define the ion-diffusion pathways and electron-transport behaviour, which require quantitative correlation with conductivity for meaningful evaluation. **Figure 4** illustrates the spinel crystal structure of $Ni_{0.4}Cu_{0.6}Mn_2O_4$.

The A-site of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel is commonly occupied by Ni^{2+} and Cu^{2+} ions, while Mn ions predominantly occupy the B-sites, although cation distribution varies with synthesis conditions, leading to partial inversion where A- and B-site cations exchange positions. Cation redistribution in spinel structures alters the electron-hopping pathways, particularly between Mn^{3+}/Mn^{4+} couples at octahedral sites, which governs the electronic conductivity.[70] This cation redistribution modifies the electronic structure, oxygen vacancy formation, and catalytic activity. Despite this, most studies do not quantify the inversion degree, limiting a comparison across synthesis routes. The lattice parameter varies with ionic radii and composition.[71]

The phase composition of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel is governed by the cation distribution, synthesis conditions, and processing parameters such as calcination temperature and precursor ratio. For instance, calcination above 800 °C generally promotes phase purity but may induce grain growth, reducing surface area and catalytic activity.[72] Deviations from optimal stoichiometry can result in secondary-phase formation or deviations from the ideal spinel structure, which alter conductivity and catalytic behaviour. The degree of cation ordering is also important. A fully ordered spinel promotes predictable transport properties, while disordered structures introduce defect states that may enhance the conductivity but reduce the structural stability.

Secondary phases such as NiO, CuO, and MnO influence the properties of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel by inducing lattice distortion and phase transformations that affect the overall behaviour of the material.[73] However, these effects are highly dependent on phase composition and concentration, as secondary phases can improve structural stability in some cases while increasing resistivity and limiting charge transport in others.[74,75] Additionally, phase composition affects oxygen vacancy concentration, which is essential for ionic conductivity. Higher oxygen-vacancy concentration can enhance ion transport, although excessive defects may reduce the structural stability. Quantitative control of the vacancy concentration remains poorly reported, limiting the reproducibility of electrochemical performance. The arrangement of transition-metal cations within the lattice influences the vacancy formation and distribution, thereby affecting the electrochemical performance.[76]

Overall, the crystal structure and phase composition of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel are closely interconnected with its functional properties. Optimization requires balancing the phase purity, cation distribution, and defect concentration to achieve the desired performance. Careful control of the synthesis conditions enables systematic tuning of these parameters. However, current literature rarely correlates structural parameters such as lattice constant, inversion degree, and crystallite size with measurable SOFC metrics such as power density or polarization resistance. This limits the development of predictive material-design strategies. A systematic framework linking crystal structure, defect chemistry, and electrochemical performance is required to establish $Ni_{0.4}Cu_{0.6}Mn_2O_4$ as a competitive SOFC material.

2.2 Synthesis Method

Overview of Common Synthesis Techniques

Various methods are used to synthesize $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel, including sol–gel, co-precipitation, hydrothermal, and glycine–nitrate processes, to control phase purity, particle size, and morphology. The synthesis route strongly influences the cation distribution, defect formation, and microstructure, which directly affect the electrochemical performance. Solution-based methods generally produce finer particles with higher surface area, while solid-state approaches often result in larger grains with a lower surface reactivity. **Table 2** summarizes the common synthesis techniques and their structural implications.

Among the synthesis methods, sol–gel and glycine–nitrate processes provide better control over the homogeneity and particle size, as widely reported in spinel and SOFC material-synthesis studies. Quantitatively, sol–gel-derived materials often exhibit improved catalytic activity due to a higher surface area, whereas combustion-based methods may show reduced conductivity due to residual impurities. However, most studies do not report direct electrochemical metrics such as power density or polarization resistance, limiting an objective comparison between synthesis routes. In contrast, co-precipitation offers scalability but may result in a broader particle size distribution and a lower phase purity. Hydrothermal methods produce highly crystalline materials but are generally less suitable for large-scale production.

Synthesis parameters strongly influence the spinel's characteristics, including phase composition, particle size, and morphology. Key variables such as precursor concentration, calcination temperature, and reaction conditions directly affect the phase formation, microstructure, and particle distribution, leading to significant variation in the reported material properties.[92–96] Similarly, calcination temperature plays a dual role. Although an increased calcination temperature improves the crystallinity and phase purity, it reduces the surface area, highlighting a trade-off between structural order and reactivity. Most studies treat these parameters independently, with limited use of multivariate optimization or statistical modelling approaches.[97–101]

Particle size and distribution are critical for catalytic efficiency. Dynamic light scattering (DLS) analysis shows an average particle size of approximately 600 nm. However, a direct comparison with FESEM observations should be made with caution due to potential discrepancies between the measurement techniques. Mixing time during the glycine–nitrate process has minimal effect on primary particle size but significantly influences the polydispersity index (PdI).[54] As shown in **Figure 5a**, the particle size distribution remains relatively constant across different mixing durations, while **Figure 5b** shows the variation in PdI values. A PdI above 0.3 indicates particle agglomeration due to interionic interactions. Agglomeration reduces accessible surface area and limits gas-diffusion pathways, which can increase polarization resistance during SOFC operation. This reduction in surface accessibility decreases the triple-phase-boundary density, which directly increases polarization resistance and reduces overall SOFC performance. Higher PdI values correspond to reduced dispersion and lower effective surface area.[54] This demonstrates that particle distribution has a stronger influence on catalytic performance than average particle size alone.

The particle morphology is influenced by both the mixing duration and the calcination temperature. **Figure 5c** shows that longer mixing times produce more uniform and finely distributed particles, indicating more complete precursor reaction. Shorter mixing times result in heterogeneous particle morphology and incomplete

Table 2: Summary of synthesis techniques for SOFC applications

No.	Synthesis technique	Process	Advantages	References
1.	Sol-Gel Method	The sol-gel method converts metal precursors in solution into a solid spinel oxide through hydrolysis and condensation. The resulting gel is dried and calcined to achieve the final crystalline phase.	This method allows precise control of stoichiometry and homogeneity, yielding uniform, nanoscale particles with high surface area suitable for catalytic applications.	77–80
2.	Combustion-Glycine-Nitrate Process (GNP)	GNP is a combustion method using metal nitrates as oxidizers and glycine as fuel. Upon ignition, a rapid exothermic reaction forms spinel oxide efficiently.	GNP is a rapid, straightforward method offering stoichiometric control. It minimizes unwanted phases and yields nanoscale particles.	81–83
3.	Co-precipitation	Metal precursors are dissolved in a solvent, then precipitated as hydroxides using agents like ammonia. The precipitate is filtered, dried, and calcined to produce spinel oxide.	Co-precipitation allows particle size control and is suitable for large-scale synthesis. It also accommodates dopant incorporation during formation.	84–88
4.	Hydrothermal Synthesis	Crystallisation of spinel oxides from aqueous precursors in sealed autoclaves under controlled conditions enables direct formation of crystalline materials.	Provides precise control of particle size, morphology, and composition, yielding highly crystalline materials and enabling scalable synthesis at moderate temperatures.	89–91

phase development, which can negatively affect the electrochemical performance.[102] Such heterogeneity can lead to an uneven current distribution and localized degradation during operation. Calcination promotes particle growth and may lead to agglomeration and fusion, reducing the surface area and porosity. As a result, excessive grain growth reduces the catalytic activity by limiting the number of active surface sites, which negatively affects the fuel-oxidation and oxygen-reduction reactions in SOFC operation. These morphological changes influence the catalytic behaviour by decreasing the available surface and electrode–electrolyte interface area for the reaction. Recent studies show that porous microstructures improve the gas diffusion and enhance the electrochemical performance compared with dense morphologies due to increased surface area and improved transport pathways.[103–105] Therefore, optimization requires balancing particle growth with surface accessibility and structural uniformity.

The thermal stability is essential for SOFC operation at high temperatures (600–1000 °C). The spinel structure provides inherent stability, supported by the incorporation of transition-metal cations such as Ni, Cu, and Mn within the lattice. Cu and Mn contribute to the thermal expansion behaviour and catalytic activity, while the overall structure maintains stability under prolonged operating conditions.[47,106–108] In high-temperature environments, Ni–Cu–Mn spinel structures exhibit strong thermal stability, where Ni–Cu interactions enhance the phase stability and resistance to thermal degradation.[47,109] For example, Ni-Cu–Mn spinel systems exhibit stable operation with improved conductivity of up to ≈54 $S \cdot cm^{-1}$ at 750 °C, attributed to enhanced small polaron hopping and cation interaction.[110] Mn contributes to redox stability and electrical conductivity through Mn^{3+}/Mn^{4+} redox behaviour, achieving values of ≈12.1 $S \cdot cm^{-1}$ at 800 °C.[47] The reported thermal expansion coefficients (≈12.8 × 10^{-6} K^{-1}) are compatible with common SOFC electrolytes such as YSZ, reducing the interfacial stress and improving the structural reliability during operation.[107] However, the activation energy trends shown in **Figure 5d** are derived from alloy systems and may not fully represent spinel behaviour under SOFC conditions. This limits direct interpretation and indicates the need for spinel-specific thermal analysis.

Electrical conductivity is a key parameter for SOFC materials. $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel exhibits mixed ionic–electronic conductivity, where cation interactions facilitate the electron-transport and redox processes. The arrangement of Ni^{2+} and Cu^{2+} ions facilitate electron hopping, which becomes more active at elevated temperatures. The temperature-dependent conductivity of $Cu_{1.3}Mn_{1.7}O_4$ shown in **Figure 5e** demonstrates thermally activated conduction behaviour.[111] However, using a different composition limits any direct comparison and introduces uncertainty in interpreting the performance of the $Ni_{0.4}Cu_{0.6}Mn_2O_4$. Optimization of the Ni, Cu, and Mn ratios remains necessary, as deviations from stoichio-

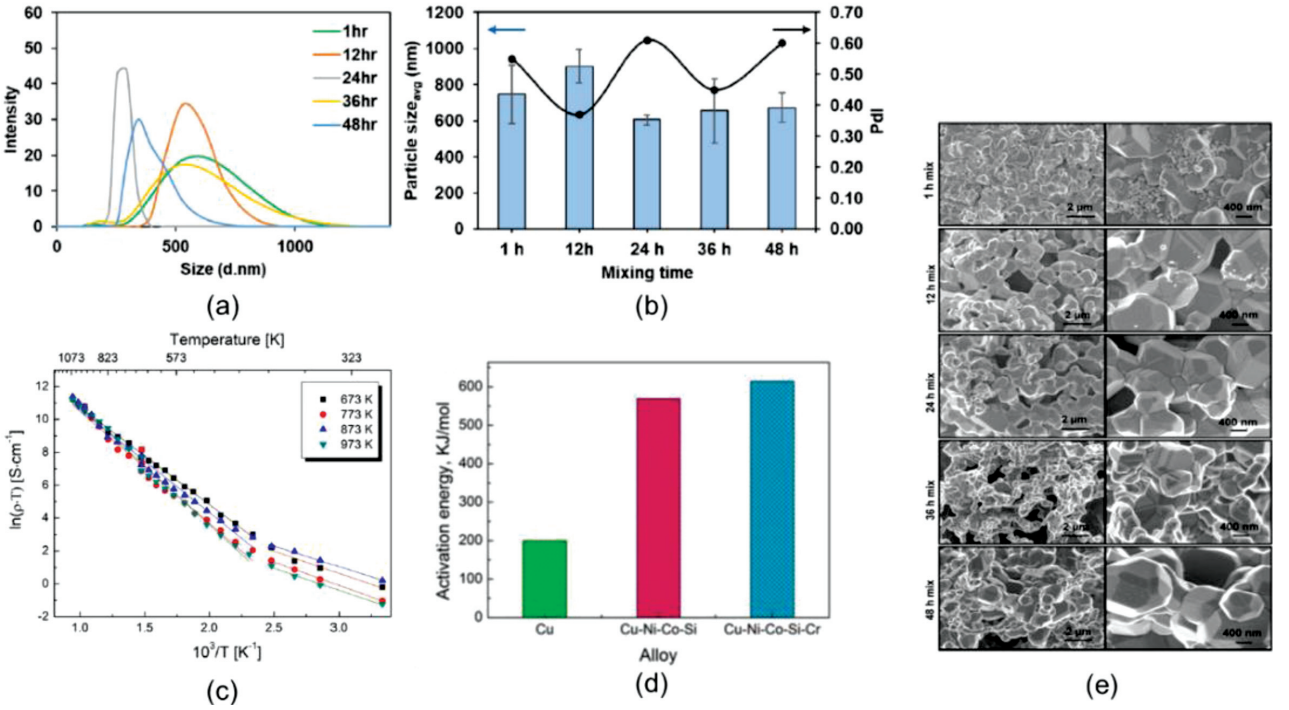

Figure 5: Collage of material-characterization results. a) Aggregated particle size distribution of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ powders at different mixing times.[54] b) Relationship between PdI value and particle size for the same $Ni_{0.4}Cu_{0.6}Mn_2O_4$ powders at different mixing times.[54] c) Temperature-dependent electrical conductivity of $Cu_{1.3}Mn_{1.7}O_4$.[111] d) Deformation activation energy of an alloy.[112] e) FESEM micrographs of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ powders prepared with different mixing times.[54]

metry can lead to phase segregation and altered conductivity. Although mixed conductivity is achieved, it remains lower than that of advanced electrode materials, indicating the need for further improvement.

Figure 5 summarizes the particle size distribution, morphology, and electrical behaviour of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ under different synthesis conditions. However, several subfigures such as conductivity and activation energy are derived from related systems rather than the exact composition, which limits the strength of the conclusions drawn. This indicates that particle distribution and agglomeration have a direct impact on the catalytic performance, as higher polydispersity reduces the effective active surface area and limits the reaction efficiency despite similar particle size. A more rigorous approach would integrate direct electrochemical measurements, such as impedance spectroscopy, to validate the structure–property relationships. These datasets are used to illustrate general trends rather than a direct quantitative comparison due to compositional differences. However, the absence of direct electrochemical validation limits the ability to correlate these structural observations with actual SOFC performance.

2.3 Catalytic Properties of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ Spinel in SOFC

The catalytic activity of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel catalysts for fuel oxidation in SOFCs has been widely investigated due to their potential to improve cell performance and efficiency. Recent studies show that dual-phase $Ni_{0.4}Cu_{0.6}Mn_2O_4$ and (Cu, Mn)$_3O_4$ spinel catalysts produced by the glycine–nitrate process (GNP) exhibit improved catalytic performance, associated with inverse spinel structures, distorted cation configurations, and strong metal–support interactions. These features improve the reducibility and facilitate fuel adsorption, leading to enhanced oxidation reactions.[37,47,72]

Further enhancing their catalytic potential, the spinel catalysts displayed three distinct stages of reduction, with metallic Ni and Cu forming within the MnO matrix after reduction at approximately 450 °C.[54] Catalysts synthesised with a 24-hour mixing time during the glycine–nitrate process (GNP) shows the highest catalytic activity, which was attributed to optimised metal–support interactions (MSI) and improved particle size distribution.[54] Similar trends have been reported in other spinel systems, where synthesis conditions such as temperature, cation distribution, and defect structure strongly influence the catalytic performance and reducibility.[113–116] These findings emphasize that the careful control of the synthesis parameters, particularly mixing time and thermal treatment, is required to optimize the catalytic activity for fuel oxidation in SOFC applications.

Besides fuel oxidation, the oxygen reduction reaction (ORR) is a key process in SOFCs, governing cell efficiency and power output. $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel catalysts have been evaluated for ORR activity, with an emphasis on their structural and electrical properties. The inverse spinel structure of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ and (Cu, Mn)$_3O_4$ has been shown to enhance ORR activity by facilitating oxygen adsorption and dissociation.[54,117] Furthermore, catalysts synthesized with a 24-hour mixing time during the GNP exhibit enhanced reducibility and increased bulk porosity, which are beneficial for ORR processes.[54] At elevated temperatures, reduction behaviour indicates active redox processes associated with oxygen interaction, although quantitative ORR performance metrics remain limited. These characteristics indicate the potential of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel catalysts for improving a SOFC's performance, while highlighting the need for further electrochemical evaluation.[47,54] However, reported polarization resistance values (>0.2–0.5 Ω·cm^2) remain higher than those of advanced perovskite cathodes (<0.1 Ω cm^2), indicating slower ORR kinetics.[118–120] This indicates that oxygen reduction kinetics in $Ni_{0.4}Cu_{0.6}Mn_2O_4$ are slower than in cobalt-based perovskites, which typically exhibit polarization resistance below 0.1 Ω cm^2 under similar conditions.

The performance of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel catalysts in SOFCs is influenced not only by their intrinsic properties but also by their interactions with other cell components. These catalysts must maintain structural integrity and electrochemical compatibility with the electrolytes and electrode materials under operating conditions. Previous studies report that spinel catalysts synthesised via the glycine–nitrate process (GNP) exhibit good chemical compatibility with electrolyte materials, maintaining structural integrity at elevated temperatures without significant phase degradation.[54,121] Furthermore, long-term studies on related spinel systems demonstrate stable structural behaviour over extended operation, with minimal degradation and no significant elemental segregation.[121] However, full-cell performance, interfacial compatibility, and long-term stability remain insufficiently investigated for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel systems, limiting any direct assessment of practical applicability.[47] Future research should focus on systematic evaluation of interfacial interactions under realistic operating conditions to establish long-term performance and reliability in SOFC applications. Overall, although $Ni_{0.4}Cu_{0.6}Mn_2O_4$ demonstrates improved catalytic behaviour compared with undoped spinels, its electrochemical performance remains inferior to conventional electrode materials, indicating the need for systematic optimization and benchmarking.

2.4 Stability of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ Spinel in SOFC Environments

The stability of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel materials in SOFC environments has attracted significant attention due to their favourable thermal and electrochemical

properties. Ni–Cu–Mn spinel systems demonstrate high chemical and thermal stability under SOFC operating conditions, with conductivity values reported up to ≈54 S·cm^{-1} at 750 °C.[108] CuNi-based spinels have also shown excellent phase stability, low area-specific resistance, and improved sinterability, supporting their suitability for intermediate-temperature SOFC applications.[109] In addition, $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel exhibits an area-specific resistance of ≈0.32 Ω·cm^2 at 750 °C and demonstrates resistance to carbon deposition and thermal degradation compared with conventional Ni-YSZ materials.[47] Furthermore, these spinel systems exhibit resistance to chromium diffusion, which contributes to improved durability in SOFC environments.[108] However, most studies report stability over limited durations, typically up to ≈1000 h, and long-term performance under practical SOFC conditions remains insufficiently characterized.[122]

A critical advantage of Ni–Cu–Mn spinel systems is their ability to mitigate chromium volatilization, a well-known issue in SOFC operation. Chromium volatilization under a high oxygen partial pressure leads to the formation of volatile chromium species that migrate and poison the cathode, resulting in performance degradation. Cu–Mn-based spinel coatings, particularly with Ni incorporation, have been shown to reduce chromium diffusion and deposition at the cathode interface, thereby improving the durability.[109,123] The incorporation of Ni into Cu–Mn spinels enhances the resistance to chromium transport and improves the phase stability, making these materials suitable as protective coatings in SOFC interconnect systems.[109] However, most studies focus on Cu–Mn spinels with Ni doping rather than a single Ni–Cu–Mn composition, and the specific mechanisms governing chromium suppression remain incompletely understood.

The structural integrity of the $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel has direct implications for its catalytic activity, particularly in reforming reactions within SOFC systems. The catalytic performance of this material is closely related to its reducibility and cation distribution, which influence the formation of active metallic sites under the operating conditions. Studies have shown that inverse spinel structures with distorted cation configurations enhance the reducibility, enabling the formation of catalytically active species and promoting fuel-reforming reactions.[54] While the exsolution of metallic nanoparticles is a recognised mechanism in related oxide systems, direct evidence for Ni and Cu exsolution in $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel remains limited. However, strong metal–support interactions within the spinel structure contribute to catalytic activity and stability under reducing conditions.[54,124] Furthermore, spinel materials generally exhibit good structural stability during redox processes, although long-term multi-cycle behaviour for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ specifically is not yet fully established.

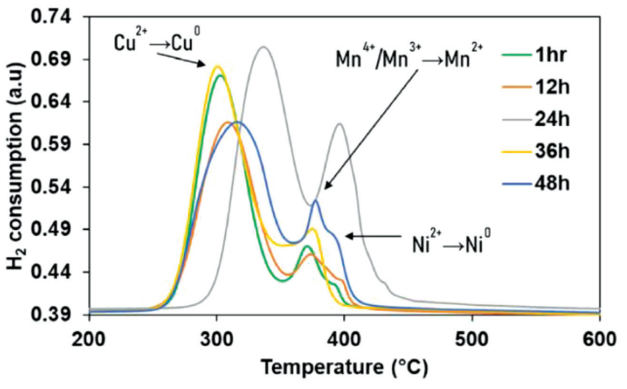

Figure 6: H2-TPR profiles of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel at various mixing times.[54]

As demonstrated in **Figure 6**, H_2-TPR profiles reveal the multi-step reduction behaviour of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel powders prepared with different mixing times. The reduction process includes distinct regions associated with the reduction of Cu^{2+} to Cu^0 at lower temperatures, followed by the reduction of Mn species (Mn^{4+}/Mn^{3+} to Mn^{2+}), and finally the reduction of Ni^{2+} to Ni^0 at higher temperatures. The sample prepared with a 24-hour mixing time exhibits sharper and more defined reduction peaks, indicating enhanced reducibility and improved cation distribution.[54] This behaviour is associated with stronger metal–support interactions and more homogeneous particle formation, which contribute to an improved catalytic activity under SOFC operating conditions.[54] The enhanced reducibility facilitates the formation of active metallic sites, which improves the catalytic activity for fuel-oxidation reactions under SOFC operating conditions.

Another important aspect of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel stability is its resistance to carbon deposition, a common challenge in SOFCs operating with hydrocarbon fuels. Ni-based catalysts, while highly effective for methane reforming, are prone to carbon accumulation, which can deactivate the catalyst and block fuel pathways. $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel has been reported to exhibit improved resistance to carbon deposition compared with conventional Ni–YSZ systems, demonstrating methane tolerance with minimal carbon formation.[47] However, the mechanisms underlying this behaviour remain incompletely understood. Studies on related materials suggest that Cu incorporation can reduce carbon affinity, while Mn-containing oxides may facilitate the oxidation of carbon species under the operating conditions.[125,126] These effects likely contribute to the observed carbon resistance, although direct mechanistic evidence for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel remains limited.

Finally, the microstructural characteristics of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel, including its porous morphology and particle distribution, are expected to contribute to its catalytic performance in SOFC environments by providing a higher density of active sites for electrochemical reactions. $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel has demonstrated

promising electrochemical properties, including electrical conductivity of up to ≈12.1 $S \cdot cm^{-1}$ at 800 °C and area-specific resistance of ≈0.32 $\Omega \cdot cm^2$ at 750 °C, along with resistance to carbon deposition and thermal degradation.[47] However, despite these favourable properties, full-cell performance, interfacial compatibility, and long-term stability remain insufficiently evaluated.[47] Therefore, while $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel shows potential for SOFC applications, further systematic studies are required to establish its durability and practical applicability under realistic operating conditions. This highlights the need for standardized benchmarking and long-term testing to establish the practical viability of Ni–Cu–Mn spinel systems in SOFC applications.

3 PROSPECTS OF $Ni_{0.4}Cu_{0.6}Mn_2O_4$ SPINEL AS A BIFUNCTIONAL ELECTRODE AND CATALYST IN SOFC

3.1 $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel as a bifunctional electrode material in SOFC

The prospect of employing Ni–Cu–Mn spinel materials as bifunctional electrode candidates in SOFCs presents a promising approach for advancing cell design and manufacturing. Symmetrical SOFC configurations, which utilize the same material for both anode and cathode, have been shown to simplify fabrication processes, reduce material requirements, and improve interfacial compatibility between cell components.[27,127] These advantages can lower production costs and minimise interfacial resistance, thereby enhancing charge transfer efficiency. However, while $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel has demonstrated favourable electrochemical properties as an anode material, its bifunctional performance as both anode and cathode remains insufficiently validated.[47] Therefore, further investigation is required to assess its electrochemical activity, stability, and compatibility under symmetrical SOFC operating conditions.

However, realizing the full potential of this dual-functionality requires a comprehensive understanding of the associated challenges and their mitigation. Currently, SOFCs typically employ distinct anode materials, such as Ni-based cermets (e.g., Ni–YSZ), and cathode materials, such as perovskites including $La_{1-x}Sr_xMnO_3$ (LSM).[128] Symmetrical SOFC systems, which utilise a single material for both electrodes, face significant challenges in maintaining structural and electrochemical stability under both reducing and oxidizing environments.[127] The anode operates under reducing conditions, requiring high catalytic activity for fuel oxidation, whereas the cathode operates under oxidising conditions, necessitating efficient oxygen reduction.[129] Therefore, candidate materials such as Ni–Cu–Mn spinels must maintain stable catalytic performance and structural integrity across these contrasting conditions. In addition, degradation mechanisms including sintering, particle coarsening, and poisoning remain critical concerns that can limit long-term durability.[54] These challenges highlight the need for systematic evaluation of material stability and performance under realistic SOFC operating conditions.

Another important consideration is the potential for species migration between anode and cathode environments, which can affect SOFC performance and stability. While this issue is well recognised in SOFC systems, specific strategies for mitigating cross-contamination in Ni–Cu–Mn spinel-based electrodes remains not yet fully established. More generally, optimization of electrode microstructure, including porosity, particle size distribution, and interfacial contact area, has been shown to influence electrochemical performance and mass transport behaviour.[47,130] In addition, compositional tuning of Ni–Cu–Mn spinels, particularly the relative ratios of Ni, Cu, and Mn, plays a key role in balancing electronic conductivity, catalytic activity, and stability.[25,47] Control of microstructural features such as particle size, pore distribution, and surface area is also critical for improving electrochemical performance.[130] Advanced characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), and electrochemical impedance spectroscopy (EIS), are widely used to analyze structure–property relationships and identify the key parameters governing spinel behaviour.[25,130] However, direct evidence linking these strategies to dual-function electrode performance in Ni–Cu–Mn spinel systems remains limited, highlighting the need for further systematic investigation.

In conclusion, the use of Ni–Cu–Mn spinel materials as bifunctional electrode candidates in SOFCs represents a promising approach to simplifying cell design and reducing manufacturing complexity. Symmetrical configurations have demonstrated potential for cost reduction and improved component compatibility in SOFC systems. However, for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel specifically, experimental validation of bifunctional performance remains limited, with key aspects such as full-cell operation, interfacial compatibility, and long-term stability not yet fully established. Although spinel-based electrodes in related systems have achieved high electrochemical performance, these results cannot be directly generalised to Ni–Cu–Mn compositions without further investigation. Therefore, realizing the full potential of this approach necessitates systematic studies integrating materials synthesis, advanced characterization, electrochemical evaluation, and modelling to address limitations in catalytic activity, stability, and durability under practical SOFC operating conditions.

3.2 Enhanced Catalysis through Doping and Composite Formation

The catalytic performance of Ni–Cu–Mn spinel materials can be enhanced through selective doping and composite formation. Doping involves the incorporation of small amounts of additional elements, such as La, Co, or

Fe, into the spinel lattice, which can modify the electronic structure and improve the catalytic behaviour. Studies on related spinel systems have shown that compositional tuning can significantly enhance the electrical conductivity and electrochemical performance.[59,131] In addition, the formation of composite materials, for example, by combining spinels with ceria-based electrolytes or perovskite-type oxides, has been reported to improve the chemical stability and electrical conductivity.[132] These composite systems can also reduce sintering effects and enhance the catalytic performance under SOFC operating conditions. However, most of these improvements have been demonstrated in related spinel compositions, and direct evidence for optimized doping and composite strategies in $Ni_{0.4}Cu_{0.6}Mn_2O_4$ remains limited. In contrast, direct experimental validation for $Ni_{0.4}Cu_{0.6}Mn_2O_4$ remains limited, making it difficult to confirm whether similar performance enhancements can be achieved. Therefore, further investigation is required to establish the effectiveness of these approaches for this specific system.

The role of composite design in modifying the catalytic behaviour remains largely supported by mechanistic insights rather than direct experimental validation. Recent studies on transition-metal oxide spinels show that catalytic activity is strongly governed by electron-hopping processes and cation-redox behaviour, particularly involving Mn^{3+}/Mn^{4+} couples, which directly influence oxygen electrocatalysis.[133] These findings suggest that interactions between spinel phases and secondary materials may alter the surface reactivity and charge-transport properties. However, there is currently no direct evidence confirming the enhanced performance of Ni–Cu–Mn spinel composites with ceria-based or perovskite materials. Therefore, the effectiveness of composite strategies depends on factors such as cation distribution, electronic structure, and interfacial interactions, which remain insufficiently understood. Further systematic studies are required to establish the role of composite formation in improving the catalytic performance for SOFC applications.

Overall, doping and composite strategies provide potential routes to optimise $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel for SOFC applications. These approaches enable the tuning of structural and electrochemical properties, but their impact requires validation using quantitative performance metrics such as electrical conductivity and area-specific resistance (ASR).[47] Although improved electrochemical properties have been reported, including a conductivity of 12.1 $S \cdot cm^{-1}$ at 800 °C and an area-specific resistance of 0.32 $\Omega \cdot cm^2$ at 750 °C, full-cell performance, interfacial compatibility, and long-term stability remain untested.[47] Most studies focus on structural and catalytic behaviour without reporting device-level performance, limiting direct comparison with conventional electrodes such as Ni–YSZ or perovskite materials. In addition, systematic benchmarking against these established materials is largely absent. Therefore, future research should include standardised electrochemical evaluation, including impedance spectroscopy and extended durability testing (>1000 h), to validate the effectiveness of doping and composite strategies under practical SOFC operating conditions. This highlights the need for rigorous benchmarking to establish the practical advantages of Ni–Cu–Mn spinel systems over conventional SOFC electrodes.

3.3 $Ni_{0.4}Cu_{0.6}Mn_2O_4$ Spinel in Other Energy-Conversion Devices

Ni–Cu–Mn spinel materials have been extensively investigated for SOFC applications, but their potential in other energy-conversion and storage systems remains largely unexplored. While spinel oxides in general have demonstrated catalytic activity in applications such as direct methanol fuel cells (DMFCs), proton-exchange-membrane fuel cells (PEMFCs), electrolysis systems, and batteries, direct evidence for Ni–Cu–Mn spinel in these technologies is currently limited.[47,59,107,134,135] Related spinel materials have shown promising performance in these applications due to their mixed ionic–electronic conductivity and catalytic versatility, suggesting that Ni–Cu–Mn systems may also exhibit similar potential. However, further experimental validation is required to assess their suitability, performance, and stability in these alternative energy systems. Therefore, expanding research beyond SOFC applications could provide new insights into the functional capabilities of Ni–Cu–Mn spinel materials and support the development of advanced energy technologies.

Ni–Cu–Mn spinel materials have also been investigated for energy-storage applications, particularly in battery systems, although direct studies on $Ni_{0.4}Cu_{0.6}Mn_2O_4$ remain limited. The presence of multiple oxidation states in transition metals such as Ni, Cu, and Mn enables reversible redox reactions, which are favourable for charge-storage processes. Studies on related Mn-based spinels report specific capacities in the range 100–300 $mAh \cdot g^{-1}$, depending on composition and cycling conditions.[136] In addition, a related multi-metal spinel, $(Ni_{0.4}Co_{0.4}Mn_{0.2})_3O_4$, has demonstrated higher capacities of up to 779 $mAh \cdot g^{-1}$ after extended cycling, although this behaviour is associated with conversion-type reactions and is not directly comparable to Ni–Cu–Mn spinel systems.[136] However, cycle stability, capacity retention, and electrical conductivity remain key challenges. Capacity fading in spinel systems has been associated with structural distortion and transition-metal dissolution during repeated cycling, although these mechanisms are not yet fully established for Ni–Cu–Mn compositions.[136] Integration with conductive matrices, such as carbon-based materials, has been shown in related systems to improve the charge transport and cycling stability, leading to enhanced rate capability.[137] Nevertheless, long-term stability and performance vali-

dation for $Ni_{0.4}Cu_{0.6}Mn_2O_4$-based systems remain insufficiently explored, requiring further systematic investigation.

Overall, $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel demonstrates broad functional potential across multiple energy-related applications, although current evidence remains limited and largely exploratory. Existing studies primarily report laboratory-scale or half-cell performance, with limited benchmarking against established electrode materials. For example, while promising electrochemical properties have been observed, key aspects including full-cell performance, interfacial compatibility, and long-term stability remain untested. Furthermore, no studies report extended durability evaluation exceeding 1000 h or systematic comparison with commercial catalysts or electrodes. As a result, the practical viability of this material cannot yet be established. Future research should focus on device-level evaluation under application-specific conditions, alongside improvements in electrical conductivity and durability. In addition, standardised testing protocols, including long-term stability assessment (>1000 h or >1000 cycles), are required to enable meaningful comparison with existing technologies.

4 CHALLENGES AND OPPORTUNITIES IN $Ni_{0.4}Cu_{0.6}Mn_2O_4$ SPINEL RESEARCH

Current research on Ni–Cu–Mn spinel materials identifies several key challenges that limit their practical application in SOFC systems. These include phase-stability issues at high temperatures, difficulties in optimising sintering conditions, catalyst degradation over prolonged operation, and the complexity of cation distribution within the spinel lattice. As illustrated in **Figure 7**, these factors are closely linked to the structural and electrochemical behaviour of $Ni_{0.4}Cu_{0.6}Mn_2O_4$. Although progress has been made in synthesis and electrochemical evaluation, the relationship between synthesis parameters, phase purity, and microstructure remains insufficiently understood. This lack of understanding prevents the establishment of predictive design strategies for optimizing electrochemical performance. In addition, long-term stability under realistic operating conditions is not fully established, with most studies reporting only intermediate durability (100–1000 h). Furthermore, integration into full SOFC systems remains underexplored, with interfacial compatibility, full-cell performance, and long-term operation not yet systematically evaluated.

The schematic highlights the progression from synthesis parameters to structural properties, defect formation, and ultimately electrochemical performance, providing a framework for systematic material optimization. At the same time, significant opportunities exist to improve the performance of Ni–Cu–Mn spinel materials. Optimization of the cation distribution and electron transport pathways can enhance the electrical conductivity, while the development of durable catalysts with improved resistance to degradation remains a key research focus. Microstructure engineering, including control of particle size, porosity, and surface area, provides a direct route to improve catalytic activity and mass transport behaviour. In addition, integration with renewable fuel systems, particularly hydrogen-based technologies, represents an important direction for expanding the application of these materials beyond conventional SOFC operation. These opportunities highlight the importance of advanced material design strategies aimed at improving both electrochemical performance and long-term stability.

Despite these opportunities, several technological challenges must be addressed to enable practical deployment. The scalability of synthesis methods remains a major limitation, as variations in processing conditions can significantly affect phase purity, particle size distribution, and electrical performance. Achieving consistent material quality during large-scale production is therefore difficult, and the development of cost-effective synthesis routes is required to improve the economic feasi-

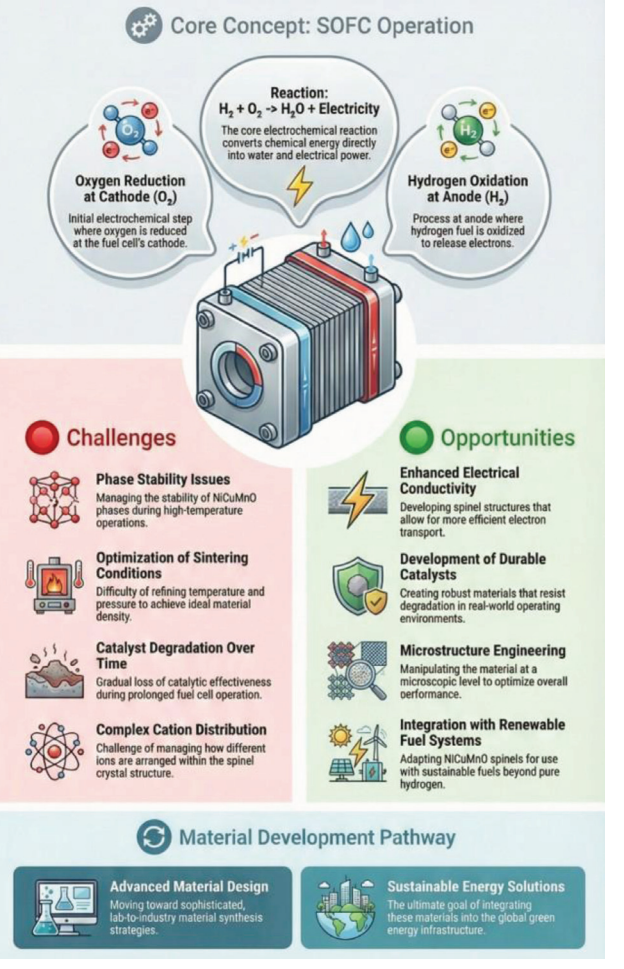

Figure 7: Schematic illustration of the development pathway of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel for SOFC applications, showing the relationship between synthesis, structure, defect chemistry, and electrochemical performance.

bility. Furthermore, integration into complete SOFC systems requires a careful evaluation of the compatibility with other components and validation under realistic operating conditions. A systematic material development pathway combining synthesis optimization, microstructure control, and device-level evaluation is therefore required. Future research should focus on extended durability testing, standardized electrochemical evaluation, and validation under practical conditions, including renewable fuel environments, to establish $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel as a viable material for next-generation SOFC technologies.

5 CONCLUSION

$Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel demonstrates potential as an alternative SOFC electrode material due to its structural stability, mixed ionic–electronic conductivity, and catalytic activity, although its performance remains below that of conventional materials. The material exhibits favourable redox behaviour and resistance to degradation mechanisms such as carbon deposition and chromium poisoning, but its electrochemical performance is strongly dependent on synthesis conditions, cation distribution, and microstructural control. Despite progress in understanding catalytic behaviour and material properties, quantitative benchmarks such as power density and polarization resistance remain insufficiently reported, and full-cell validation is lacking. Furthermore, strategies including doping, composite formation, and microstructure engineering show potential for performance improvement but require systematic evaluation. Therefore, future research should focus on establishing clear structure–property–performance relationships, alongside standardized electrochemical testing and long-term durability assessment (>1000 h), to determine the practical viability of $Ni_{0.4}Cu_{0.6}Mn_2O_4$ spinel for SOFC and related energy applications.

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Data Availability Statement

Data sharing is not applicable: no new data is generated.

Declaration of Generative AI and AI-Assisted Technologies in The Writing Process

During the preparation of this work, the author(s) used Elicit, Connected Papers, Julius AI, and ChatGPT to assist with literature review, idea exploration, outlining the content, and enhancing the clarity and coherence of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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