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An investigation on characterization techniques and real-time applications of double perovskite material La_2NiMnO_6

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ABSTRACT— **A double perovskite material, La_2NiMnO_6 (LNMO) shows remarkable ferromagnetic properties as well as semiconducting properties which makes it a promising candidate material for applications such as spintronics, catalysis, energy storage devices and many more. In this review, we present an in-depth characterization of the structural, magnetic, and electronic properties of LNMO using x-ray diffraction (XRD), Raman spectroscopy, vibrating sample magnetometry (VSM) and others. Monoclinic (P21/n) structural studies and near-room-temperature ferromagnetic ordering subject to antistites ordering are highlighted by magnetic analyses. Doping studies utilize elements such as Sr and Ba to also emphasize the tunable electronic characteristics of the material, for instance bandgap tunability for photovoltaic and dielectric purpose. The multifunctionality of LNMO is evidenced by practical implementations in oxygen evolution catalysis, supercapacitors and spintronic devices. These results highlight the importance of accurate characterization methods in enabling the continued advances in double perovskite materials for next-generation technologies.**

Keywords*— *Double perovskite, structural characterization, magnetic properties, spintronics, energy storage.

I. INTRODUCTION

Double perovskite materials with the general formula $A_2BB'O_6$ (where A is a rare earth metal and B, either a metal or a transition metal) have attracted much attention over the past decade in the field of advanced materials for their superior multifunctionality and promise for application. These allow for substitution at both the A and B sites and so are unique in their structural flexibility. Because of their significant characteristics, these materials offer a quite huge range of all the possible uses that can include phase shifters, RF (Radio Frequency) filters, some memory devices and also sensors. Efforts have been made in past to produce multiple-function materials along with their electric orderings and magnetic orderings, due to their growing demand for next generation electronic equipment to have more functionality and reduced power usage [1]. This flexibility also allows the electronic, magnetic, and optical properties to be tailored for a given application. LNMO is an important double perovskite belonging to a class of compounds characterized by their unusual semiconducting and ferromagnetic properties at approximately room temperature, which is quite different from the behaviour of conventional perovskites [2, 3].

In LNMO, the ferromagnetism emerges from a super exchange between Ni^{2+} and Mn^{4+} super exchange between super exchange mediated by oxygen. As a result, there is a high Curie temperature (~280 K), which is appropriate for spintronic devices that can be operated close to ambient conditions. The semiconducting character of the material, characterized by a tuneable bandgap via doping, increases the applicability of the material in energy storage/conversion devices like solar cells and supercapacitors [4]. The dielectric and catalytic properties of it also emphasize its multifunctional characteristics for applicating in magnetodielectric devices, bifunctional catalyst, and high-performance electronics [5]. LNMO exhibits structural and functional properties that are intimately related to its crystallographic ordering and cation distributions. Nevertheless, antistites disorder (Ni and Mn ions misplacement) and oxygen vacancies can dramatically affect its behavior. Hence, an in-depth study of such properties using advanced characterization techniques is crucial to the functionality of the material and to achieve total utility [6, 7].

In the branches of Solid-State Physics and Solid-State Chemistry, those kinds of compounds are investigated the most which crystallizes in the structure of perovskites among all the materials. Double perovskite materials are being defined by a huge number of chemical properties and physical properties which have the ability to define the term of superconductivity, a variety of magnetic orderings which ranges from antiferromagnetic to that of the ferromagnetic and even the displacement of atoms in ferric materials along with its catalytic properties. As discussed above, these kinds of materials can also have the electronic structure which ranges from the insulating properties to the metallic properties, and even half-metallic along with the spin polarized electrical conductivity. Also, perovskites can contain multiple characteristics at once that opens a door towards a new type of characteristic combination such as multiferroicity. Therefore, perovskite materials are very much interesting from a point of view of technology [8].

Research organizations worldwide have investigated the properties of the double perovskites, including ferroelectricity, multiferroelectricity, dielectricity, magnetic properties and luminescence [9–11]. The electric, magnetic, crystal structure and magneto transport properties are compiled from previous research in this review. For the construction of complex oxides, a thorough understanding of chemical and structural ordering is especially crucial since these properties control a wide range of practical electrical, magnetic, and optical functions [12]. One of the best advancements in the area of the deposition technique which gives accurate results is Molecular beam epitaxy (MBE) and it has made it possible to build premium oxide heterostructures [13–15] . Also, some more techniques such as the non-local XRD (X-Ray Diffraction) scattering methods and much higher localized observations regarding electron microscopy are still used in the matter of characterization of these types of oxides. It was noted that this combination is somewhat insufficient for sufficiently correlation of macroscale structure and atomic-level structure. A detailed strategy which can make the use of models, use of characterization along with the synthesis insights is needed for separation of the complex web regarding conflicting effects which is being searched in many of the component systems. We investigated that double perovskite LMNO is able to function as a modelling system whereas the macroscale magnetic behaviour can be reliably interpreted by combining insights from the calculations of first principles along with multiscale approaches [16]. La_2NiMnO_6 (LMNO) highlights the complexities and debates inherent in engineering of structural properties regarding many multicomponent systems. Double perovskite material La_2NiMnO_6 is a ferromagnetic (FM) semiconductor that inhibits much higher FM Curie temperature (which is nearly equivalent to 280 K), we can even justify the fact that LMNO is a quite promising agent in case of its important application in thermoelectric fields and it is even worth using in the field of spintronic applications.

In today's most recent times, a huge deal of research has done on the subject of double perovskite La_2NiMnO_6 and the magnetocaloric effect that was present inside the crystal structure of LNMO was examined. The geometrical structure, electronic structure as well as all the optical characteristics regarding both ordering and disordering of double perovskite material LNMO ($LaNi_{0.5}Mn_{0.5}O_3$) thin films [17–19]. Many of the computational methods regarding the analysis have investigated that these materials' electronic structure interactions are very much dependent upon the magnetism. The observation of ground state was suggested to be of great use of Ni-e_g electronic states along with the Mn-$2t_g$ electronic spins which was indicated by the ordering and disordering of phases by the use of models that includes super-exchange and double exchange. It should also be observed that the nanoparticles of this particular compound exhibit the multiferroic behavior along with relaxor ferroelectricity [20].

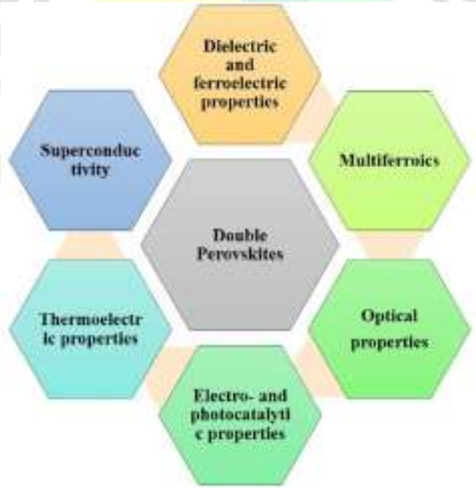

Fig. 1. Different attributes of double perovskite oxides[21]

Fig. 1. shows the graphical representation of many different properties of the double perovskite material which also justifies that double perovskites are really of the great importance because of their different characteristics and among every double perovskite material, LNMO is the cost friendly material that can be easily influenced by different magnetic and electrical orderings.

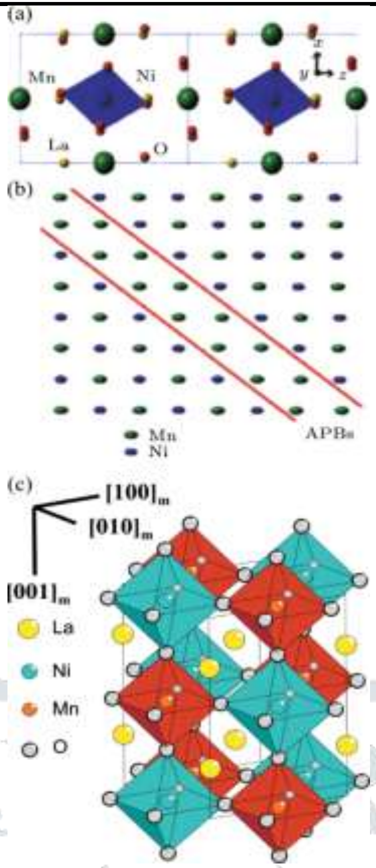

Fig. 2. (a) An illustration of the crystal structure of double perovskite LNMO (b) Domain with differently ordered anti-site phase border (c)The LNMO’s crystallographic structure[22]

Fig. 2. (a) describes the typical structure of double perovskite which is attached along with its two different B-sites. Fig 2 (b) analyses the normal ordering of Ni and Mn and fig 2 (c) simply describes the crystallographic structure of LNMO.

The aim of this review is to summarize many of these characterization techniques applied to LNMO and how these techniques have been useful for understanding its structural, magnetic, and electronic properties. Different key techniques including X-ray diffraction (XRD), Raman spectroscopy, vibrating sample magnetometry (VSM), and density functional theory (DFT) calculations are elaborated on for elucidating the structure and functional behavior relationship of the material. This work is motivated by a desire to help fill in the missing links of how structural information such as cation ordering, antistites defects, and doping govern macroscopic properties of this material in general. This review reviews the current achievements, challenges, and perspectives of LNMO from experimental and theoretical studies towards application in spintronics, energy storage, and catalytic systems. Such an extensive overview is meant to provide a roadmap for further development of this promising material toward real-world applications by the scientific community.

II. STRUCTURAL CHARACTERIZATION

A. *X-Ray diffraction analysis*

The crystallographic structure of LNMO is critical to its multi-functional properties, especially its ferromagnetism and semiconducting properties. The structure is characterized X-ray diffraction (XRD), a powerful analytical technique that reveals phase purity, crystal structure, and lattice parameters. LNMO is generally characterized by a monoclinic crystal structure with the P21/n space group at room temperature, where Ni^{2+} and Mn^{4+} octahedra are arranged in a long-range ordered pattern [6, 7]. This preferential cation ordering enables certain super exchange interactions between Ni^{2+} and Mn^{4+} ions, which are responsible for the ferromagnetism of the material [2, 4]. Rietveld refinement of XRD data provides high-end quantitative information relative to structure such as bond lengths, bond angles and unit cell dimensions as well. Reference bond lengths for Ni−O and Mn−O bonds further support B-site cation charge ordering, with precise refinement however providing evidence that the bond lengths are unique. While this ordering is beneficial for magnetic moment stabilization and electronic conductivity, antistites disorder, where Ni and Mn ions are interchange, can disrupt this ordering and cause a severe loss in both magnetic moment and electronic conductivity [7]. The disorder in these compounds can be determined from peak broadening and intensity ratio from the diffraction pattern, which is indirect evidence of deterioration of the form of LNMO. XRD studies as a function of temperature have shown that the monoclinic phase gives way to a rhombohedral state at higher temperatures. Simultaneously, such structural transformation will alter electronic and magnetic properties highlighting a close competition of structure and functionality. Moreover, the high–pressure XRD studies [4–6] have shown that the cation ordering can be enhanced and the wanted ferromagnetic phase can be stabilized by the compressive stress [4, 7]. Additionally, Table 1 represents synthesis techniques and different structural characteristics of LNMO and Table 2 represents comparison of La_2NiMnO_6 magnetic properties under varying synthesis conditions.

Double perovskite LNMO exhibits Monoclinic structure at the lower temperatures and it can even be converted to Rhombohedral structure at high temperatures. This analysis is done from this XRD technique only. Vishwajit M. Gaikwad[23]have prepared LMNO nanorods by making the use of hydrothermal process (The remaining dried powder was being calcinated at around 1000°C for 6 hours) and the synthesized sample was tested by the help of Powder X-ray Diffraction (PXRD) that was being carried out along with the help of Bruker D8 diffractometer which ranges from 10 degrees to 90 degrees (slow scan of 0.0046°/C). He demonstrated that the synthesized sample belongs to the pure monoclinic form (space group $P2_1/n$). M.P. Singh [17] have prepared the sample of LNMO with the help of sol-gel technique and the resulting powder was pressed into the pallets and further, that pallet was normally sintered at 1200°C temperature for almost two different durations (i.e 4 hours and 24 hours). Afterwards, the synthesized sample was observed to be triphasic that includes $P2_1/n$, Pbnm and also R-3c symmetries of crystal that is present in it. Dass et al.[24] have investigated that when the sample was synthesized by using the method of Pechini technique in which the proper arrangement of Ni^{2+} and Mn^{4+} ions result into the interactions of ferromagnetic type Ni^{2+}-O-Mn^{4+} that can transform directly the Pbnm orthorhombic phase into the monoclinic phase $P2_1/n$ and even the rhombohedral phase group R-3c into the space group R-3m. Shah Aarif Ul Islam [25] investigated the structural and morphological characteristics of double perovskite LNMO easily by doping Barium (Ba) for somewhat three different proportions at lanthanum (La) site and even confirms the monoclinic structure (single-phase) of all the structures. It was observed that according to the refinement structural parameters, every diffraction peaks are to be indexed with monoclinic phase $P2_1/n$. Also, a very good fit (Chi^2 having value of 1.17) was observed in case of the monoclinic structure. Javed Ahmad [26] have doped Yttrium (Y) into the double perovskite LNMO and came to a conclusion that the synthesized product was being refined to the two space groups i.e. the first group was monoclinic $P2_1/n$ and the second phase group observed was Pbnm (orthorhombic). It was noticed that the monoclinic phase group was because of the perfectly ordered distribution of the atoms of B-sites i.e. Ni^{2+}, Mn^{4+} and on the different side, the Pbnm phase group was confirmed by observing the disordering of the atoms which were situated at the B-sites i.e. Ni^{3+}, Mn^{3+}. Farheen N. Sayed [27] have noted the activities of the annealing conditions which includes the ferromagnetic properties and dielectric characteristics of double perovskite material LNMO. According to the obtained X-ray diffraction patterns as shown in fig 3, it clearly indicated the coexistence of both the phase groups i.e. rhombohedral phase group and orthorhombic phase group and even it was being clearly observed that no specific changes or differences detected when they were being observed with different trials along with the ordering of cation or the disordering of models.

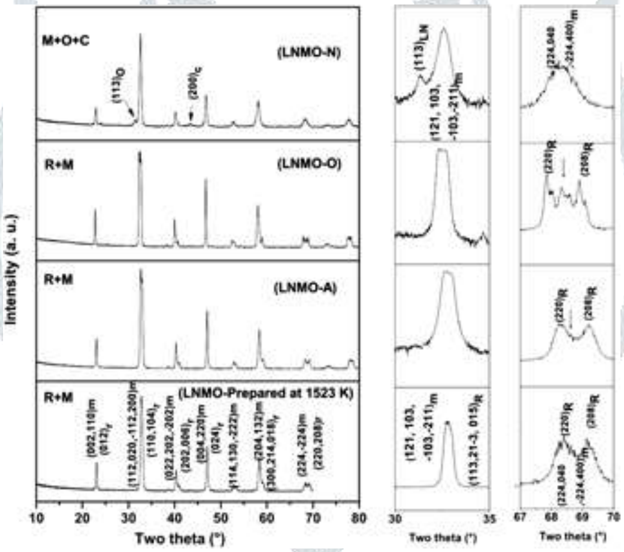

Fig. 3. Powder XRD images of La_2NiMnO_6 sample (Indices of the investigated peaks are marked; here 'R' indicates Rhombohedral phase and 'M' indicates Monoclinic phase) [27]

According to the previous results, it was being observed that crystal structure may be influenced by the different parameters such as ionic radius, instabilities regarding the electronic properties, content of oxygen, ordering of B-site cation and many more. Investigating the phases which are having little differing structures in the laboratory, X-ray diffraction can be more and more challenging [28]. If the sample is not of a good quality, then it can have a major effect on the outcoming results of the structural analysis. The identification of the compounds can be more difficult even the synthesized samples are of nice quality [21].

Many parameters can be calculated using the XRD technique. We can measure crystallite size of the composition that can be measured by using the Scherrer's formula [29–34],

$$t = \frac{K\lambda}{\beta\cos\theta} \tag{1}$$

Where, t is crystallite size, K= 0.94 (Scherrer constant), λ is represented as the wavelength of X-ray, β is the line width at half maximum height and θ is the angle of diffraction.

Additionally, according to the Hirsch approach, the FT (Fourier transform) of the X-ray intensity curve can be obtained by the following formula [35],

$$P(u) = 2\int_0^{\infty} \cos(2\pi us)\frac{S\,I}{f^2}\,ds \tag{2}$$

Here, S is represented as the reciprocal lattice, f is denoted as the scattering factor, I is represented as Intensity, P(u) represents the probability of searching the layer that is situated at a distance “u” with normal to a given layer.
The minima in P(u) can be calculated using the following equation [35],

$$f(n) = \frac{P(n-1) - 2P(n) + P(n+1)}{P(1) - P(2)};\, n \geq 2 \tag{3}$$

Here, n is called the stacking number.
The broadening caused by strain can be calculated by using following formula [36],

$$\varepsilon = \frac{\beta}{4\tan\theta} \tag{4}$$

The dislocation density can be given by following equation [37]

$$\rho = \frac{1}{t^2} \tag{5}$$

where ρ is the dislocation density.

Properties of the unit cell can be useful for recognizing the most appropriate structure of the crystal. When the errors in the structure are minimum, double perovskites have the ability to show considerable pseudosymmetry. The unit cell parameters may not be able to represent the real structure accurately because of the fluctuations in the intensity of peaks [21, 38–41].

Table 1: Structural Parameters and Synthesis Methods of La2NiMnO6

Synthesis Method	**Space Group**	**Lattice Parameters (Å)**	**Observed Phase**	**Structural Features**	**Reference**
Solid-state reaction	P21/n	a = 5.522, b = 5.536, c = 7.804	Monoclinic	High cation ordering; minimal disorder	[2]
Sol-gel method	P21/n	a = 5.524, b = 5.537, c = 7.802	Monoclinic	Smaller grain size; improved homogeneity	[4]
Hydrothermal synthesis	R-3c	a = b = 5.453, c = 13.206	Rhombohedral	Enhanced phase purity; reduced porosity	[7]
Rapid quenching	P21/n	a = 5.520, b = 5.530, c = 7.800	Monoclinic	Increased antistites disorder	[42]
High-pressure annealing	P21/n	a = 5.523, b = 5.535, c = 7.805	Monoclinic	Improved cation ordering; reduced defects	[22]
Gel combustion (O_2)	P21/n	a = 5.482, b = 5.501, c = 7.770	Monoclinic	Reduced distortion; uniform structure	[43]

B. Morphology

Morphology of La_2NiMnO_6 plays an important role in the functional properties, and electrical and dielectric activity. Scanning Electron Microscopy (SEM) provides high-resolution images of the material surface, giving information on grain size, shape, and porosity. La_2NiMnO_6 samples of excellent quality show dense, well-connected grains and low porosity, which improve conduction and dielectric properties [4]. The synthesis method is important for the ascertainment of the morphology. For instance, in comparison with the solid-state reactions, which generally yield larger pieces with the irregular shapes, sol–gel routes produce smaller and more equiaxed grains [5]. While SEM belongs to the category of bulk examination techniques, Transmission Electron Microscopy (TEM) is capable of probing the same specimens but at nanoscale imaging resolution enabling examinations of inner structure such as grain boundary, defects and interfaces. TEM studies have found that oxygen vacancies and antistites defects at grain boundaries can play a dominant role in the electronic and magnetic properties of the material. They can, for example, break the super exchange path that leads to soften ferromagnetism and change the conductivity due to a formation of oxygen vacancies [44].

In addition, EDX which is done either with SEM or TEM, is often applied to verify the elemental composition and stoichiometry of the material. In this regard, it is crucial to ensure stoichiometric accuracy, as variation can result in either secondary phases or structural instabilities that will negatively affect the properties of the material [5].

C. Raman Spectroscopy

Technique like Raman Spectroscopy is a type of method that can be used to observe the vibrational energy modes of the molecules in that particular substance. This technique works by incidence of laser on the synthesized sample and investigating the scattering light. The laser light comes in the contact of the vibrating bonds in the molecules that creates a tiny shift in the energy of the scattering light. This type of shifted light is known to be as Raman Scattering Light. We can also say that Raman Spectroscopy is a harmless chemical technique which offers the regarding the phases, chemical structure, information regarding the crystal structure, polymorphism and the interactions of the molecules. It has been predicted that even if certain cubic perovskite structures didn't contain any Raman modes of vibration, ideal structure modifications can able for their activation [21].

In case of the monoclinic structure, phonon modes 24 ($12A_g + 12B_g$) are considered to be Raman allowed while in case of the rhombohedral structure, phonon modes 8 ($4A_g + 4B_g$) are expected to be Raman allowed [21]. M.N. IIiev [45] observed the Raman spectra of the thin film of LNMO onto the substrate of $LaAlO_3$ which have already been measured in various configurations of exact scattering occurring between 12K and 773K. He observed that despite of some of the small differences in case of the phonon line parameters, the results regarding the spectrum and its variation along with the scattering configuration matches nearly with the La_2CoMnO_6 (LCMO). An extremely high frequency peak obtained of $A_g(P12_1/n)$ symmetry around 676 cm^{-1} is being able to traced to the breathing vibrations of the (Ni/Mn) O_6 octahedral which was definitely confirmed by the analysis of LCMO and even the similarity of LNMO-LCMO. The radiating signal near 530 cm^{-1} suggests so many similarities of A_g and B_g in the structure of $P12_1/n$ including the anti-stretching and also the bending of (Ni/Mn) O_6 structure. Rotation of the octahedral or we can also say the tilting of the octahedral, ordering of the B-site atoms and also the displacement occurring in the A cation or B cation can create errors from the symmetry of cubic. These types of errors can lead towards the increment of that specific unit cell and the reduction in the symmetry [46]. Mohd Nasir [47] have performed the experiment of Raman spectra on the LNMO samples to study the purity of the phase and also the disordering of cation which is present in the respective samples. He has observed the stretching of (Ni/Mn) O_6 octahedral along with La-O bonds. Investigating the stacked Raman spectrum regarding various annealing temperatures (900˚C, 1100˚C, 1250˚C and 1400˚C), he confirmed the two intensive bands A_g (value nearer to 670 cm^{-1}) and B_g (value nearer to 533 cm^{-1}). The mixed modes of anti-stretching along with the vibrations of bending were calculated around 525 cm^{-1}. Kumar et al. [48] have even observed the similar type of findings. The octahedral of MnO_6 possess both kind of stretching modes i.e. symmetric stretching mode and asymmetric stretching modes that can explain the similarity in the structure. Raman analysis has the ability to support all the observations in which the monoclinic phase structure P21/n structure at the lower temperatures and it was even investigated that the co-existence of P21/n and R3 structure phases at the room temperature along with the very much slow conversion to the rhombohedral phases at quite high temperatures.

Dexin Yang [49] observed the data of Raman Spectra which was collected using a LABRAM-HR Evolution confocal laser by using 514 nm line of an Ar-ion laser along with the the spectral resolution of 0.5 cm^{-1}. It was observed that at the room temperature, the results were perfectly similar to that of the data which were previously observed [50–52] Primary spectra which is obtained between 80K and 650K as shown in fig 4 (a). It is clear from the data that the major properties of this particular information are the strong peaks which is around 640 cm^{-1} and 530 cm^{-1} as shown in fig 4 (b). The (Ni, Mn) O_6 octahedra's breathing (stretching) vibrations causes the mode at 640 cm^{-1} and on the other side antisymmetric stretching causes the mode at 530 cm^{-1} [45, 50].These two specific broad peaks are actually composed of the overlapping peaks from orthorhombic and monoclinic structure [50, 53].

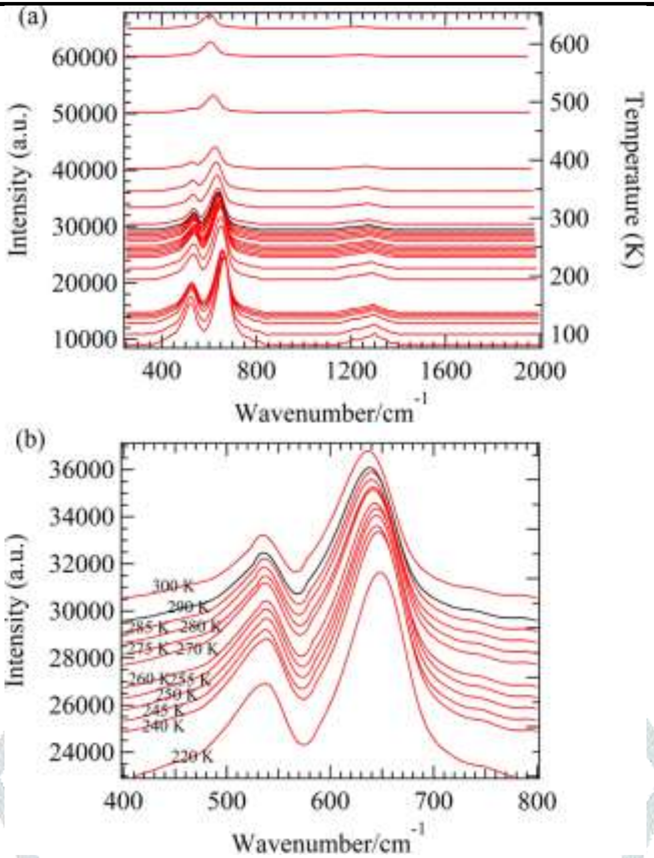

Fig. 4. (a) LNMO Raman spectra in the temperature range of 80K to 650K which is being stacked into the proportions to that temperatures at which they are being collected. (b) The black spectrum was being gathered at 290K and portions of the spectrum is closer to that of the change of magnetic ordering [49]

According to the previous experiments and results, it has been observed that there is very little observations regarding vibrational modes of the cubical double perovskite structures. The main reason behind that is whenever an electromagnetic field interacts within the bonds of the molecules, it has ability to make a dipole which have the dipole moment proportional to that of the externally applied electric field. $P = \alpha E$, whereas α denotes the polarizability of that molecule. Here the term “Polarizability” defines to the degree of which an electric cloud varies along with its specific typical shape. Generally, Raman scattering takes place whenever the polarizability got changes inside that bond. The intensity of the scattering has a specific relation with the square of that induced dipole moment. The analysis of Raman Spectroscopy needs noticeable change inside a molecule’s polarizability. The derivative of the polarizability can result into the lower Raman band intensity and even the value can occur nearer to zero if the particular vibration has very less amount of effect on the polarizability [21].

Ultimately, the integration of Raman with additional techniques (like XRD and TEM) should provide a complete picture of the structural characteristics of La_2NiMnO_6. Because even slight structural changes can lead to substantial alterations in its magnetic and electronic properties, such an integrated approach is critical to use the material effectively in practical applications.

D. *Neutron Diffraction Method*

Neutron diffraction technique is a very powerful analytical technique which is used to investigate the atomic structure or the magnetic structure of a material. Generally, it is very much similar to that of X-ray diffraction method. The difference is only that X-ray uses an electromagnetic wave while the neutron diffraction technique makes use of the neutrons as the probing particles. The source of neutron is Nuclear Reactors or it can even be spallation sources. Neutrons interact with the atoms’ nuclei instead of that of the electron clouds (in case of X-ray spectroscopy). Neutrons even have a particular kind of magnetic moment that allows the neutron diffraction to be used in case of studying the magnetic structures and even the crystal structures. This is very significant advantage of Neutron Diffraction method as compared to that X-ray diffraction technique. It has also been discovered that neutrons have a very high penetration depth in most materials which makes them suitable for gaining information in bulk properties instead of just surface properties. In short, Neutron Diffraction is very much versatile tool that can complement other diffraction techniques and have the ability to provide different and much unique insights into structural properties as well as magnetic properties of the material.

According to the previously investigated data, it has been observed that at the ambient temperature, the two-phase structures i.e. rhombohedral structure and monoclinic structure are mixed together and it was also noticed that around 3.5K, the orthorhombic structure is being fully transformed into monoclinic form [54]. It was observed that the co-existence of the two phases i.e. Monoclinic phase and orthorhombic phase at the intermediate temperature was also later confirmed by the technique of neutron diffraction of the double perovskite LMNO in which it was studied that whenever the temperature drops, the rising is being observed in the monoclinic phase fraction [27]. Christopher J. Ridley [55] have discovered the technique of neutron diffraction at quite low temperature and it was also investigated that when the particular double perovskite sample was discovered under a room temperature, a mixture of the two phases i.e. monoclinic phase and rhombohedral phase were obtained with the definite proportions of 77% of weight and 22% of weight respectively. It is quite interesting to know that what is the contribution of the remaining 1% in the specific mixture. So, it was discovered that 1% weight of the mixture was occupied by nickel oxide (NiO) phase impurity. Past records on the phase coexistence in this material attribute towards the lanthanide's non-uniform extrusion as La_2O_3. However, the reported work doesn't identify any kind of phases. The phase of high temperature is generally occupied at room temperature settings along with extremely gradual cooling which absolutely suggests that the phase co-existence is a type of feature of sensitive distortive structure of first order of that transition. Many types of defects can be experienced if there is phase co-existence along with a significant volume variation that affects the homogeneity of the sample [55] . Additionally, Bull et al [46] have applied the neutron powder diffraction at lower temperatures and higher temperatures for the refinement of the structure of double perovskite La_2NiMnO_6. He has investigated the ordering of monoclinic structure ($P2_1/n$) at the lower temperature of 25°C while on the other side, the ordering of rhombohedral structure at higher temperatures of 350°C to 400°C manufactures the best work.

III. MAGNETIC PROPERTIES

A. *Ferromagnetic behaviour*

La_2NiMnO_6 is known to be one of the strong ferromagnetic materials with the Curie temperature (Tc) about 280K, which is quite close to room temperature. Such magnetic ordering originates from the super exchange interactions among the Ni^{2+} and Mn^{4+} ions through the oxygen ions in the Ni–O–Mn bond framework. The ferromagnetic super exchange mechanism favors the alignment of spins from Ni^{2+} and Mn^{4+} ions through a 180° bond angle, which enhances the interactive energy and stabilizes the ferromagnetic phase [22, 44]. And the spintronic devices typically require some sort of magnetic ordering in order to manipulate the currents by the spin, La_2NiMnO_6 have those magnetic properties which made it more attractive for spintronic applications. This near-room-temperature Tc is especially fruitful because it permits for a practical application at ambient conditions whereas other materials do not achieve similar performance until cryogenic temperatures are reached.

Nevertheless, the ferromagnetism of La_2NiMnO_6 is very dependent on details of the structure, e.g., changes in bond angles and bond lengths directly affect the super exchange strength. The angle between Mn–O–Ni, for example, should be 180° to favor ferromagnetic coupling. Structural distortions, antisite disorder or external stress create a mismatch in this ideal angle, leading to a weaker interaction and thus reduced total magnetization.; on the other hand, such distortions can also create competing antiferromagnetic interactions that lower Tc and degrade magnetic performance of the material [44]. The coupling between the magnetic and thermal energy scales appears to be strong, as temperature-dependent magnetization studies reveal a ferromagnetic to paramagnetic transition at temperature Tc. Moreover, it has been claimed that depending on the synthesis conditions, high coercivity field [6] and magnetic anisotropy [7] are present, making it possible to tailor these properties for specific applications.

TABLE 2: COMPARISON OF MAGNETIC PROPERTIES OF LA2NIMNO6 UNDER DIFFERENT SYNTHESIS CONDITIONS

Synthesis Method	**Curie Temperature (Tc, K)**	**Saturation Magnetization (Ms, emu/g)**	**Coercivity (Hc, Oe)**	**Magnetic Anisotropy**	**Reference**
Solid-state reaction	280	5.6	150	Moderate	[44]
Sol-gel method	278	5.3	135	Low	[42]
Hydrothermal synthesis	282	5.8	140	Moderate	[7]
Rapid quenching	270	4.8	170	High	[22]
High-pressure annealing	283	6	120	Low	[56]
Gel combustion (N_2)	280	5.9	140	Enhanced stability	[57]

B. *Anti-site disorder and its impacts*

Among many factors affecting the magnetic properties of La_2NiMnO_6, one of the major types of disorder is anti-site, which includes an exchange of positions of Ni and Mn ions in the crystal lattice. The disorder disrupts the periodic staggering of Ni^{2+} and Mn^{4+} ions in the lattice, which is required to sustain robust ferromagnetic super-exchange interactions. Anti site defects create regions of competing antiferromagnetic interactions, leading to decreased net magnetization and lowered Tc [42, 56].

Synthetic conditions, especially the sample preparation temperature and cooling rates, affect the degree of antistites disorder. Since the cation ordering is increased and Voronoi antistites defects are reduced with high heat treatment and slow cooling. On the other hand, rapid cooling or non-ideal synthesis methods increase disorder which reduces the magnetic properties. Disorder from antistites can also yield wider magnetic transition curves in temperature-dependent magnetization experiments where the presence of disordered regions result in an ensemble of local Tc values. One of the manifestations of this behavior can be seen as a broadening of the magnetic hysteresis loop in field dependent magnetization measurements, corresponding to the different local magnetic environment that material feels. Antistites disorder is one of the most important issues to tackle in order to further develop LNMO for industrial applications. This has led to several techniques implemented to address the problem including controlled annealing, tuning of synthesis parameters and doping strategies. An example of this is Doping Sr or Ba at the La site that has been proven to improve cation ordering but also improve magnetic properties [56].

C. *Methods for magnetic characterization*

The magnetic properties of La_2NiMnO_6 are investigated using advanced experimental techniques, including vibrating sample magnetometry (VSM) and superconducting quantum interference device (SQUID) magnetometry. These approaches allow for precise measurement of the material's magnetic behavior and facilitate the exploration of subtle structural and electronic interaction phenomena.

Vibrating Sample Magnetometry (VSM) is a technique that measures the magnetic response of a sample by using a pick-up coil to detect the voltage as the sample vibrates in an applied magnetic field. It is especially used for measuring fundamental magnetic parameters including saturation magnetization (Ms), remanence (Mr) and coercivity (Hc). La_2NiMnO_6 has been the subject of studies using VSM, which has indicated its certainly ferromagnetic characteristics, with narrow magnetic hysteresis loops consistent with a high degree of magnetic order. VSM is also commonly implemented for temperature-dependent measurements to find Tc and for change tracking in magnetic characteristics under different temperature conditions [7, 22]. SQUID magnetometry is one of the most sensitive techniques to magnetic signals, with the ability to detect small magnetization changes. It is especially utilized for LNMO to resolve its magnetic transitions; in determining the values of Tc accurately and tapping low-temperature magnetic features. Antisite disorder had been long purported to significantly modify the magnetic properties of this material, so the availability of high-resolution SQUID data for the temperature and field dependence of magnetization was exceptionally useful [44].

D. *Magneto-resistance property*

The magnetoresistance (MR) effect in any material's resistance has been attracted a lot of attention in today's generation because of its complex physics and industrial applications[58–60]. The different categories of magnetoresistance have been observed such as Anisotropic magnetoresistance (AMR) [58, 59, 61, 62], Giant magnetoresistance (GMR) [61, 63, 64], Tunnelling magnetoresistance (TMR) [65] and massive magnetoresistance (MMR) [66] in which materials are being divided on the basis of their driving mechanisms. It has been discovered that the ferromagnetic structure is obtained by super-exchange interactions between the ordering of Ni^{+2} and ordered $Mn^{+4.}$ It is obvious that Ni/Mn disordering will be arise which will lead towards the antiferromagnetic configurations regarding Ni^{+2}-O_2-Ni^{+2} and Mn^{4+}-O_2-Mn^{4+} [67]. In polycrystalline samples, magnetoresistance results from extrinsic intergranular tunnelling, which is reliant on the quantity and the quality of grain boundaries. Because double perovskites include antiphase boundaries that originate from the distinctive B/B' cation disorder, the tunnelling process in materials can be activated even without a grain [22, 68].

La_2NiMnO_6 may be a strong contender for a material with a nearly ambient temperature. TMR effect given its magnetic structure similar to that of Sr_2FeMoO_6. La_2NiMnO_6 has been shown to have distinct magnetic resonance effect at almost room temperature. It has been observed that magnetic resonance can be divided into the two sectors; the first sector is regarded as 'low field magnetoresistance' and the second sector is regarded as 'high field magnetoresistance'. When the electrical properties and magnetic properties of the samples were combined by conducting an experiment, it was predicted that magnetoresistance observed at lower field could attribute to the phenomenon of tunnelling between the various neighboring ferromagnetic domains, magnetoresistance could be attribute towards the compression of the scattering occurred from spin defects which are being caused by disordering of Ni/Mn [21, 69].

IV. ELECTRONIC PROPERTIES

A. *Bandgap analysis*

The electronic bandgap of La_2NiMnO_6 is a critical factor in its semiconducting properties for diverse applications in photovoltaics, optoelectronics, and spintronics. Depending on synthesis conditions and structural ordering, pristine material characteristically has an indirect bandgap between 1.0 and 1.5 eV (also cited as approximately 2.2 eV when treating it as a direct gap). The bandgap mainly originates from the configuration of the Ni^{2+} and Mn^{4+} ions and their coupling through the oxygen ions [70]

Doping strategies for bandgap tunability in La_2NiMnO_6 working on A-site (eg, Sr^{2+}, Ba^{2+}) or B-site (eg, Co^{3+}, Fe^{3+}) level by introducing localized states stemmed from the introduction of example Sr^{2+}, Ba^{2+}), or B-site (e.g, Co^{3+}, Fe^{3+}) eg enable to introduce example Sr^{2+}, Sr^{2+}, Ba^{2+}) or B-site (eg Co^{3+}, Fe^{3+}) site introduction local of localized states or other of example. For instance; Sr^{2+} substitutes La^{3+} reducing the effective ionic radius at A-site and creates lattice strain as well as change in Mn–O–Ni bond angles. This leads to a bandgap relocation that has demonstrated an increase in photocatalytic potential [70] for solar-driven applications. Due to the larger ionic radius of Ba^{2+}, the ionic substitution of Ba^{2+}, which also induces a larger lattice with the increases of the lattice parameters, results change in the crystal field and change in the electronic band structures. This type of tunning narrows the bandgap to allow the material to absorb visible-light to be potentially useful in solar application [71]. One of the many factors that can affect the bandgap is temperature and pressure as both induce slight variations in bond lengths and bond angles. Bandgap is shown to narrow in high-pressure studies due to enhanced Ni 3d–Mn 3d orbital overlap via oxygen. Such effects highlight as well the remarkable tunability of La_2NiMnO_6 electronic properties suitable for device-oriented applications. Table 3 represents bandgap variation along with doping.

Among the different optical techniques, Diffuse Reflectance Spectroscopy (DRS) is commonly employed and regarded as a dependable approach for determining the band gap of materials. These optical methods for estimating energy band gaps remain unaffected by temperature variations or uncertainties related to surface states. A modified K-M function was being utilized, resulting in the following expression,

$$\alpha h\nu = A\left(h\nu - E_g\right)^{\frac{n}{2}} \tag{6}$$

Here, α is the extinction co-efficient which has the direct proportionality regarding the relationship with that of F(R) and A stands for the absorption constant. Therefore, the final equation becomes:

$$F(R)\, h\nu = A\left(h\nu - E_g\right)^{\frac{n}{2}} \tag{7}$$

The value of n is determined by the nature of the optical transition in the material being studied: n is set to 4 for an indirect optical transition and 2 for a direct optical transition.

When Yiran Tang [72] discovered the UV-Vis spectroscopy of the sample $LaAMnNiO_6$ where A = La, Pr and Sm, he observed that Conventional semiconductor photocatalysts primarily absorb light in the ultraviolet region, whereas LaAMnNiO6 (A = La, Pr, Sm) shows strong light absorption across the entire spectral range of 200–700 nm. This indicates that La_2NiMnO_6 (A = La, Pr, Sm) overcomes the narrow absorption range and low photon absorption associated with narrow band gaps in ordinary semiconductor photocatalysts. As a result, they can effectively absorb light across the whole spectrum and exhibit efficient photocatalysis.

TABLE 3: BANDGAP VARIATION WITH DOPING

Dopant	Bandgap (eV)	Electronic Transition Type	Magnetic Moment (μB)	Reference
Sr	1.2	Indirect	5.8	[70]
Ba	1.1	Indirect	5.6	[71]
Co	1	Direct	5.9	[73]
Fe	1.3	Indirect	5.7	[74]
No doping	1.4	Indirect	5.5	[22]

B. Dielectric studies

Dielectric characterization shows that La_2NiMnO_6 presents interesting frequency- and temperature-dependent dielectrics properties that make it a good candidate for energy storage and high-k dielectric applications. The interfacial polarization mechanisms dominate in La_2NiMnO_6 dielectric constant which is the consequence of the migration of the charge carriers in the grain boundaries and in the grains [75] Table 4 represents comparison of dielectric properties under different doping approaches. This is frequency-dependent behavior, in which contributions of space charge polarization lead toward the high dielectric constant at low frequencies. While the contributions decrease as the frequency increases, at very high frequency only the intrinsic mechanisms, like dipolar and ionic polarization, survive. As a result, the dielectric constant decreases with frequency. Likewise, the dielectric loss behaves in a comparable way, with marked frequency dependence at low frequencies [25]. The stable dielectric response of the material at low temperatures and the contribution of thermally activated charge carriers to polarization at high temperatures cause a rapid increase of the dielectric constant. Doping with elements, such as Ba or Sr, has been shown to improve dielectric stability through the decrease in oxygen vacancies [75], which can be a major cause of high dielectric loss at high temperatures. The dielectric properties of the material make it an attractive option for capacitor applications, where high dielectric constants and low losses are beneficial. Furthermore, the stability against temperature of the dielectric response is important when considering the practical devices in which reliability is required.

TABLE 4: COMPARISON OF DIELECTRIC PROPERTIES ACROSS DOPING STRATEGIES

Dopant	Dielectric Constant (1 kHz)	Dielectric Loss (%)	Frequency Stability (Hz)	Reference
Sr	1500	0.5	Stable up to 1 MHz	[75]
Ba	1600	0.3	Stable up to 1 MHz	[25]
Co	1400	0.4	Stable up to 1 MHz	[73]
Fe	1450	0.6	Stable up to 1 MHz	[74]
No doping	1300	1	Stable up to 100 kHz	[42]

Dielectric measurements enable the determination of various parameters, including real and imaginary permittivity, loss tangent, real and imaginary modulus etc can be determined.

The real permittivity can be calculated by using the following equation [36],

$$\varepsilon' = \frac{cd}{A\varepsilon_0} \tag{08}$$

Whereas "c" is the capacitance, "d" is thickness of the pallet, A = area of the sample and ε_0 represents permittivity of free space ($8.85*10^{-12}$ F/m).

The imaginary permittivity can be calculated by using the following equation,

$$\varepsilon'' = \varepsilon' \tan\delta \tag{09}$$

whereas $\tan\delta$ is the tangent loss.

The tangent loss can be calculated by using the following equation,

$$\tan\delta = \frac{1}{2\pi f C_p R_p} \tag{10}$$

C. *Computational insights*

The DFT has been widely used to investigate the electronic structure and properties of La_2NiMnO_6. Such computational studies afford information of the underlying origin of the electronic properties and the manner in which the material assimilates structural changes. Electronic structure: La_2NiMnO_6 has a bandgap due to the splitting of the Ni 3d and Mn 3d states via the coupling to the O 2p states. Ni 3d states mainly dominate in the conduction band, whereas Mn 3d and O 2p states contribute mainly in the valence band. Antisite disorder disturbs the Ni^{2+}/Mn^{4+} order and creates mid-gap states that lower the effective bandgap controlling the semiconducting properties of the material [76].

DFT simulations also investigate doping effects to the electronic structure. In particular Sr doping at A-site would both shift down conduction band minimum and valence band maximum, leading to a smaller bandgap. In contrast, Ba doping generates states localized near the edge of the conduction band, increasing the optical absorption of the material in the visible range [71, 76]. DFT results-based evidence of the strong coupling between magnetic and electronic properties in La_2NiMnO_6. The lattice distortions or doping can change the Ni–O–Mn bond angles that directly influence the exchange interactions and thus the bandgap. Such a large coupling which makes La_2NiMnO_6 a model system to study magnetoelectric effects.

V. REAL-TIME APPLICATIONS

A. *Spintronics*

LNMO is a material of great interest in spintronics because of its magnetic high-temperature ferromagnetism as well as a potential half-metallicity. Spintronics utilizes the spin as well as charge of electrons, relying on the existence of sufficiently strong magnetic ordering and high spin polarization. La_2NiMnO_6 fulfils these requirements, showing a Curie temperature of about 280 K which is near room temperature, and therefore good for testing in metal-insulator spintronic devices [73, 77]. The half-metallicity of LNMO is an important feature for spintronics owing to its electronic structure. Half-metallic systems exhibit metallic character for one spin-channel and insulating character for the other, such that there is perfect spin polarization at the Fermi level. It increases the effectiveness of spin-polarized current injection into devices like magnetic tunnel junctions and spin valves. Second, preliminary experimental work, in combination with density functional theory (DFT) calculations, has showed the possibility to further tailor the electronic structure of the material via the doping or the strain engineering pathways in order to maximize spin polarization [73].

In addition, this ferromagnetic nature of the material along with its coupling with electric fields provide opportunities for magnetoelectric devices that control magnetic properties by electric fields stimuli. This could prove as an important function towards achieving ultra-low power and high efficiency memory and logic device.

B. Catalysis

La_2NiMnO_6 has gradually been established as new catalyst, especially for OER and ORR, which have of great importance for energy-conversion technologies, including fuel cells and water electrolysers. The synergistic effect between Ni and Mn ions that lowers the reaction barrier of oxygen molecules adsorption and activation on the surface gives rise to the bifunctional catalytic performance of the material [71, 74].

In case of Oxygen Evolution Reaction (OER), LNMO has been found to be facilitated by the high catalytic activity achieved through the mixed-valence states in both the perovskite (Ni^{2+}/Ni^{3+} and Mn^{4+}/Mn^{3+}) [7]. These valence states generate active sites that facilitate the oxidation of water to oxygen. This activity can be even more enhanced with some form of doping or surface non-dissertation. Further, La site doping through alkali or alkaline earth metals (e.g., Ba or Sr) have been experimentally proven to increase the number of active sites and subsequently improve the conductivity to give rise to higher OER performance [74]. In Oxygen Reduction Reaction (ORR), the oxygen molecules reduced to H_2O or OH^- ions, the La_2NiMnO_6 also presents a good catalytic performance. The peculiar electronic structure of the material enables the rapid transfer of charge that the lattice oxygen becomes the active site during the catalytic process. Such excellent bifunctionality, an OER performance and the same time ORR activity, qualifies La_2NiMnO_6 as an attractive candidate for rechargeable metal–air batteries and other energy devices. Its catalytic properties can consequently be tuned by approaches such as nano structuring, doping and antistites disorder control to embrace such a potential for next-generation energy conversion systems. Table 5 shows the information regarding Catalytic performance of La_2NiMnO_6 for OER and ORR under various doping conditions.

TABLE 5: CATALYTIC ACTIVITY OF LA2NIMNO6 FOR OER AND ORR UNDER DIFFERENT DOPING CONDITIONS

Dopant	**OER Overpotential (mV)**	**ORR Overpotential (mV)**	**Current Density (mA/cm²)**	**Tafel Slope (mV/dec)**	**Stability (hours)**	**Reference**
Sr	360	440	10	58	40	[74]
Ba	340	420	12	55	50	[71]
Co	310	400	15	50	60	[73]
Fe	330	415	14	53	45	[74]
No doping	380	450	8	62	30	[42]

C. Energy Storage

La_2NiMnO_6 has attracted much attention in terms of promising applications in supercapacitors and in dielectric materials [73, 78], but the corresponding energy storage potential of the material itself has not yet been investigated. Due to its exceptional properties of semiconducting and magnetic including high dielectric constant, it is a perfect candidate for potential multifunction energy storage devices [5, 70]. As an electrode material of supercapacitors, LNMO has both high specific capacitance and good cycling stability. The porosity of this material and its mixed-valence states contribute to rapid charge storage and transfer. The studies show specific capacitance more than 700 F/g, and it shows that it also has the potential of the high-performance energy storage [7]. Doping with Sr or Ba extends the ultimate surface area and further conductivity, resulting in higher energy and power densities [70].

Due to its high dielectric constant and low dielectric loss, La_2NiMnO_6 can be used for capacitors, especially in high frequency circuits and energy storage systems. Dielectric properties of the material can be rendered to a high performance via sufficient optimization of synthesis conditions, grain size and doping. For example, doping with Ba increases the dielectric stability and reduces the leakage currents, and thereby can be applied in advanced electronic materials for future applications [5].

D. Gas sensing applications

In general, gas sensing applications are thought to measure the concentration of a particular analyte such as carbon dioxide (CO_2), carbon monoxide (CO), Sulphur dioxide (SO_2) etc and it also does not require any kind of knowledge regarding methodologies which include optical absorption, catalytic beads etc [21]. Using the technique of impedance measurements, a fresh approach to the application of LNMO as a gas sensor has been detected. Through the use of a lock-in amplifier, impedance was measured. Reports have indicated that the electrical conduction is susceptible to concentration and gaseous surroundings. As grain boundaries and electrode interfaces come together to form space charge, the gases are absorbed there [79]. As we are very well-known of the fact that the impedance measurements acquire an advantage over the DC resistance measurements which are in terms of contributions from bulk materials along with their grain boundaries, so they investigated the electrical conduction mechanism regarding sensors relating to its effect upon space charges which are using impedance spectroscopy [79]. At high temperatures, resistance exhibits two separate activation regimes with varying energies. At a magnetic field of 1 Tesla, nitrogen has virtually zero magneto impedance, while oxygen has a positive value and argon has a negative one. Under a 1 Tesla magnetic field, the highest magnetoimpedance value is around 5%. In the near future, thin films of La_2NiMnO_6 will be used to create a sensor device capable of detecting the concentration of gas at its ppm level or even for many dangerous gases [22].

E. *Magnetic Applications*

The arrangement of cations in rare earth double perovskites typically promotes a certain level of coupling or super-exchange interactions between cations with non-zero spins (or unpaired electrons), which can result in bulk magnetic orderings such as ferromagnetism or antiferromagnetism.

Additionally, whenever there is strong coupling between the magnetism and some other physical occurring, the properties of rare earth double perovskites like spins, electric charges, dielectric behaviour, thermal properties, and optical characteristics—can be influenced by magnetic and/or electric fields [80]. Certain factors like bio-separation, gene delivery and medication among all the applications of biological and other medicinal uses. Tang reported the actual size of the crystal which is about 34 nm to 40 nm after synthesizing LNMO nanoparticle by the co-precipitation method [81] This kind of nanoparticles contains extremely good qualities regarding the protein Bovine Serum Albumin, having the greatest capacity of adsorption of 219.6 mg/g whenever the nanoparticles were being pre-annealed at 850°C and it was even noticed that whenever the materials exist as nanoparticles, new physical situation can may take place [80]. In the recent days, Ravi S. [82]discovered the Curie temperature which was actually about 27° C for the nanoscale of LNMO that was much higher than that of the bulk LNMO which was equivalent to that of 7°C. Spintronics, which is the short name of spin electronics is the most emerging division of the devices that combines the branches of magnetics and electronics which occurs by the disturbance of electronic spins. This type of branch offers such a great potential for the kind of functionalities that are non-conventional and which are not possible at all for the semiconductor devices like quantum computation [80]

F. *Applications in Photocatalysts*

The enhanced oxygen content and redox capability of the double perovskite catalyst $LaPrNiMnO_6$, achieved through Pr doping in LNMO, make it suitable for photothermal degradation of gaseous toluene. Its mesoporous structure, with a high specific surface area, greatly improves catalytic reactivity. $LaPrNiMnO_6$ demonstrates a strong ability for oxygen adsorption and light absorption, as confirmed by UV-Vis and XPS spectral analyses, facilitating catalytic oxidation through the Mars–van Krevelen redox cycle. Furthermore, reaction kinetics studies reveal that $LaPrNiMnO_6$ exhibits excellent catalytic performance due to its lower activation energy. These properties suggest that RNMO and its modified versions have broad applications in the degradation of volatile organic pollutants [83].

G. *Implications for Real-World Applications*

The different functionalities of La_2NiMnO_6 in spintronics, catalysis, and energy storage highlight its promise as a multi-functional material for advanced technologies. Exploiting its tuneable magnetic, electronic and catalytic properties, devices may be designed that combine many functions in a single element, such as spin-based logic devices that are also energy storage devices. Further improvements in synthesis methods and characterization will continue to resolve issues like antistites disorder and scalability, leading to the commercial application of LNMO based technologies.

VI. CHALLENGES AND FUTURE DIRECTIONS

A. *Increased Cation Ordering and Decreased Antistites Disorder*

One of the main difficulties in fine-tuning La_2NiMnO_6 is the trade-off between optimizing cation ordering and suppressing antistites disordering. The alternating distribution of Ni^{2+} and Mn^{4+} ions across the crystal lattice are important for strong ferromagnetic super exchange interactions and appropriate electronic properties. Nonetheless, under certain synthesis conditions featuring rapid cooling or un-optimized annealing temperatures, the long-range order can be disrupted by antisite defects in which Ni and Mn ions occupy the wrong crystallographic positions [42, 78].

Antisites disorder is known to significantly affect the magnetic and electronic properties of the material, diminishing its saturation magnetization, Curie temperature, and semiconducting behaviour. Here are some considerations to avoid this:

- The cation ordering is significantly enhanced by the optimization of synthesis parameters: This controlled annealing at an elevated temperature and a low cooling rate.

- Doping Schemes: Substitution at the La or Ni/Mn sites can change both the lattice strain and the bond angles, indirectly decreasing the disorder tendency. Doping, such as Sr and Ba, tends to stabilize the ordered phase and increase the magnetic properties [78].

- Sophisticated synthesis methods: Using methods such as chemical vapor deposition (CVD), sol-gel processing, or high-pressure synthesis might produce excellent crystallinity and have better cation control.

- Predictive models and real-time monitoring techniques (in situ x-ray diffraction or electron microscopy) that can follow cation ordering during synthesis should be developed in future studies.

B. Generalization Strategies for Synthesis in Industry

Although LNMO has shown promise for advanced applications in laboratory-scale synthesis, scaling-up these processes for industrial production is a major challenge. However, challenges such as maintaining phase purity, stabilizing grain size, and defects have been reported in possible bulk production [4, 44].

Potential solutions include enabling scalable approaches in which many techniques (e.g., spray pyrolysis, sol-gel processing, or hydrothermal synthesis) are naturally scalable and can be adapted for large scale fabrication. Typically phase composition and actual properties of bulk material can be affected by a number of impurities. These may lead to the problems mentioned before, but rather wide dispersion of compositional homogeneity can be avoided with a standard synthesis protocol and employing the high-purity precursors. High emission dependent annealing or the use of costly precursors raises production costs. Searching for cheaper or plenty of alternative dopants may also facilitate the commercial usability of LNMO. Moreover, the coupling of synthesis methods using automated manufacturing systems as well as machine-learning models for the optimization of different processes may speed up the long-awaited transition to the industrial scale of production.

C. Study of the New Dopants and Co-Dopants for Adjusting Properties

We show here that doping is a potent tool for enhancing tailoring the La_2NiMnO_6 structural, magnetic and electronic properties. While most of the current research has centered around single dopants, e.g., Sr, or Ba, or Co, the co-doping strategies (combination Sr−Ba and Ni−Fe substitution) provides a novel stimulus for property improvement [22, 75].

Key directions include:

In A-site doping, A replacement of La^{3+} with ions that are larger or smaller (Sr^{2+}, Ba^{2+}, or Ca^{2+}) can provide lattice strain, change the bandgap and establish preferential magnetic phases. In case of A-site or B-site doping, Partial replacement of Ni or Mn with transition metals (like Co^{3+}, Fe^{3+} or Cr^{3+}) often distorts the local coordination environment, modifying the super exchange pathways and thereby allowing the tuning of Curie temperature, magnetic anisotropy, and dielectric behaviour. In Co-doping schemes, doping both the A and B sites simultaneously can lead to synergistic effects, for example improving cation ordering or combining the enhancement of magnetic and electronic properties. Abundant experimental works evidenced that Sr and Co co-doping can be used for suppressing antistites disorder as well as improving catalytic performance. Theoretical studies, e.g., DFT studies, can help with dopant selections and their associated properties in LNMO. Smaller systematic experimental studies of dopant concentrations and combinations are also required to pinpoint the best compositions for particular applications.

D. Future Outlook

High cation ordering is critical to exploit the full potential of such materials, but also not very scalable while we go to the stability and make it as applicable as possible. ML and AI can be used to identify synthesis conditions and to predict the performance of a material. We can explore additional dopants and co-dopants to increase the potential of the LNMO for new technologies such as quantum computing and multi-function devices. Bringing experimental, theoretical and computational approaches into a feedback loop will catalysis advances in this area and ensure LNMO transitions from a promising domain of research to a bedrock of next generation technology.

VII. CONCLUSION AND CLOSING REMARKS

A particularly promising double perovskite material for spintronics, catalysis, energy storage, gas sensing applications, magnetic applications, photocatalysts application is La_2NiMnO_6, known for its impressive ferromagnetic and semiconducting characters. Using advanced characterization techniques including X-ray diffraction, Raman spectroscopy, magnetometry, the structural, magnetic, and electronic properties of the material have been characterized. The critical nature of cation ordering and the deleterious impact of antisite disorder on functional performance have been revealed in these studies. LNMO is a unique materials platform that can connect many different technological fields, and hence, delivers multifunctional potential. The high ferromagnetism at or near room temperature makes it a desirable material for spintronics and its bifunctional catalytic activity in oxygen evolution and reduction reactions makes it suitable for energy conversion systems. Moreover, the dielectric and electronic proper-137 ties highlight its potential application in energy 138 storage. While definitely an exciting material, cation ordering still needs to be addressed to minimize antisite disorder, and synthesis methods need to be scaled for industrial use. Looking forward, additional doping strategies, the further optimization of syntheses, as well as the underlying mechanisms revealed by computations are all needed to truly realize the potential of La_2NiMnO_6. If these challenges are overcome, LNMO may become a promising platform material which could lead to breakthroughs in diverse aspects of energy, electronics, and more. A precise characterization and interdisciplinary approach in working with these materials will be critical for achieving the huge potential of LNMO and similar multifunctional materials, and this review thus highlights a path towards this goal.

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