Physiochemical characterization of highly biocompatible, and colloidal LaF₃:Yb/Er upconversion nanoparticles

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Abstract

Highly colloidal upconversion nanoparticles (UCNPs) were synthesized at low temperatures by the thermal decomposition process. The structure, morphology, crystallinity, surface chemistry, and optical properties were systematically optimized and studied through various spectroscopic techniques. X-ray diffraction (XRD) patterns have shown the formation of single-phase, highly purified, well-crystalline, hexagonal LaF₃ NPs, while the TEM micrographs show small, irregular sizes, spherically shaped, and aggregated polycrystalline UCNPs with an average crystalline size of about 8–15 nm. The Negative Zeta Potential value exhibits good biocompatibility of the UCNPs, which supports the idea that surface-anchored hydroxyl groups facilitate the stabilization of the NPs in aqueous media, as well as enhance biomolecules' tagging efficiency. The absorption spectrum, Zeta Potential, and hydrodynamic size that were measured in aqueous media illustrate excellent dispersibility, colloidal stability, biocompatibility, and cytotoxicity character of the UCNPs. Zeta potential and MTT assay studies illustrated high biocompatibility, it could be due to the surface-anchored hydroxyl groups. The nanoparticle demonstrates an excellent UC luminescence spectrum (i.e., prominent green emission $^4S_{3/2} \rightarrow ^4I_{15/2}$) upon irradiation by the 980-nm laser diode. TEM micrographs, further, revealed that this optically active material with aqueous sensitivities, porous crystal structure, and excellent UCNPs, could be a favorable candidate for potential photonics-based bio-related applications.

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Graphic abstract

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1 Introduction

In the last few years, fluorescent nanomaterials (NMs) have appealed an extensive consideration due to their prospective applications in various fields including solid-state, laser, panel displays, optical amplifiers, solar-cells, photocatalysts, optical sensors/detection devices, especially in bioimaging, therapy, and drug delivery, etc. [1–4]. Various fluorescent materials, such as those used in organic dye, quantum dots, semiconductors, and plasmonic nanoparticles (NPs), have been widely applied in photonics-based applications [5–7], due to their photochemical stability, photobleaching, and autofluorescence. However, less biocompatibility, toxic behavior, and short decay time factors have also limited their applications in laser-based material, as well as in biomedical technology. Nevertheless, it is of current interest to explore alternative, but more efficient fluorescent materials with enhanced photochemical and thermal robustness, excellent biocompatible, less toxic, and superior optical and luminescent properties.

The significant problems preventing further useful photonics applications of fluorescent materials, can be resolved by expanding the study and focus on another range of biomaterials via the utilization of rare-earth (RE) substituted

NPs [8–26]. RE-doped NPs are emerging materials that have been gaining much popularity lately, because of their exceptional luminescence characteristics, including narrow absorption and emission transitions, bright luminescence, huge quantum yields, extensive decay times, and excellent photo-chemical robustness, which could interestingly resolve these strategic problems [16, 17, 20–22, 27, 28]. Through sequential absorption of dual/multi-photon, or energy transfer, RE-doped NPs can produce lower wavelength luminescence (visible) from higher wavelength irradiation (near-infrared), via a process known as upconversion (UC). Minimum photo-bleaching, free of auto-fluorescence, large decay time, tunable multicolor, and improved signal-to-noise ratio are just a few of the benefits of upconverting NMs, which make them ideal candidates for bio-related applications [29–33].

With the fast-growing demand for fluorescent NMs in the health care system, the shape, size, and surface properties are most of the challenging tasks to overcome in particular with photonics-based bio-related applications.

Generally, controlled shape and size fluorescent NPs are prepared, either, at a higher temperature, or in hydrophobic and toxic conditions, with long-chain hydrocarbons. So far, the prepared NPs through these methods are hydrophobic

with restricted dispersibility and colloidal stability in aqueous media [34–37]. Therefore, because these materials lack organic surface functional groups over the exterior of controlled shaped NPs, they exhibited hydrophobicity, resulting in limited applicability in biological systems [38–40].

The reactive surface functional groups/sites facilitate conjugation, or coupling, either covalently, or through coordination bonds with biomolecules [41–43]. To date, synthesis conditions play a significant and sensitive impact on the sizes and surface properties of the NPs nanomaterials, because the growth of the nanocrystals is often limited by the difficulty in material preparation. The majority of researches in literature are focused on controlled morphology, experimental processes, and other phenomena [44–46]. However, a perfect luminescent probe should have powerful emission, small crystalline sizes, good colloidal stability, excellent biocompatibility, and less toxicity. Because of these, we presented a facile-single step synthesis of highly aqueous colloidal $\text{LaF}_3\text{:Yb/Er}$ UCNPs through decomposition of citric acid from the metal complex at a lower temperature. The crystallographic structure, phase purity, morphology, colloidal stability, biocompatibility, thermal stability, outward chemistry, optical properties, and luminescence properties were successfully evaluated by X-ray diffraction pattern (XRD), Thermogravimetric/thermal differential analysis (TGA/DTA), Scanning Electron microscopy (SEM), transmission electron microscopy (TEM), Energy-Dispersive X-ray (EDX) spectroscopy, Fourier-transform Infrared (FTIR), UV/Visible and upconversion photoluminescence spectroscopic methods. The prepared UCNPs are found to be highly dispersed, from colloidal solution in aqueous media. Since citric acid was utilized from the chelating complex with lanthanide ions, the form metal complex decomposes slowly in the presence of ammonium fluoride on increasing the temperature. It is well accepted that synthesizing NPs synthesis is particularly influenced by the preparation conditions. Thus, the orderliness of NMs growth is often concealed by the possibility of the material preparation procedure. In this study, we explained the synthesis of non-surface functionalized UCNPs and presented their high colloidal stability, which could be deemed highly applicable in tagging of biomolecules for further use in biomedical applications. Furthermore, the large specific surface area and rough and porous surface of these UCNPs allow one to design multi-directional systems for simultaneous theranostics, therapeutic, and drug delivery applications.

2 Experimental

2.1 Materials and methods

$\text{La}(\text{NO}_3)_3 \cdot 7\text{H}_2\text{O}$ (99.9%, BDH chemicals, UK), $\text{Yb}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.9%, Alfa Aesar, Germany),

$\text{Er}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.9% Alfa Aesar, Germany), ammonium fluoride (BDH Chemicals, England), citric acid (E-Merck, Germany), and ethanol were of analytical grade and used directly for synthesis as received from the companies without further processing. Milli-Q (Millipore, Bedford, MA, USA) H_2O was utilized for the synthesis and characterization of the materials.

2.2 Synthesis of $\text{LaF}_3\text{:Yb/Er}$ UCNPs

For the synthesis of $\text{LaF}_3\text{:Yb, Er}$ UCNPs, 2.948 g $\text{La}(\text{NO}_3)_3 \cdot 7\text{H}_2\text{O}$, 0.444 g $\text{Yb}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$, and 0.106 g $\text{Er}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ were dissolved in 100 ml Milli-Q water, and the mixed solution was then heated on a hotplate under mechanically stirring at 100 °C. Then, a 1:1 equal molar amount of citric acid was dissolved in Milli-Q water and was slowly added into the strongly stirred metal-ions reaction mixture during the heating process. The reaction was allowed to proceed for 2 h for complete complexation reaction, and/or until the appearance transparent solution mixture. Later, a 1:3 molar amount of ammonium fluoride (1.158 g), or in excess, was introduced slowly into the vigorously stirred ongoing reaction and the reaction was allowed to proceed for another 1 h [16, 18, 47–51]. After the addition of NH_4F solution, the reaction becomes turbid and the precipitation reaction was started. During the appearance of precipitates reaction, the milky suspension undergoes refluxed conditions for 3 h at 150 °C for crystallization and complete conversion of the metal complex into metal fluoride. The resulting precipitates were isolated by centrifugation, washed several times with Milli-Q H_2O and $\text{C}_2\text{H}_5\text{OH}$ to eliminate unreacted reactants. The obtained product was dehydrated in an oven at 100 °C and was used for further characterization.

2.3 Characterization

The powder XRD pattern was obtained using the Rigaku-Dmax-2500 diffractometer with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5404 \text{ \AA}$) from 10 to 80° under 40 kV accelerating voltage. The SEM (JSEM-7600F, JEOL, Japan) equipped with EDX operating an accelerating voltage 5 to 10 kV, was used to study the outer morphology of the samples. The as-synthesized powder sample was lightly scattered onto a sample holder with carbon tape and was then coated with a conducting Pt layer of 3 s for SEM analysis. The inner morphology of the power was scanned using the FE-TEM (JEM-2100F, JEOL, Japan) equipped with EDX operating at 200 kV accelerating voltage. TG and DTA were performed using the Thermogravimetric Analyzer (Mettler Toledo, Expository CH-8603 Schwarzenbach, Switzerland) with a 10°/min heating rate from 25 to 800 °C. Zeta Potential and particle size through Dynamic Light Scattering (DLS) method were

determined from Zeta PALS 90 and Particle Size Analyzer (Brookhaven Instrument Corporation, USA), respectively. The surface chemistry through organic functional groups over the surface of UCNP was determined using the FTIR Perkin-Elmer-580B spectrometer in the 400–4000 cm^{-1} frequency range using the KBr pellet technique. The UV/Visible absorption spectra were obtained from the Cary 60 UV/Vis spectrophotometer (Agilent Technologies, USA) in the 200–700 nm wavelength. The UC spectrum was recorded from iHR320 spectrophotometer (Horiba Jobin Yvon) equipped 980-nm diode laser and an irradiation source with 2.4 W maximum power and the R928P photon-counting photomultiplier tube.

2.4 MTT assay

The toxic potentiality of the $\text{LaF}_3\text{:Yb,Er}$ UCNP was determined by the MTT assays following the Mosmann method [52]. In a 96-well culture plate, 1×10^4 HT-29 cells were plated in each well and allowed to observe overnight in a 5% CO_2 incubator at 37 °C. For the next 24 h, cells were treated to various concentrations (2–200 $\mu\text{g/mL}$) of $\text{LaF}_3\text{:Yb,Er}$ UCNP. After treatment of UCNP with cells, each well received 10 μL MTT (5 mg/mL) and plates were incubated for another 4 h. Finally, the supernatant from all wells was thrown away, and 200 μL of dimethyl sulfoxide was added to each well and stirred well for proper normalization.

3 Results and discussion

3.1 Crystal phase and thermal studies

The X-ray diffraction pattern was performed to investigate the crystallinity, crystal phase, and phase purity of the prepared UCNP. Fig. 1 shows the well-defined diffraction peaks, which are well-indexed with the standard hexagonal phase of pure form LaF_3 space group (JCPDS Card No. 32–0483) [14, 49, 50, 53–56]. The bandwidth of the diffraction lines is noticeably broad as observed in Fig. 1, revealing the material's nanocrystalline nature. The absence of any impurity peaks signifies that either the Yb^{3+} or Er^{3+} ions have been homogeneously assimilated into the LaF_3 crystal lattice sites, or that the volume of reactants is too insignificant to be identified by the XRD. The enlargement of the reflection peaks suggests that the $\text{LaF}_3\text{:Yb,Er}$ NPs synthesized using complex-based decomposition process are of nanoscale in size. The typical particle size of the nanoproducts assessed from the Debye–Scherrer equation ($D_{\text{hkl}} = K\lambda/(\beta \cos \theta)$) using full-width-at-half maxima of the most dominant reflection plane observed at 43.77° is to be ~ 12.3 nm [53, 57, 58].

TGA and DTA were utilized to inspect the thermal steadiness and phase pureness of the sample. As shown in Fig. 2, the TGA curve exhibited sluggish weight loss of approximately 10.5% between 25 and 500 °C, along with two little shoulders at 220 °C and 340 °C. This implies that first degradation occurs because the surface-adsorbed water molecules are eliminated, and then successively organic moieties (citric acid) are removed while increasing the temperature. Subsequently, crystalline or coordinating water molecules are also removed from the UCNP [15, 59–63]. Furthermore, after 500 °C temperature, no weight loss was detected.

3.2 Morphological studies

The morphology of the nano-product was first inspected from the SEM photographs of the as-synthesized $\text{LaF}_3\text{:Yb,Er}$ UCNP. The SEM images in Fig. 3 showed irregular size, spherical-shaped, well-agglomerated nanoparticles with an average crystalline size are about 80–100 nm (Fig. 3A). As observed from images at high-magnification in Fig. 3B, the particles' surfaces are observed to be rugged with porous structures, which are closely interconnected. This may be because they were prepared in aqueous solution, resulting then in the exterior rugged surface of the NPs that are highly hydrophilic. EDX analysis, as shown in Fig. 3C, confirms the occurrence of most of the chemical constituents of the as-synthesized UCNP including lanthanum (La), fluorine (F), ytterbium (Yb), and erbium (Er) ions, respectively. This indicates the successful formation of single-phase UCNP.

The shapes of the particles were further analyzed by the TEM. It is clear from the TEM micrographs that the particles are small in size, irregularly spherical in shape, rough and shallow, porous structure, well-dispersed, having narrow size distribution with an average crystalline size of 8–15 nm. As shown in Fig. 4, the particles are aggregated, because of their hydrophilic surfaces, which are interconnected to each other through hydrogen bondings and of the existence of citric acids over the outward of nanocrystals (Fig. 4A–C). The high-magnification TEM image in Fig. 4C, E demonstrates well-determined lattice fringes of an individual crystal, connoting the high crystalline nature of the materials. An estimated interplanar spacing of 0.222 nm between the adjacent lattice fringes is well-indexed to the (111) plane of hexagonal LaF_3 crystal (Fig. 4F) [64]. The selected area electron diffraction pattern of an individual particle in Fig. 4D, illustrates the well-defined diffraction rings corresponding to (002), (111), (300), (302), (411), and (330) planes, which therefore confirms the high crystalline nature of the materials [64–66]. Additionally, the existence of all possible lattice reflection rings in the spectrum reflects the formation of the crystallites in the same orientation. Also notably, we observed variations in the particle size, as measured by different techniques, such as XRD, SEM,

Fig. 1 A X-ray diffraction pattern along with (B) crystal structure of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

TEM, and particle size distribution. The discrepancy in the particle sizes could be due to the variation in experimental procedures used for measuring the size, and sample preparation method. For example, in the SEM method, the samples are prepared like film, which could cause nanomaterials to agglomerate, whereas in TEM, the powder is ultrasonically dispersed in a solvent giving high-magnification images, thus giving more accurate details of the morphology and size of the particles. While TEM measures the whole particle composed of crystallines, XRD measures crystallites. Hence, the disparity in crystal sizes as defined by TEM and XRD may be attributable to the agglomeration of crystallites forming a particle, the existence of imperfections, as well as some types of anisotropy in the particle unity duration,

which reasons the XRD diffraction lines to expand even further. The EDX profile in Fig. 5, confirms the presence of all possible elements (La, F, Yb, and Er) in the $\text{LaF}_3\text{:Yb, Er}$ UCNPs.

3.3 Colloidal stability, biocompatibility & surface chemistry

The dynamic light scattering (DLS) method was utilized to monitor the hydrodynamic size of the particles. When the average particle size distribution of the UCNPs was greatly enhanced, it could be due to the high agglomeration of the ultra-small size NPs (Fig. 6A). Although the DLS spectrum exhibited polydispersibility of the UCNPs because of

Fig. 2 Thermogravimetric/thermal differential analysis of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

Fig. 3 SEM micrographs of **A** low resolution **B** high resolution and **C** EDX spectrum of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

Fig. 4 TEM micrographs of **A** low-resolution **B** high-resolution **C** high magnifying image **D** SAED pattern **E** lattice fringe in the high magnifying image **F** d-spacing value of the $\text{LaF}_3\text{:Yb/Er}$ UCNP

the hydrophilic surface, NPs are sticky and forms clusters, which results in a high particle size distribution compared to the XRD, SEM, and TEM micrographs. Since UCNP form clustering in aqueous media as indicated in the DLS curves, when measured multi-time, the observed hydrodynamic size of the UCNP is typically bigger than the actual particle sizes from TEM data [67, 68]. This zeta potential and DLS study exhibit superior dispersibility with excellent colloidal stability. Further, the observed negative charge value of the UCNP would be highly beneficial in photonics-based bio-tagging agents or luminescent bio-probe, since determining the colloidal stability of the prepared UCNP in biological

environments is a fundamental requirement for optimizing preparation conditions and determining the UCNP fate in either in-vivo/in-vitro experiments.

The dispersibility, colloidal stability, hydrophilicity, and biocompatibility of the synthesized UCNP aqueous solution are the key parameters that could open the door for their practical use in bio-related applications [29–31, 69]. The colloidal stability, surface charge, or biocompatibility were determined from Zeta Potential. An observed zeta potential value of the UCNP at physiological pH 7.0 was -17.0 mV (Fig. 6B). The negative zeta potential value is evidence of the surface-attached hydroxyl groups,

Fig. 5 EDX spectrum and in the inset of the $\text{LaF}_3\text{:Yb/Er}$ UCNP

which form hydrogen bondings in an aqueous solution. Notably, as observed from TEM micrographs, the UCNP are in very small crystalline size, rough, porous structure that could be easily deprotonated in an aqueous solution. Because of this, these ultra-small size features of the UCNP upsurge the specific surface area resulting in enhancing the external charge, and endorsing their steadiness in aqueous solution at neutral pH or physiological conditions. We, therefore, expect that the surface hydroxyl groups offer a potent claw for the UCNP to make covalent bonds with various biomolecules.

The surface chemistry of the as-prepared UCNP was investigated by FTIR spectroscopy. Figure 7 displays the highly dominant diffused infrared absorption peaks found at 3427 cm^{-1} , along with the sharp 1232 and 618 cm^{-1} peaks are assigned to the asymmetric/symmetric stretching $\nu(\text{OH})$, bending $\delta(\text{OH})$, and wagging $\gamma(\text{OH})$ vibrational modes of the surface-bound water molecules, respectively [13–15, 17, 47, 70, 71]. Observed infrared absorption peaks positioned at 1723 , 1590 , and 1397 cm^{-1} are assigned to the asymmetric/symmetric stretching, bending vibrational modes of the carboxylic ion ($-\text{COO}^-$) of surface-attached citric acid, respectively [13, 14, 37, 47, 72, 73]. A weak intensity peak detected at 414 cm^{-1} is attributed to the metal–oxygen framework. These observations are in good agreement with the previous TGA results.

3.4 Optical properties

The UV/visible spectra were recorded in aqueous media to optimize the optical properties, colloidal dispersibility of the as-prepared UCNP. The absorption spectrum of UCNP in Fig. 8A exhibited significant absorption in the visible region, but the absorption band is highly uplifted in the ultraviolet region. It is a known fact that the lanthanum is optically inactive and diamagnetic, however, the prepared LaF_3 host matrix shows significant absorption in the UV/Visible region. This implies that the UCNP are well dispersible and make excellent colloidal solutions in aqueous media. An optical absorption spectrum was utilized to estimate the energy bandgap value of the material. An estimated bandgap value from the spectrum is about 3.7 eV , according to the Tac and Menth formula (Fig. 8B) [13, 47, 50, 63, 74, 75].

3.5 Upconversion luminescence properties

Upconversion luminescence spectrum of the as-prepared $\text{LaF}_3\text{:Yb/Er}$ UCNP was recorded to investigate the effective substitution of Yb^{3+} and Er^{3+} ions into the crystal lattice. The UC spectrum in Fig. 9A reveals the most of the dominant transitions observed at 655 , 630 , 580 , 540 , 40 , 450 , and 420 nm , that are assigned to the $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$, $^4\text{I}_{9/2} \rightarrow ^4\text{I}_{15/2}$, $^2\text{H}_{9/2} \rightarrow ^4\text{I}_{15/2}$, $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$, $^4\text{F}_{7/2} \rightarrow ^4\text{I}_{15/2}$, $^4\text{F}_{5/2}$, $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{15/2}$, and $^2\text{H}_{9/2} \rightarrow ^4\text{I}_{15/2}$ intra-configurationally

Fig. 6 A particle size distribution curve B Zeta potential study of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

Fig. 7 FTIR spectrum of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

$4f-4f$ transitions of Er^{3+} ions, respectively [58, 64, 66, 76, 77]. As observed in the UC spectrum, the green emission corresponding to the $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ is highly dominant in the

spectrum, whereas the red emission transition is located at 655 nm ($^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$) exhibits weak intensity. These results show that the as-prepared highly biocompatible UCNPs

Fig. 8 A UV/visible spectrum and B optical band gap curve of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

Fig. 9 A UC luminescence spectrum along with B energy diagram of the $\text{LaF}_3\text{:Yb/Er}$ UCNPs

reveal enough extreme UCL emissions in the visible region. The UC spectrum in Fig. 9 shows weak emissions, which could be either due to the increased crystalline diameter in

the specific surface area, and to the surface defects that scattered the incident light, or the loss of excitation energy of the luminescent centers, which result in relatively sharp/weak emission transitions. The energy curves and UC processes of Er^{3+} ions in UCNPs are exhibited in Fig. 9B. The ground-state absorption (GSA) and later the excited-state absorption (ESA), or energy transfer UC (ETU) phenomenon can populate the $^4\text{F}_{7/2}$ level under the 980-nm excitation. The Er^{3+} ion in the $^4\text{F}_{7/2}$ level, then, speedily relaxes to the lesser $^2\text{H}_{11/2}$, $^4\text{S}_{3/2}$, and $^4\text{F}_{9/2}$ levels. In conclusion, radiative transitions from $^2\text{H}_{11/2}$, $^4\text{S}_{3/2}$, and $^4\text{F}_{9/2}$ levels to $^4\text{I}_{15/2}$ levels create green (517 and 541 nm) and red (653 nm) emissions, respectively [78]. In addition, the very weak emission intensity of the red transition confirms that the nonradiative transition development of $^4\text{S}_{3/2} \rightarrow ^4\text{F}_{9/2}$ is primarily responsible for the population of the $^4\text{F}_{9/2}$ level, which is less probable to occur due to the high energy gap between $^4\text{S}_{3/2}$ and $^4\text{F}_{9/2}$ levels ($\Delta E = \sim 3200 \text{ cm}^{-1}$).

3.6 Toxic potentiality by MTT assay

To assess the toxic potentiality of the as-prepared UCNPs dose-dependent cell viability was monitored by MTT assay as illustrated in Fig. 10. To assess cell survival after treatment of serum cells with UCNPs, an MTT test was used to determine mitochondrial activity and membrane outflow. As demonstrated in Fig. 10, the cell viability slightly increased could be due to the higher biocompatibility of the UCNPs. On increasing the dose of UCNPs the cell viability was sharply reduced which is strong support to the zeta potential observed results. It advocates that the surface-anchored hydroxyl groups attached to the cell membrane affect cell growth, resulting in enhancement of cell viability and suppressed toxicity [70, 79]. These surface hydroxyl groups are predicted to be vulnerable to further biomodification without limitations since the positively charged surface might result

Fig. 10 Cell viability by MTT assay measurement at 2–200 mg/mL for 24 h

in non-specific adsorption on cell membranes for biological applications.

4 Conclusion

A facile-synthesis route was employed to prepare UCNPs at lower temperatures via a complex-based thermolysis process. The XRD pattern verified the crystallographic structure, phase identification, crystallinity, with hexagonal LaF_3 crystal structure. TEM and SEM micrographs determine the UCNPs materials to be of irregular size, spherical-shaped, rugged surface, porous nature with very small size (sizes 8–15 nm). High aqueous dispersibility, good colloidal stability, and biocompatibility of the UCNPs were tested by the negative zeta potential value and absorption spectrum measured in an aqueous solution. Surface chemistry shows a strong infrared band indicating the presence of active hydroxyl groups, which would be easily available for conjugation with biomolecules. The presence of surface-anchored hydroxyl groups exhibits high colloidal stability along with a negative zeta potential value and high cell viability as measured from the MTT assay. A dominant green UC emission was observed at 540 nm, which corresponds to the $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transition of the Er ions. Optical absorption spectrum, FTIR, particle size distribution, zeta potential, and EDX analysis show and confirm the surface adherence of active functional groups, which are highly immensely

required for their future use in photonics-based biomedical sciences.

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Declarations

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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