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State-of-the-Art Developments in Luminescent Nanophosphors for Solid-State Technologies

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Abstract

The luminescent nanophosphors are advanced functional materials with excellent optical performance, tunable emission characteristics, high quantum efficiency, and good thermal and chemical stability, suitable for next-generation solid-state technologies. This review summarizes the recent advances in luminescent nanophosphors by highlighting the Principles of photoluminescence, host materials, luminescence mechanisms, enhancement methods, characterization methods, and technological applications of these phosphors. The effects of rare-earth and transition-metal doping, energy transfer phenomena, core–shell structures, quantum confinement, and plasmonic effects on the enhancement of the photoluminescence properties are critically analyzed. Advanced characterization techniques which permit the correlation of structural, optical, compositional, and thermal properties with luminescence behavior are also reviewed. Moreover, the paper emphasizes the growing possibilities of using nanophosphors in phosphor converted white light emitting diodes, optical thermometry, high resolution display techniques, and anti-counterfeiting and forensic devices. Although marked advances have been made, there are still problems of concentration quenching, thermal degradation, scale production, and long-term stability. Future studies that combine defect engineering, computational materials design, and sustainable synthesis will likely help to speed the advancement of the highly efficient nanophosphors necessary for new photonic and optoelectronic technologies.

Keywords; Luminescent nanophosphors; Rare-earth-doped phosphors; Solid-state lighting (WLEDs); Optical thermometry; Solid-state technologies

INTRODUCTION

In recent years, luminescent nanophosphors have become one of the most important groups of functional nanomaterials, due to their optical properties, high chemical stability, and ability to be tuned. These materials are made up of nanoscale phosphors that can absorb energy from external sources like ultraviolet, visible, or electron-beam excitation, and then emit light at particular wavelengths via radiative electronic transitions [1]. Nanophosphors have many advantages when compared to the conventional bulk phosphors, such as larger surface area, lower scattering losses, better color purity and compositional engineering, particle size control and surface modification to produce a range of desired properties. The addition of activator ions, especially rare-earth elements (RDEs, such as Eu^{3+}, Tb^{3+}, Ce^{3+}, Dy^{3+}, and Er^{3+}) in appropriate host lattices has greatly broadened the emission color range and enhanced the luminescence performance [2]. In addition, the recent progress of nanotechnology has paved the way for the synthesis of highly efficient nanophosphors characterized by their high quantum yield, thermal stability, and photostability, which has made them promising for many optical applications [3].

Solid-state technologies have been rapidly evolving and the need for luminescent materials that can provide high efficiency and a longer operating life and better optical properties is growing. One of the key application fields in which nanophosphors significantly contribute to the colour conversion, luminous efficacy, and color rendering is solid-state lighting, especially white light emitting diodes (WLEDs).

In addition to lighting applications, luminescent nanophosphors are used in display technologies, optical communication and telecommunication systems, lasers, photonic devices, anti-counterfeiting systems and advanced sensing platforms. They are also capable of upconversion, downconversion, persistent luminescence and temperature-dependent emission, which extends their potential application in the modern optoelectronic devices and energy-efficient applications [4].

The recent research efforts have concentrated on strategies to alleviate problems such as concentration quenching, thermal degradation and low absorption efficiency, such as new synthetic pathways, defect engineering, core–shell structures and optimized dopant distribution. The developments have significantly enhanced the optical performance of nanophosphors and speeded up their integration with next-generation solid-state systems. The review provides a detailed account of the basic principles of luminescent nanophosphors, factors affecting their luminescent efficiency, recent research directions for improving their performance, characterization techniques and a wide variety of application areas in solid-state technologies including practical challenges and future research.

Fundamentals of Luminescent Nanophosphors

Luminescent nanophosphors are nanoscale (nm) phosphor materials, which can convert the absorbed energy into the visible or near-visible light by well-defined electronic transitions. The optical effects of these depend on the interaction between the crystal host, luminescent centers, and the source of the excitation [5]. Nanophosphors have a high surface area to volume ratio, tunable morphology and size dependent optical properties that lead to better emission efficiency and compatibility with modern optoelectronic devices. In addition to the properties of the constituents, their performance is influenced by various factors, including crystal structure, dopant concentration, defect states, and energy transfer processes. Thus, comprehensive knowledge of the basic principles that govern the behaviour of luminescent nanophosphors is crucial to the design of materials which possess high quantum efficiency, good thermal stability, and desired emission properties for solid state technologies [4].

Principles of Photoluminescence

Photoluminescence is the process when material absorbs photons of higher energy and then emits other photons of lower energy after a given relaxation time. It is one of the most important optical processes employed to investigate the performance of luminescent nanophosphors as it gives valuable information about electronic structure, defect states, recombination processes, and energy transfer mechanisms [6]. Rare-earth doped nanophosphors have photoluminescence caused by transitions among the partially filled 4f shells of the dopant ions that are protected by outer shells of electrons [7]. As a result, such materials have a small band of emission, high colour purity and exceptional photo-stability. The photoluminescence process can be divided into several stages and the totality of them determines the properties of nanophosphors, their emission.

1. **Photon Absorption:** Photoluminescence process starts with the absorption of photons that have the energy equal to or greater than the energy gap between the ground state and the excited electronic state. This energy is absorbed by the electrons in the luminescent centers, exciting them to higher energy states. The efficiency of the photon absorption will depend on the properties of the photon namely its wavelength, absorption cross-section and the electronic structure of the activator ions.
2. **Excitation of Electrons:** After absorption of a photon, electrons are found in unstable excited states. Rare-earth doped phosphors have their excited states as a series of energy levels that are specific to the dopant ions. The process of excitation will affect the number of excited electrons that become available for subsequent emission and directly influence the intensity of the luminescence.
3. **Non-Radiative Relaxation:** The excited electrons typically release some of their excess energy by nonradiative interactions via lattice vibrations (phonons) or with crystal defects before they can emit light. At this time, electrons return to the lowest excited state without the emission of photons. Non-radiative relaxation should be minimized because if the loss of energy is too great, the overall luminescence efficiency will be less.
4. **Radiative Emission:** Once in a stable excited state, electrons return to lower energy states by emitting a photon. This radiative transition gives rise to the characteristic luminescence from nanophosphors. The wavelength and the intensity of the emitted light is dependent upon the energy gap between the excited and the ground state and upon the nature of the host lattice and of the activator ions.

5. **Stokes Shift:** For most of the photoluminescent materials there is a loss of energy during the non-radiative relaxation of the absorbed photons and the emitted photons have lower energy and longer wavelength. The difference between the wavelengths of the exciting light and emitted light is called the Stokes shift. Appropriate Stokes shift can minimize the self-absorption and enhance the overall optical efficiency of the phosphor materials.

Luminescence Mechanisms

There are several mechanisms for excitation and emission of nanophosphors which govern the luminescence behavior and determine the conversion of absorbed energy to light. These mechanisms are dependent on the electronic structure of the host material, the type of the dopant ion, crystal defects, and the interaction between the neighbouring luminescent centers [8]. These mechanisms are important for enhancing the emission intensity, color purity, and quantum efficiency of solid-state optical devices.

1. **Down-Conversion Luminescence:** When a photon of high energy is absorbed and changed into one low-energy photon, it is undergoing down-conversion. This mechanism is extensively used in the phosphor-converted white LED where the UV or blue stimulations are converted to visible light with high efficiency [3].
2. **Upconversion Luminescence:** Upconversion is the process of two or more low energy photons being absorbed sequentially to give one high energy photon. That's because rare-earth ion pairs like Yb^{3+}–Er^{3+}, Yb^{3+}–Tm^{3+}, and Yb^{3+}–Ho^{3+} are often employed to achieve efficient upconversion. This mechanism is widely used in bio-imaging, optical sensing, lasers and anti-counterfeiting [9].
3. **Energy Transfer Luminescence:** Excitation energy is transferred from one ion, or molecule (sensitiser) to another (activator) without the emission of a photon. Efficient energy transfer increases the intensity of the emission and widens the range of excitation wavelengths, especially for the use of high-performance luminescent materials [10].
4. **Persistent Luminescence:** Persistent luminescence (afterglow) is the continued emission of light after the exciting source has been withdrawn. This phenomenon is due to the trapping of charge carriers within crystal defects which are consequently released over time. Persistent phosphors have many applications including emergency signage, biomedical imaging and security applications [11].
5. **Quantum Confinement Effects:** By reducing the size of phosphor particles to nanometer scale, quantum confinement has an effect on the electronic energy levels. This effect changes the optical band gap and emission properties, which can be controlled by designing the particle size to achieve desired luminescence properties [12].

Core Components: Host Lattices, Activator Ions, and Sensitizers

The three major components of nanophosphors are host lattice, activator ions and sensitiser ions that all have to cooperate to achieve luminescent performance. Every component has a specific role in the process of absorbing, transferring and emitting energy. The choice and optimization of these components are crucial for obtaining a high quantum yield, good thermal stability, wide band of excitation and efficient light emission.

1. **Host Lattices:** The host lattice is the structure in which luminescent ions are accommodated and thus maintains the stability of the crystal. The host material should have good chemical stability, low phonon energy and have good thermal conductivity and excellent optical transparency. Common host materials are oxides, fluorides, phosphates, silicates, aluminates, tungstates, molybdates, and garnets. Crystal-field splitting, energy transfer efficiency, defect formation and thermal quenching behavior depend on the crystal structure of the host, and thus greatly influence the luminescent performance [13]. A list of some of the prominent phosphor hosts is mentioned in Figure 1.
2. **Activator Ions:** The main luminescent centers responsible for light emission are the activator ions. These ions change the electronic structure of the host lattice and create energy levels inside the lattice, so that characteristic optical transitions can occur when the lattice is excited. The most frequently employed activators are rare-earth ions like Eu^{3+}, Tb^{3+}, Ce^{3+}, Dy^{3+}, Sm^{3+}, Tm^{3+}, Er^{3+} and Ho^{3+} with their narrow emission spectra and high photochemical stability. Other transition metal ions like Mn^{2+}, Cr^{3+}, and Ni^{2+}, are also used to get broadband emission and specific color output. It is important to carefully optimize concentration of activator ions in order to maximize the emission without concentration quenching [14].

3. **Sensitizer Ions:** The sensitizer ions are added for better absorption of excitation energy and efficient transfer of the excitation energy to the activator ions. Typically their absorption cross-sections are larger than the ones of the activators and they allow to excite over wider wavelength ranges. One of the most commonly employed sensitizers is Yb^{3+} because of its ability to absorb energy in the near 980 nm range, and because it has a high energy transfer efficiency to other activators, such as Er^{3+}, Tm^{3+}, and Ho^{3+}, in upconversion systems. Other sensitizers, like Ce^{3+} and Bi^{3+} are also used depending on the host material and application. The matching of the sensitizer and the activator energy levels is crucial for achieving high energy transfer efficiency and excellent luminescent properties [15].

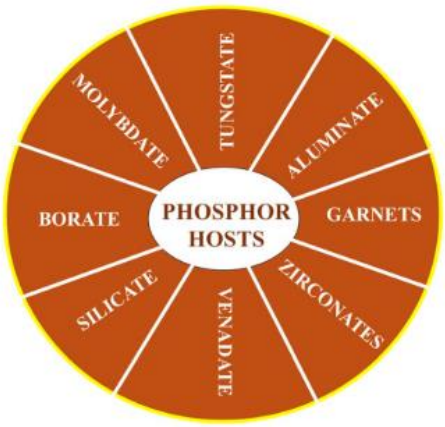


Figure 1: List of phosphor hosts [7]

The optical properties of luminescent nanophosphors are determined by the combination of the host lattice, the activator ions and the sensitizers, which create the structural and electronic framework. Their meticulous design and optimization form the basis of the development of novel and efficient phosphor materials for solid-state lighting, display technologies, optical sensors, as well as for emerging photonic applications.

Factors influencing luminescence efficiency

One of the most significant performance measures of nanophosphors is their luminescence efficiency, which reflects the efficiency of the conversion of the absorbed excitation energy into visible or near IR emission. It is typically measured by the photoluminescence quantum yield (PLQY), lifetime and thermal stability. The efficiency of luminescent nanophosphors is affected by a number of intrinsic and extrinsic factors such as host lattice properties, dopant concentration, particle morphology, surface defects, energy transfer processes, and working temperature. All these factors collectively control the competition between the radiative and non-radiative transitions and thus the brightness and stability of phosphor materials. In recent years, efforts to optimize these parameters have been made to enable the creation of highly efficient nanophosphors for solid-state lighting, for display technology, for sensors and for photonic technology applications [16].

Host Lattice Composition and Crystal Structure

The host lattice determines the crystal field strength, the energy of phonons, and the formation of defects, which are all important factors in the efficiency of luminescence. Materials with low phonon energies give a reduction in multiphonon relaxation and thus enhance radiative emission as host material. The phonon energies of fluoride hosts are lower, thus giving them superior optical efficiency, while oxide hosts have excellent chemical and thermal stability. The crystal phase and optical properties of Eu-doped La_2O_3, Gd_2O_3 and Y_2O_3 nanoparticles were also distinctly different as proved by Ansari et al. (2023), showing that the emission intensity and spectral properties are highly influenced by the host lattice [13]. Similarly, Li et al., (2024) found that the upconversion efficiency of $LiLnF_4$ was lower than that of $NaLnF_4$, which was attributed to the favorable crystal environment and lower phonon energy of $NaLnF_4$. The results highlight the importance of selecting a suitable host lattice for high luminescence efficiency in figure 2 [17]. The graph categorizes upconversion luminescence (UCL) into four groups: (1) green emission, (2) red emission, (3) three-photon upconversion, and (4) four-photon upconversion. These classifications indicate the emission color and number of absorbed photons involved in the Yb^{3+}–Er^{3+} energy-transfer processes.

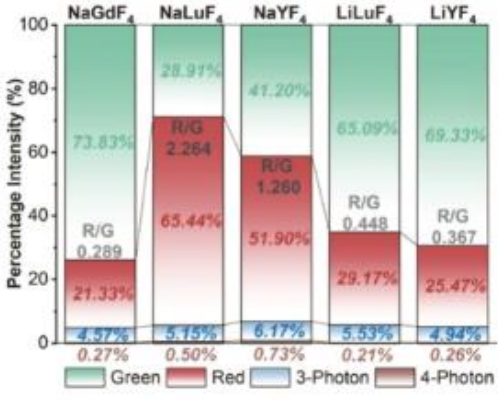


Figure 2: Percentage intensity of different luminescence components of $AREF_4$:Yb/Er MCs in 0−1 ms [17]**.**

Activator Ion Concentration

The number of luminescent centres available for photon emission is directly related to the concentration of activator ions. Increasing the concentration of the dopant increases the emission intensity initially due to the fact that more excitation energy is converted into radiative transitions. But too much activator concentration causes to lessen the average distance between the neighboring ions, which leads to concentration quenching due to non-radiative energy migration. Hence, it is necessary to determine the optimum concentration of the dopant in each host material. Karacaoğlu and Karasu (2015) have reported that the emission characteristics of different rare-earth ions were different in $Ca_2MgSi_2O_7$ phosphors, and the luminescence properties were significantly dependent on the calcination conditions [18]. Kiran et al. (2025) also reported that optimized rare-earth doping results in enhanced emission efficiency and chromaticity due to the favourable electronic transitions in the 4f-orbitals [7].

Particle Size and Morphology

Particle size and morphology considerably influence the optical properties of nanophosphors. The nanoscale phosphor size increases surface area and increases light extraction efficiency, but too small particles increase surface defect density and increase non-radiative recombination. The morphology also influences the crystallinity, particle packing and optical scattering. Through their study, Souza et al. (2012) found that smaller particles of $SrTiO_3$ exhibited stronger photoluminescence due to better crystallinity and the control of nanostructure formation [19]. Similarly, Wang et al. (2017) showed that the emission intensity and quantum efficiency of the morphology-controlled Dy^{3+}-activated phosphors were improved, which proved that the particle engineering technique is effective in improving the luminescence performance [20].

Surface Defects and Surface Passivation

Non-radiative recombination centers on the surface defects (dangling bonds, lattice disturbances) decrease the luminescence efficiency. Minimizing surface defects is crucial to obtain strong emission when using nanophosphors, due to their high surface-to-volume ratio. Inert coatings or core–shell structures are effective methods of surface passivation that help suppress defect-related energy losses and enhance chemical stability. According to Hyun et al. (2021), Eu^{3+} doped Y_2O_3 core-shell nanophosphors showed remarkably higher emission intensity and quantum yields compared to core only nanophosphors, because they had improved crystallinity and less quenching on the surface [21]. In the same manner, Hiruoka et al. (2011) showed that the luminescence of silicon nanoparticles with oxygen passivated surfaces was not affected in an aqueous media, as surface oxidation helped prevent defect formation [22].

Energy Transfer Efficiency

One of the most important mechanisms by which the luminescence efficiency is improved is the efficient energy transfer between sensitizer and activator ions. The transfer efficiency is sensitive to the spectral overlap, interionic distance, distribution of the dopant ions, and their energy-level compatibility. Zheng et al. (2021) demonstrated that the rational design of crystal structure could greatly improve the energy transfer efficiency of Ce^{3+} to Eu^{2+}, thus increasing the phosphor emission efficiency [14]. Analogously, Burikov et al. (2024) have shown that optimization of the Yb^{3+} and Tm^{3+} concentrations boosted the sensitizer to activator energy transfer and changed the upconversion dynamics [15]. Liu and Qiu (2015) also highlighted the importance of efficient resonance energy transfer for enhancing the luminescence of light sources, solar energy conversion devices, sensors, and biomedical imagers [23].

Thermal Stability and Thermal Quenching

Phosphors used for high-power applications must be thermally stable, since high temperatures lead to activation of non-radiative relaxation channels which reduce the emission intensity by thermal quenching. Thermal degradation is more resistant in host lattices that have high structural rigidity, phonon energies, and chemical bonding. By utilizing the Ce^{3+} co-doping method, Liang et al. (2025) showed that the quantum efficiency and thermal stability of Eu^{2+}-activated phosphors were greatly improved [24]. Similarly, the introduction of Gd^{3+} was found to enhance efficient energy transfer and reduce thermal quenching effect in Eu^{3+} activated phosphors by Zhu et al. (2025) [25]. The recent progress summarized by Zhang and Manna (2026) suggests that other possible strategies for future high-power lighting and laser applications are the enhancement of the lattice rigidity and the design of anti-thermal-quenching phosphors [26].

Quantum Yield and Radiative Lifetime

The overall luminescence efficiency of nanophosphors is evaluated by the main parameters of photoluminescence quantum yield and radiative lifetime. A high quantum yield means that the absorbed photons are converted by the material to emitted photons with high efficiency, while an appropriate radiative lifetime means that the absorbed photons lose very little energy to non-radiative pathways.

The properties of these are controlled by the composition of the host, its crystallinity, the amount of the dopants, and the synthesis conditions. In this work, Hyun et al. (2021) showed that the quantum yield of core–shell nanophosphors of $Y_2O_3:Eu^{3+}$ was greatly enhanced by optimizing the annealing process to increase crystallinity [21]. Similarly, Liu et al. (2021) also showed that structure and bandgap engineering could be used to improve both quantum yield and thermal stability in $(Ba,Sr)_3SiO_5:Eu^{2+}$ phosphors, highlighting the importance of structure optimization for high performance solid state lighting materials [27].

RECENT ADVANCES IN LUMINESCENCE ENHANCEMENT OF NANOPHOSPHORS

The growing need for highly efficient, thermally stable and colour tunable materials in solid-state lighting, display technology, optical sensing, bioimaging, and photonic devices has led to recent progress in luminescent nanophosphors. Despite good optical properties, conventional phosphors can have several drawbacks, such as concentration quenching, thermal degradation, surface defects, and poor energy efficiency. As a result, much attention has been devoted to the development of engineering approaches for the materials (material engineering) which would enhance radiative transitions and reduce non-radiative recombination. The photoluminescence quantum yield (PLQY), emission stability, and operational reliability have been dramatically improved due to advances in rare-earth and transition-metal doping, energy transfer engineering, core–shell nanostructures, quantum confinement, plasmonic enhancement and thermal management. The progress has enabled nanophosphors to be used in future generation solid-state optical technologies.

Rare-Earth and Transition-Metal Doping

Doping is one of the most powerful means for modifying the optical properties of nanophosphors, providing luminescent centers in an appropriate host lattice. The unique properties of rare-earth ions, such as their sharp emission bands, long luminescence lifetime, and excellent chemical stability, make them ideal for a wide range of applications. Activator ions like Eu^{3+}, Tb^{3+}, Dy^{3+}, Sm^{3+} and Ce^{3+} are mostly employed to achieve red, green, yellow, orange and blue emissions, whereas Yb^{3+} co-doped with Er^{3+}, Ho^{3+} and Tm^{3+} are most frequently used in upconversion systems. Recent research has proven that multi-doping with multiple rare-earth ions can widen the excitation wavelength, increase the energy transfer efficiency, and achieve multi-color emission while minimizing concentration quenching [7]. List of rare-earth (RE) elements along with electronic configuration and oxidation states mention in table 1. Similarly, Morebodi et al. (2024) demonstrated the efficient energy transfer from Sm^{3+} to Eu^{3+} in $Na_6Mg(SO_4)_4$ nanophosphors, which facilitated the effective tuning of colors and increased red emission for display and LED applications [28].

Transition-metal ions such as Mn^{2+}, Cr^{3+}, Ni^{2+}, Fe^{3+} and Cu^{2+} are promising alternatives or complementary activators due to their d–d electronic transitions, which give rise to wide emission bands. Rare-earth and transition metal ions are frequently used together, with their synergistic effect resulting in a better color rendition, higher emission intensity and flexibility of the excitation process. Preethi et al. (2026) showed that the addition of transition-metal oxide nanoparticles in combination with rare-earth ions changes the glass network, enhances optical band gaps and increases the photoluminescence of solid-state lasers and white LEDs show in figure 3 [29].

Similarly, Ghubish et al. (2026) showed that Li^+ co-doping effectively increased the quantum efficiency, luminescence lifetime, and color purity of Tb^{3+}-activated $SrMoO_4$ nanophosphors by reducing non-radiative losses and facilitating energy transfer. The results underscore the importance of accurate dopant design for high efficiency nanophosphors [30]. The schematic representation of visualization of LFPs using optimized $SrMoO_4:0.006Tb^{3+},0.006\ Li^+$ by the smooth brushing method show in figure 4.

Table 1: List of RE elements along with electronic configuration and oxidation states [7]

Rare earth element	Atomic number	Symbol	Electronic configuration	Oxidation states
Scandium	21	Sc	$[Ar]3d^14s^2$	+3
Yttrium	39	Y	$[Kr]4d^15s^2$	+3
Lanthanum	57	La	$[Xe]4f^05d^16s^2$	+3
Cerium	58	Ce	$[Xe]4f^15d^16s^2$	+3, +4
Praseodymium	59	Pm	$[Xe]4f^36s^2$	+3, +4
Neodymium	60	Nd	$[Xe]4f^46s^2$	+3, +4
Promethium	61	Pr	$[Xe]4f^56s^2$	+3
Samarium	62	Sm	$[Xe]4f^66s^2$	+2, +3
Europium	63	Eu	$[Xe]4f^76s^2$	+2, +3
Gadolinium	64	Gd	$[Xe]4f^75d^16s^2$	+3
Terbium	65	Tb	$[Xe]4f^96s^2$	+3, +4
Dysprosium	66	Dy	$[Xe]4f^{10}6s^2$	+3, +4
Holmium	67	Ho	$[Xe]4f^{11}6s^2$	+3
Erbium	68	Er	$[Xe]4f^{12}6s^2$	+3
Thulium	69	Tm	$[Xe]4f^{13}6s^2$	+2, +3
Ytterbium	70	Yb	$[Xe]4f^{14}6s^2$	+2, +3
Lutetium	71	Lu	$[Xe]4f^{14}5d^16s^2$	+3

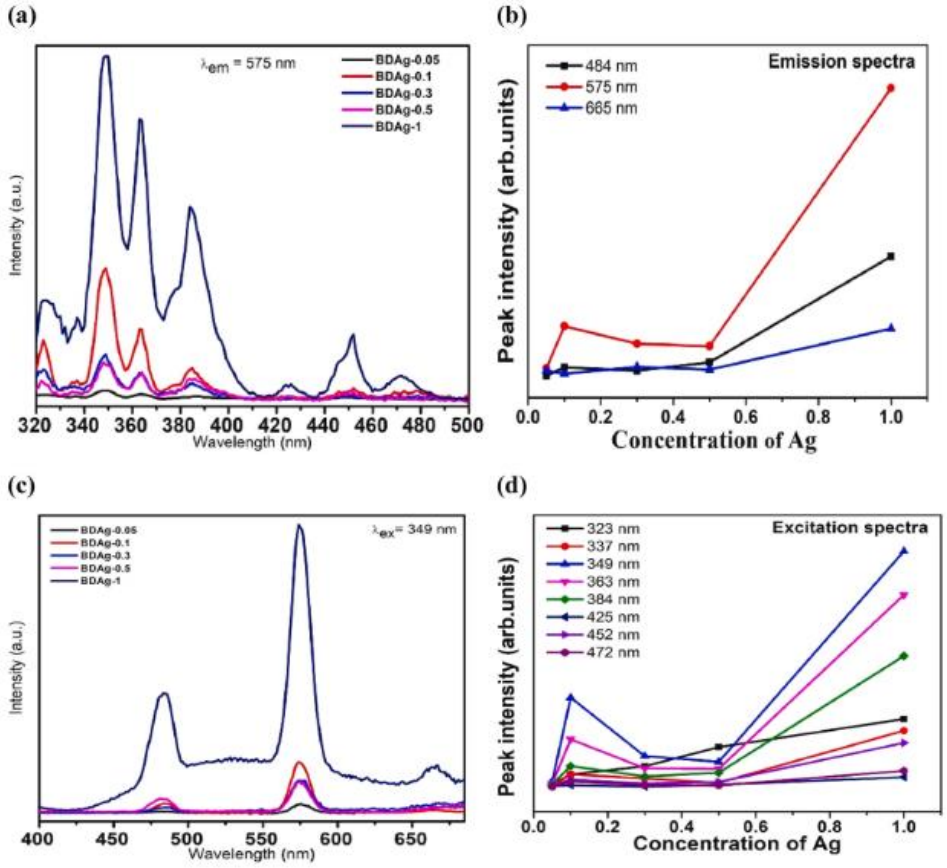


Figure 3: (a) Luminescence spectra emission at 575 nm and (b) with its corresponding peak intensity of BDAg glass system (c) Excitation spectra of BDAg glasses at 349 nm along (d) with respective peak intensity [29]**.**

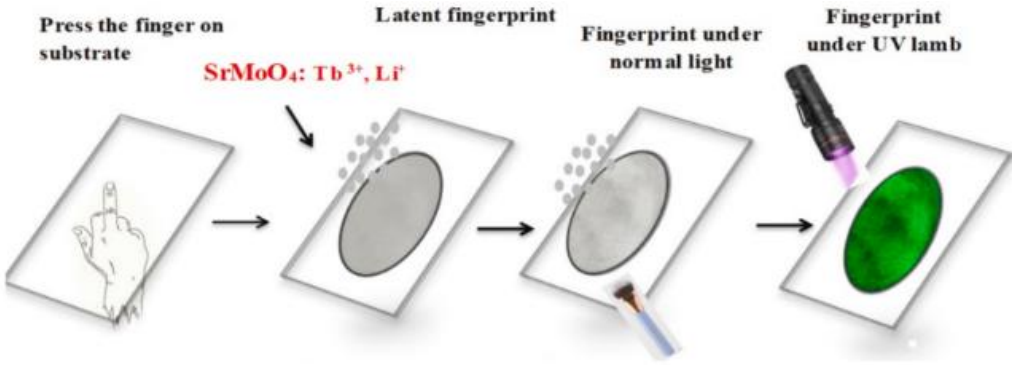


Figure 4: The schematic representation of visualization of LFPs using optimized $SrMoO_4$:0.006Tb^{3+},0.006 Li^+ by the smooth brushing method [30]**.**

Energy Transfer Mechanisms

To achieve high luminescence efficiencies, the energy must be efficiently transferred to the luminescence center so that the absorbed excitation energy can be efficiently used and non-radiative relaxation can be minimized. Rare-earth-doped nanophosphors involve the absorption of the energy of excitation by sensitizer ions, which have large absorption cross-sections, and then transfer the energy to the activator ions that have higher emission probabilities. The most widely studied systems are those containing Yb^{3+}–Er^{3+}, Yb^{3+}–Tm^{3+} and Yb^{3+}–Ho^{3+}, which have outstanding upconversion efficiency when excited near-infrared. These systems are effective if there is a suitable overlap in the light spectrum, the distance between the donor and the acceptor, and matching of energy levels.

Besides sensitizer–activator interactions, resonant energy transfer through dipole–dipole, dipole–quadrupole, and exchange interactions significantly influences luminescence performance. By carefully controlling the distribution of dopants in space and concentration, the concentration quenching effect can be minimized and efficient radiative transitions can be maximized. Further regulatory processes of excitation dynamics involve cooperative sensitization and cross-relaxation processes, which can increase or decrease the emission, depending on the energy-level configuration. Thus, recent material engineering efforts have concentrated on improving these interactions to increase the quantum yield and wider the excitation window. The enhancement in energy migration properties as reported by Kiran et al. (2025) and Morebodi et al. (2024) clearly shows that rational control of donor–acceptor interactions greatly improves the efficiency of photoluminescence in advanced nanophosphors [7], [28].

Core–Shell Nanostructures

One of the most effective ways to enhance the optical properties of luminescent nanophosphors, namely, to significantly reduce the surface related quenching, is the core–shell approach

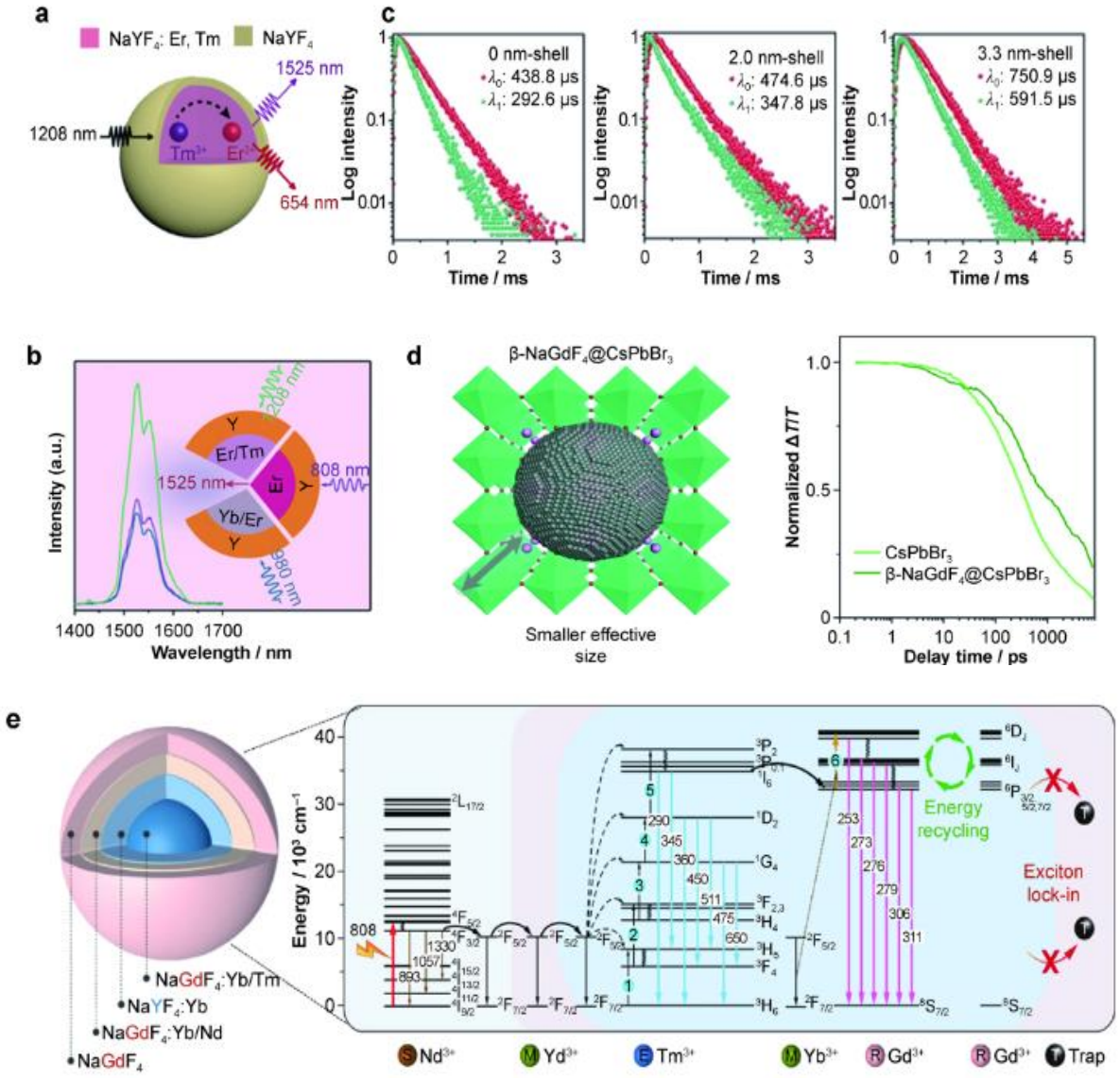
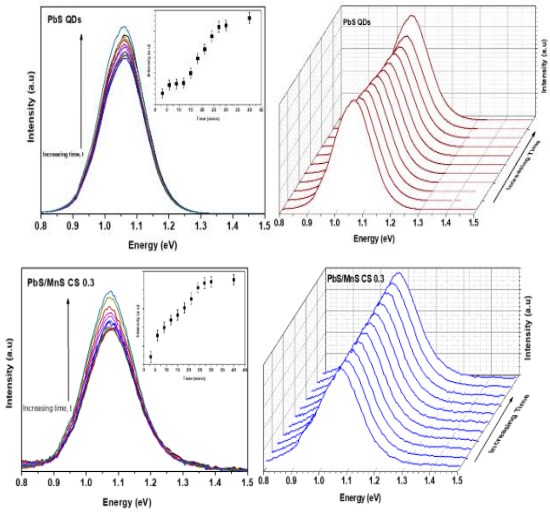


Figure 5: Surface defect passivation and multi-layer core-shell energy migrating optimization based on luminescence modulation [31].

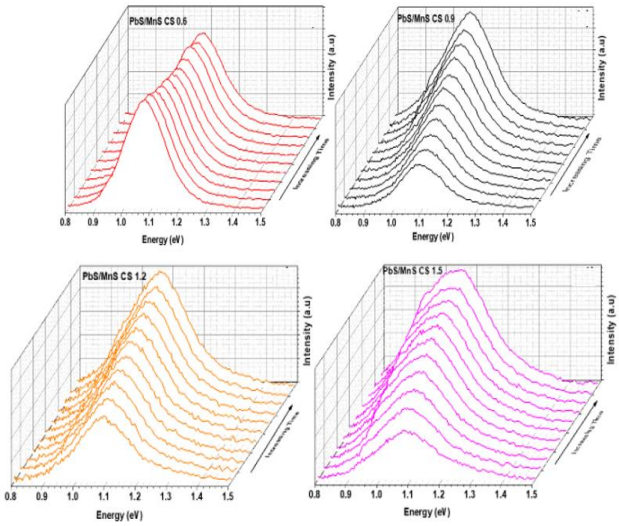
. Emission intensity is often reduced by defects at the surface which can act as non-radiative recombination centres as a result of the high surface-to-volume ratio of nanoparticles. The luminescent core can be surrounded by a shell of a non-luminescent material, such as $NaYF_4$, SiO_2, or a stable layer of oxides, which help to isolate the luminescent ions from environmental impurities and reduce surface defects and chemical and photothermal instability. As a result, the resulting inert core–shell structures have much higher PL intensity and higher operational lifetimes.

Further benefits are obtained by incorporating luminescent ions into both the core and shell, which allows for the design of multicolored emission and controlled energy migration, as in the case of active core–shell structures. The cross-relaxation can be minimized and the efficiency of the excitation maximized by engineering the interface and distributing the dopants by layers. Sheng et al. (2026) highlighted the importance of optimized core–shell upconversion nanoparticles that enhance the quantum yields, photostability and multicolour emission by surface defect passivation and control of energy migration (figure 5) [31]. Similarly, the quantum confinement and the photoluminescence of quantum dots consisting of core PbS and shell MnS were found to be improved compared to uncapped PbS nanoparticles as the shell could effectively confine the charge carriers and minimize energy loss due to surface defects (figure 6 and 7) [32].



(a) (b)

Figure 6: PL spectra of PbS core QDs (a) showing enhancement of PL intensity, including the intensity trend over time (inset). PL spectra of PbS/MnS CS 0.3 (b) exposed to laser of power p = 100 mW and time exposure for 40 min at room temperature. [32]



(a) (b) (c) (d)

Figure 7: PL spectra of PbS/MnS (a) CS 0.6, (b) CS 0.9, (c) CS 1.2 and (d) CS 1.5 exposed to laser of power p = 100 mW and time exposure up to 40 min at room temperature. [32]

Quantum Confinement and Plasmonic Enhancement

The optical properties of luminescent materials have been significantly improved by two new nano-scale approaches, namely quantum confinement and plasmon-assisted luminescence. When the particle size is scaled down to the vicinity of the exciton Bohr radius, the optical band gap, excitation properties, and emission wavelength are changed. The 4f shells of rare-earth elements are relatively insensitive to particle size, but the semiconductors energy transfer process and lattice influence in phosphors with semiconductors are affected by quantum confinement. Zaini et al. (2020) showed that the confinement effect of the core–shell quantum dots, composed of PbS/MnS, was more effective and the emission efficiency was more stable by efficiently trapping the charges [32].

Plasmonic enhancement relies on the generation of localized surface plasmon resonance (LSPR) by metallic nanoparticles like Au and Ag as a way to enhance the local electromagnetic fields and boost excitation efficiency and rates of radiative emission. Gao et al. (2023) found that plasmon-enhanced luminescence can significantly enhance the sensitivity of biosensors and the performance of bioimaging by boosting the signal strength and background noise suppression [33]. Similarly, Pham et al. (2026) realized a significant improvement of the upconversion emission in Au dendrite coupled α-$NaGdF_4$:Yb^{3+},Er^{3+} nanophosphors, which illustrates the potential of plasmonic

architectures designed with precision for applications in lighting, bioimaging, and photovoltaics [34].

Thermal Stability and Quantum Efficiency Improvement

A major challenge for practical solid-state applications is maintaining high luminescence efficiency at high operating temperatures. Phonon-assisted non-radiative relaxation causes a reduction in the emission intensity and the performance of any device due to thermal quenching. There has been recent interest in optimizing the host lattice, engineering defects, controlling dopant distribution and developing new synthesis methods to enhance thermal stability and quantum efficiency. The hydrothermally, microwave-assisted and solvothermally synthesized high-crystallinity nanophosphors have reduced structural defects, and enhanced quantum yield of their photoluminescence compared to conventional ones [7].

Recent investigations also show the effectiveness of defect engineering and crystal structure optimization of suppressing thermal quenching and maintaining high emission intensity. Zhou and Ji (2026)[35] demonstrated that some strategies in lattice engineering, defect control and heat dissipation can promote the saturation level of luminescence in high power laser phosphors, while Sharma et al. (2025) [10] reported the excellent thermal stability and efficient radiative transitions of Gd^{3+}-activated $CaMgSi_2O_6$ for ultraviolet phototherapy applications (figure 8). All of these advances suggest that a pathway to high performance luminescent nanophosphors with the necessary attributes for the increasingly stringent requirements of modern solid-state optical technologies is possible by optimizing the doping, efficient energy transfer, nanoscale structural engineering, plasmonic enhancement, and thermal management.

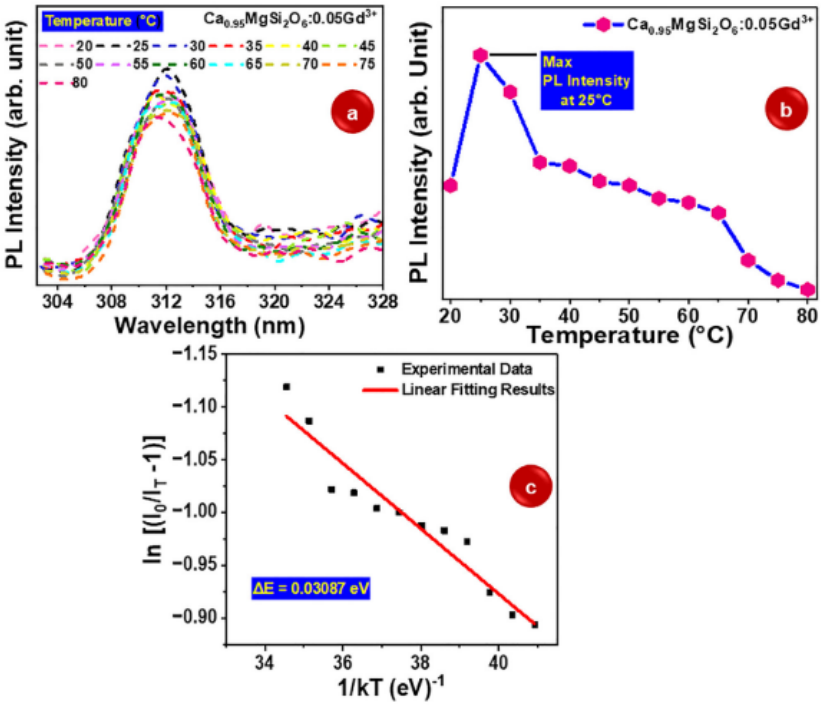


Figure 8: (a) TDPL plot of optimized phosphor at different temperatures, (b) Variation of PL intensity with temperature, and (c) Activation energy determination by the linear fitting method using the Arrhenius equation [10]**.**

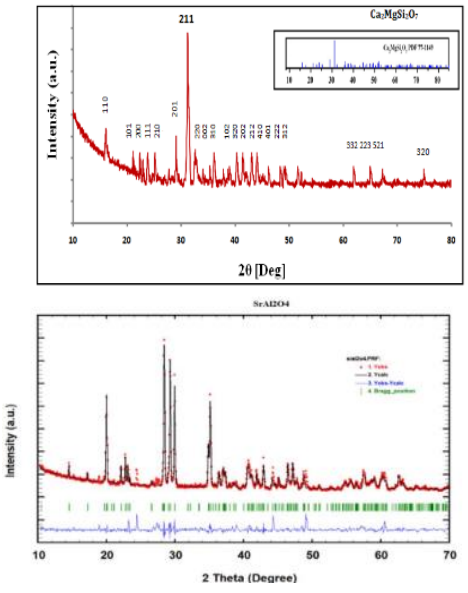
Characterization Techniques for Luminescent Nanophosphors

The high performance of luminescent nanophosphors is determined by the crystal structure, morphology, chemical composition, defect states, and thermal stability of the nanophosphor, and comprehensive characterization is essential for developing high performance nanophosphors. Advanced characterization techniques provide researchers with a clear link between the synthesis parameters, microstructural characteristics and luminescence properties, which allow the design of phosphor materials to be rationally optimized for solid state lighting, displays, optical sensing, bioimaging, and photonic devices. A structural, optical, compositional, thermal and spectroscopic

characterization is thus necessary to assess phase purity, dopant incorporation, energy transfer processes and operational stability. New developments in analytical instrumentation have also enhanced the accuracy of the study of the structure and optical properties of nanoscale materials and structures, thereby speeding up the optimization of high-efficiency luminescent materials.

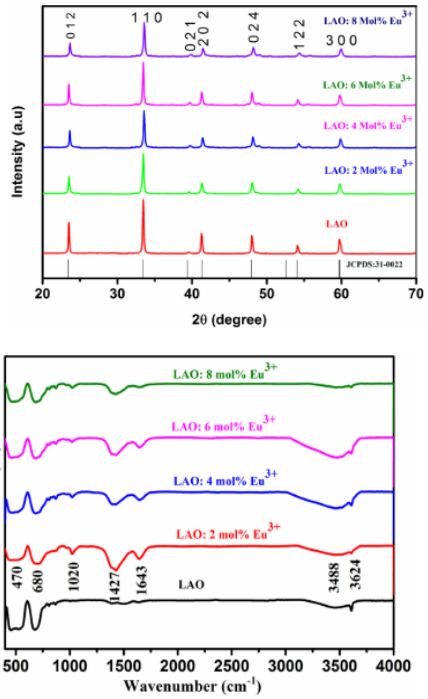
Structural Characterization

Structural characterization is the foundation of knowing how crystal structure relates to the luminescence properties. X-ray Diffraction (XRD) is one of the most commonly used techniques for determining the phase composition, crystallinity, lattice parameters, crystallite size, and lattice distortions which result from incorporation of dopant species. The diffraction patterns measured are mostly compared with standard crystallographic databases and the Rietveld refinement is used to determine the lattice parameters and properties of defects in the substituted lattice. Sharma et al. (2012) highlighted the irreplaceable role of XRD in studying the crystal quality, grain size, strain and defect structures of nanomaterials [36]. Similarly, Sharma et al. (2021) successfully synthesized tetragonal $Ca_2MgSi_2O_7$ phosphors using XRD analysis show in figure 9, and Litoriya et al. (2023) achieved excellent crystallinity of $Sr_{1-x}Al_2O_4$ phosphor which is a single-phase monoclinic structure suitable for optoelectronic applications [37], [38].



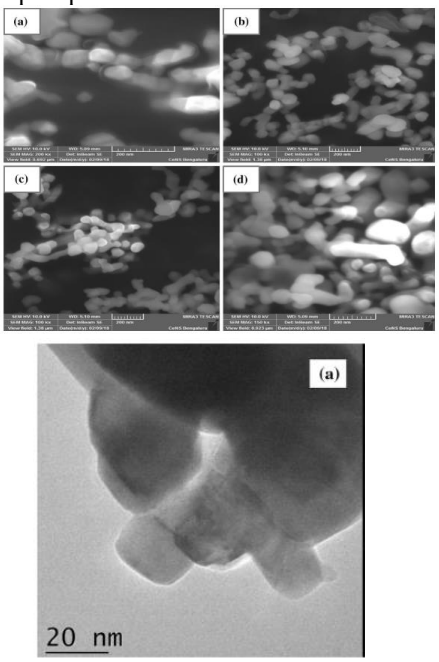
(a) (b)

Figure 9: XRD Pattern of (a) $Ca_2MgSi_2O_7$ Phosphor [37]; (b) $SrAl_2O_4$ [38].



PXRD pattern of $La_{1-x}AlO_3$: xEu^{3+} nanophosphors

FTIR spectra of $La_{1-x}AlO_3$: xEu^{3+}



FESEM micrographs of $La_{1-x}AlO_3$: xEu^{3+} (a) 2 mol% (b) 4 mol% (c) 6 mol% and (d) 8 mol% nanophosphors

TEM image of $LaAlO_3$: 6 mol% Eu^{3+} nanophosphor

Figure 10: XRD, FESEM, HRTEM, and FTIR analyses [39]

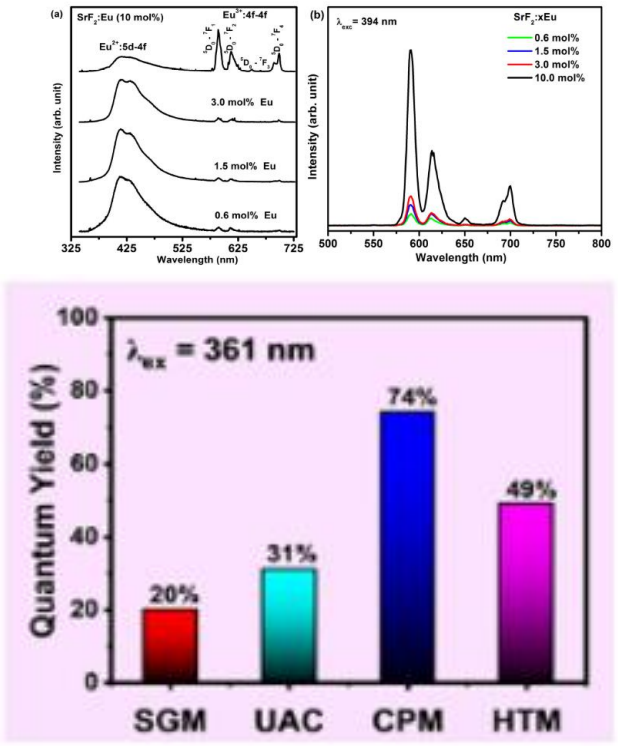
In addition to XRD, microscopic techniques can be used to visually observe the particle morphology and microstructure, complementing XRD. Scanning electron microscopy (SEM) is widely applied for the study of particle size, distribution of the number of grains, agglomeration and surface texture, all of which affect the light scattering and the luminescence efficiency. Transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) can provide nanoscale structural information such as lattice fringes, crystal defects, and interface structures. To correlate the enhanced red emission with the structural evolution of Eu^{3+}-doped $LaAlO_3$ nanophosphors, Ankoji and Rudramadevi (2018) successfully attempted to use XRD, FESEM, HRTEM and FTIR methods (figure 10) [39]. In comparison, Heydarian et al. (2022) have used TEM and Rietveld refinement to show that the particle size and crystal structure of the material were successfully modified by Ag^{+} and Gd^{3+} doping, thus achieving enhanced luminescence intensity [40]. Selected area electron diffraction (SAED) is often used for structural investigations to confirm crystallinity as well as crystal orientation of the sample, especially in the case of nanostructured and core–shell phosphor systems.

Optical Characterization

The optical characterization is indispensable for analyzing the luminescence property of nanophosphors and their applicability for the practical application of solid-state sources. The main method to investigate the emission properties, such as emission wavelengths, intensities, spectral bandwidth, radiative efficiencies, is referred to as photoluminescence (PL) spectroscopy. The emission spectra also yield important information about energy transfer processes and the concentration of energy levels in the host lattice and crystal-field effects. Photoluminescence excitation (PLE) spectroscopy is used to complement PL measurements to determine the optimal excitation wavelengths, which will help to select appropriate UV or blue LED excitation sources.

Additional information about excited state lifetimes and the separation of radiative and non-radiative relaxation processes is obtained by time-resolved photoluminescence (TRPL). However, lifetime measurements are especially valuable for assessing concentration quenching, donor–acceptor interactions and energy transfer efficiency. The emission intensity was found to be increased with concentration of rare earth elements up to an optimum concentration [C1] and then decreased with increasing concentration due to concentration quenching, as confirmed from lifetime analysis, as shown by Kumari and Choudhary (2025) [41]. Similarly, Yagoub et al. (2015) confirmed the effectiveness of co-doping strategy by showing efficient energy transfer between Ce^{3+} and Eu^{2+} in SrF_2 nanophosphors using PL spectroscopy (figure 11) [42].

The photoluminescence quantum yield (PLQY) of a phosphor is one of the most significant parameters for assessing the efficiency of photon conversion and it has been gaining importance over the years. Rakshita et al. (2025) found that the nanophosphors of $Zn_3V_2O_8$ have a very high quantum yield of about 74% and have very good colour rendering properties, making them suitable for use in phosphor converted white LED (figure 11) [43]. Optimized dopant concentrations were found to enhance color purity, emission tunability and chromaticity by studies of Ankoji and Rudramadevi (2018), Litoriya et al. (2023) and Maleho et al. (2026) which made these materials promising to be used in white LEDs, display devices, and advanced optoelectronic systems (figure 12 and 13) [38], [39], [44]. In table 2, CIE coordinates, color purity, and calculated correlated color temperature are illustrated.



Photoluminescence spectra of SrF_2:xEu | Quantum yield of ZnVO synthesized

Figure 11: Photoluminescence spectra and Quantum yield [42], [43]

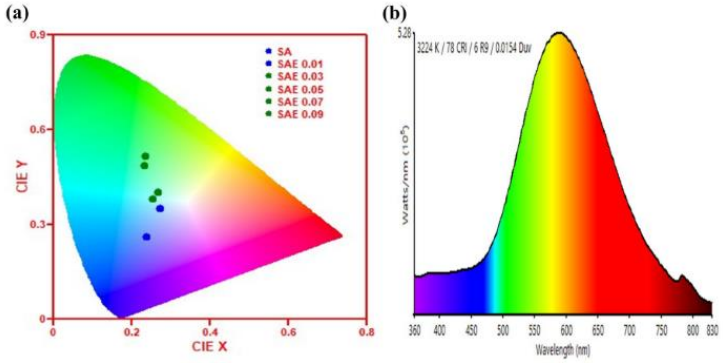
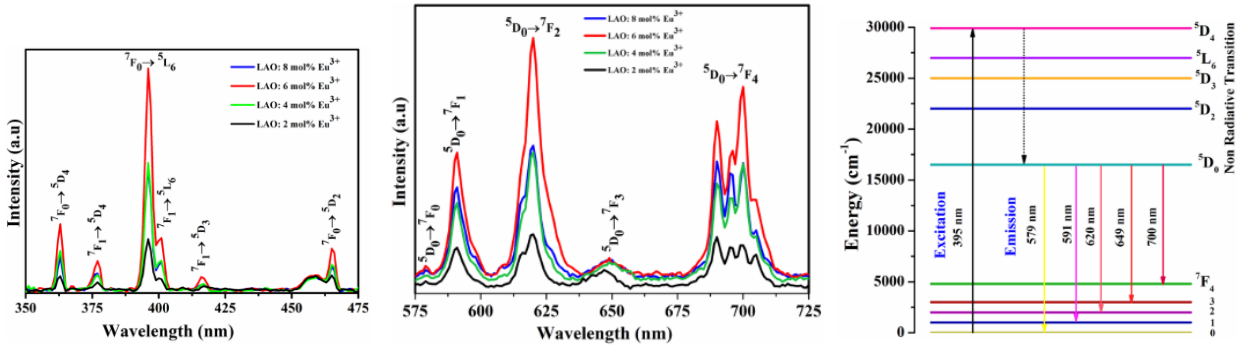


Figure 12: Photoluminescence CIE diagram of $Sr_{1-x}Al_2O_4:Eu_x$ (x = 0.00, 0.01, 0.03, 0.05, 0.07, and 0.09) phosphor (SAE phosphor) (a), Typical spectrum graph for $Sr_{1-x}Al_2O_4:Eu_x$ (x = 0.05) (SAE 0.05) phosphor (b). [38]



(a) (b) (c)

Figure 13: (a) Excitation spectra; (b) Emission spectra; (c) Schematic energy level diagram of $La_{1-x}AlO_3$: xEu^{3+} (x = 2, 4, 6 and 8 mol%) nanophosphors [39]

Table 2: CIE coordinates, color purity, and calculated correlated color temperature of $ZnO:Sm^{3+}$, $Zn_4B_6O_{13}:Sm^{3+}$, $Zn_2P_2O_7:Sm^{3+}$, and $ZnO\text{-}SO_4:Sm^{3+}$ materials [44].

Sample	Chromaticity Coordinates				Color Purity (%)	CCT (K)	Color Range
	x	y	x_d	y_d			
$ZnO:Sm^{3+}$	0.430	0.400	0.557	0.458	46	3090	Yellow
$Zn_4B_6O_{13}:Sm^{3+}$	0.600	0.400	0.606	0.402	98	1713	Orange
$Zn_2P_2O_7:Sm^{3+}$	0.520	0.400	0.606	0.402	71	1740	Orange
$ZnO\text{-}SO_4:Sm^{3+}$	0.420	0.360	0.672	0.347	27	2914	Yellow

Surface and Compositional Analysis

Surface defects and impurity states are common and important non-radiative recombination centers, and the chemical composition and topographic properties of nanophosphors are significant factors determining the luminescence efficiency. Therefore, it is important to perform accurate compositional analysis to ensure a successful incorporation of the dopant and to gain insight in the defect chemistry. X-ray photoelectron spectroscopy (XPS) is the technique commonly used for elemental composition, oxidation state and chemical bonding environment determination and for surface defects determination. The role of XPS and other surface-sensitive techniques in determining the valence state of dopants and the structures of the defects that govern luminescence behavior were emphasized by Swart (2017) show in figure 14 [45]. Similarly, Yagoub et al. (2015) successfully incorporated Eu and Ce ions into the SrF_2 lattice by XPS and Maleho et al. (2026) confirmed the oxidation state of Sm ions by XPS and correlated the structural modifications with the improved photoluminescence in figure 15 [42], [44].

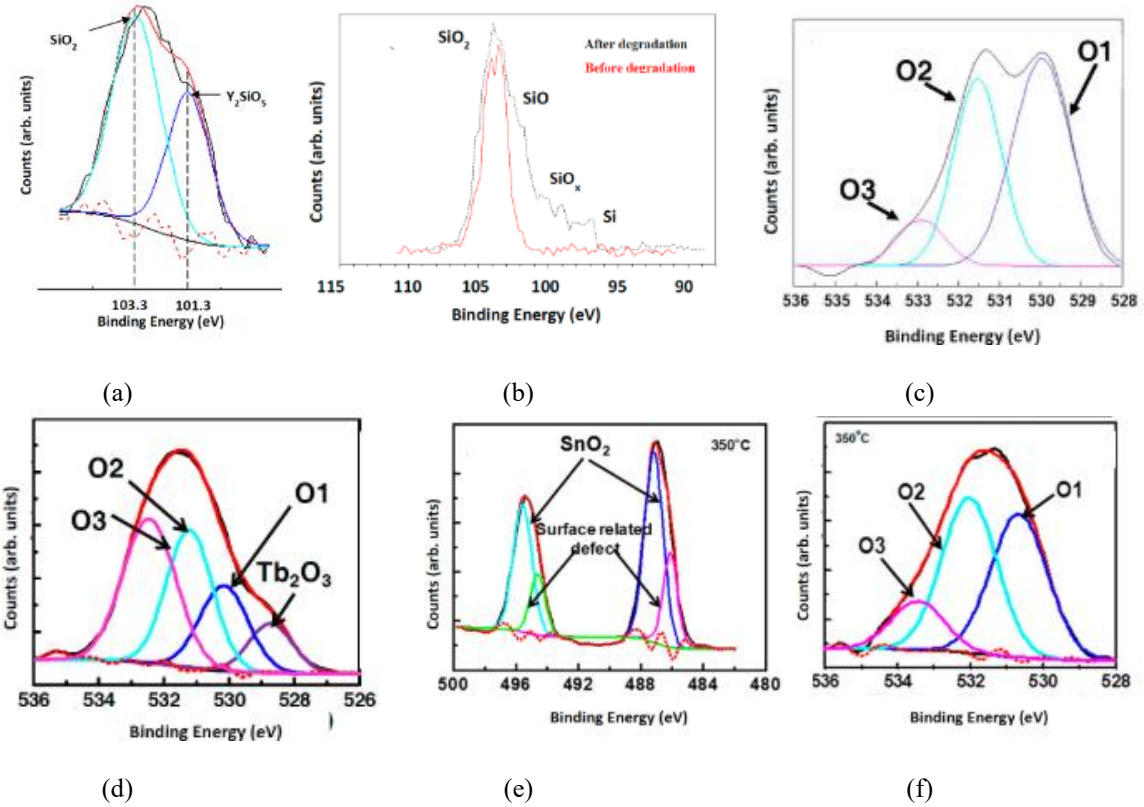
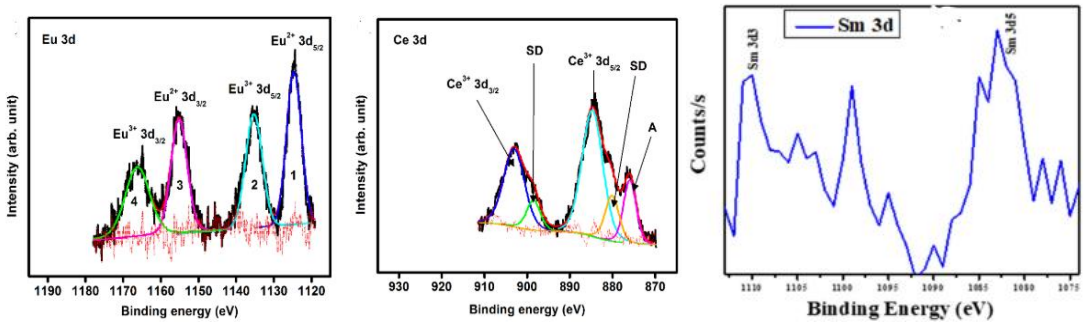


Figure 14: XPS fitted results for (a) Si 2p in the Y_2SiO_5:Ce after degradation; (b) SiO_2:PbS nanoparticles before and after degradation; (c) defect containing ZnO; (d) ZnO with 6 mol % doping of Tb; (e) Sn-3d$_{5/2}$ and Sn-3d$_{3/2}$ peaks of SnO_2; and (f) O-1s of SnO_2 [45]

SEM or TEM combined with energy-dispersive X-ray spectroscopy (EDS) can be used to get qualitative and semi-quantitative elemental analysis and elemental mapping, which can be helpful in assessing dopant homogeneity. To accurately measure the trace dopant concentrations, inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) are often used. Fourier transform infrared spectroscopy (FTIR) is also a useful tool to complement these methods and is used to identify chemical bonds, functional groups and surface modifications that can have an impact on the luminescence performance. The integrated compositional characterization was demonstrated to be useful by Pratibha et al. (2024) and Sharma et al. (2021), who successfully combined FTIR with structural analyses to confirm host lattice formation and dopant incorporation [37], [46].



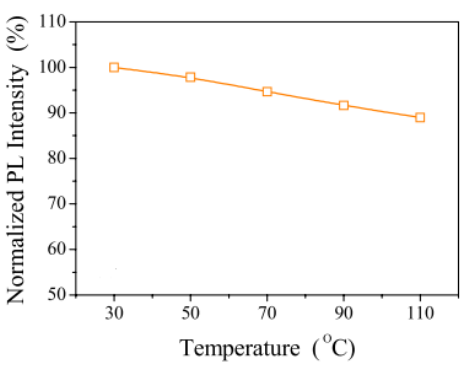
High resolution XPS peaks of Sr 3d High-resolution XPS spectra of Sm 3d

Figure 15: High resolution XPS [42], [44]

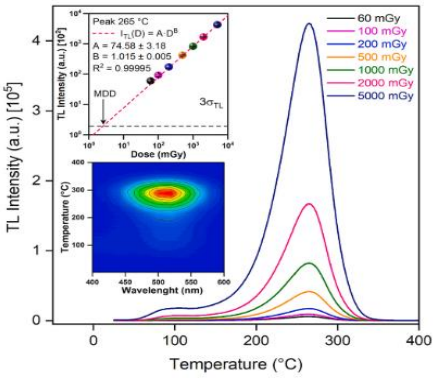
Thermal and Spectroscopic Characterization

Thermal stability is an important criterion for phosphors used in high-power LEDs, lasers, and other solid-state optical devices as high-temperature can cause thermal quenching and diminish the emission intensity. Thermogravimetric analysis (TGA) and Differential scanning calorimetry (DSC) are typically used to analyse thermal decomposition, crystallization behaviour, phase transitions and thermal durability. Temperature-dependent photoluminescence spectroscopy also gives direct information about the stability of the emitted radiation under operating conditions through the measurement of activation energies of thermally activated nonradiative relaxation.

The information that can be obtained from the Raman spectra complements thermal characterization in terms of the lattice vibrations, phonon modes, structural disorder, and distortions due to defects, all of which can affect non-radiative energy transfer. Determination of optical band gaps and the determination of excitation characteristics is achieved routinely by UV–Visible absorption spectroscopy, which can aid the understanding of the photoluminescence behavior. To determine the defect centers responsible for luminescence processes in Tb-doped Zn_2SiO_4 phosphors, Perez-Montano et al. (2026) has used thermoluminescence (TL) and electron paramagnetic resonance (EPR) analysis in figure 16 [47]. Similarly, excellent thermal stability and long fluorescence lifetimes were obtained in Eu^{3+}- and Mn^{4+}-activated nanophosphors (figure 16) by Hua et al. (2021), and time-resolved upconversion spectroscopy was used by Sevic et al. (2020) to examine the thermal dependent luminescence for optical thermometry [48], [49]. Together, these complementary techniques set the groundwork for establishing relationships between structural integrity, defect chemistry, thermal stability, and optical performance; this is critical to designing highly efficient luminescent nanophosphors that could facilitate the next-generation solid-state technologies.



Stability of ZSO:Eu^{3+} heated from 30 to 110 °C



TL glow curves of Tb-doped Zn_2SiO_4 phosphor irradiated with beta-ray doses of 60 Gy up to 5000 mGy

Figure 16: Thermal Stability and Effect of irradiation [47], [48]

Applications of Luminescent Nanophosphors in Solid-State Technologies

Luminescent nanophosphors possess outstanding optical properties and are irreplaceable parts of modern solid state technologies. The high photoluminescence efficiency, narrow emission bandwidths, tunable emission wavelengths, excellent color purity, long operational lifetime and superior thermal and chemical stability make them suitable for a variety of optoelectronic devices. Nanophosphors also have other desirable properties due to their nanoscale size, such as increased surface reactivity, increased dispersibility and modulation of optical properties by particle-size engineering and defect modulation, compared with conventional phosphor materials. In recent years, further improvements in their quantum efficiency, thermal stability, and emission performance have been realized by utilizing rare-earth and transition-metal doping, core–shell architectures, and energy transfer engineering. As a result, luminescent nanophosphors have become important functional materials in applications such as white light emitting diodes (WLEDs), optical thermometry, advanced display systems, anti-counterfeit and forensic applications.

Solid-State Lighting (WLEDs)

Solid-state lighting is one of the most significant commercial applications of luminescent nanophosphors and is especially important for applications such as phosphor-

converted white light-emitting diodes (pc-WLEDs). When compared to incandescent and fluorescent lighting systems, WLEDs have better energy efficiency, longer lifespan, lower maintenance needs, fast switching time, and less environmental impact. However, the optical efficiency of the WLED is more dependent on the efficiency and the spectra of the phosphor materials used for wavelength-converted LEDs.

The rare-earth-doped nanophosphors (Eu^{3+}-, Ce^{3+}-, Tb^{3+}-, and Dy^{3+}-activation systems) are widely used due to their high efficiency (red, green, blue, and yellow emission), excellent color purity, and photochemical stability. Multiple phosphors are used to create broad visible emission, which leads to high colour rendering index (CRI), optimised correlated colour temperature (CCT) and high luminous efficacy. Wang et al. (2024) noted that recent studies have moved beyond the focus of increasing luminous efficiency to creating healthy lighting systems that possess higher CRI, lower blue-light hazards, and greater light uniformity [50]. Similarly, Cantarano et al. (2020) showed that synthesis methods, crystallinity, particle shape and doping of lanthanides have a significant impact on the internal quantum yield and emission properties of nanophosphors for LED applications [51].

The present work also involves thermal quenching reduction, concentration quenching suppression and high-power operation long-term photostability reduction. The core–shell nanostructure and surface-passivated nanophosphors techniques have proven to be effective to reduce non-radiative recombination on the surface and increase the light extraction efficiency. In addition, new environmentally friendly phosphor materials with lower reliance on toxic heavy metals are being developed to enable sustainable lighting technologies. The advances keep enhancing the role of luminescent nanophosphors as essential materials for the future generation of residential, industrial, automotive and architectural lighting systems.

Optical Thermometry

Due to its capability to monitor temperature without contact, optical thermometry has become a key application of luminescent nanophosphors in environments where traditional thermometers cannot be used. Luminescent Thermometers do not require a power supply and are unaffected by electromagnetic interference, offer high spatial resolution, and are capable of measuring temperature in hazardous and remote environments, and even miniaturized sensors.

Sensing principle is based on changes in the intensity, life-time, position or fluorescence intensity ratio (FIR) of the photoluminescence. Rare-earth ions, like Er^{3+}, Ho^{3+}, Tm^{3+}, and Dy^{3+}, have energy levels that are closely spaced and whose thermal population redistribution results in predictable optical responses. Fluorescence intensity ratio thermometry is especially appealing because it yields self-referenced measurements, and is relatively independent of excitation intensity and sample concentration.

The near-infrared excitation efficiency, low background fluorescence and excellent temperature sensitivity make up-conversion nanophosphors, co-doped with Yb^{3+} and Er^{3+}, a subject of great interest. Fhoula et al. (2024) showed that $Na_2SrP_2O_7$ phosphors doped with Er^{3+}/Yb^{3+} have high absolute and relative sensitivities and excellent temperature resolution over a wide operating range, making them suitable for scientific and industrial thermometry applications [52]. In the same way, Sevic et al., (2020) reported the reliable temperature sensing up to 550 K by Er^{3+}/Yb^{3+} doped Gd_2O_3 nanophosphors adopting the method of luminescence intensity ratio [49]. The developments have led to the utilization of luminescent nanophosphors in microelectronics, biomedical diagnostics, aerospace systems, microfluidic devices and systems in which precise remote measurement of temperature is necessary. The several luminescent materials for biological detection are presented in Table 3.

Table 3: Comparison of several luminescent materials for biological detection [53]**.**

Material	Excitation	Emission	Quantum Yield	Lifetime	Biological Characteristics	SNR
Organic dyes	UV-Vis-NIR	Vis-NIR-II	Medium, dependence structure	Nanosecond	Low toxicity, poor stability, low penetration ability	Low
Quantum dots	UV-Vis-NIR	UV-Vis-NIR-III	High, strong absorption	Nanosecond	High toxicity, good stability, middle biocompatibility	Middle

Upconversion nanoparticles	NIR	UV-Vis-NIR-II	Low, dependence on doped ions	Nanosecond	Low toxicity, continuous external excitation	High
Long persistent luminescent nanoparticles	X-rays-UV-Vis-NIR	UV-Vis-NIR-III	Medium	Up to tens of hours	Low toxicity, no continuous external excitation	Ultra-high

Display Technology

The significant advantages that these nanophosphors offer, including their high brightness, high color purity, narrow emission bands, and superior photostability, have made them an essential element of modern display technologies. For high-definition televisions, smart phones, computer monitors, projectors and new Micro LED displays, phosphors that can provide saturated primary colors with a high energy efficiency and long operating life are required.

Rare-earth-doped nanophosphors provide highly efficient red, green, and blue emissions through well-defined electronic transitions, enabling wide color gamuts and improved display quality. Their nanoscale dimensions facilitate uniform thin-film fabrication, reduced scattering losses, and compatibility with advanced lithographic processing. Furthermore, improvements in quantum confinement, defect engineering, and surface passivation have enhanced emission efficiency and operational stability.

Recent developments have expanded the role of nanophosphors in next-generation display platforms. Triana et al. (2022) highlighted the growing importance of quantum dots and perovskite nanocrystals as highly efficient color-conversion materials for photoluminescence-based displays, while emphasizing their potential in flexible healthcare display devices [54]. More recently, Pei et al. (2026) demonstrated a full-color Micro-LED display based on photolithographically patterned nanophosphor thin films, achieving high internal quantum efficiency, excellent thermal stability, and chromaticity close to the D65 standard [55]. These achievements illustrate how luminescent nanophosphors are enabling scalable, high-resolution display technologies for applications including wearable electronics, augmented reality (AR), virtual reality (VR), and advanced visualization systems.

Anti-Counterfeiting and Forensics

The unique excitation-dependent luminescence, excellent photostability, and highly tunable optical signatures of nanophosphors have created significant opportunities in anti-counterfeiting technologies and forensic science. Their ability to generate distinct emissions under ultraviolet, visible, or near-infrared excitation enables the fabrication of multi-level security features that are extremely difficult to replicate using conventional printing techniques.

Rare-earth-doped nanophosphors are increasingly incorporated into security inks, banknotes, passports, legal documents, pharmaceutical packaging, and product authentication labels. Upconversion, down-conversion, persistent luminescence, and excitation-dependent color switching provide multiple authentication pathways that significantly improve resistance to forgery. Pradhan et al. (2025) demonstrated that Eu^{3+}-doped Y_2SrZnO_5 nanophosphors exhibit exceptional photostability, thermal resistance, solvent durability, and nearly 100% color purity, making them highly suitable for secure luminescent inks [56]. Similarly, Kuang et al. (2023) reported that persistent luminescent phosphors enable multicolor, dynamic, and stimulus-responsive optical coding systems with greatly enhanced anti-counterfeiting capability [57]. Cheol et al. (2026) further emphasized that integrating fluorescent nanomaterials with advanced printing technologies, smartphone-based authentication, and artificial intelligence has opened new opportunities for programmable and user-friendly security systems [12].

In forensic science, luminescent nanophosphors have become valuable tools for latent fingerprint visualization, trace evidence analysis, document authentication, and crime scene investigation. Upconversion nanophosphors are particularly advantageous because near-infrared excitation minimizes background autofluorescence, thereby improving image contrast and detection sensitivity. Persistent luminescent materials also permit prolonged imaging after excitation ceases, facilitating the examination of weak or concealed evidence. Consequently, multifunctional nanophosphors that combine luminescent, magnetic, and sensing capabilities are attracting increasing attention for next-generation forensic imaging and secure information storage.

Overall, the expanding applications of luminescent nanophosphors demonstrate their transformative role in modern solid-state technologies. Continuous progress in material synthesis, defect engineering, nanoscale

architecture, and luminescence optimization has significantly improved their efficiency, stability, and functional versatility. As research increasingly integrates advanced computational design, multifunctional nanostructures, and sustainable material development, luminescent nanophosphors are expected to remain central to future innovations in energy-efficient lighting, intelligent sensing, high-performance displays, secure authentication, and emerging photonic technologies.

CONCLUSION

Luminescent nanophosphors have become indispensable materials for modern solid-state technologies owing to their superior photoluminescence efficiency, tunable emission properties, excellent color purity, and remarkable thermal and chemical stability. This review has highlighted recent advances in host lattice engineering, rare-earth and transition-metal doping, energy transfer mechanisms, core–shell nanostructures, quantum confinement, and plasmon-assisted luminescence, all of which have substantially enhanced optical performance and quantum efficiency. Equally important, advanced structural, optical, compositional, and thermal characterization techniques have provided valuable insights into the relationships between crystal structure, defect chemistry, and luminescence behavior, enabling rational material design and optimization. The review also demonstrates the growing impact of luminescent nanophosphors in phosphor-converted white light-emitting diodes, optical thermometry, high-resolution display technologies, and anti-counterfeiting and forensic applications. Although challenges such as concentration quenching, thermal quenching, synthesis scalability, and environmental sustainability remain, continuous progress in nanoscale engineering, computational material design, and multifunctional architectures is expected to overcome these limitations. Consequently, luminescent nanophosphors are poised to play a pivotal role in the development of next-generation energy-efficient lighting, intelligent sensing, advanced photonic devices, and emerging optoelectronic technologies.

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