


 Cite this: *RSC Adv.*, 2020, 10, 36241

# New ferromagnetic half-metallic perovskites for spintronic applications: BaMO<sub>3</sub> (M = Mg and Ca)

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Herein, first principles computer-based simulations were performed to predict the ground-state structure, mechanical stability, and magneto-electronic properties of BaMO<sub>3</sub> (M = Mg and Ca) perovskites, which have not been experimentally synthesized to date. Structural optimization authenticates the stability in the cubic structure for BaMO<sub>3</sub> perovskites having symmetry of the *Pm3m* space group. The tolerance factor and cohesive energy further validate the stability of BaMO<sub>3</sub> in the cubic phase. Moreover, mechanical stability was confirmed by the positive elastic constants, satisfying the necessary stability conditions. The band structure and density of states at the optimized lattice constants revealed the ferromagnetic half-metallic character of BaMO<sub>3</sub> materials, with O-p states playing a prominent role. The half-metallic character originates from the partial filling of the O-p states in the spin-down channel. Spatial charge distribution indicated the dominant ionic character of bonding. No change in the magnetic moment of perovskites was observed upon changing the M-site atoms. Various elastic parameters suggested that these perovskites are ductile in nature with highly anisotropic character. The three-dimensional graphical representation of different elastic moduli revealed that the linear compressibility is isotropic, whereas the shear modulus, Young's modulus, and Poisson's ratio of these perovskites are highly anisotropic. The results obtained in this study are in agreement with those reported in the literature for other similar perovskites.

 Received 4th August 2020  
 Accepted 11th September 2020

DOI: 10.1039/d0ra06739c

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## Introduction

Via integrated circuit (IC) technology, a number of minute transistors can be mounted on a single microchip (normally composed of silicon) to fabricate faster and economic circuits. According to Moore, the number of transistors on an integrated chip doubles at regular intervals; thus, the speed and capability of electronic devices increases, leading to high performance of these devices at lower cost.<sup>1</sup> Although an IC transfers information at high speed and has excellent reliability, but it has volatile memory storage and thus loses information upon power cut-off.<sup>2,3</sup> On the other hand, the magnetic drives store data in the magnetically polarized small patches of surface coating. The magnetic hard disk IBM 350 was developed in 1956, which had 2000 bit per square inch areal density. However, in the year 2015, hard drives with a density of 1.34 terabyte (TB) per square inch, *i.e.*, 600 million-fold that of the IBM 350, were introduced. The storage capacity of these drives is expected to increase further in the near future.<sup>2,4</sup> The main advantage of magnetic memory devices is that they have non-volatile data storage. These devices are fabricated from spintronic materials with high spin polarization.<sup>5,6</sup>

Spintronics is emerging as a key technology for next generations and has enabled the utilization of electron spin for various applications.<sup>7-9</sup> Spin-polarized currents do not dissipate energy as heat, and thereby resolve the heat problems very often confronted in IC and other electronic devices. For application in spintronic technology, materials must have high spin polarization, high magnetic moment, and high magnetic phase transition temperature (at least close to room temperature). The ratio of the density of states (DOS) of spin-up and -down channels at the Fermi level quantifies the magnitude of spin polarization (SP);  $SP = |DOS_{\uparrow} - DOS_{\downarrow}| / |DOS_{\uparrow} + DOS_{\downarrow}|$ .<sup>10</sup> Diamagnetic and paramagnetic materials have symmetric DOS of the spin-up and -down channels; therefore, they do not exhibit spin polarization. However, ferromagnetic materials demonstrate asymmetric DOS; thus, their SP is always greater than zero but less than unity. Contrarily, in half-metallic ferromagnetic materials, the band structure in one spin channel is metallic, indicating the presence of states at the Fermi level, whereas the band structure in the other spin channel is semiconducting/insulating.<sup>11</sup> Therefore, these materials demonstrate 100% spin polarization at the Fermi level and are considered suitable candidates for spintronic technology.

Over the last few years, large number of compounds, including Heusler alloys (half, full, as well as quaternary<sup>12,13</sup>), transition metal oxides (CrO<sub>2</sub> (ref. 14)), dilute magnetic

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semiconductors (Cu-doped ZnO<sup>15</sup>), spinels (Fe<sub>3</sub>O<sub>4</sub> (ref. 16)), perovskites (BaBkO<sub>3</sub> (ref. 17)), double perovskites (Ba<sub>2</sub>CoUO<sub>6</sub> (ref. 18)), halide double perovskites (Cs<sub>2</sub>NaMCl<sub>6</sub>; M = Ti, V, Mn, Co, and Ni<sup>5,19</sup>), with different chemical compositions and structural symmetries have been reported to show half-metallic character. One of the most important family of compounds among them is oxide perovskites with the stoichiometric composition ABO<sub>3</sub>, where A is mostly an s-block element, B is a transition/inner-transition element or can rarely be an sp-element, and O is oxygen. Exploration of new members of perovskites and their modification/tailoring to achieve desired properties are an active area of research. These materials have been the focus of various studies because of their better oxidation resistance and diverse physical properties. In addition, half-metallic perovskites have been reported to demonstrate ferroelectricity,<sup>20</sup> piezoelectricity,<sup>21</sup> ionic conductivity,<sup>22</sup> good thermoelectric performance,<sup>23</sup> superconductivity,<sup>24</sup> and colossal magnetoresistance.<sup>25</sup> Due to these unparallel properties, perovskites are suitable for various fascinating technological applications including optoelectronics, waste heat encapsulation, solid oxygen fuel cells, spintronics, gas sensing, and shape memory devices.<sup>26–29</sup>

Recently, Mahmood *et al.* have reported half-metallic ferromagnetic character in XBeO<sub>3</sub> (X = Mg, Ca, Sr, and Ba) perovskites with diamagnetic/paramagnetic constituents.<sup>30</sup> The stability of these perovskites was estimated *via* the optimization of their structure and evaluation of their formulation energy. The X-site atom remains neutral in characterizing the electronic structure of these perovskites, as no change in the magneto-electronic character was observed upon changing X from Mg to Ba. Half-metallicity was maintained even when Sr and Ca partially occupied the X-site in XBeO<sub>3</sub>.<sup>31</sup> However, the magnetic moment increased by unity (1 μ<sub>B</sub>) when the first group element K occupied the X-site.<sup>32</sup> In the present study, we have investigated the possible changes in the magneto-electronic profile of XBeO<sub>3</sub> that might occur if the Be-site atom is replaced by other alkaline earth elements. Therefore, herein study based on the DFT calculations, we have analyzed the structural, electronic, magnetic, and thermophysical properties of BaMO<sub>3</sub> (M = Mg and Ca) perovskites.

## Computational details

The ground-state structures and electronic and magnetic properties of the BaMO<sub>3</sub> (M = Mg and Ca) perovskites were explored by iteratively solving the Kohn–Sham (K–S) equation *via* spin-polarized calculations using the Wien2k simulation code.<sup>33</sup> Computationally, the stability and ground-state structure can be determined by minimizing the crystal energy with respect to volume. The Birch–Murnaghan equation of state was incorporated to optimize the structure.<sup>34,35</sup>

$$E(V) = E_0 + \frac{9B_0V_0}{16} \left\{ \left[ \left( \frac{V_0}{V} \right)^{2/3} - 1 \right] B'_0 + \left[ \left( \frac{V_0}{V} \right)^{2/3} - 1 \right]^2 \left[ 6 - 4 \left( \frac{V_0}{V} \right)^{2/3} \right] \right\}$$

here  $E_0$ ,  $B_0$ ,  $V_0$ , and  $B'_0$  represent the energy, bulk modulus, volume, and pressure derivative of  $B_0$ , respectively, in the relaxed state. The potential from the core as well as of valence electrons was considered for solving the K–S equation. The exchange–correlation effects were estimated by the well-known generalized gradient approximation (GGA).<sup>36</sup> Moreover, the Tran–Blaha-modified Becke–Johnson potential (mBJ) was used to analyse the magneto-electronic property of perovskites.<sup>37</sup> The unit cell volume is shared between muffin-tin spheres (with the radii  $R_{\text{MT}}$ ) surrounding the atomic sites and interstitial space. A linearized augmented plane wave basis set was used to describe the behaviour of electrons within the muffin-tin sphere as well as in the interstitial space. The atomic-like wave functions within spheres were extended up to  $l_{\text{Max}} = 10$ , whereas in the interstitial space, the plane wave cut-off was set to  $R_{\text{MT}}K_{\text{Max}} = 7$ . A  $k$ -mesh of 2500 points was used to integrate the irreducible Brillouin zone, and the separation between the core and valence states was set to  $-6.0$  Ry. The convergence criteria used for energy was 0.0001 Ry, whereas the charge was converged up to 0.0001 $e$ .

## Structural properties

In order to predict the stable structural configuration of the BaMO<sub>3</sub> (M = Mg, Ca) perovskites, which have not been experimentally synthesized to date, we first evaluated the tolerance ( $\tau$ ) factor. The  $\tau$ -factor is an empirical parameter widely used to predict the possible stable structure of new perovskites.<sup>38</sup> In the ideal perovskite (ABO<sub>3</sub>) structure, the ionic radii follow the relation  $r_A + r_O = \sqrt{2}(r_B + r_O)$ . According to this relation, tolerance factor is defined as  $\tau = \frac{r_A + r_O}{\sqrt{2}(r_B + r_O)}$ . The ideal perovskite structure free from any bonding strain follows the symmetry of the  $Pm3m$  space group when  $\tau = 1$ . When  $\tau$  is not equal to 1, the system has different strain effects on its bonds. To overcome these stresses and enhance bonding among constituents, the system allows tilting of BO<sub>6</sub> octahedra. This distortion results in fascinating magneto-electronic features. The divergence of the tolerance factor from unity decreases the probability of the formation of a cubic structure as the stable phase, whereas increases the probability of the formation of less symmetric states. However, the cubic structure is stable over a range of  $\tau = 0.9–1$ .<sup>38</sup> The  $\tau$ -values calculated for the BaMO<sub>3</sub> perovskites are provided in Table 1, confirming the stability of the cubic structure. After ascertaining the tolerance factor, we evaluated the cubic lattice constant for the BaMO<sub>3</sub> systems using ionic radii based on the following relation:  $r = \alpha + \beta(r_{\text{Ba}} + r_{\text{O}}) + \gamma(r_{\text{M}} + r_{\text{O}})$ , where  $\alpha = 0.064$ ,  $\beta = 0.4912$ , and  $\gamma = 1.2921$  are constants.<sup>39</sup> Subsequently, using these computed lattice constants, we optimized the  $Pm3m$  symmetric cubic structure *via* spin-polarized calculations. The parabolic nature of the optimization curves depicted in Fig. 1 suggests that the perovskites are stable in  $Pm3m$  structure. The minimum in the curve shows the optimized energy corresponding to the relaxed lattice constant. The optimized parameters of the cubic phase are presented in Table 1. The unit cell structure is also shown in Fig. 1. The constituents Ba, B, and O within the cell are cited at



**Table 1** Ground-state structural parameters *viz* bond distance (in Å), tolerance factor ( $\tau$ ), lattice constant ( $a$  in Å), crystal energy ( $E_0$  in eV), cohesive energy ( $E_{\text{Coh}}$  in eV), and enthalpy of formation ( $H_f$  in eV)

Perovskite	Bond distance		$\tau$		$a$		$E_0$	$E_{\text{Coh}}$	$H_f$
	Ba–O	M–O	Ionic radii	Bond distance	Analytical	Optimized			
BaMgO <sub>3</sub>	2.92	2.06	1.0	1.0	4.16	4.12	–232984.47	22.45	–1.63
BaCaO <sub>3</sub>	3.15	2.22	0.9	1.0	4.55	4.44	–246041.86	22.52	–1.46
BaBeO <sub>3</sub> (ref. 30)			1.03		3.81				–1.85

the 4a (corners), 4b (centre), and 3d (faces) Wyckoff positions following the symmetry  $m3m$ ,  $m3m$ , and  $4/mmm$ , respectively. In order to ensure that these perovskites can be experimentally synthesized, we determined the enthalpy of formation ( $H_f$ ) of these perovskites from their optimized energy and energy of the constituent elements in their stable phases.<sup>30</sup> The enthalpy of formations were below zero, as shown in Table 1. The negative  $H_f$  signifies that the BaMO<sub>3</sub> materials can be experimentally prepared. Moreover, we determined the cohesive energy ( $E_{\text{Coh}}$ ) of the perovskites to confirm their stability in the cubic phase. The positive  $E_{\text{Coh}}$  signifies that energy is required to rupture the bonds, verifying the stability of the BaMO<sub>3</sub> (M = Mg and Ca) perovskites.

## Mechanical stability and anisotropic character

To further investigate the mechanical stability of the titled perovskites, the elastic constants were computed. If a system is arbitrarily deformed under equilibrium conditions through a small strain “ $e$ ”, the change in energy would be

$$U_{\text{elast}} = \frac{V_0}{2} \sum_{ij=1}^6 C_{ij} e_i e_j + \text{H(O)}; \text{ (HO) is used for higher-order strain terms.}^{40}$$
 Symmetry reduces the number of independent

elastic constants that could completely reveal the mechanical behavior of a system. Only  $C_{11}$ ,  $C_{12}$ , and  $C_{44}$  are required to completely describe the mechanical behavior of a cubic symmetric system. Therefore, the above mentioned equation for the cubic system reduces to

$$U_{\text{elast}} = \frac{V_0}{2} (C_{11} - C_{12})(e_1^2 + e_2^2 + e_3^2) + C_{12}(e_1 + e_2 + e_3)^2 + C_{44}(e_4^2 + e_5^2 + e_6^2) + \text{H(O)}$$

The system would be dynamically stable if and only if the deformed system is at higher energy *i.e.*,  $U_{\text{elast}}$  should be positive. This condition restricts the values of elastic constants, which have been mathematically outlined as necessary stability conditions by Born.<sup>41,42</sup> The cubic structure is dynamically stable if and only if  $C_{11} > 0$ ;  $C_{11} - C_{12} > 0$ ;  $C_{44} > 0$ ; and  $C_{11} + 2C_{12} > 0$  are followed.

The elastic constants of the titled perovskites were computed by applying tetrahedral and rhombohedral distortions to the optimized structure under a constant volume constraint. The computed values of the elastic constants presented in Table 2 are positive and follow the stability criteria, thereby authenticating the stability of the perovskites. Moreover, the magnitude of elastic constants for the BaMO<sub>3</sub> (M = Mg and Ca) perovskites decreases in the order  $C_{11} > C_{12} > C_{44}$ , signifying that these

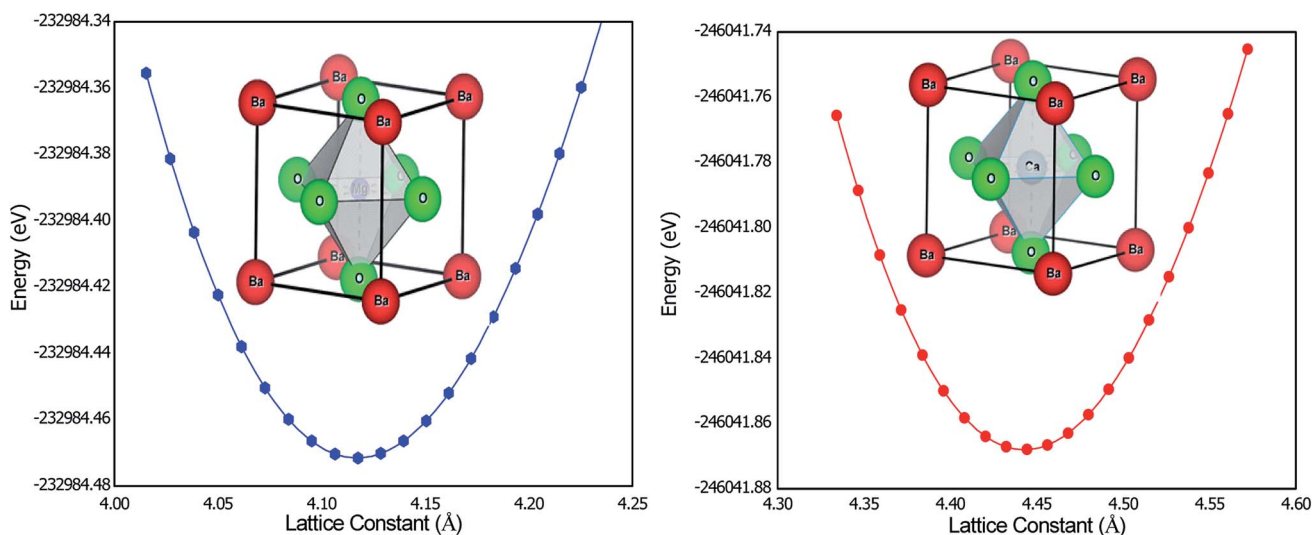
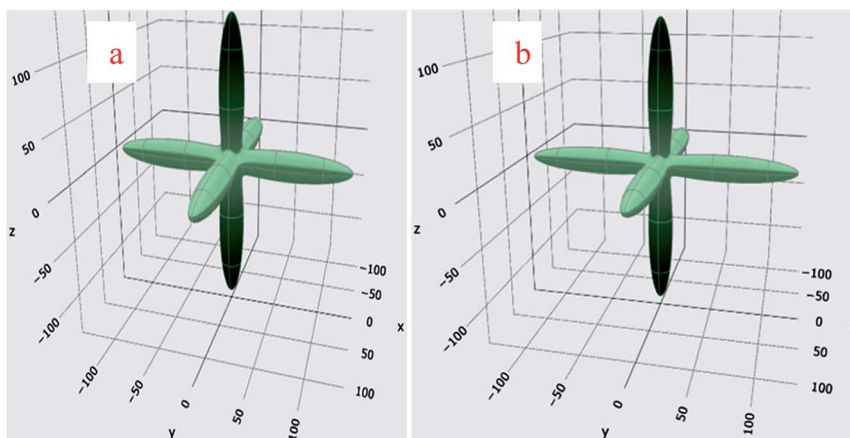
**Fig. 1** Optimization curves along with the unit cell structure of BaMO<sub>3</sub> (M = Mg and Ca) perovskites determined *via* spin-polarized calculations.

Table 2 Elastic constants determined by DFT calculations and the maximal and minimal values along with anisotropies of various elastic moduli

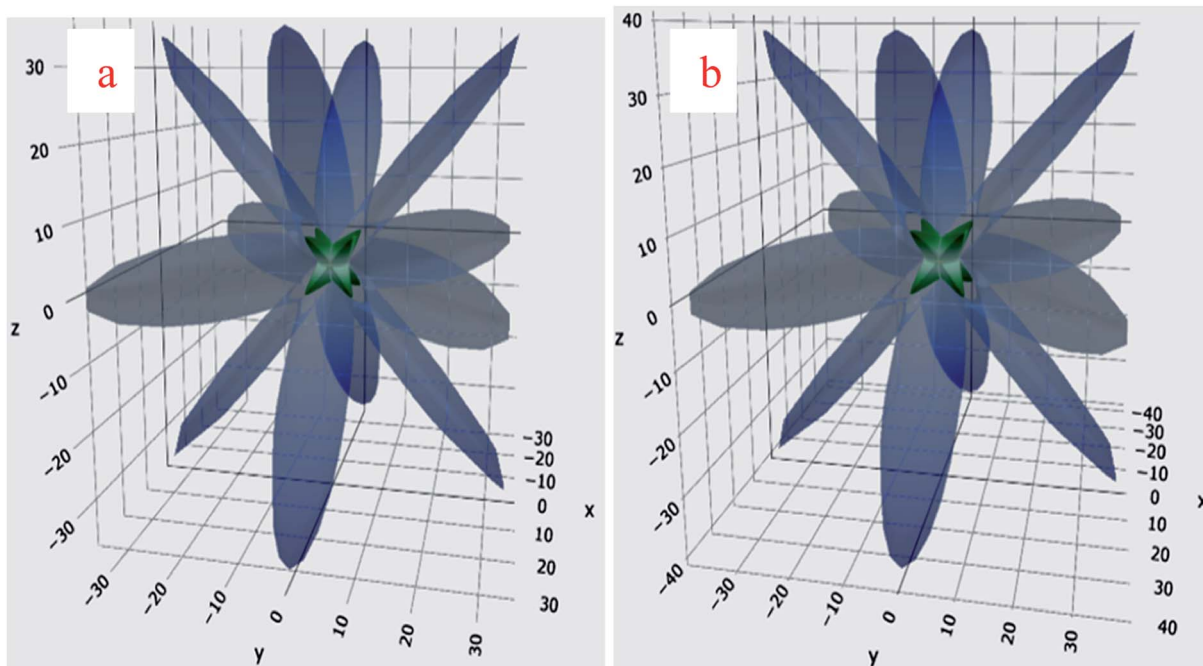
Perovskite	$C_{ij}$ (GPa)			$A^U$	$Y$ (GPa)			$G$ (GPa)			$\sigma$		
	$C_{11}$	$C_{12}$	$C_{44}$		$Y_{\min}$	$Y_{\max}$	$A_Y$	$G_{\min}$	$G_{\max}$	$A_G$	$\sigma_{\min}$	$\sigma_{\max}$	$A_\sigma$
BaMgO <sub>3</sub>	151.2	52.4	3.08	16.96	9.1	124.2	13.6	3.08	49.42	16.0	0.024	0.92	37.7
BaCaO <sub>3</sub>	135.3	25.7	3.8	14.99	11.2	127.1	11.4	3.8	54.79	14.8	0.018	0.90	19.6
KMgO <sub>3</sub> (ref. 22)	121.5	32.5	9.03										

Fig. 2 Directional dependence of Young's modulus for (a) BaMgO<sub>3</sub> and (b) BaCaO<sub>3</sub>.

perovskites offer higher resistance towards unidirectional deformation than pure shear deformation.

Using these elastic constants, we have analyzed the anisotropic character of the perovskites by evaluating the universal anisotropy index ( $A^U$ ). The deviation of  $A^U$  from zero, as shown

in Table 2, signifies the presence of anisotropy. The elastic matrices were supplied to the 'ELATE: elastic tensor analysis' tool to visualize the three-dimensional orientation dependence of various elastic moduli.<sup>43</sup>

Fig. 3 Angular dependence of shear modulus for (a) BaMgO<sub>3</sub> and (b) BaCaO<sub>3</sub>.

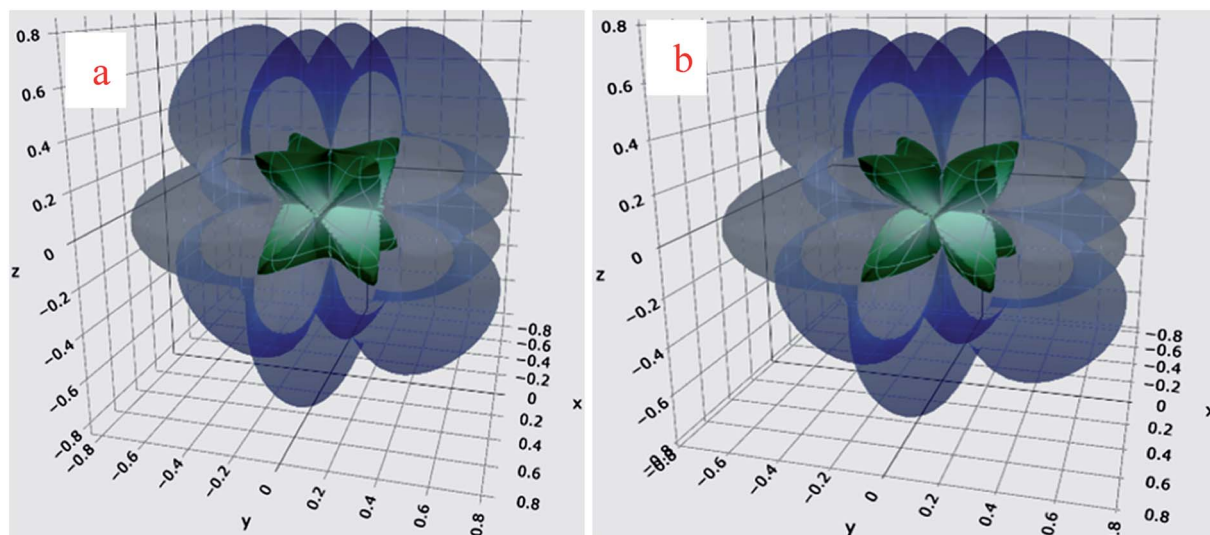


Fig. 4 Three-dimensional graphical representation of Poisson's ratio for (a) BaMgO<sub>3</sub> and (b) BaCaO<sub>3</sub>.

The graphical representation of the Young's modulus ( $Y$ ) of BaMgO<sub>3</sub> and BaCaO<sub>3</sub> is shown in Fig. 2. The maximum values of  $Y$  reached 124.2 (127.1) along the [100], [001], and [010] directions and reduced to the minimum value 9.1 (11.2) along the body diagonals for the Mg (Ca)-based perovskites. The ratio  $A_Y = E_{\max}/E_{\min}$  is about 13.6 and 11.4 for BaMgO<sub>3</sub> and BaCaO<sub>3</sub>, respectively, and characterize the anisotropy in the  $Y$ -modulus. The anisotropy originates from the large difference in the longitudinal and shear elastic constants. The directional deformation of shear modulus is illustrated in Fig. 3. The star-like behavior of shear modulus, exhibiting different values along different directions, reveals the anisotropic character of the perovskites. The highest and lowest values of  $G$  are provided in Table 2 along with the shear anisotropy ( $A_G$ ) ratio. The maximum value of  $G$  is equal to  $C' = (C_{11} - C_{12})/2$ , representing the resistance to shear in the (110) plane. On the other hand,  $G_{\min} = C_{44}$  represents the resistance to shear in the (100) plane.<sup>44</sup>

Poisson's ratio  $\sigma = -e_j/e_i$  is the ratio of transverse to axial strain. The ratio varies over  $-1 < \sigma < 0.5$  range.<sup>45</sup> The angular dependence of  $\sigma$  for the BaMO<sub>3</sub> framework is shown in Fig. 4(a and b). The ranges over which  $\sigma$  varies for the titled perovskites as well as anisotropy  $A_\sigma$  are shown in Table 2. For a ductile solid,  $\sigma$  is usually larger than 0.26, and the average of  $\sigma_{\max}$  and  $\sigma_{\min}$  is greater than 0.26, indicating ductile character of the perovskites.

The mean values of the bulk ( $B$ ) and shear ( $G$ ) moduli of these highly anisotropic perovskites were estimated by adopting the Voigt–Reuss–Hill-scheme using elastic constants and are provided in Table 3.<sup>42,45</sup> The same values of  $B_V$ ,  $B_R$ , and  $B_H$  signify that the bulk modulus is isotropic. The isotropy of  $B$  can also be confirmed from the spherical shape of linear compressibility shown in Fig. 5(a and b), reflecting angular independence. The Pugh's ratio ( $B/G$ ) and  $\sigma$  are often used to characterize the mechanical behavior of ductility or brittleness. The index values of these parameters are 1.75 and 0.26. If the value of these parameters is above the index value, the perovskite is most likely to have a ductile character. The calculated values of these decisive parameters signified that the BaMO<sub>3</sub> perovskites are highly ductile in nature.

## Electronic and magnetic properties

The magneto-electronic behavior of the titled perovskites was investigated based on the optimized lattice constant. The exchange–correlation potential was approximated by the generalized gradient approximation, which works well for systems with sp-electrons. However, we also added the mBJ potential to GGA in order to more precisely describe the electron profile. The spin-polarized electronic band structures determined *via* the GGA approximation are shown in Fig. 6(a and b). The energy bands of the spin-down channel clearly reflect the

Table 3 Mean elastic parameters of BaMO<sub>3</sub> perovskites

Perovskites	$B$			$G$			$Y$			$\sigma$			$B/G$
	$B_V$	$B_R$	$B_H$	$G_V$	$G_R$	$G_H$	$Y_G$	$Y_R$	$Y_H$	$\sigma_V$	$\sigma_R$	$\sigma_H$	
BaMgO <sub>3</sub>	85.42	85.42	85.42	21.61	4.92	13.27	59.80	14.50	37.95	0.38	0.47	0.42	6.4
BaCaO <sub>3</sub>	62.31	62.31	62.31	24.19	6.05	15.12	64.27	17.59	41.97	0.32	0.45	0.38	4.12
KMgO <sub>3</sub> (ref. 22)	62.22			23.21			49.84			0.36			2.68



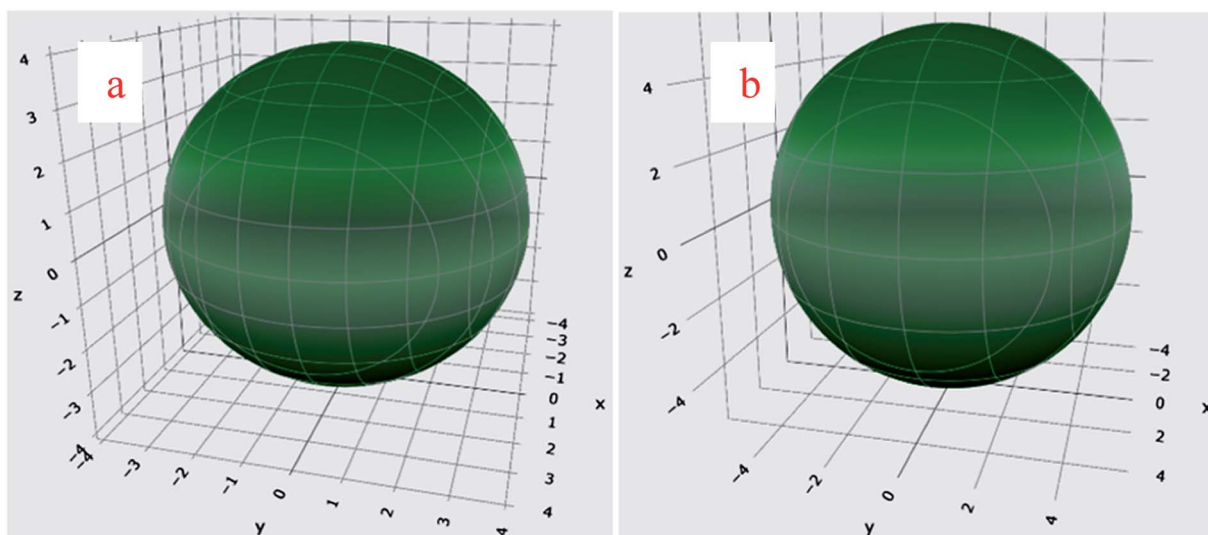


Fig. 5 Orientation dependence of linear compressibility for (a) BaMgO<sub>3</sub> and (b) BaCaO<sub>3</sub>.

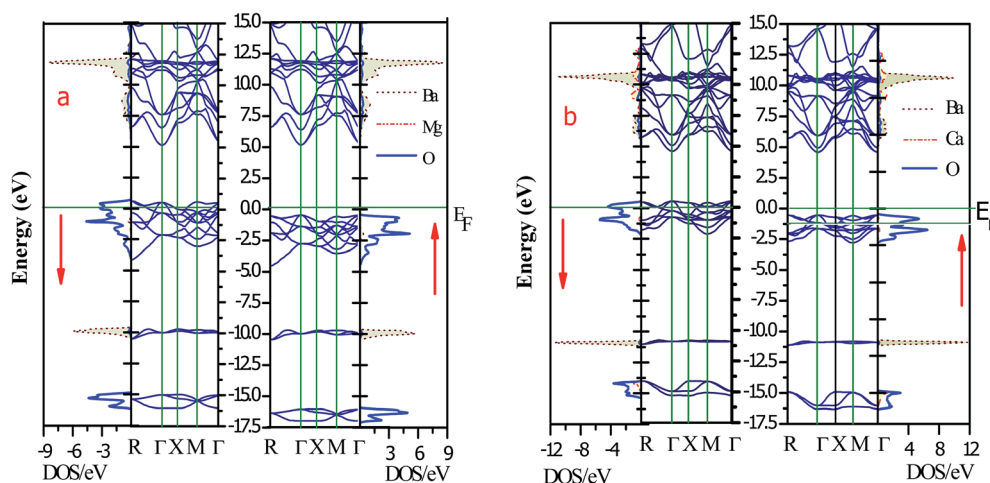


Fig. 6 Spin-polarized band structure and density of states determined *via* GGA calculations: (a) BaMgO<sub>3</sub> and (b) BaCaO<sub>3</sub>. The distribution of energy bands reflects the semi-conducting character of the spin-up channel and metallic character of the spin-down channel.

metallic character as the bands crosses over the Fermi level. Contrarily, in the spin-up channel, the Fermi level remained vacant. The wide band gap separating the top of the valence band (VBM) and minimum of the conduction band (CBM) indicates insulating nature of the respective spin channel. The presence of bands at the Fermi level in one spin channel and the vacant Fermi level in the other spin channel signify that these perovskites have 100% spin polarization at the Fermi level. The band structure also indicates the presence of large pseudo-gaps. The spin-flip (half-metallic) gap is determined from the energy difference between the Fermi level (zero energy) and VBM because of its closeness to the Fermi level than to the CBM for a semiconducting channel. This expresses the minimum energy required to flip an electron from the top of the occupied valence to the Fermi level.<sup>46</sup> The HM gap is a significant parameter to determine the minimum energy required for spin excitation to

induce holes in the minority spin channel. The wider HM gap suggested that the BaMO<sub>3</sub> materials are suitable HM ferromagnets for potential spintronic applications. The mBJ band structure also demonstrated half-metallic electronic character

Table 4 Band gap (eV), half-metallic gap (eV), spin-splitting gap ( $\downarrow_{\text{VBM}} - \uparrow_{\text{VBM}}$  in eV), and magnetic moment ( $\mu_{\text{B}}$ ) of the BaMO<sub>3</sub> perovskites determined *via* the GGA and mBJ approximation

Parameter	Band gap		Half-metallic gap		$\downarrow_{\text{VBM}} - \uparrow_{\text{VBM}}$		Magnetic moment	
	GGA	mBJ	GGA	mBJ	GGA	mBJ	GGA	mBJ
BaMgO <sub>3</sub>	5.67	7.61	0.49	0.62	1.08	2.75	2.0	2.0
BaCaO <sub>3</sub>	5.16	7.16	0.58	0.60	1.09	2.47	2.0	2.0



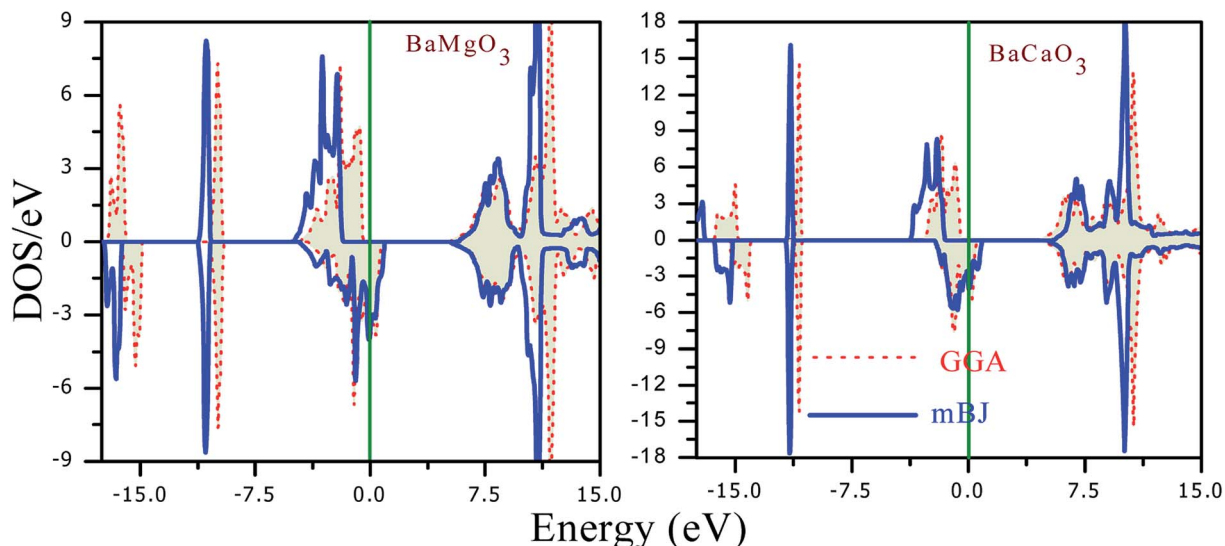


Fig. 7 Total density of states of BaMgO<sub>3</sub> and BaCaO<sub>3</sub> perovskites obtained through the GGA and mBJ methods. The energy peaks depict a slight shift with the mBJ potential.

of the BaMO<sub>3</sub> (M = Mg and Ca) perovskites. However, the band gap in the spin-up channel and spin-splitting values were modified, as presented in Table 4. The effect of mBJ on the

energy states can be determined from the density of states illustrated in Fig. 7, where it is evident that the energy states show a marginal shift away from the Fermi level in the spin-up

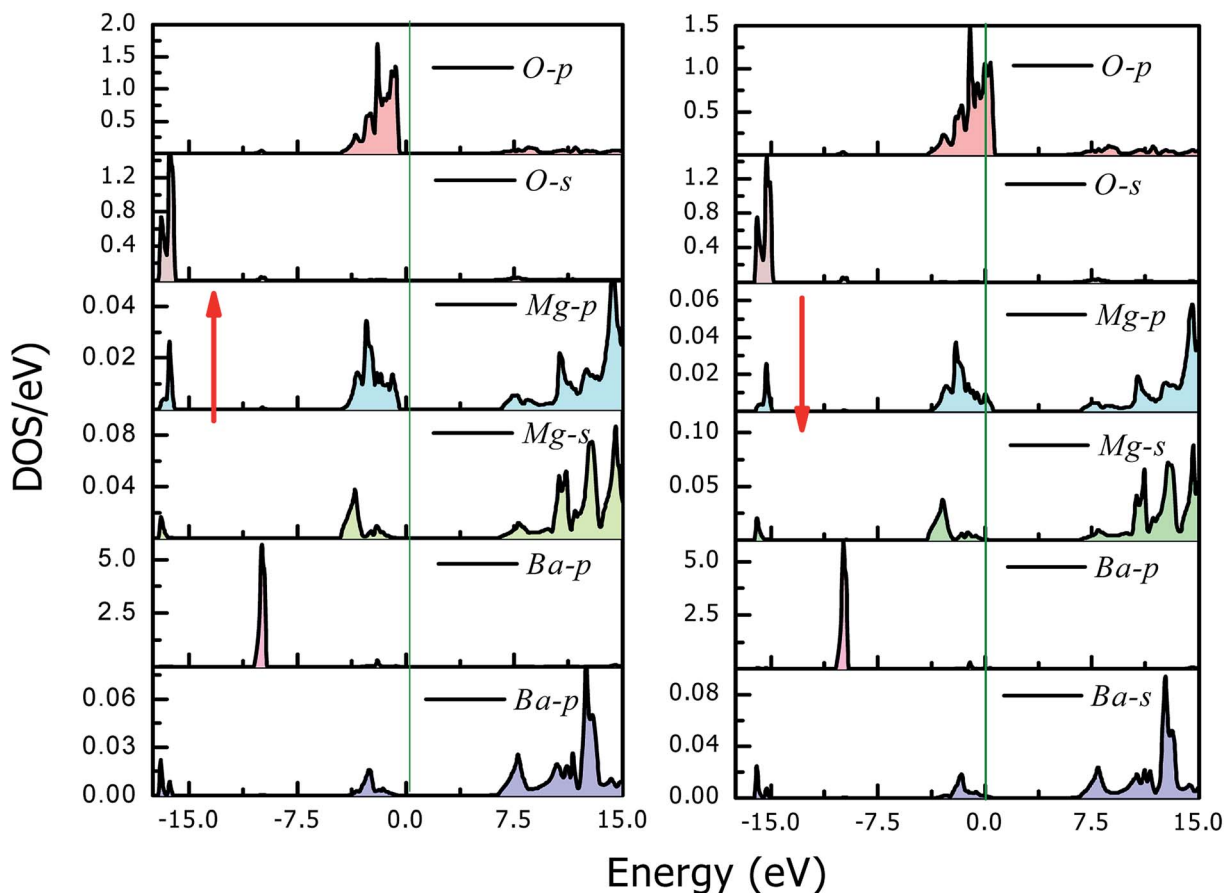


Fig. 8 Projected density of states for BaMgO<sub>3</sub>. It is evident that the O-p states are responsible for the ferromagnetic half-metallic character of these perovskites.



channel. However, the energy bands at the Fermi level in the spin-down state did not shift, thereby maintaining the half-metallicity. In order to exploit and extract more information from the band structure and understand hybridization within perovskites, we plotted projected density of states (PDOS), which can indicate both quantitative as well as qualitative behavior of states at a particular energy value. Since both perovskites have a similar band and DOS profiles, herein, we have shown only the pDOS of BaMgO<sub>3</sub> in Fig. 8. The distribution of the valence states reveals that the oxygen p-states are responsible for the half-metallicity of these perovskites as they occupy the Fermi level in the spin-down channel. The presence of the oxygen p-states at different energy values in the spin-up and down channels indicates that the electrons in these channels do not cancel each other's magnetic moment and thereby lead to ferromagnetic character. However, the presence of Ba and M-atom states at the same energy value in the spin-up and down channels reflects symmetric character of the valence states of these atoms. This implies complete cancellation of the magnetic moment of these constituents. The valence s-states of the Ba and Mg-site atoms are in the conduction band, whereas

their inner lying p-states constitute the DOS peaks in the valence band, as can be observed in the pDOS plots shown in Fig. 8.

The total spin magnetic moment and individual contributions to it are presented in Table 2. The magnetic moment for any system originates from the number of unpaired electrons with each unpaired electron contributing 1  $\mu_B$ . Perovskites mostly demonstrate A<sup>2+</sup>B<sup>4+</sup>O<sub>3</sub><sup>2-</sup> or A<sup>3+</sup>B<sup>3+</sup>O<sub>3</sub><sup>2-</sup> oxidation states, in which all the oxygen atoms are in the -2 oxidation state. However, in BaMO<sub>3</sub>, the Ba and M-site atoms belong to the II group of the periodic table and have +2 oxidation state. Therefore, to maintain charge stability, individual oxygen atoms demonstrate different oxidation states. Among the three oxygen atoms per formula, two have the oxidation state of -1 and one oxygen atom depicts the oxidation state of -2. Accordingly, the oxidation state of oxygen in the BaMO<sub>3</sub> perovskites is 4/3. The average oxidation state was obtained by summing the different oxidation states of the oxygen atoms and dividing the obtained value by the total oxygen atoms per formula. This configuration reveals the presence of two unpaired electrons at the oxygen sites partially filling the p-states in the spin-down channel. The

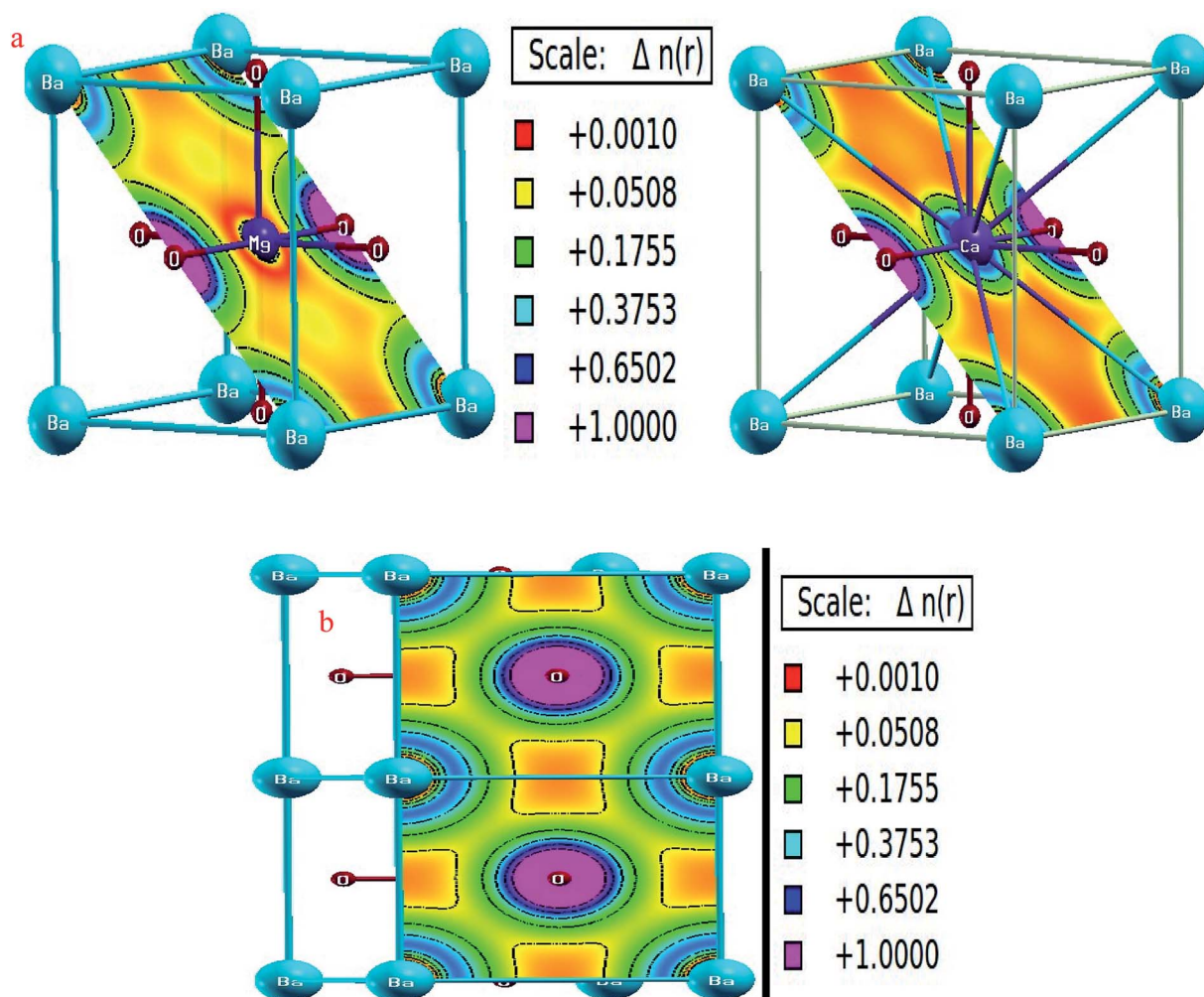


Fig. 9 Charge density distribution in the (a) [011] and (b) [001] planes.



unpaired electrons would lead to the magnetic character of perovskites with a magnetic moment of  $2 \mu_B$ . Upon replacing the Ba-atom with potassium (K),  $K^{1+}Mg^{2+}O_3^{1-}$  can be obtained. The number of unpaired electrons as well as the magnetic moment increases to three. The partial filling of the p-states in the spin-down channel pushes the valence band to cross over the Fermi level. Thus, the valence band maxima (VBM) in the spin-up and down channels are obtained at different values. Therefore, we evaluated the spin-splitting gap ( $\downarrow_{VBM} - \uparrow_{VBM}$ ), which is reported in Table 2.

## Charge density and characteristic bonding

The constituent atoms within a perovskite can be linked together by different kinds of bonds with different spatial charge distribution. Covalent bonds are characterized by the mutual sharing of electrons and therefore have non-zero charge density along the bond distance. However, in ionic bonding, the

inter-atomic distances are free from any type of charge density owing to the complete transfer of charge from one atom to another. For the titled perovskites, we have analyzed charge distribution in the (011) and (001) planes, as shown in Fig. 9. The O-atoms are nearest neighbors to the Ba and M-site atoms; therefore, we examined the bonding among them. The charge distribution around the three constituents is almost spherical, indicating ionic bonding. However, the charge distribution around Mg and Ca is typically different, as shown in Fig. 9(a). Charge accumulation around Ca is more as compared to that around Mg because of higher number of electrons in Ca due to which the charge of Ca extends to almost up to the charge of O. Nevertheless, almost negligible charge at half of the distances from the centers of the Ca and O atoms conveys ionic character of the Ca–O bonds. The ionic character of bonding is dominant because alkaline earth metals have highly electropositive character, whereas oxygen is one of the most electronegative elements.

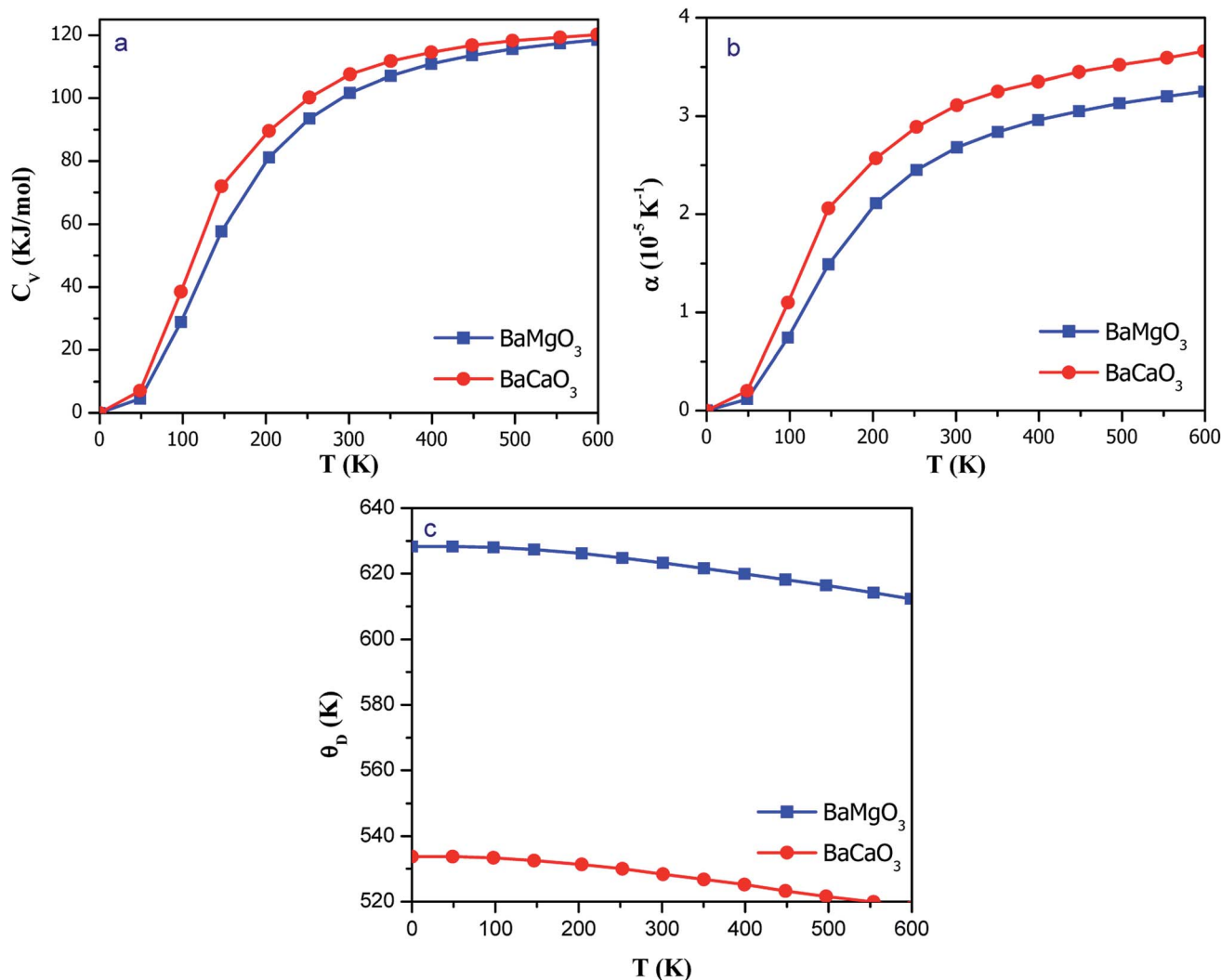


Fig. 10 Variation in the thermodynamic properties of perovskites against temperature: (a) specific heat; (b) thermal expansion; and (c) Debye temperature.



## Thermodynamic properties

Within the regimes of the quasi-harmonic approximation, we deduced the thermodynamic parameters using the GIBBS2 code.<sup>47</sup> The variation in the various thermodynamic properties against temperature and pressure can be evaluated using this program with the aid of fitted input E–V data-generated from Birch–Murnaghan equation. The advantage of deriving the thermodynamic properties under different temperature and pressure conditions from the DFT calculations is the ease in modeling these parameters under extreme conditions, which could be harsh experimentally. The variation in the specific heat at constant volume ( $C_V$ ) is illustrated in Fig. 10(a). The specific heat abruptly increases at low temperatures, following the Debye  $T^3$ -law. However, at higher temperatures,  $C_V$  tends towards a constant value of  $3nR = 121 \text{ J mol}^{-1} \text{ K}^{-1}$ , where  $R$  is the gas constant.  $C_V$  shows a rapid increase with an increase in  $T$  from absolute zero possibly due to an increase in thermal vibrations at elevated temperatures. However, all vibration modes are thermally excited at higher temperatures, corresponding to the Dulong–Petit limit for specific heat. With an increase in temperature, the atoms start vibrating vigorously, and thus, the inter-atomic distances are increased, leading to thermal expansion. Almost all the solids expand to some extent with an increase in temperature; however, materials with weak inter-atomic bonding show greater degree of expansion. The ratio of change in the length to the original length is known as thermal coefficient ( $\alpha$ ), and the variation in this coefficient with temperature is shown in Fig. 10(b). At higher temperatures, the value of  $\alpha$  tends towards a saturation value. However, at lower temperatures, it sharply increases, exhibiting similar character as  $C_V$ .

Debye temperature ( $\theta_D$ ) is one of the important thermo-elastic parameters of solids. It represents the highest value of temperature up to which the constituents exhibit coupled vibrations and the vibrations reach the maximum possible modes. It is a good indicator of the hardness of materials; materials with high  $\theta_D$  exhibit high hardness and are comparatively rigid than the materials with low  $\theta_D$ . The  $\theta_D$  as a function of temperature is shown in Fig. 10(c); it is clear that  $\theta_D$  decreases with an increase in temperature. At low temperatures, the thermal expansion as well as anharmonicity are small, resulting in an almost constant Debye temperature. The high-frequency modes can be considered frozen at low temperatures, *i.e.*, only the acoustic modes are excited. The  $\theta_D$  decreases with an increase in temperature; thus, the vibration spectra of the atoms change with an increase in temperature. The room-temperature values of Debye temperature are 623.2 and 528.3 K for  $\text{BaMgO}_3$  and  $\text{BaCaO}_3$ , respectively. The high value of the Debye temperature suggests that the perovskites can be used for application purposes even at higher temperatures.

## Conclusion

In the study, we successfully established the structural and mechanical stabilities of  $\text{BaMO}_3$  ( $M = \text{Mg}$  and  $\text{Ca}$ ) perovskites. The structural optimization, tolerance factor, cohesive energy,

and stability criteria indicate the stability of these perovskites in the cubic symmetric  $Pm3m$  structure. The electronic profile demonstrates 100% spin polarization at the Fermi level with a wide band gap in the spin-up channel. Both the perovskites show a magnetic moment of  $2 \mu_B$  with sole contribution from the oxygen p-electrons. Using quasi-harmonic approximation, we demonstrated the variation in thermodynamic properties against temperature. The magnitude of the bulk and shear moduli suggests higher these perovskites show higher resistance towards volumetric deformation as compared to shape deformation. The Pugh's ratio and Poisson's ratio signify highly ductile character of these perovskites. The high anisotropy of these perovskites was verified by analysing 3D graphical representation of various elastic parameters. Our successful prediction of structural and mechanical stability would be helpful for the synthesis of these novel perovskites.

## Funding

The research work is not funded by any agency.

## Data availability

The datasets generated during and/or analyzed during the current study would be available from the corresponding author on reasonable request.

## Author contributions

All the authors have significantly contributed to the research. Shabir Ahmad Mir: conceptualization, methodology (partially), writing – original draft, revision; Ab Quyoom Seh: methodology (partially), editing write-up; and Dinesh C. Gupta: supervision, software, validation, writing – review & modification.

## Conflicts of interest

The authors declare that they have no conflict of interest for this work.

## Acknowledgements

The authors are greatly thankful to Jiwaji University for providing the facilities to carry out the research work.

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