

REVIEW ARTICLE

Enhanced Functionalities of Co-Doped Sr-Eu Lanthanum Nickel Manganese Oxide ($\text{La}_2\text{NiMnO}_6$): A Review of Properties and Applications

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ABSTRACT: This review article provides a detailed exploration of the multifunctional properties of $\text{La}_2\text{NiMnO}_6$ (LNMO), a double perovskite compound with vast potential in advanced technological applications. As an oxide material, LNMO exhibits a unique combination of half-metallicity, ferromagnetic Curie temperature, and dielectric as well as magnetic ordering. These properties, along with the material's adaptability for various technological innovations, have drawn significant research interest. Specifically, the performance of LNMO in applications such as hydrogen generation, fuel cells, photocatalytic degradation, gas sensing, and lead-free perovskite solar cells underlines its versatility. The article delves into how co-doping with strontium (Sr) and europium (Eu) at the A- and B-sites, respectively, influences these properties, opening pathways for new advancements in energy storage, spintronics, and optoelectronics. This review compiles key findings from recent studies on LNMO, focusing on its structural versatility, adaptability to various dopants, and the resulting effects on electronic, magnetic, and catalytic properties. Additionally, the influence of atomic-scale substitutions on the electronic and magnetic characteristics of LNMO are examined, underscoring its potential in environmentally friendly and high-efficiency devices. By analyzing the latest developments in material performance and applications, this article provides valuable insights into optimizing LNMO for emerging technologies, including spin-based transistors, light-emitting diodes, and photovoltaic devices. Further research directions to enhance the stability, efficiency, and environmental impact of LNMO are also discussed.

Keywords: Perovskites, Double Perovskites, LNMO, Spintronics, Co-Doping, Magneto-Resistance, Functional Materials.

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1. INTRODUCTION

In recent years, the study of perovskite materials has significantly advanced, positioning them at the forefront of material science due to their diverse structural, electronic, and magnetic properties. Perovskites, with a general chemical formula of ABX_3 , are characterized by their cubic crystal structure, where “A” typically represents a larger

alkali or alkaline earth metal cation, “B” a smaller transition metal cation, and “X” a halogen or oxygen anion. Originally discovered in 1839 by the Russian mineralogist Lev Aleksevich von Perovski with the calcium titanium oxide (CaTiO_3), perovskites have since attracted attention due to their remarkable properties and potential applications in various fields, including optoelectronics, spintronics, and energy storage systems [1-3].

The fundamental properties of perovskites—such as ferroelectricity, high dielectric constants, and low exciton binding energy—provide unique advantages for practical applications. These attributes have positioned perovskites as a viable material class for spintronic devices, energy storage applications, and optoelectronic instruments [4-6]. A key

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period of innovation for perovskites emerged in the 1950s and 1960s, during which time researchers made substantial advances in understanding their magnetic properties and electron transport behavior, particularly through the study of magnetic oxides. Significant discoveries included the Zener double-exchange mechanism, Jahn-Teller distortion, and superexchange interactions [7-9]. These advances laid the foundation for subsequent developments in perovskite research, enabling perovskites to become integral to fields as varied as superconductivity, ferroelectricity, and semiconductor physics.

In the last two decades, halide perovskites (e.g., ABX_3 , where X is typically a halide ion) and chalcogenide perovskites (e.g., AMo_3 , where M is a chalcogen) have received considerable research attention. The halide perovskite cesium lead halide (CsPbX_3) was first studied in 1958 and was later joined by methylammonium lead halide ($\text{MeNH}_3\text{PbX}_3$), which has seen applications in photovoltaic cells due to its excellent optical and electronic properties, including high absorption coefficients and transport efficiency [10-12]. Methylammonium lead halides, with notable photophysical characteristics such as long diffusion lengths and high absorption coefficients, became a breakthrough material for light-absorbing applications, especially in photovoltaic cells and light-emitting diodes (LEDs) [13, 14]. The development of perovskite-based thin films led to significant efficiency improvements, with photovoltaic devices based on these materials reaching efficiencies of up to 22.7%, a marked increase from an initial efficiency of just 3.8%. This success has spurred further exploration into low-dimensional perovskites, which offer enhanced stability and tailored electronic properties for diverse applications.

The ongoing refinement of perovskite materials has uncovered their potential as highly adaptable structures capable of tuning electronic and magnetic properties to suit specific applications. Double perovskites, such as $\text{La}_2\text{NiMnO}_6$ (LNMO), have become an area of particular interest due to their unique half-metallic properties, Curie temperature modulation, and magnetic ordering capabilities. LNMO, a rare earth-based double perovskite with both magnetic and dielectric functionalities, has found uses in energy storage devices, hydrogen generation, gas sensing, and even lead-free perovskite solar cells [15-17]. This versatility results from the compound's highly ordered arrangement of Ni and Mn ions, which are separated by nonmagnetic La ions. Such structures can be manipulated by targeted doping at the A- and B-sites, allowing for modifications in structural, magnetic, and electronic characteristics, which, in turn, facilitate application-specific optimizations.

Co-doping $\text{La}_2\text{NiMnO}_6$ with strontium (Sr) and europium (Eu) at its A- and B-sites, respectively, provides an effective strategy for enhancing its intrinsic properties. This process introduces controlled substitutions that can influence the material's electronic structure and magnetic interactions, potentially improving its performance in fields such as spintronics, optoelectronics, and renewable energy systems

[18-20]. Studies have shown that Sr-doped LNMO exhibits notable improvements in magnetic properties, while Eu doping at the B-site optimizes electronic and dielectric behaviors, yielding enhanced performance across various applications. The ability to introduce such dopants and fine-tune their concentrations highlights the flexibility and adaptability of double perovskites, making them promising candidates for next-generation technologies.

Beyond their physical properties, the adaptability of perovskite materials to various atomic-scale modifications provides further opportunities for advancing high-efficiency, environmentally friendly applications. The potential to align LNMO's structural and electronic properties with specific technological requirements has encouraged its study for applications in energy-efficient devices like spin-based transistors, LEDs, and photovoltaic devices [21, 22]. Continued research into the effects of co-doping on LNMO's multifunctional properties aims to maximize stability, performance, and environmental compatibility, underscoring the value of these materials in advancing sustainable technology. By consolidating current knowledge on LNMO's structural versatility and electronic adaptability, this review will provide a comprehensive overview of its enhanced functionalities, establishing a framework for future research directions that seek to optimize perovskites for emerging technological applications.

Table 1 provides a summary of previously discovered perovskite materials and their properties. Each compound exhibits specialized properties such as dielectric behavior, piezoelectricity, magnetoresistance, or proton conductivity, making them integral to advanced devices, from microwave components and memory devices to fuel cells and hard drives. Each compound in the Table 1 is selected for its potential to impact specific applications through its intrinsic material properties. For instance, CaTiO_3 's dielectric property is ideal for microwave applications, while the giant magnetoresistance of LaMnO_{3-x} enhances data storage in hard drives. These compounds are at the forefront of material science research, contributing to developments in energy storage, electronic memory, and sensing technologies.

2. CATEGORIZATION OF PEROVSKITES

Perovskites are a class of materials distinguished by their flexible crystal structure and a wide range of electronic, magnetic, and optical properties, allowing them to serve numerous technological applications. Based on their structural configuration, perovskites are categorized into the following types:

2.1. Single Perovskite

Single perovskites have a chemical formula of ABO_3 , where "A" and "B" represent cations, typically from Group 1, Group 2, or Groups 3-12 in the periodic table. In this configuration, the "A" cation has a larger ionic radius compared to the "B"

cation. The structure of single perovskites includes twelve A-site cations and six smaller B-site cations, coordinated with oxide ions. The oxidation states of these cations vary, such as (+2, +4), (+3, +3), and (+1, +5), which influences their transport properties and mechanisms across various applications. Single perovskites can exhibit several polymorphic structures, ranging from simple cubic to orthorhombic.

The ideal single perovskite structure is cubic, as illustrated in Figure 1, though many perovskites deviate from this ideal arrangement, leading to distortions that can significantly affect their physical properties, especially in terms of ferromagnetism and ferroelectricity.

The cations present in perovskites (A, B) and the anion i.e. O²⁻ are related to each other by following generalizations.

$$r_A + r_{Oxy} = 1.414 (r_B + r_{Oxy})$$

The relationship between the ionic radii of cations in perovskites can be described by the tolerance factor (T), calculated as follows:

$$T = (r_A + r_{Oxy}) / 1.414 (r_B + r_{Oxy})$$

where r_A , r_B , and r_O denote the ionic radii of the A and B cations and oxygen anion, respectively. An ideal perovskite has a tolerance factor of 1. Deviations in this factor (typically ranging from 0.8 to 1.1) indicate structural distortions that shift the unit cell from cubic symmetry toward triclinic or other configurations, affecting stability. Notably, doping at the B-site with a different cation (denoted B') can produce double perovskites, while further modifications may lead to the formation of triple perovskites.

Table 1. A summary of previously discovered perovskite materials and their properties.

S. No	Chemical Formula	Properties	Applications
1	CaTiO ₃	Dielectric	Microwave technology
2	PbTiO ₃	Piezoelectric, Pyroelectric	Pyro-detectors, Transducers
3	BiFeO ₃	High Curie Temperature, Magnetoelectric Coupling	Memory devices, Magnetic field detectors
4	LaMnO ₃	Colossal Magnetoresistance	Spintronics
5	Pb(ZrTi)O ₃	Dielectric, Pyroelectric, Piezoelectric	Pyro-detectors, Non-Volatile Memories
6	BeCeO ₃	Proton Conductivity	Oxygen Fuel Cells
7	LaMnO _{3-x}	Giant Magnetoresistance	Hard Drives

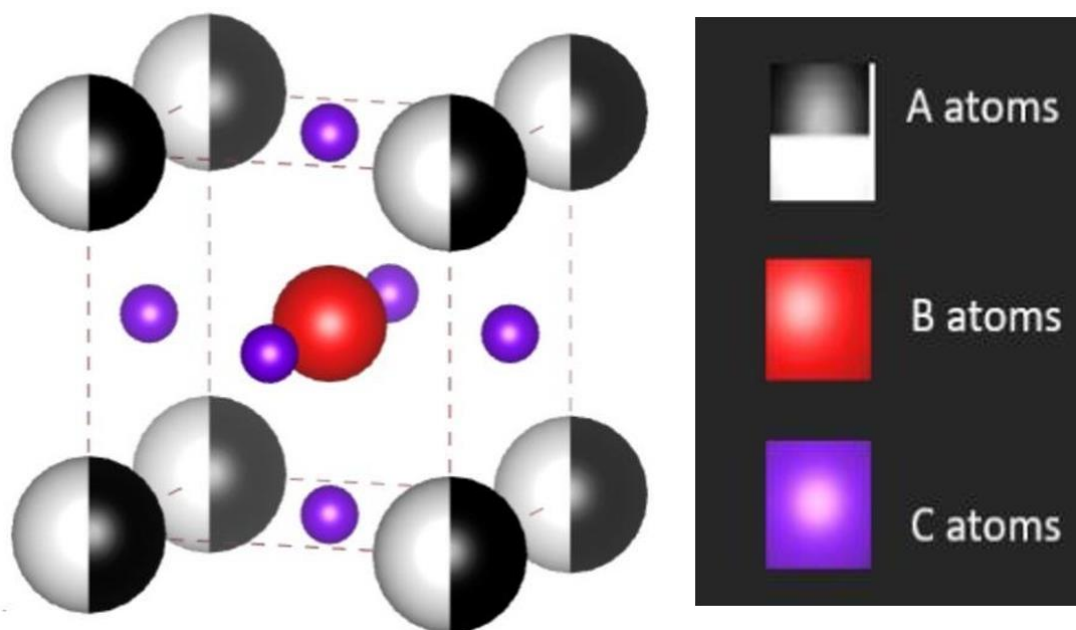


Fig. 1. Ideal single perovskite structure.

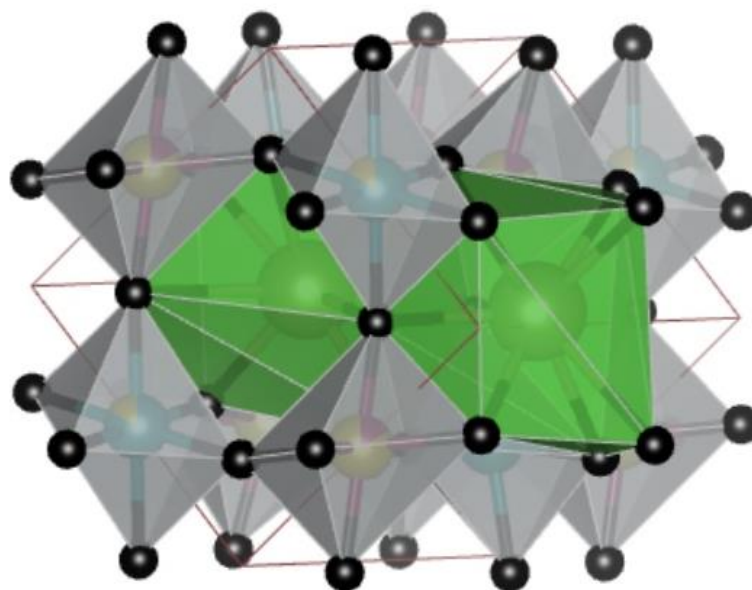


Fig. 2. Crystal structure of double perovskite material.

2.2. Double Perovskite

Double perovskites, represented by the formula $\text{A}_2\text{BB}'\text{O}_6$, are created by combining two single perovskite unit cells. In these structures, the A-site is usually occupied by either alkaline earth metals (Group 2) or rare earth metals (Group 14) and has a coordination number of 12 due to surrounding oxygen atoms. The B-site generally hosts d-block elements that exhibit magnetic properties, such as Fe, Co, Mn, and Ni, while the B'-site commonly accommodates non-magnetic elements, such as tungsten or molybdenum. In certain cases, such as A_2NiMnO_6 , both B and B' sites are occupied by cations with magnetic properties, allowing the material to exhibit unique magnetic phases. [Figure 2](#) exhibits the crystal structure of double perovskite material.

Double perovskites exhibit both electronic and magnetic phases due to the broad range of possible cation combinations at the B and B' sites, enabling tailored properties for various technological applications. In an ideal double perovskite structure, the BO_6 and $\text{B}'\text{O}_6$ octahedra alternate within the lattice. However, deviations from this ideal structure often occur due to factors like temperature and pressure, resulting in antisite disorders where the B and B' cations swap positions. This disorder significantly impacts physical properties by altering the material's electronic and magnetic characteristics.

The development of double perovskites as a research area began in 1961, when Longo et al. identified ferromagnetic properties in double perovskites with rare earth metals at room temperature [23]. This was further validated by Patterson et al. in 1963, who reported ferromagnetism in molybdenum- and tungsten-based double perovskites [24]. Research on Re- and Mo-based double perovskites revealed their high conductivity [25, 26]. In 1998, Kobayashi reported

the half-metallic nature of double perovskites, specifically with $\text{A}=\text{Sr}$, positioning them as strong candidates for spintronic applications due to their half-metallic nature. Subsequent studies uncovered additional properties, such as colossal magnetoresistance, magnetodielectric properties, and ionic conductivity [27, 28]. These properties make double perovskites valuable in memory devices, energy storage solutions, and spintronic applications, enabling lower power consumption and faster data processing [29, 30]. Further understanding of double perovskites requires an exploration of the intrinsic behavior that governs their distinctive properties.

3. MAGNETISM IN PEROVSKITE

3.1. Magnetic Interactions

Magnetism arises from the movement and alignment of magnetic flux, particularly in materials where electrons are exchanged between specific orbitals. In the case of double perovskites or manganates, magnetic interactions stem from the exchange between the p-orbitals of oxygen atoms and the d-orbitals of transition metals, such as manganese (Mn). This exchange relies on an intermediary ion, resulting in what is known as an *indirect exchange interaction*. This form of exchange is localized, meaning it involves the magnetic moments of metal ions through conduction electrons. Different mechanisms, such as superexchange and double exchange, govern this electron exchange, influencing the arrangement of magnetic moments and defining the material's magnetic properties.

3.2. Double Exchange

The concept of double exchange was first proposed by Zener [13]. This interaction occurs when electrons are exchanged between cations with different oxidation states, as seen in manganates, where Mn^{3+} and Mn^{4+} ions couple in a parallel alignment. In this interaction, an electron from Mn^{3+} pairs with Mn^{4+} without altering its spin state, and the resulting orbitals align according to Hund's rule, promoting a ferromagnetic arrangement. In this mechanism, two electrons play a role in the exchange: one moves from the d-orbital of Mn^{3+} to the 2p orbital of oxygen, while the second electron moves from another 2p orbital of oxygen to Mn^{4+} . This results in a net ferromagnetic interaction, a phenomenon named double exchange by Hasegawa et al. [31, 32]. Additionally, it was observed that this exchange interaction in manganates often manifests as localized polarons, which are small, mobile regions with distinct magnetic properties. Figure 3 exhibits the double exchange phenomena.

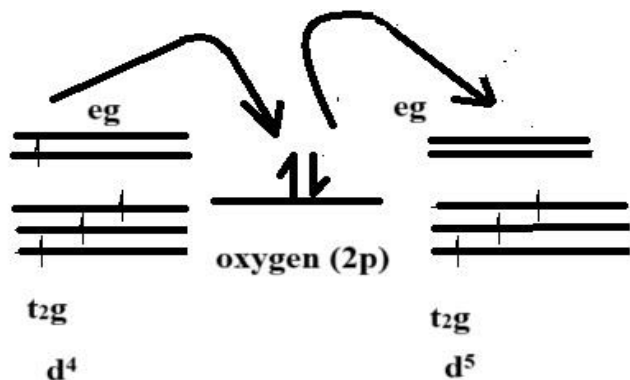


Fig. 3. Double exchange phenomena.

3.3. Super Exchange

Superexchange is a magnetic exchange mechanism in which interactions occur between magnetic cations mediated by a non-magnetic anion, usually oxygen. This indirect exchange, which involves overlapping orbitals of the cations and the anion, gives rise to different magnetic orderings—either ferromagnetic or antiferromagnetic—based on the orbital interactions involved. If the exchange occurs between a filled and a half-filled d-orbital of the magnetic cations, the alignment tends to be ferromagnetic due to favorable spin alignments. Conversely, when two half-filled d-orbitals are involved, the interaction typically results in antiferromagnetic ordering, as the spins align oppositely to minimize energy. In cases where a half-filled or filled orbital interacts with a vacant orbital, the exchange can lead to either ferromagnetic or antiferromagnetic alignment depending on the spatial and electronic arrangement. Superexchange plays a crucial role in determining the magnetic properties of materials, influencing applications in spintronics and magnetic storage.

4. LANTHANUM NICKEL MANGANESE OXIDE (LNMO)

Lanthanum Nickel Manganese Oxide or $\text{La}_2\text{NiMnO}_6$ (LNMO), is a notable member of the manganate family, classified as a double perovskite structure. Figure 4 shows the crystal structure for $\text{La}_2\text{NiMnO}_6$. This transition metal oxide exhibits tailored multifunctional properties, demonstrating both electric and magnetic ordering. Due to its unique combination of properties, LNMO has been extensively studied in recent decades and shows strong potential for next-generation electronic devices, where its multifunctionality can be leveraged in diverse applications [33-40]. LNMO possesses a range of advanced properties, including semiconductivity, ferromagnetism, magneto-capacitance, and magnetoresistance, all of which arise from alterations in the B-site, specifically through interactions between Ni^{2+} -O- Mn^{4+} ions.

The level of cation disorder in LNMO is crucial in determining its crystal structure and properties. The disorder at either the A- or B-site influences the physicochemical characteristics, including piezoelectricity, superconductivity, colossal magnetoresistance, ionic and electronic conductivity, magnetic ordering, and multiferroic behavior [41-43].

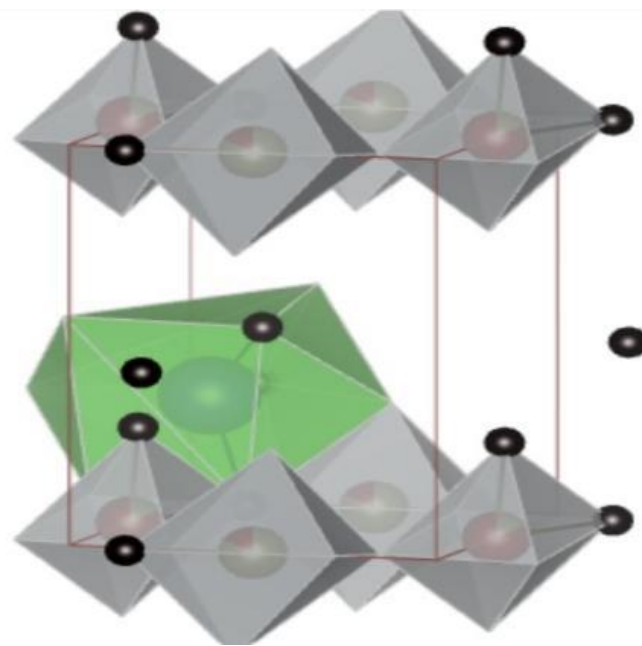


Fig. 4. Crystal structure of $\text{La}_2\text{NiMnO}_6$.

The B- and B'-sites, which typically host ions with differing charges and ionic radii, are generally stable; in LNMO, for instance, Ni and Mn occupy these positions in oxidation states of +2 and +4, respectively. Variations in the oxidation states and ionic radii between Ni and Mn play a role in the stability of the structure. Research shows that LNMO typically crystallizes in monoclinic ($P2_1/n$) or rhombohedral ($R-3m$) symmetries when ordered, while

distortions lead to orthorhombic (Pbnm) or rhombohedral (R-3c) structures where Ni and Mn may both be in the +3 oxidation state. The final structure—ordered or distorted—depends heavily on the synthesis method and thermal conditions used during preparation, which affect the degree of order or disorder in the crystal lattice [44].

The dual influences of differing oxidation states, which promote cation ordering, and similar ionic radii, which favor cation disordering, drive the formation of multiple crystal structures within LNMO. As a result, studies have presented varying conclusions on cation ordering, with some observing significant cation disorder and others finding complete or partial ordering [45].

LNMO is also considered biphasic, meaning it can exist in two different phases depending on temperature. At room temperature, LNMO typically forms either monoclinic or orthorhombic structures, but at elevated temperatures, it transforms into a rhombohedral phase. This double-phase behavior, evident across a range of temperatures including room temperature, highlights the material's adaptability and suitability for applications across diverse thermal conditions.

5. PROPERTIES OF LANTHANUM NICKEL MANGANESE OXIDE

5.1. Electronic properties

The Electronic properties of Double perovskites largely depend on the B-site cation. Due to flexibility in Double Perovskites, the combination of various elements can be done. For instance, d-block elements with different oxidation states, lanthanides and Actinides with different oxidation states can be placed at B and B', respectively. Due to these combinations various materials can be synthesized which include half metallic nature, ferroelectricity, superconducting and semiconducting materials. Compounds containing d-block elements often showcase interesting properties with related to electrical properties.

5.1.1. Electronic Structure

The electrical properties for a solid largely depends on the band structure, intra-atomic electron-electronic interactions (U) and Electronic Bandwidth W. if W is less than U, it depicts the electrons are localized in nature. If W is greater than U, the electrons travel from one region to other. The electronic bandwidth of these double perovskites depends on the overlapping of the orbitals of different elements which in turn depends upon the orbital's spatial distribution. The orbital spatial distribution finally relies on the crystal structure of the lattice. With respect to W, it can be calculated by calculating the bond length as well as the bond angle. As we move across the period the nuclear charge increases due to which the 3-d orbitals contract result in weakening of

overlapping of orbitals with neighboring atoms. Hence the bandwidth of double perovskites LNMO is very low as LNMO contains both elements containing 3-d orbitals i.e. Ni and Mn, hence the effective overlapping with oxygen 2p orbitals by Ni and Mn is weak in nature. As a result, the inter-electronic repulsion is quite often observable.

The orbitals possessing same energies in the case of B and B' is rare, as there are various factors that affect the energies. In d-block element as we move across the period, due to increase in the nuclear charge, the energy of the orbitals decrease. It can be represented as:

$$\text{Energy of orbitals} \propto \frac{1}{\text{eff.Nuclear charge}}$$

The next important factor is crystal field splitting energy (CFSE), as we come across the period the ionic radii as well as bond covalency decreases, due to which the CFSE also decreases which in-turn resorts to difference in energies for Ni & Mn. For higher oxidation state the electron are found in t_{2g} orbitals, whereas for orbitals having lower oxidation and are high spin complex in nature, the electrons resort to eg orbitals as well. And the next corresponding factor that also plays a pivotal role in hindering the electron transfer is symmetry. In case of ordered structure of LNMO, the Ni show d^8 electronic configuration and exists as Ni^{2+} ($d^8 = t_{2g}^6 eg^2$, $\text{Sym}=2/2$) and for manganese it follows d^3 electronic configuration and exists as Mn^{4+} ($d^3 = t_{2g}^3 eg^0$, $\text{Sym}=3/2$). Thus, the electron transfer in the ordered LNMO is very rare and is possible only when orbital energies are comparable and symmetries are favorable & corrected.

5.1.2. Electrical transport properties

As mentioned in the reports LNMO is a substance of ferromagnetism and is semiconductor in nature with a curie temperature of around $T_c = 280\text{k}$ [47-48]. However, in non-stoichiometry state it is usually insulating in nature [49]. In 2015 Ullah et al. marked out electronic, magnetic and thermoelectric properties of LNMO & $\text{La}_2\text{CoMnO}_6$. On calculation of band structures along with reduced zone scheme while finding high symmetry points by using GGA+U [50]. It showed indirect band nature for spin up and spin down states. For spin up states, it marked the minima for conduction band which occurs at T symmetry point while as Y symmetry was located and reported for the maxima of valence band in the Brillouin zone. The (T-Y) indirectly reports the bandgap of 1.6 eV. On the other hand, the Conduction band for minima was reported at T symmetry, whereas the maxima for valence band were noted out at Z symmetry of Brillouin zone in spin down state and the indirect band gap reported were calculated out to be 4.4 eV which is due to (T-Z) symmetry points.

5.1.3. Thermoelectric properties

To understand the pathway or mechanism of electrical transport under the influence thermal variations, it is pertinent to go deep insights the material with focus on thermoelectric properties. As report in 2015 by Ullah, he explored the properties like electrical conductivity, thermal conductivity, sea beck coefficient, and power factor (function of temperature).

5.1.4. Crystal field splitting theory

This theory is most important in explaining the systema of the coordination compounds and can further describes the aspects of properties related to cation as well the fascinating concept belonging to the structure with regards to perovskites. Since as we are aware the perovskites or the magnates consists of central atom that is transition metal, also oxygen forms octahedron around it. As a result, it causes distortion in the d orbitals forming two sets of orbitals i.e. t_{2g} and e_g orbitals, the t_{2g} set is of lower energy and is known as triply degenerate and e_g is of higher energy and is called as doubly degenerate and the difference in the two energy sets is equal to 1.5 eV [46]. In case of magnates, it shows variable oxidation states and are localized in nature. The electrons usually interact with the e_g electrons through oxygen atom. On the contrary the electrons present in the t_{2g} are also localized and have net magnetic moment of $3/2 \mu_B$. Figure 5 shows the crystal field splitting phenomena.

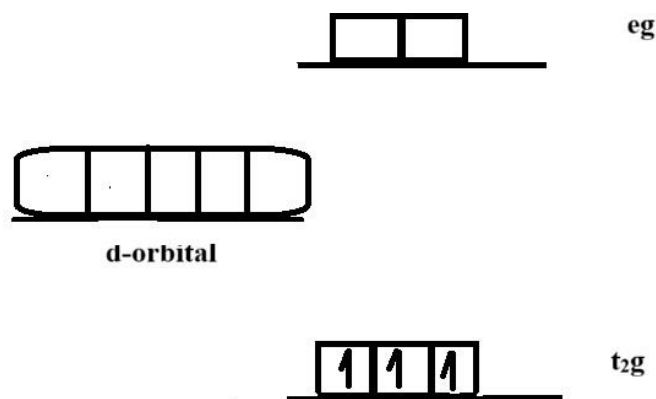


Fig. 5. Crystal field splitting phenomena.

5.1.5. Electrical conductivity (σ)

It is the measure of flow of charge in the substance or the material. The passage of charge determines the nature of the substance whether it behaves as insulator, semiconductor or the conductor. However, the electrical conductivity is seen to be varying with change of temperature. In the case of LNMO on calculation of electrical conductivity upon relaxation time (function of temperature). For spin up configuration, it is found the electrical conductivity has shown marked increase as a function of temperature. When

the temperature is around 200 K (Low Temperature) the value of electrical conductivity is reported as $0.50 (\Omega \text{ m K})^{-1}$. At temperature around 800 K, there was a jump in the value which arises up to $6.4 (\Omega \text{ m K})^{-1}$. Hence the sharp increase proves to be effective in thermoelectric industries. In 2005 Rogado et al reported the semiconducting nature with resistivity equal to $102 \Omega \text{ cm}$ [47].

5.1.6. Thermal conductivity (K)

One of the important property of materials is thermal conductivity which describes the characteristics of insulation for transportation of heat. Materials having high thermal conductivity are used in heat sink. Whereas, thermal insulation corresponds to low thermal conductivity. There is also zero thermal conductivity shown by LNMO and is observed in down spin channel, however the thermal conductivity is seen maximum when temperature reach a maximum value of 800k.

5.1.7. Seebeck coefficient

Most of the times the electron shows an orientation from warmer to colder region. The motion of electron generates the electric field and this happens due to increases of electron holes on both the sides respectively. The difference in voltage to the difference in temperature between two regions refers as seebeck coefficient. One of the most important parameters for determining the efficiency in thermocouples is seebeck coefficient. It is observed there is no change in the spin up channel whereas for spin down configuration the coefficient.

5.1.8. Power factor

It is observed in LNMO, for spin up configuration the thermoelectric power increase with the rise in temperature. However, in spin down configuration it corresponds to zero. Thus, LNMO spin up state can be used in application belonging to thermoelectric the maximum value is attained around 200K.

5.2. Electrocatalytic and photocatalytic properties

Sunlight is considered as Non diminishable resource and is free and abundant in nature. Nowadays, sunlight is used for water photolysis and is done with the help of a cell known as photoelectrochemical cell. This approach is one the finest methods used against fossil fuels and hence the environment can be saved from the pollution which are caused these fossil fuels. Various semiconducting materials and structures were investigated to find out the most efficient photoelectrochemical cell for better production of H_2 gas in the fuel cells. However, limited light absorption is the key issue in determining the overall power conversion. The

process like fast charging recombination rate and degradation of electrode overall in the mechanism cause the energy loss. Hence to overcome the limitations few exotic materials with tailored functionalities were produced sheikh et al introduced the concept of double perovskite in Photo-electrochemical catalyst properties in BiFeO_3 and $\text{La}_2\text{NiMnO}_6$. The light harvesting property was evaluated by using the BiFeO_3 and $\text{La}_2\text{NiMnO}_6$ as photo-anodes for water photolysis in Photoelectrochemical cells. Other reports suggest that LNMO is promising candidate for generating molecular oxygen for energy storage devices respectively popularly known as Oxygen Evolution reaction. [51-54]

Methane (CH_4) is the next compound which cause greenhouse gas effect and is profound 20 times stronger in greenhouse gas effect than CO_2 . In 2013, Ding [55] reported a method for the elimination of the methane gas produced from power plants as well as from natural gas engines by using composite oxide of $\text{La}_2\text{NiMnO}_6$ - MgO which can be used for high catalytic combustion of the methane gas respectively. Similarly, as reported by Ting et al. [56] when mesoporous double perovskite is used, photothermal synergistic degradation has taken place in the toluene gas. In 2016, as reported by Shi et al. [57] the demonstrations reported the oxychlorination of ethane by using oxide catalyst of perovskite type.

5.3. Ferroelectrics

As per HIF (Hybrid Improper Ferroelectricity) theory, when oxygen is combined in octahedral rotations in 3-D structure as well as layered Ion ordering, it causes antipolar motion at A-site in the case of perovskites. [58-59]. Majority of the reports thus suggest the ferroelectric properties in the compound LNMO [60-62]. It was reported by Zhao et al. [63] that LNMO superlattices occur in (-b) direction which can exhibit strong ferromagnetic ordering as well as electric polarization nearly at room temperature. Takahashi et al. mentioned the ferroelectricity directing at A-site in B-site ordered ferromagnetic LNMO crystals.[64] while on calculations with Density Functional Theory, it showed stretching of epitaxial strain in rhombohedral crystal lattice in cubic direction of LNMO. Involving displacement at A-site in the double Perovskite lattice. The distortion taking place A-site stabilizes the ferroelectric polar state of the crystal lattice of LNMO. The appearance of ferroelectric nature only appears in rhombohedral LNMO phase.

5.4. Optical properties of LNMO

The optical properties of $\text{La}_2\text{NiMnO}_6$ (LNMO) encompass significant characteristics such as fluorescence, luminescence, and bandgap, providing insight into its functional capabilities. LNMO has been widely studied over the years, consistently revealing new facets of its behavior [18, 65-68]. Kitamura et al. [69] conducted the earliest study, reporting an optical bandgap of 1.5 eV in epitaxial thin films

deposited on SrTiO_3 via pulsed laser deposition. Optical conductivity was later used to confirm this value. Further analysis using the Pechini method [44] showed that LNMO's bandgap varies by symmetry: 1.4 eV in the monoclinic phase and 1.2 eV in the rhombohedral phase. The monoclinic structure's bandgap, close to the ideal value for solar cell applications, highlights LNMO's potential for light-harvesting technologies. Ahmad et al. [68] found a bandgap of 1.33 eV, indicating its semiconducting nature, and noted that yttrium doping could adjust this value to 1.46 eV. Sit was observed that the high charge carrier lifetime and narrow bandgap (1.33 eV) of LNMO is ideal for single-junction solar cells [68, 70]. Additional photophysical properties, such as diffusion length and conductivity, improved with photoirradiation, further supporting LNMO's exploration for photo-responsive applications.

5.5. Magnetic Properties

LNMO's magnetic properties are manipulable through electric and magnetic fields, affecting spin and dielectric properties, especially at room temperature, a promising feature for spintronics [47, 71-73]. In ordered LNMO structures, it behaves as a ferromagnetic semiconductor, with a Curie temperature around 280K [74-77]. Nickel (Ni^{2+}) and manganese (Mn^{4+}) ions occupy distinct lattice sites in the perovskite structure, leading to ferromagnetic ordering through 180° superexchange between Ni^{2+} and Mn^{4+} orbitals, as described by Kanamori-Goodenough rules [78-87]. Disordered LNMO, however, displays dual ferromagnetic phases: high Curie temperature ($\sim 266\text{K}$) arising from Ni^{2+} -O- Mn^{4+} superexchange and low Curie temperature ($\sim 100\text{K}$) from Ni^{3+} -O- Mn^{3+} exchange [88-90]. Contrasting findings by Choudhury et al. described a glassy magnetic state due to antiferromagnetic transitions in Ni^{2+} and Mn^{4+} pairs [91]. Singh et al. (2009) noted the sensitivity of Curie temperature to Ni and Mn atomic ordering, with lower values ($\sim 138\text{K}$) for disordered films and higher values ($\sim 270\text{K}$) in ordered configurations. Further research by Nasir et al. confirmed a high Curie temperature of $\sim 280\text{K}$ independent of annealing temperature [48]. Theoretical saturation magnetization of LNMO is $5 \mu\text{B}/\text{f.u.}$, but experimental results vary ($2.2 \mu\text{B}/\text{f.u.}$ to $3.2 \mu\text{B}/\text{f.u.}$ for ordered and $1.2 \mu\text{B}/\text{f.u.}$ for disordered LNMO) due to antisite disorders that reduce magnetization by introducing antiferromagnetic coupling, impacting LNMO's electrical and magnetic properties.

5.6. Dielectric properties

The dielectric behavior of materials encompasses various parameters, with the dielectric constant being the primary indicator of a material's dielectric properties. Numerous studies have investigated the origins and mechanisms of dielectric behavior in double perovskites. For example, the dielectric relaxation in $\text{Ho}_2\text{CdZrO}_6$ was attributed to polaron hopping at alternating cationic sites, following a variable

range hopping conduction mechanism [45]. In $\text{La}_2\text{NiMnO}_6$ (LNMO), dielectric properties are associated with the oxidation states of cations, particularly nickel (Ni) and manganese (Mn), which influence the oxygen valency, charge carriers, and interfacial polarization. One study reported that the high dielectric constant and relaxation behavior of LNMO arise from the presence of oxygen vacancies [45]. Comparisons have also been made to LuFe_2O_4 , noting similar dielectric behavior patterns [92-94]. Further research has demonstrated that LNMO's dielectric properties improve with yttrium (Y) doping, enhancing its dielectric constant [65]. Additionally, titanium (Ti) doping has shown relaxor-like behavior, while another study reported a significantly high dielectric constant in LNMO due to extrinsic interfacial polarization, as confirmed by impedance spectroscopy [95].

5.7. Spintronics

Spintronics, or spin electronics, is based on the alignment of electron spin magnetic moments, specifically where a material's spins are aligned in one direction, creating a net magnetic moment. In typical non-magnetic materials, electron spins are oriented so that the spin-up and spin-down moments cancel each other out, resulting in zero net spin. However, in LNMO, which is a ferromagnetic semiconductor, electrons are distributed non-uniformly across spin states. Electrons in higher-energy spin states occupy the spin-majority channel, while those in lower-energy states move to the spin-minority channel, producing a net spin magnetic moment. This spin alignment can be quantified through spin polarization, calculated as follows:

$$\text{Spin polarization} = \frac{d_{\text{spin up}} + d_{\text{spin down}}}{d_{\text{spin up}} + d_{\text{spin down}}}$$

where $d_{\text{spin up}}$ represents the density of states for spin-up electrons at the Fermi level, and $d_{\text{spin down}}$ is the density of states for spin-down electrons at the Fermi level. This measure is critical for understanding the spin transport properties of LNMO in spintronic applications.

6. DOPING TO IMPROVE THE PHYSICAL PROPERTIES OF $\text{La}_2\text{NiMnO}_6$

Though the study of physical properties is very broad and vast, still there is always a scope for improvement to accomplish requirements of modern-day population which are not technological only but multifunctional in nature. Numerous methods are present for tailoring the properties to desired values. To discuss in brief, only the technique which is studied across the paper is discussed only. It is one of the traditional and conventional techniques adopted for tuning the material properties in particular. In this process foreign impurities are added externally in the compound, so that the overall properties

of the compound are shifted. In case of perovskites as well as double perovskites they have high end flexibility. The flexibility lies in terms of structure, symmetry as well as in constituent elements on which substitution or doping can be done, which includes the sites of A as well as B/B' respectively. Consequently, by doping or substitution of the foreign impurities either by adding small or varying concentration, it alters the physical properties of the substance which include dielectric constant, transport properties, Curie temperature, magnetization etc. Thus, the demanding applications can be extracted and synthesized which nowadays include the solar applications, magnetoresistance, mechanical strength, spintronics, and so on [96-100].

6.1. Doping at A-site

The substitution at A-site in the case of LNMO by any suitable dopant creates a huge scope for tuning the physical properties to desired values. Time to time various studies and researches are conducted which brings lime-light about the substitution and its effects when doped at A site. Even today researches are conducted across LNMO both on bulk and thin films to improve the properties to desired states. Recently Yu et al. [101] reported the substitution caused by Sr caused a degradation in the tetracycline in 240 min, respectively. Cao [95] et al. reported huge achievement in dielectric tunability in the LNMO when co-doped by Sr-Sb. Kim et al. [102] marked the doping done Sr induces half-metallic character. Guo et al. reported the exchange bias effect with increase in antisite disorder. Ting et al. [103] observed the weak ferromagnetic interaction and increased antiferromagnetic interactions along with considerable increase in the exchange bias effect in LNMO when doped by calcium (Ca). Thus, valuable properties can be obtained in the field of magnetic, optical, electric etc.

6.2. Doping at B-site

The doping done at B/B' site in the LNMO opens a gateway for physiochemical properties of this compound as well as the modifications that can change the nature of the compound. The selection of dopants at these sites largely influences the cation ordering or disordering which overall their physical properties, respectively. Gan et al. reported improvement in the magnetic moment in LNMO when doped by Co (cobalt) at B site [104]. In the same study it was reported that with the increase in varying concentration of Co the magnetic saturation increased from 3.85 $\mu\text{s/f.u.}$ to 4.86 $\mu\text{s/f.u.}$ [104]. In another research researchers pointed out the transformation of phase structure from P2₁n to R-3 phase, along with increase in magnetic performance with change in magnetic saturation by a factor of 25% as that of pure LNMO when doped by varying concentration of Mg at Ni site. It has been reported that the substitution at Mn site by Ti greatly effects the magnetic, dielectric as well as crystallographic properties in LNMO [105]. Hence it can be concluded at B-site tremendous opportunities for present for the enhancement of physical properties relatively.

7. APPLICATIONS OF $\text{La}_2\text{NiMnO}_6$ (LNMO)

The double perovskite $\text{La}_2\text{NiMnO}_6$ (LNMO) holds great promise due to its wide range of applications across multiple domains, including solar energy, gas sensing, and biomedical applications. Its unique structural, electronic, and magnetic properties make it a versatile material with potential in various fields, as outlined below.

7.1. Solar Cells

Since their introduction, perovskite solar cells have demonstrated a superior alternative to organic dye-based solar cells, achieving significant efficiency milestones. These advancements in perovskite solar cells have placed them as serious contenders against traditional silicon-based solar cells, primarily due to their high power conversion efficiency (PCE), which can reach approximately 21% [38, 106-107]. This high efficiency is attributed to the optimal bandgap and charge carrier mobility of perovskite materials, which are essential for effective light-to-electricity conversion.

Among the perovskites, methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$) with a bandgap of 1.5 eV has shown exceptional promise due to its high absorption coefficient and carrier mobility. However, the use of lead in $\text{CH}_3\text{NH}_3\text{PbI}_3$ raises environmental and health concerns due to its toxicity, making lead-free alternatives highly desirable [108]. LNMO, with its bandgap of around 1.5 eV, meets the requirements of high stability and lower toxicity, making it a promising candidate for photovoltaic applications. In one study, LNMO's photovoltaic potential was evaluated both theoretically and experimentally by synthesizing the material at annealing temperatures of 600°C and 900°C in an oxygen environment [109]. This process yielded LNMO samples with different crystal symmetries, including monoclinic and rhombohedral structures. The monoclinic LNMO sample, with a bandgap of 1.4 eV, showed great potential for light harvesting due to its optimal bandgap for photovoltaic applications, positioning LNMO as a viable alternative in the next generation of perovskite solar cells.

7.2. Gas Sensing

Gas sensors are essential for detecting toxic, flammable, and hazardous gases, particularly in industrial settings where accidental gas leaks can pose serious health and safety risks. Gas sensors are used to monitor leaks and alert control systems, enabling personnel to take protective actions when hazardous gases are detected. LNMO has shown promise as a gas-sensing material, demonstrating sensitivity to different gases through changes in electrical conduction based on gas concentration and environmental conditions. Biswal et al. studied LNMO's potential as a gas sensor and observed impedance variations that correlate with gas concentration [110]. This interaction occurs as gases adsorb onto the electrode surface, altering the sensor's electrical resistance

through the formation of space charge at the grain boundary interface.

Gas sensing behavior in LNMO has been investigated for gases like oxygen, argon, and nitrogen at various temperatures, revealing a strong correlation between electrical resistance and gas concentration. As gas concentration increases, a critical threshold is reached where a sudden change in resistance is observed, indicating LNMO's sensitivity to changes in gas composition and concentration [111]. This makes LNMO a valuable material for gas sensing applications, especially in environments requiring precise monitoring of air quality and gas presence.

7.3. Biological Applications

Perovskite materials, particularly magnetic nano-perovskites like LNMO, exhibit excellent potential in biomedical and biological applications due to their unique magnetic and structural properties. In the medical field, these materials are being explored for uses in targeted drug delivery, hypothermia treatments, quantitative immunoassays, and bio-separation processes [112-114]. To utilize LNMO nanoparticles in biomedical applications, mono-dispersion of the nanoparticles is essential to enhance their interaction with macromolecules such as proteins. In aqueous solutions, proteins tend to aggregate on solid surfaces, which facilitates adsorption onto LNMO, making it suitable for biomedical engineering, environmental science, and biotechnology applications [115-117].

One of the key properties that make LNMO suitable for biomedical applications is its high adsorption capacity, which is influenced by the material's annealing temperature [118]. This property enables LNMO to act as an effective adsorbent for various biomolecules, allowing for applications such as bio-separation and targeted drug delivery. In bio-separation processes, LNMO nanoparticles can selectively bind to specific biomolecules, facilitating their isolation from complex mixtures. Similarly, in drug delivery, the magnetic properties of LNMO allow for the controlled targeting and release of therapeutic agents, potentially improving the efficiency and precision of treatments.

The magnetic properties of LNMO are also being explored in hyperthermia treatments for cancer. In magnetic hyperthermia, magnetic nanoparticles like LNMO are introduced into tumor cells and then subjected to an alternating magnetic field, generating localized heat. This heat can selectively destroy cancerous cells while minimizing damage to surrounding healthy tissue. The application of LNMO in hyperthermia thus holds potential as a minimally invasive cancer treatment method. Additionally, LNMO's compatibility with biological systems and its potential for functionalization with various biomolecules make it a valuable material for developing advanced biosensors and therapeutic agents.

7.4. Environmental Applications

LNMO also shows promise in environmental applications, particularly in pollutant detection and removal. The high surface area and adsorption capacity of LNMO nanoparticles make them suitable for capturing pollutants in water and air, providing a potential solution for environmental remediation. LNMO's adsorption capabilities can be further enhanced by modifying the material's surface properties, allowing for the selective capture of specific contaminants.

In wastewater treatment, LNMO can be used to remove heavy metals and other toxic pollutants from water. Its high adsorption efficiency, combined with magnetic properties, allows for easy separation of the material from treated water, reducing the risk of secondary pollution. Moreover, LNMO's stability in harsh environmental conditions makes it suitable for long-term use in water treatment facilities.

Another potential environmental application for LNMO is in the development of air purifiers. The material's gas-sensing capabilities can be applied to detect harmful airborne pollutants, while its adsorption properties can be used to capture and neutralize these pollutants, contributing to cleaner and safer air in industrial and urban areas. Through these applications, LNMO can play a significant role in addressing environmental challenges, particularly in areas affected by industrial pollution.

7.5. Energy Storage

Beyond solar cells, LNMO has potential applications in energy storage devices, such as supercapacitors and batteries. The material's high dielectric constant and stability make it a suitable candidate for energy storage, where it can help improve the energy density and charge-discharge efficiency of devices. In supercapacitors, LNMO can contribute to high capacitance values due to its unique electronic structure and charge storage mechanisms. Additionally, doping LNMO with other elements can enhance its electrochemical properties, making it even more effective for energy storage applications.

The versatile properties of LNMO enable its use in a wide array of applications, including solar energy, gas sensing, biomedical engineering, environmental remediation, and energy storage. Its unique combination of magnetic, dielectric, and adsorption properties make LNMO a valuable material for developing advanced technologies across various fields. As research continues, the potential applications of LNMO are likely to expand, further establishing it as a key material in the fields of renewable energy, environmental science, and biomedicine.

8. CONCLUSION

This review emphasizes the multifaceted potential of $\text{La}_2\text{NiMnO}_6$ (LNMO) as a double perovskite oxide material for cutting-edge applications. LNMO's co-doping with strontium (Sr) and europium (Eu) has proven to influence its

magnetic, electronic, and catalytic properties significantly, making it an attractive candidate for energy storage devices, optoelectronic devices, and applications in spintronics. The unique half-metallicity and robust Curie temperature exhibited by LNMO reflect its suitability for high-performance magnetic and spin-based devices, where stability and enhanced electron correlations are crucial. These advancements suggest a growing opportunity for LNMO in eco-friendly, lead-free solar cells and efficient hydrogen generation technologies.

The diverse applications of LNMO and the versatility afforded by its co-doped structure underscore the importance of atomic-level tuning to maximize performance. Research indicates that subtle changes in dopant concentrations at A- and B-sites affect LNMO's response to magnetic and dielectric stimuli, making it responsive to various environmental and operational demands. For instance, Sr and Eu co-doping can modify the crystal lattice, which directly influences electron mobility, thus impacting LNMO's performance in devices that require rapid charge and discharge cycles, such as supercapacitors. Additionally, this review highlights the potential for further research into optimizing the stability of LNMO under operational conditions to enhance device durability and reduce environmental impact.

Given the advantages demonstrated by co-doped LNMO in terms of magnetic, electrical, and chemical behavior, future research may focus on exploring its potential in more complex multi-functional devices. In conclusion, LNMO holds promising prospects for advancing green energy technologies, efficient optoelectronic systems, and high-performance spintronics, with the potential to shape future applications in sustainable, high-efficiency devices.

9. FUTURE PROSPECTIVES

To further advance LNMO (Lithium Nickel Manganese Oxide) for diverse applications, several key areas warrant deeper exploration and development. Future research should target both the material's fundamental properties and practical application challenges. Below are the outlined directions, expanded for clarity and depth:

Enhanced Structural Stability: LNMO's structural robustness is essential for stability under varying and often challenging environmental conditions. Future research should focus on optimizing the material's crystalline structure, grain boundaries, and bonding through controlled modifications. These could include surface coatings, particle morphology adjustments, and doping strategies to enhance LNMO's resilience in high-temperature and corrosive settings, ensuring reliable performance in industrial and field applications, such as high-voltage and high-temperature electronics.

Optimization of Co-Doping Combinations: Co-doping

with elements like Sr and Eu has shown promising effects on LNMO's properties; however, further exploration is needed to identify other potential co-dopants. Investigating combinations of transition metals, rare earth elements, or even non-metals could unveil enhancements in magnetic ordering, dielectric constants, and thermal stability. Computational studies and high-throughput screening could accelerate the discovery of optimal co-dopant pairs to fine-tune LNMO's properties for targeted applications, from electromagnetic interference shielding to energy-efficient magnetoelectric devices.

Scale-Up for Industrial Applications: While LNMO's synthesis is effective on a laboratory scale, the challenge remains to develop scalable, cost-effective synthesis processes. Emphasis should be placed on green synthesis routes, reduction in the use of rare or expensive precursors, and the development of methods that maintain material uniformity on a larger scale. Furthermore, methods such as sol-gel processing, hydrothermal techniques, and mechanochemical synthesis could be refined to facilitate large-scale production, making LNMO a feasible option for mass production in consumer electronics, electric vehicle batteries, and other industrial devices.

Exploration in Energy Harvesting: LNMO's unique properties make it an exciting candidate for energy harvesting and storage applications. Research should investigate its thermoelectric performance for devices that convert heat to electricity, as well as potential integrations in hybrid solar cells. Studies could focus on designing LNMO-based composites that leverage its magnetic and electrical properties to increase the efficiency of solar energy conversion, piezoelectricity, and thermoelectric power generation. This could enable innovative applications in renewable energy and sustainable power systems, potentially integrating LNMO into smart grids or self-powering devices.

Environmental Sustainability: As the demand for environmentally benign materials grows, it is critical to evaluate LNMO's stability and performance with non-toxic, eco-friendly components. Future work could involve substituting hazardous substances with lead-free, low-toxicity elements, aiming to improve environmental compatibility for applications in green energy technologies. By exploring LNMO's compatibility with materials used in fuel cells and photocatalytic systems, researchers can develop solutions for sustainable solar energy conversion and water purification, aligning with global sustainability goals.

Advanced Characterization Techniques: Understanding the effects of co-doping on LNMO's electronic structure and magnetic properties is key to unlocking its full potential. Employing advanced in-situ and ex-situ techniques, such as X-ray absorption spectroscopy (XAS), neutron diffraction, and magnetic resonance imaging, could reveal insights into electronic transitions, atomic bonding, and magnetic ordering at the nanoscale. These studies would allow a more

granular understanding of the interplay between structural modifications and functional properties, helping to tailor LNMO for specific high-performance applications in spintronics, dielectric devices, and beyond.

By pursuing these future directions, the development of LNMO can lead to breakthrough applications across sustainable energy, advanced electronics, and environmental technologies, potentially setting new standards for multifunctional materials that address modern energy and technological challenges.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

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