

Probing structural and luminescence properties of Ce³⁺ doped MgO nanocrystals via XAS, PL, and TL studies

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ABSTRACT

MgO:Ce and MgO:CeLi nanocrystals have been prepared using the solution combustion method and investigated for structural, electronic structure, photoluminescence, and thermoluminescence properties. X-ray diffraction (XRD) analysis revealed the single-phase formation of MgO:Ce and MgO:CeLi compounds up to 0.1 mol% of Ce doping. The formation of CeO₂ phase has been observed at 2 mol% Ce doping in MgO. Low energy shift in the Mg K-edge X-ray absorption near edge structure (XANES) spectra conveys favorable tetrahedral site occupancy of Mg²⁺ ions in MgO:Ce nanocrystals. The enhanced intensity of the O K-edge XANES feature, in MgO:Ce samples, reveals a more, *p*-projected, unoccupied density of states and significant hybridization of Ce 4f and O 2p states. Ce L₃ edge XANES spectra confirmed the coexistence of Ce⁴⁺ and Ce³⁺ ions in the samples. Photoluminescence (PL) experiments, conducted with UV LED excitation at 275 nm and 310 nm, showed emissions in two regions; a blue region centered at 430 nm and a red region at 670 nm in pure MgO. Additionally, distinct emission bands corresponding to Ce 5d-4f transitions were observed and the Li co-doping could enhance the PL intensity. Thermoluminescence (TL) studies of the samples were conducted after being exposed to the different doses (100 Gy, 500 Gy, 1 kGy) of gamma radiation. The deconvolution of TL peaks has confirmed the presence of multiple traps. Kinetic parameters of TL glow peaks revealed re-trapping and closely spaced traps within the forbidden band gap. The stability and linear behavior of TL peaks demonstrated the excellent dosimetry characteristics of prepared MgO:CeLi nano phosphors.

1. Introduction

MgO is an insulating oxide with a band gap of ~7 eV and obeys FCC crystal structure with a space group of Fm-3 m. The Mg cations are placed in the octahedron made up of oxygen anions in the lattice. Although this compound has a very large band gap, it is highly studied for luminescent properties due to the imperfection in lattice [1,2]. The presence of charged neutral color centers due to the oxygen vacancies, interstitial defects, and Mg vacancies makes this compound suitable for probing the defects-based studies [3–5] which have been investigated using optical techniques. Interesting optical properties of MgO have extensively attracted researchers for illumination, medical, and pharmaceutical applications [6,7]. In 1964, it was recognized as a thermoluminescence (TL) phosphor, and afterward, its optimization for optical application has been continuously studied by varying different

parameters such as its synthesis process, doping of rare earth and transition elements, changing irradiations, etc. [8]. However, due to the non-stability of its TL peaks, it is not considered a commercial dosimeter in industry. In the last few years, various rare earth elements have been doped in MgO to design nano phosphors for light and dosimetry applications [4,9,10]. Lanthanide elements have exceptional characteristics of forbidden f-f transition due to their potential optical properties which are controlled by host emission is a key factor for luminescence applications. Therefore, doping of RE elements influences the luminescence of MgO which may be due to the modification in density of defects, surface defects, aggregations of intrinsic defects, and recreation of new traps.

Ce³⁺ is widely studied for its large absorption cross sections and shorter decay time due to its f-d transition [11,12]. The characteristic emission due to f-d transitions of Ce ions is confirmed by using

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photoluminescence, thermoluminescence, and radioluminescence studies. *M. Oglakci et al.* report the formation of X-ray irradiation-induced multiple traps in $\text{LaBa}_3\text{O}_6\text{:Ce}$ system and the emission characteristics are confirmed by Ce f-d transitions [13]. In their other work, the $\text{NaBaBO}_3\text{:Ce}^{3+}$ system showed different TL glow curve peaks during TL readout after irradiating samples with beta radiation [14]. Additionally, this lanthanide is doped in $(\text{Y, Gd})_3(\text{Al, Ga})_5\text{O}_{12}$ excited by blue light and emits yellow light which is now used as a yellow emitter WLEDs [15–17]. Its f-d transitions are highly affected by surroundings because of which its emission varies from UV to red light depending on the host material. In YPO_4 , when Ce is doped it substitutes the Y^{3+} and does not require any kind of charge compensator [18]. But when this RE element substitutes the divalent Mg ions, charge compensation is required. In literature, various reports have been presented for TL studies of MgO with Ce and Li dopants [19–22]. The study reports have been restricted to the luminescence characteristics of host and host-controlled Ce ions. An intriguing aspect to investigate is the luminescence behavior of the system when Ce is doped. Recently, it has been reported characteristics emission from Ce^{4+} in Sr_2CeO_4 [23]. It is also reported that in some host materials, Ce^{4+} behaves as an intermediate state and enhances the Ce^{3+} emission by charge transfer from the host [16,23,24]. These intermediate states arising from the co-existence of Ce^{3+} and Ce^{4+} may influence the transition mechanism and interaction of dopants with intrinsic defects of host. Therefore, it is interesting to study the modifications in the structure around the dopant and host cations and anions present in the lattice which is crucial for luminescence characteristics. Detailed analysis of structural distortion, and phonon–phonon interactions could be achieved by advanced elemental techniques.

In this context, the present study investigates the influence of intrinsic defects and dopant elements on the structural and luminescence properties of MgO. Subsequently, the effects of varying concentrations of Ce and Ce-Li ions on the structural geometry of host ions, particularly, the generation of new defects and their interaction with the existing defects have been investigated. The present study also targets the color shift, from blue to white, by engineering the distribution of defects using the UV excitation wavelengths (275 nm and 310 nm). Further, an assessment is made to understand the trap distribution in post-gamma irradiated MgO, MgO: Ce, and MgO: CeLi samples.

2. Material and methods

2.1. Synthesis

The pure MgO, MgO: Ce and MgO: CeLi phosphors were prepared using the solution combustion method. The oxidizers utilized were Magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) with a purity of 99 %, Cerium nitrate $\text{Ce}(\text{NO}_3)_3 \cdot \text{H}_2\text{O}$, and Lithium nitrate ($\text{Li}(\text{NO}_3)_3$). The fuel used was urea (NH_2CONH_2) (CDH). All the precursors and fuel were mixed in 100 ml distilled water after being taken according to stoichiometric ratio. The homogenous solution was prepared by stirring for half an hour. The solution was heated in a furnace at a temperature of 600 °C. After completion of the combustion process, the obtained white fluffy product was crushed into fine powder. Five different compositions with varying molar ratios were prepared with the same synthesis process. Pristine MgO, Ce with 0.05 mol%, 0.1 mol%, 0.2 mol% and Ce with 0.1 mol%; Li with 3 mol% is referred as C0, C1, C2, C3 and CL for further analysis.

2.2. Characterization

X-ray diffraction measurements are performed using a Bruker-D8 Advance EcoPro Diffractometer with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5408 \text{ \AA}$). The low energy X-ray absorption near-edge structure (XANES) spectra at O K-edge and Mg K-edge are collected in total fluorescence yield mode at the soft X-ray beamline (10D XAS KIST-PAL). Ce L_3 -edge XANES spectra are collected at the 1D X-ray scattering beamline of the Pohang

Accelerator Laboratory, South Korea. The room temperature, photoluminescence spectroscopy has been conducted utilizing a RIMS spectrometer with two independent UV LED sources of 275 nm and 310 nm with a long pass filter of 370 nm. For thermoluminescence experiments, samples were irradiated with gamma radiation at different doses with a ^{60}Co source in gamma chamber 1200. Samples were heated at 500 Celsius for 2 h before irradiating for removal of unstable shallow traps. TL curves have been read out using the Harshaw TL Analyzer Model-3500 instrument with a heating rate of 5 Celsius per second.

3. Results and discussion

3.1. Structural study

Fig. 1 shows the XRD patterns of all compositions after annealing at 900 °C for 3 h at the rate of 5 deg Celsius per min. No secondary phase is observed in 0.05 mol%, 0.1 mol%, and in CeLi co-doped MgO samples. In the case of Ce 0.2 mol% doping, an impure phase of CeO_2 has been observed and presented in the enlarged image of Fig. 1. It indicates that up to 0.1 mol% of Ce, the dopants ions are favorably incorporated in the host lattice. However, afterward, incorporation became difficult and CeO_2 phase was developed in MgO. In this work, further studies have been conducted up to 0.1 mol% of Ce and for co-doped composition. From XRD patterns shown in Fig. 1, it has also been observed that peaks are shifted towards lower angles as the concentration increases up to 0.1 mol% Ce doping. The change in lattice parameter of doped samples is due to the difference in ionic radii of Ce^{3+} (0.103 nm) and Mg^{2+} (0.072 nm) cations and indicates that Ce ions substitute the host cations instead of creating interstitial defects. Furthermore, the charge difference in both the cations creates lattice distortion by inducing the strain. To balance the charge difference in the host, the Li is also added with Ce ions. In literature, co-doping of Li ions not only reduced the strain but also enhanced the emission intensity. Li behaves as the charge compensator as well as the sensitizer for activator ions [25,26]. In the present report, for the co-doped sample, the incorporation of Li ions causes a reduction in lattice parameters because of the smaller ionic radii of Li ions than that of the host ions. The peak shifting towards higher angles and increase in the intensity of XRD peaks indicate the substitutional occupations of Li ions and the promotion of crystallinity. The monovalent Li ions act as charge compensators by neutralizing the charge disturbance created due to the charge difference between the Ce dopant and Mg ions.

3.2. X-ray absorption spectroscopy

Fig. 2(a–d) shows the Mg and O K-edge XANES spectra of all samples. The features observed at 1305.2 eV, 1311.1 eV, 1322.5 eV, and 1350.6 eV are marked by letters **u**, **v**, **w**, and **x**, respectively. All the features observed in the XANES spectra are well matched with the previously reported spectral features of MgO and confirm the rock salt MgO structure in which Mg^{2+} ions lie in the octahedron of oxygen anions in the lattice [27,28]. It is known that the edge energy position of tetrahedrally coordinated Mg^{2+} sites always lies lower in energy compared to that of octahedrally coordinated Mg^{2+} sites [5,29]. Fig. 2 (b) shows that the edge energy position of Mg K-edge XANES of MgO:Ce samples shifts to lower energy. This conveys a net enhancement in the tetrahedrally coordinated Mg^{2+} ions as a function of Ce doping. It is anticipated that Mg-O6 octahedrons are deformed into Mg-O4 tetrahedrons upon Ce doping via the formation of oxygen vacancies for charge compensation of MgO:Ce system. The other spectral features namely, **v**, **w**, **x** (at higher energy; 1308–1360 eV) show a diminished intensity compared to that of pure MgO. The higher energy features are due to multiple scattering events and their lesser intensity shows fewer Mg-O networks due to the Ce substitution at the Mg sites and tetrahedral distortion in the Ce-doped MgO samples.

In O K-edge XANES spectra (Fig. 2(c–d)), features at 533.1 eV, 538 eV

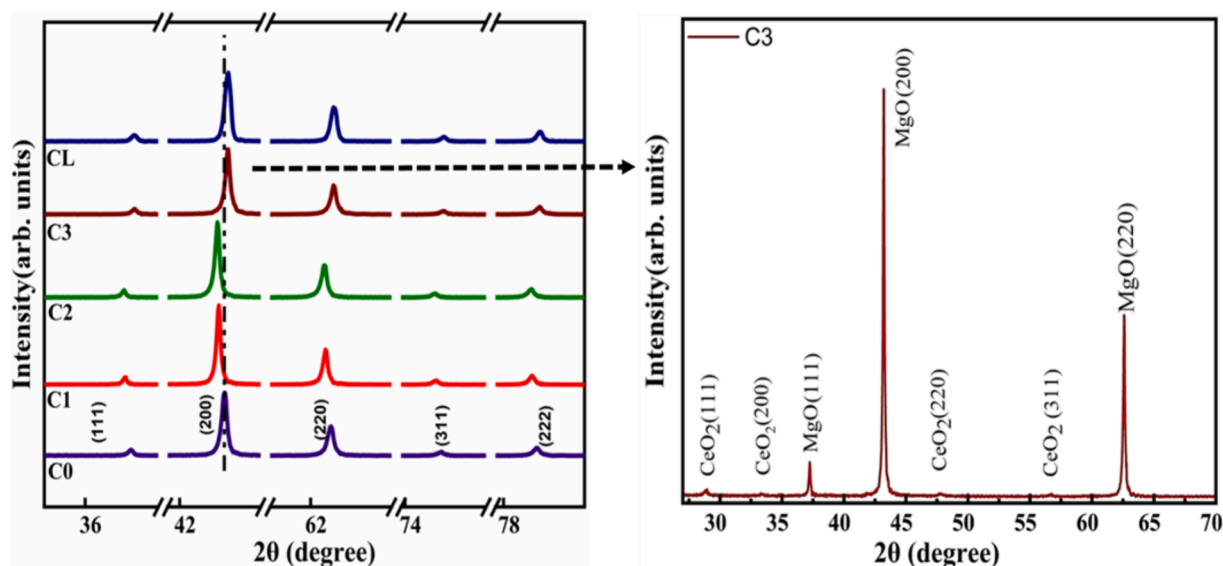


Fig. 1. XRD of Pure and Ce doped MgO with an enlarged image of C3 composition.

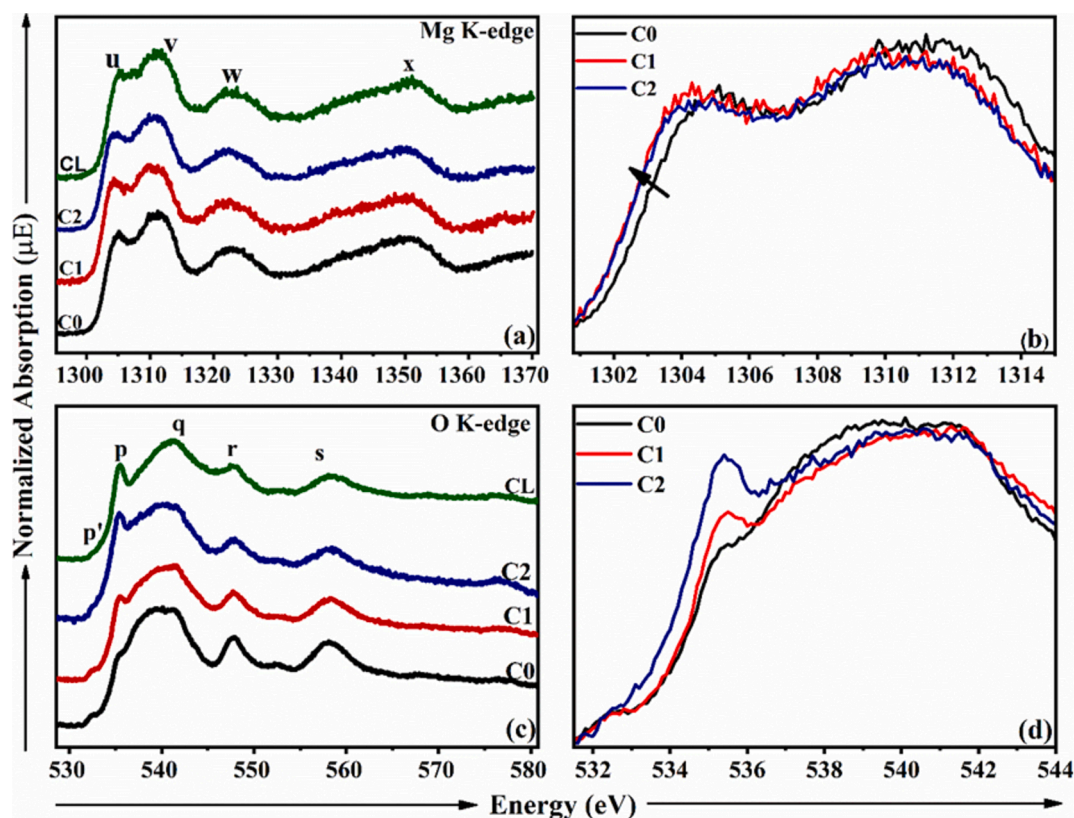


Fig. 2. (a) Mg K-edge XANES spectra; (b) Enlarged image of Mg K edge; (c) O K-edge XANES spectra; (d) Enlarged image of near edge features of O K-edge.

–542.1 eV, 546.7 eV, 551.2 eV, and 559.1 eV are marked as *p*, *q*, *r*, *s*. Pre-edge feature *p'* (531.9 eV) is well resolved in pure MgO sample. In ionic oxides, the transition between the O-1s to O-2p is forbidden as *p* shells are occupied but the interaction of Mg-3s and O-2p reduces this occupation and causes localized bound states, additionally, the surface defects are responsible for pre-edge features [29–31]. It is noticeable that the pre-edge feature exists in all samples and conveys the existence of similar surface-related defects in MgO, MgO:Ce and MgO:CeLi because of the same temperature treatment applied for all samples. The intensity of the *p* feature is enhanced with increasing the Ce-doping

concentration in MgO. The increased intensity conveys the availability of more unoccupied, *p*-projected, density of states in MgO band structure. The unoccupied density of states could be formed due to the hybridization of Ce 4f and O 2p orbitals and Mg-O6 (octahedra) to Mg-O4 (tetrahedra) alteration upon Ce doping via the formation of oxygen vacancies. A similar intensification of O K-edge features is observed in the Ga₂O₃:Sm nanoparticles via Ga-O6 (octahedra) to Ga-O4 (tetrahedra) distortion and formation of oxygen vacancies [32]. The higher energy features (*r*, and *s*) also exhibit intensity reduction with Ce doping in MgO. The higher energy features in O K-edge XANES originate from

multiple scattering effects with the O and surrounding elements or known as pseudo-XAFS oscillations because their origin is related to the hybridization of O 2p and metal ($n + 1$) sp orbitals [32]. The decreased intensity of such features shows less Mg – O hybridization because of different valance states of existing cations disturbs the charge neutrality in lattice and are compensated by the anion defects. The change in O K-edge is also supported by the Mg K-edge spectra which reveals the change in environment around Mg ions upon doping.

The Ce L-edge XANES spectra of reference CeO_2 , C1, C2, and CL samples are examined to get the variation in the oxidation state of Ce, if any. Fig. 3 shows the Ce L edge of such samples are spectral features at 5725 eV, 5728 eV, and 5735 eV are marked by the letters m, n, and o. The feature m is due to Ce^{3+} (similar to CeF_3 bulk samples) and n and o are due to Ce^{4+} [24,33,34]. Fig. 3 indicates that the spectral features of C1, C2, and CL samples are partially matching with the spectral features of bulk CeO_2 (Ce^{4+}) and previously reported features of CeF_3 (Ce^{3+}) samples. It conveys that the C1, C2, and CL samples consist of, both, Ce^{4+} and Ce^{3+} ions. The spectral features of C1 samples are less resolved because of the low Ce concentrations. To, quantitatively, evaluation of Ce^{4+} and Ce^{3+} ions, the Ce L-edge XANES spectra have been deconvoluted and presented in the Fig. 3(b–c). The ratio of peak n and o gives the information for the hybridization of Ce 4f – O 2p orbitals and the probability of hopping electrons at $2p4f^1$ and $2p4f^0$ orbitals [35]. The Ce-O interaction governs the covalent nature of the bond. At lower concentrations, all the features are merged, indicating the less covalent nature of Ce-O. The features n and o are visible along with m as shoulder in C2 (Ce 0.1 mol%) and the co-doped sample indicates the covalency of Ce-O bond due to the presence of Ce^{4+} along with Ce^{3+} . The intensity ratio of m to $n + o$ may give the $\text{Ce}^{3+}/\text{Ce}^{4+}$ concentration in the respective samples. Therefore, the area under the peak m, n and o are evaluated (within the given goodness of fitting parameter ~ 0.9 to 1.1). It has been observed that the CL sample exhibits slightly higher Ce^{3+}

content ($\text{Ce}^{3+}/\text{Ce}^{4+} = 2.135$) as compared to the C2 sample ($\text{Ce}^{3+}/\text{Ce}^{4+} = 1.503$). It is analogous to the XRD findings where a distinct CeO_2 phase was detected and conveyed more Ce^{4+} ions in the C2 sample. Moreover, enhancement in the intensity of spectral features (n and o) shows the increment in covalency ascribed to the decrease in inter-atomic distance between Ce and O due to the difference in ionic radii of Ce^{3+} (0.103 nm) and Ce^{4+} (0.87 nm).

3.3. Photoluminescence spectroscopy

To probe the intrinsic defects between host materials and modification of defects due to doping is studied by using PL spectroscopy. The pristine as well as doped samples were excited by using UV LED sources of 275 nm and 310 nm. Fig. 4 shows the PL emission of pure and doped nanophosphors excited at 275 nm and 310 nm. At the excitation of 275 nm, in pure MgO two bands are observed in the blue and red region. The region between 400 nm to 500 nm is due to the relaxation of F^+ centers to F centers which has been discussed in our previous work in detail [9,36]. The red region is due to the clustered singly charged O^- defects present near the CB [37,38]. The modification in emission due to doping is observed as shown in Fig. 4. This indicates the modification in defects present in between the band gap of MgO. The dopant diminishes the red region emission while the blue region is enhanced with increasing doping. XANES spectra indicate the strong hybridization between Ce and O orbitals which causes the transfer of electrons from the O to Ce energy levels, further decreasing the intensity of the host in the red region. At higher concentrations, the weak and sharp peaks are also visible ascribed to the 5d to 4f transition of Ce^{3+} ions [20]. In literature, the emission peaks are reported from UV to red region because the position of the emission band has a strong dependence on the host surrounding. L.G van Uitert [39] reported Ce emission in different compounds i.e. in the CaF_2 position the peak of Ce^{3+} is at 314 nm while in the Y_2O_3 peak

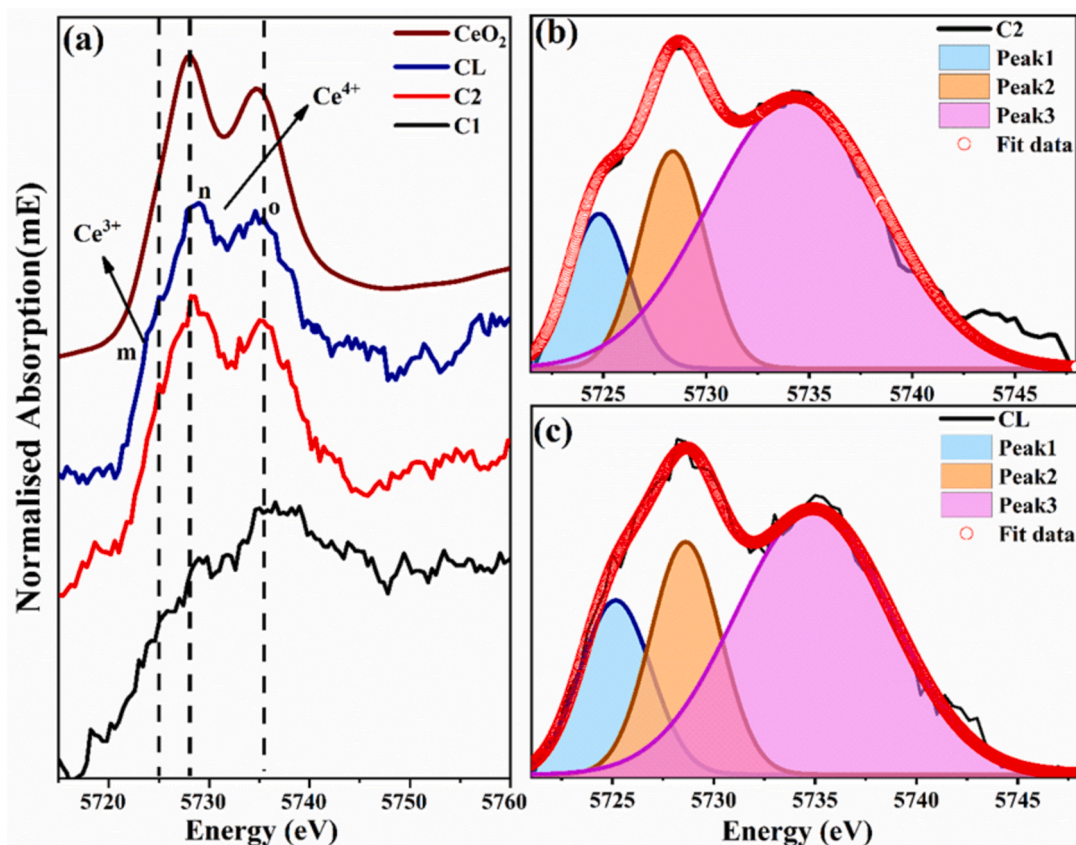


Fig. 3. (a) XANES spectra of Ce L_{3-} edge at different concentrations of Ce ions. (b, c) Deconvoluted XANES spectra of C2 and CL sample.

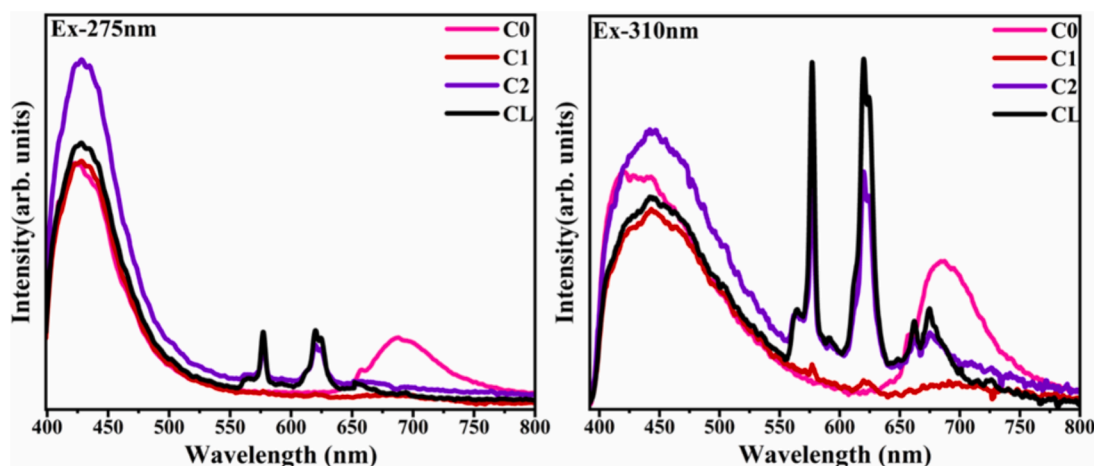


Fig. 4. PL spectra of all samples on excitation at 275 nm and 310 nm.

position is around 670 nm.

Here in the present study, the presence of two bands indicates the splitting of energy levels of Ce ions. At lower concentrations where CeO_2 phase was not observed leads to weak hybridization between Ce-O orbitals which preserve the sharpness of emission peaks. Different authors reported the presence of comparable emission bands in Ce^{3+} in different oxides during their respective studies [19,20,22,40]. On excitation by 310 nm, the emission bands of Ce are quite intense along with the blue emission. The increase in PL intensity suggests that Ce^{4+} is functioning as an intermediate state, trapping the excited electrons and leading to the excitation of Ce^{3+} levels. Upon de-excitation, the Ce^{3+} ions emit photons at wavelengths of 570 and 610 nm. The contribution of Ce^{4+} in luminescence has been documented previously in several compounds where Ce^{4+} and Ce^{3+} coexist in a comparable amount [12,15–17,41]. In the Ce and Li co-doped sample the host emission was suppressed while the Ce emission was significantly enhanced. Li ions can generate charge-deficient sites when they replace the Mg ions. Multiple authors reported that the newly formed site is capable of forming a bond with a neighboring O^{2-} and trapping a hole that functions as a recombination center for electrons [42,43]. CIE coordinates for both the excitation for all samples is shown in Fig. 5. For excitation at 275 nm, the blue region is dominating at all samples while for 310 nm coordinates shifted towards white light. All coordinates are summarised in Table 1. At 275 nm wavelength where host emission is dominant, all phosphors lie in the blue region. However, at 310 nm wavelength where dopant characteristics emission were observed, emission shifted towards white light. On excitation at 275 nm all the phosphors are warm emitters, according to all of the CCT values, however at 310 nm CCT value of co-doped sample is greater than 3200 predicting it as a cool emitter. To understand the luminescence mechanism of Ce and Li ions in MgO, a schematic diagram is shown in Fig. 6. Fig. 6(a) shows the emission scheme from Ce ions. In

Table 1

CIE coordinates of pure and Ce, Li doped MgO.

Samples	UV LED (275 nm)		UV LED (310 nm)	
	CIE(x, y)	CCT(K)	CIE(x, y)	CCT(K)
Pure	(0.179, 0.081)	1825	(0.1935, 0.1693)	1882
C1	(0.166, 0.0731)	1827	(0.1948, 0.1943)	2331
C2	(0.1977, 0.1075)	1948	(0.2568, 0.2268)	3291
CL	(0.208, 0.1083)	1968	(0.303, 0.2486)	9496

step 1; Ce^{4+} traps the electron from the conduction band and converts into Ce^{3+*} state as shown in step 2. These excited states de-excite radiatively and give characteristics of emission of Ce^{3+} ions. Fig. 6(b) shows the mechanism of co-doped samples where Li ions make centers (Li^+O^-) and capture electrons. On relaxation, it excites the Ce^{3+} and creates Ce^{3+*} centers which radiatively de-excite and generate the Ce^{3+} emission. The dual contribution from Ce^{4+} and Li^+O^- increases the intensity observed in Fig. 4(b).

3.4. Thermoluminescence

The PL spectra of pristine and doped MgO indicate defect levels in between the band gap. Here, Fig. 7 shows the results of gamma irradiation dose (100 Gy, 500 Gy, 1 kGy) on the TL glow curve, providing valuable insight into the presence of trapping states within the band gap. In pristine MgO, two peaks appeared at 335 K and 610 K decreased with dose. The observed peaks complement with earlier reported TL signals in pure MgO [42,44–46]. The peak at 335 K is attributed to Mg vacancies interaction with impurity ions. Higher temperature peaks are due to the interstitial defects and charged F centers of the host [47]. There was no significant TL observed in undoped MgO at 1 kGy, therefore it has not

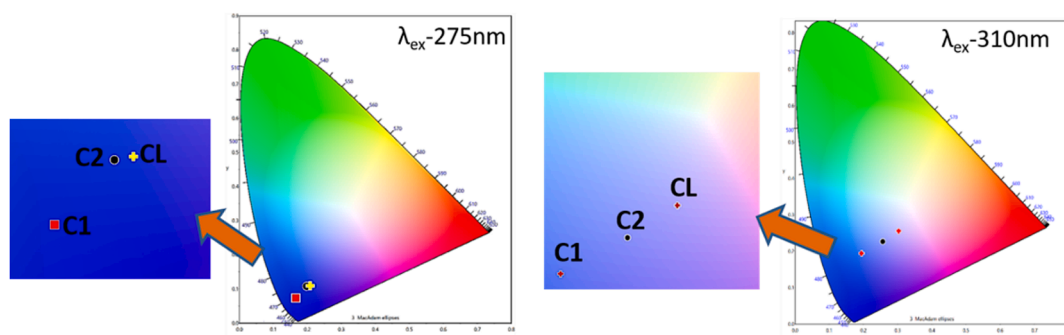


Fig. 5. CIE coordinates at excitation 275 nm and 310 nm.

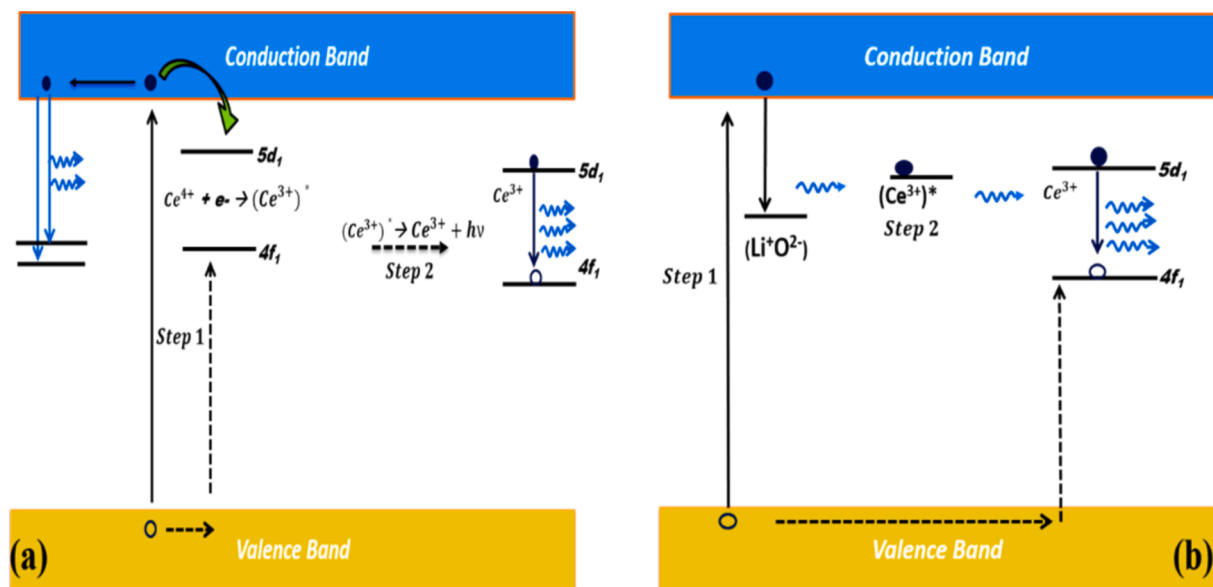


Fig. 6. Schematic diagram of luminescence and role of Ce^{4+} and Li^+ ions in luminescence mechanism. Solid circles represent the electron and shallow circles represent the holes. (a) Emission from singly doped MgO; (b) emission scheme with co-doped MgO with Li and Ce ions.

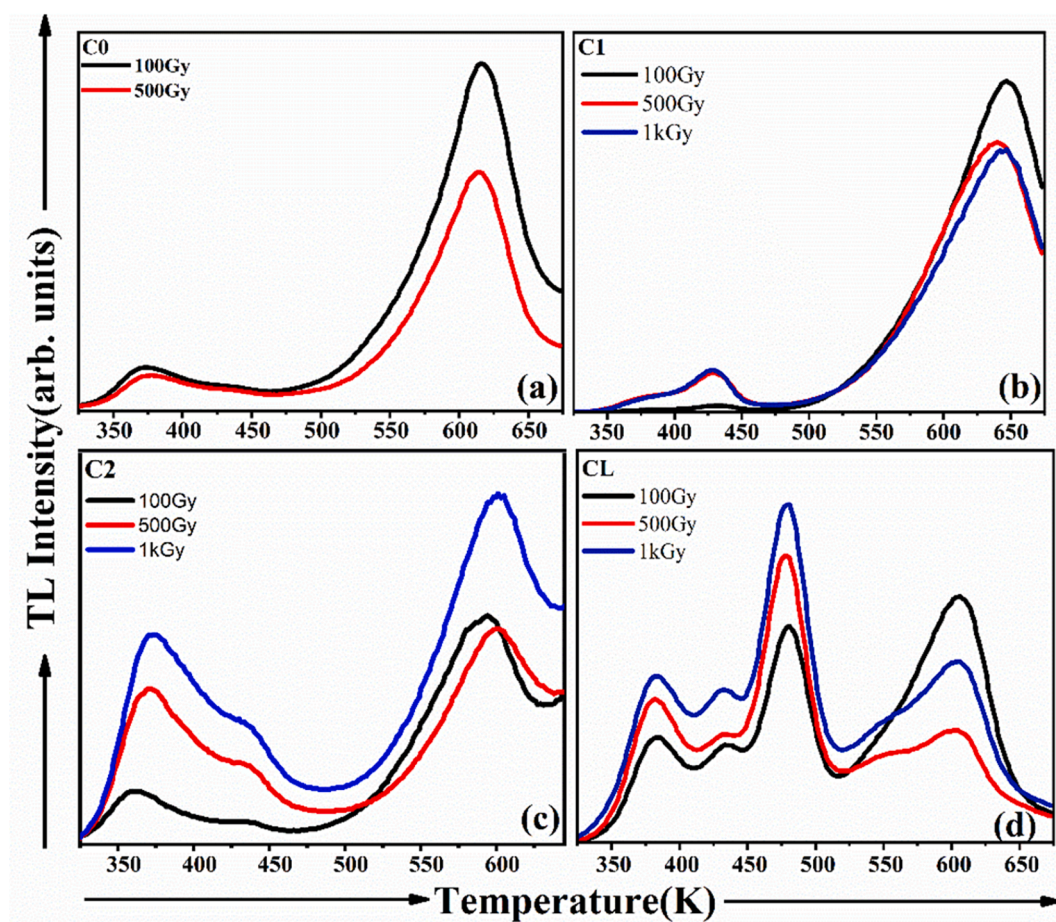


Fig. 7. TL glow curves of all samples irradiated at doses 100, 500, and 1 kGy.

been considered for this study. After doping, several other peaks have been observed which may be due to the intermediate defect levels created by dopants. The combination of Li and Ce ions favors the shallow traps and new peaks appear at 435 K in singly doped and an intense 475

K peak appeared in co-doped MgO. As discussed above, the covalency of the Ce-O bond increases with the concentration causing the saturation in TL intensity at elevated temperature which were attributed to the host defects. These peaks are well-matched with the peaks reported in the

literature [48–50]. The slight variations in the TL peaks observed in different studies are attributed to the use of different rates and detection windows by researchers. In doped samples, the TL glow curve intensity increases with dose increment and the stability of traps. Fig. 8(a) represents variation in integrated TL intensity of co-doped MgO as a function of dose–response. The overall TL signal is compared with peak (325 K–517 K) and peak at 610 K. Lower temperature peaks show linear behavior with dose but for higher temperature peaks there is saturation at 500 Gy dose afterward it increases again. As discussed earlier the doping does not favor the deeper trap which leads to a decrease in ionized tracks, but on further increase in dose, the overlapped traps are more prevalent, and overall interaction at higher temperatures results in a slight increase in enhancement in TL signal [51]. Here, we can suggest the overall increment in TL signal is mainly due to the contribution of the number of traps at lower temperatures. Multiple peaks indicate the presence of more than three traps. Thus to analyze the trap peaks for pure and doped MgO has been deconvoluted by using TLANAL software using Kitti's formula as shown in Fig. 9 and all the parameters calculated are tabulated in Table 2. C1 and C2 are concise with four traps while in CL five traps are present. The kinetics order is greater than unity for all the traps showing the retrapping behavior of all trap centers before reaching to emission centers. The energy of all traps lies between 0.87 to 1.49 eV. The stability of traps with dose and concentration indicates that doping of Ce and Li ions creates radiative traps towards lower temperatures and these trap states affect the intrinsic traps of the host.

4. Conclusion

Ce and Li-doped MgO nano phosphors were successfully synthesized via the solution combustion method and annealed at 1100 K. XRD analysis confirmed the formation of a cubic phase MgO with *Fm-3m* space group, both singly and doubly doped with Ce and Li up to a concentration of 0.1 mol%. XANES spectra of the O K-edge confirmed variations in O vacancies due to dopant introduction. Unsaturated Mg cations in the lattice were confirmed from XANES spectra at the Mg K-edge, also resulting from dopants induced in the lattice. Analysis of the Ce L_{3} edge revealed the presence of both Ce ions in +3 and +4 oxidation states, suggesting significant Ce–O hybridization increasing with concentration. The incorporation of Ce and Li ions significantly affected the local structure of the host, influencing its luminescence properties. PL spectra exhibited two emission bands at 570 nm and 610 nm attributed to 5d-4f transitions. Li co-doping enhanced characteristic Ce emission by acting as a charge compensator. A schematic diagram was proposed for the PL emission mechanism. The presence of Ce ions with various

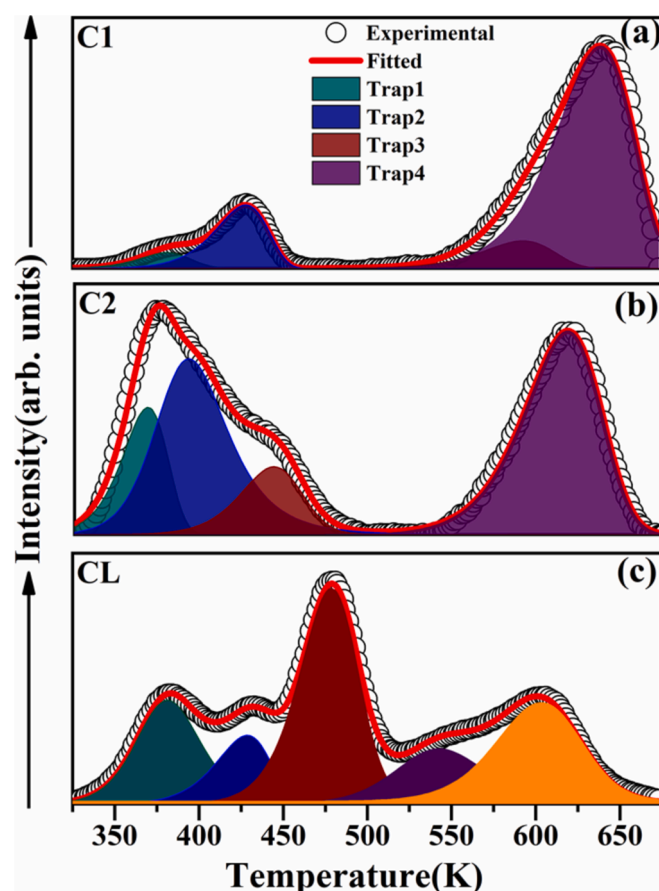


Fig. 9. Deconvolution of Ce-doped MgO at 1 kGy as a function of concentration.

valencies led to the formation of new traps within the host material, in addition to inherent defect states. TL signal stability increased with the dose for MgO: Ce and MgO: Ce, Li. The introduction of gamma-irradiated nanocrystals in Ce-doped and Ce Li-doped MgO resulted in TL peaks at temperatures of 435 K and 475 K, respectively. Kinetic parameters of the observed glow peak were calculated using TLANAL software, revealing re-trapping and closely spaced traps within the forbidden band gap. The stability and linear behavior of TL peaks demonstrated the excellent dosimetric characteristics of prepared

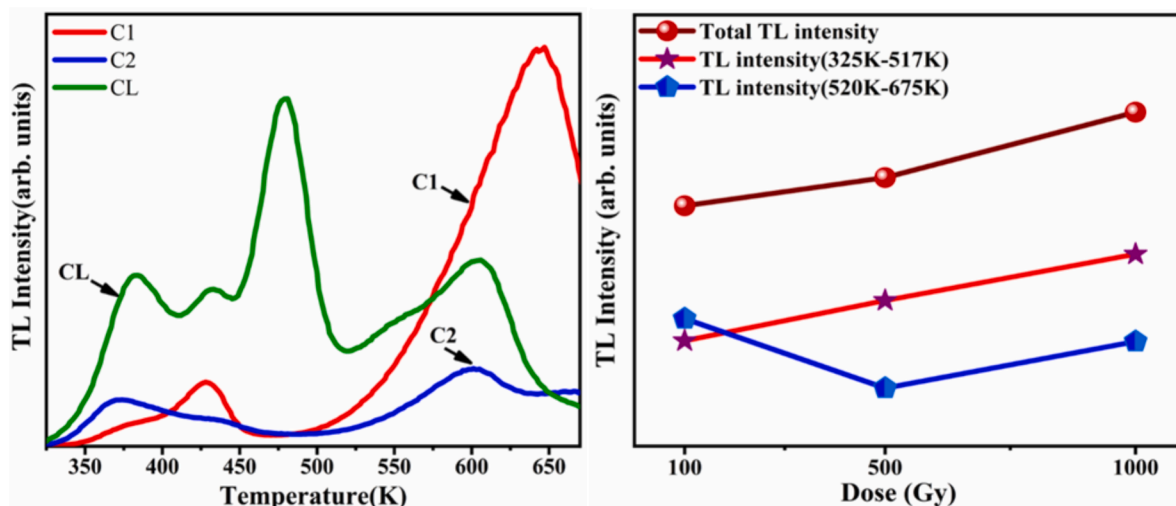


Fig. 8. (a) Behavior of CL samples at all three doses; (b) Concentration behavior of TL glow curves at 1 kGy Dose.

Table 2

Trap data of glow curves of double-doped MgO calculated by TL ANAL software.

Sample	Trap	T _m (K)	n ₀	E (eV)	S (s ⁻¹)	b	FOM (%)
C0	1	376	7.5 × 10 ⁶	0.824	3.73 × 10 ¹⁰	1.8	2.53
	2	423	2.7 × 10 ⁶	0.896	1.31 × 10 ¹⁰	1.5	
	3	586	2.0 × 10 ⁷	1.144	1.40 × 10 ⁹	1	
	4	618	4.6 × 10 ⁷	1.940	1.87 × 10 ¹⁵	1.3	
C1	1	377	1.8 × 10 ⁶	0.890	2.06 × 10 ¹¹	1.2	2.63
	2	430	7.6 × 10 ⁶	0.978	1.03 × 10 ¹¹	1	
	3	590	4.5 × 10 ⁶	1.412	2.40 × 10 ¹¹	1	
	4	635	3.4 × 10 ⁷	1.489	1.21 × 10 ¹¹	1	
C2	1	375	2.6 × 10 ⁶	0.939	3.78 × 10 ¹²	1.1	2.4
	2	389	6.1 × 10 ⁶	0.978	1.75 × 10 ¹²	2	
	3	437	1.9 × 10 ⁶	1.071	8.42 × 10 ¹¹	1.3	
	4	594	7.1 × 10 ⁶	1.489	8.98 × 10 ¹¹	1.1	
CL	1	382	2.7 × 10 ⁷	0.893	2.13 × 10 ¹¹	1.9	1.8
	2	428	1.4 × 10 ⁷	0.973	8.33 × 10 ¹⁰	1	
	3	479	5.1 × 10 ⁷	1.291	1.27 × 10 ¹³	1.3	
	4	544	2.1 × 10 ⁷	1.324	4.89 × 10 ¹¹	2	
	5	603	3.3 × 10 ⁷	1.489	3.34 × 10 ¹¹	1.4	

nanophosphors.

5. Author statement

The results reported in the manuscript are original and have been written by the stated authors, who are all aware of its content and approved its submission. It has not been published previously. It is not under consideration for publication elsewhere. No conflict of interest exists. If accepted, the article will not be published elsewhere in the same form, in any language, without the written consent of the publisher.

CRedit authorship contribution statement

Priyanka Bishnoi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aditya Sharma:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Ranjeet Brajpuriya:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis. **Keun Hwa Chae:** Writing – review & editing. **S.O. Won:** Writing – review & editing. **Ankush Vij:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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