Biocompatible Carbon Dot Decorated α-FeOOH Nanohybrid for an Effective Fluorometric Sensing of Cr (VI) in Wastewater and Living Cells

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Abstract
This article reports the fluorometric detection of toxic hexavalent chromium Cr (VI) in wastewater and Cr (VI) contaminated living cells using in-situ grown carbon quantum dots into the goethite (α-FeOOH) nano-matrix. The synthesized nano-hybrid shows enormous potential in determining the chromium contamination levels in various types of water samples. This selective fluorometric probe is enormously sensitive (LOD 81 nM) toward hexavalent chromium, which makes it a dedicated chromium sensor. Moreover, the sensing mechanism has been assessed using Stern–Volmer’s equation and fluorescence lifetime experiments showing the simultaneous occurrence of photoinduced electron transfer and the inner filter effect. This chromium sensor has also been employed to assess the contamination level in real-life industrial wastewater. The performance of this probe in a real-life wastewater sample is quite commendable. Further, this biocompatible fluorometric probe has been used to demonstrate the in-vitro sensing of Cr (VI) in HeLa cells. The rapid detection mechanism of hexavalent chromium in living cells has been validated using theoretical docking simulations. Henceforth, this fluorometric sensor material could open new avenues not only in wastewater monitoring but also in biomedical applications.

Keywords Hexavalent chromium · Fluorometric sensor · Stern–Volmer plot · Molecular docking

Introduction

Natural sources like weathering of rocks, volcanic eruptions, and mining are counted to be potential sources of heavy metal contamination [1]. Heavy metals are those that have a specific density of 5gm/cm³ and have the ability to affect the environment and living organisms [2].

Of all the heavy metals known chromium is one of the most toxic heavy metals, commonly prevalent in nature as trivalent chromium Cr (III) and hexavalent Cr (VI) [3]. Cr (VI) has been regarded as 100-fold toxic and mutagenic than its lower oxidative counterpart Cr (III) [4]. As an effluent, it is often improperly discharged mainly into waterbodies from printing, electroplating, and tanning industries and thereby promoting biomagnification, scale rot, and osmoregulatory dysfunction of fish [5]. Cast iron pipes and ductile iron pipes are mostly lined with cement mortar that contains a considerable amount of chromium and thus chromium leaches out from the cement mortar lining into the drinking water [6]. It has been seen that Cr (VI) exposure to Swiss mice causes a sharp decrease in leucocyte and erythrocytes with an additional deforming of echinocyte formation from erythrocytes [7]. Cr (VI) has been recognized as a group-1 carcinogen by World Health Organization (WHO) as it can disrupt DNA via reactive oxygen species (ROS) generation, a maximum limit of 50 µgL⁻¹ has been set by WHO [8, 9].

Considering the toxicity of the numerous organic and inorganic fluorophores and chromophores there is a need
for a cost-effective and biocompatible sensor that can detect Cr (VI) in water samples [10]. Besides, almost all of the methods of preparation were mostly two-step reactions for conjugating the fluorophores and employed robust detection techniques using the electrochemical method. Thus, it necessitates the use of quick, cheaper methods and biocompatible fluorophores that could be procured easily fabricated with the nanoparticle for the detection of chromium.

Herein, α-FeOOH nanoparticle has been modified with in situ grown C-dots to detect hexavalent chromium in wastewater fluorometrically. C-dot has a tendency to form agglomerates and thereby loses its fluorescence property rapidly. Thus, there is a pressing need to restrict such agglomeration for better fluorometric applications. There are earlier reports on C-dot immobilized on oxyhydroxides and mesoporous silica-like matrices for sensing, [11] but those matrices are way too toxic to handle as they can diffuse through the skin and pulmonary routes [12–14]. FeOOH nanoparticles have been approved and used widely as food and iron supplements [15, 16] thereby its bio-safe property makes it advantageous in employing as a heavy metal ion sensor. Further, a molecular docking study has been performed with the probe and two flavoproteins (cyt\textsubscript{b}\textsubscript{5} and cyt P450) to estimate the intercellular biosensing pathway of the sensing probe. The theoretical docking studies have been experimentally verified using fluorescence microscopy revealing the early-stage cancer detection property of the probe.

**Experimental Section**

**Materials**

The ferric nitrate, anhydrous citric acid and ethylenediamine were purchased from Merck, Germany. The chemicals were all of the pure grades and did not require any further purification. Ultra-pure Millipore water (resistivity ~ 18.2 M\textOmega\cdot cm) was used throughout the experiments. The glassware and sample holders were cleaned using aqua regia before and after each experiment.

**Synthesis C-Dot Doped α-FeOOH (FCD)**

In a one-pot synthesis process, 6.464 g of ferric nitrate was taken along with 0.323 g of citric acid in 160 mL of Millipore water and was thoroughly mixed using a magnetic stirrer at room temperature until all the chemical contents were dissolved. To this, ethylenediamine was added drop-wise until the pH of the solution reached 12. The mixture was then stirred for another 3 h and then transferred to a Teflon-lined stainless-steel autoclave. The autoclave was then heated at 180 °C for 12 h and thereafter cooled to room temperature to collect the brick red precipitate through centrifugation. After proper washing, the precipitate was dried in a vacuum chamber for 24 h and ground in an agate mortar to obtain the fine powder. Finally, the synthesized sample is named FCD and sent for characterization.

**Material Characterization**

To provide a detailed insight into the crystallographic details of the synthesized materials, X-ray crystallography was employed using X-Ray Diffraometer (Model D8 Advanced, Bruker AXS) with Cu-K\textsubscript{α} target (\(\lambda = 1.5405 \text{ Å}\)) from 10\(^{\circ}\) to 80\(^{\circ}\) in the 20 range and the scan speed was fixed at 0.02 steps/sec. The operating tube voltage was fixed at 35 kV and 35 mA to generate the X-rays. Further, the refinement of the diffractograms has been done by using the Rietveld-based program MAUD v.2.99 (Material Analysis Using Diffraction) [17] and the refined structures were visualized using VESTA v.3.0 (Visualisation for Electronic Structural Analysis) [18, 19] for better understanding. Additionally, a FTIR-8400S, Shimadzu was employed in the wavenumber ranging between 500 and 3000 cm\(^{-1}\) to observe the bonding networks present in the samples. The samples were mixed and homogenized in KBr media in a 1:50 sample to KBr ratio.

The morphological features of the synthesized materials were ascertained by an Inspet-F50, FEI Field Emission Scanning Electron Microscope (FESEM). Very small amounts of samples were placed on carbon-coated grids and used for observing the microscopic details. The accelerating voltage of the electron gun was set in between 10 and 20 kV for taking the micrographs. Further, the size of the nanoparticles was investigated by employing a Jeol-2000FX Transmission Electron Microscope (TEM). A homogenous solution of the sample was prepared by dissolving the sample in acetone and the sample was kept under ultrasonication for 2 h. The solution was then drop-casted to form a thin film over a carbon-coated copper grid (300 mesh) and then dried under a vacuum before microscopy. The TEM micrograph was taken under an excitation of 200 kV.

The optical absorption properties of the samples were analyzed using a 1900i, Shimadzu spectrophotometer. Whereas, all the fluorescence characteristics and fluorescence lifetime of the samples were performed in a Cary Eclipse, Agilent fluorescence spectrophotometer equipped with a Cary single-cell Peltier accessory, Agilent in an excitation wavelength (\(\lambda_{ex}\)) 345 nm. The excitation and emission slits were set at 5 nm throughout the experiments.

**Biological Experiments and Cell Culture**

Autodock Tools v.1.5.6 was used to prepare the proteins and the ligand molecule (cdot). The water molecules of the protein have been removed and polar hydrogen bonds and...
Kollman charges were added to the protein structures [20]. Autodock vina v.1.1.2 was used to estimate the binding affinities between the protein–ligand complexes [21, 22]. The binding pockets were identified and visualized using PyMol v.2.0.7 program [23, 24].

A human cervical cancer cell line (HeLa) was purchased from National Centre for Cell Science (NCCS Pune, India). These cells were cultured in DMEM (Dulbecco’s Modified Eagle’s Medium) medium and treated with 5% FBS (fetal bovine serum) followed by incubation at 37 ºC in a 5% CO2 atmosphere for 24 h. Further, the cells were washed with 1× PBS (phosphate buffer saline) buffer to avoid any contamination. The fresh medium was then added to the washed cells and incubated again at 37 ºC with a 5% CO2 atmosphere. HeLa cells were then divided into two parts (namely, IA and IB) and placed over two separate PV/BH@CD membranes, those have already been mounted over cell culture plates and sent for overnight incubation (37 ºC with 5% CO2 atmosphere). On the very next day, the IB sample was treated with a small drop of Cr (VI) solution of 50 µM and incubated for another 2 h to interact. After incubation, the samples were sent for microscopy under a fluorescence microscope (Leica, Germany).

Results and Discussion

Structural and Morphological Analyses

The structural information of the synthesized sample has been collected by employing X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR). The diffractogram show numerous diffraction lines (h k l planes) of the orthorhombic oxy-hydroxide phase of iron (α-FeOOH) corroborating the successful synthesis of the goethite. Figure 1 shows the diffractogram having diffraction maxima located at 17.69°, 33.34°, 35.85°, 40.99°, 49.57°, 54.35°, 62.82° and 64.18° corresponds to the (h k l) planes of (0 2 0), (1 3 0), (1 0 1), (1 2 1), (1 5 0), (2 4 0), (2 5 0) and (0 6 1) respectively that well matches with the Joint Committee on Powder Diffraction Standards (JCPDS) data card no. 81–0464. The absence of any other diffraction planes suggests the purity of the sample. Further, Rietveld refinement of the diffractogram has been performed in order to estimate the crystallite dimension, microstrain, bond angles, bond lengths, and other phase parameters like anisotropic growth. It is observed that the microstrain value, in this case, is quite high (1.26×10−3), which could arise due to the incorporation of carbon quantum dots. The microstructural parameters have been mentioned in Supplementary Table S1 for better understanding.

The presence of carbon quantum dots in goethite has also been confirmed by using FTIR spectra of the synthesized sample shown in Fig. 1. The C–C, C-O, and C=O stretching bands are assigned to the vibrations centered at 1035 and 1217 cm−1 respectively depicting the presence of carbon content in the sample [25]. While the absorption bands at 520 and 675 cm−1 are attributed to the Fe-CO and Fe–O symmetric stretching vibrations [26, 27]. The vibration maxima between 774 and 900 and 1635 cm−1 are ascribed to the O–H bending suggesting the adsorbed moisture and presence of CONH vibrations respectively in the sample [27, 28] A small vibration centered at 1525 cm−1 is assigned to the N–H bending arising from the nitrogenous carbon quantum dots [11].

The morphology and particle size of the sample have been estimated by using FESEM and TEM micrographs depicted in Fig. 1. The FESEM image of the sample shows an admixture of spherical and hexagonal particles. The hydrothermally grown carbon dot contained goethite sample (FCD) is quite agglomerated and found to be in the nano regime. In order to estimate the particle size, transmission electron microscopy has been assigned. The TEM micrograph shows 30–50 nm hexagonal/ spherical particles containing 5–7 nm dark spots. These dark spots are assigned as carbon quantum dots as seen in previous characterizations. In reality, the in-situ hydrothermal treatment successfully incorporates the carbon dots within the goethite matrix, which is visible in the TEM image.

Optical Properties of the Synthesized Sample

The optical quality of any sample can be verified by using its absorbance and emission properties shown in Fig. 2.

Herein, absorption spectroscopy has been performed to estimate the excitation energy of the nanostructure. It is observed that a small absorption maximum is located at 240 nm, which is usually ascribed to the π–π∗ transition of the sp2-hybridized carbon atoms of the carbon dot moiety [29]. Additionally, a relatively stronger absorbance has been achieved at 342 nm, suggesting the n–π∗ transition related to the surface defects of the carbon dots in C-N bonds in sp3 hybridizations sourcing from the amine (–NH2) groups from surface functionalization [9, 30, 31]. The broad absorbance bands centered between 450 and 572 nm are sourced from the Fe–Fe transitions. A similar observation has also been made by Sherman et al. in their 1985 work [32]. Further, the excitation and emission spectra have been recorded to assess the fluorescence quality of the sample. The excitation spectrum in Fig. 2 shows a significant peak centered at 345 nm, which is in accordance with the absorbance spectrum of the FCD sample. Additionally, the sample has been excited manually with a series of wavelengths ranging between 300–400 nm in order to validate the exact excitation energy. It is found that the energy which corresponds to the 345 nm wavelength is providing the optimum fluorescence emission.

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at 460 nm shown in Fig. 2 and thus this wavelength is selected to excite the fluorophores of the sample for further fluorometric experiments. Under the 345 nm excitation, the FCD sample glows with an outstanding blue fluorescence and does not alter the position of the emission peak under varying excitation wavelengths as shown in Fig. 2. In reality, the surface functional groups of the nitrogenous carbon dot introduce new energy levels and control the bandgap causing enhanced fluorescence intensity. The presence of nitrogenous dopant, which in this case has been introduced by using ethylenediamine, causes charge dislocation and efficiently promotes the electron transfer capacity of the carbon quantum dots [33–36]. This validates the FCD to be a promising fluorescent material in the blue region of the spectrum and could be employed in fluorometric applications.

**Dependence of the Fluorescence Quality on Different Ambient Conditions**

The fluorescence stability of the nano-engineered sample (FCD) is evaluated against varied ambient conditions to justify its real-life applicability. Initially, the fluorescence stability of the sample has been measured over a period of 2 h at an interval of 10 min to check for any fluorometric decay of the fluorophores. It is evident that no noticeable

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**Fig. 1** a Refined X-ray diffractogram of the prepared material; b FTIR spectrum of the synthesized material; c FESEM and d TEM images of the synthesized nanostructure
alteration has occurred in the fluorescence intensity inferring the photo-stability of the sample (Fig. 3). The FCD sample has been exposed to a varying pH environment, ranging from extreme acidic 1.8 to extreme alkaline 12.7 conditions as seen in Fig. 3. The fluorescence quenching intensity of the synthesized FCD takes place when subjected to different pH conditions. This suggests the fluorophores of the FCD sample are highly stable at these varying pH conditions.

Additionally, in Fig. 3 the thermal response to the photo-stability has been assessed by varying the working temperature (10–70 °C) of the FCD sample while measuring the fluorescence level. The fluorescence intensity does not seem to fluctuate much, but it turned out that room temperature conditions (at about 30–50 °C) are the best working temperature for the fluorescent FCD sample. The DTA-TGA (Fig. S1) results revealed there is almost no mass change over the entire range of temperature. However, the DTA results that at 40 °C there is an endotherm followed by an exotherm. The possible explanation for this can be due to the release of the adsorbed moisture in this region.

**FCD as a Fluorometric Sensing Probe for Hexavalent Chromium (Cr (VI))**

Selectivity and Sensitivity Assays of the Synthesized Probe

Selectivity and sensitivity are the utmost important parameters to rationalize the sensing efficacy of a probe. Figure 4 shows that the synthesized fluorometric probe (FCD) has been exposed to a wide range of cations and anions (As\(^{3+}\), Ca\(^{2+}\), Cd\(^{2+}\), Mg\(^{2+}\), Pb\(^{2+}\), Hg\(^{2+}\), K\(^+\), Cr\(^{6+}\), Cl\(^-\), CO\(_3\)\(^{2-}\), SO\(_4\)\(^{2-}\), OH\(^-\), S\(^2-\), NO\(_3\)\(^-\)) in order to assess its selectivity.
Initially, each ionic solution has been separately prepared at 500 µM concentration and added to the sensing probe (FCD) to measure the fluorescence intensity. Although no notable changes have been observed in the fluorescence intensity of the probe for any ionic environment, however in the case of Cr (VI) the fluorescence intensity quenches drastically, which can be visualized even through naked eyes. Additionally, in Fig. 4 the colorimetric analysis of this sensing phenomenon has been validated using the CIE-1931 plot. The fluorometric colour coordinates of the chromium-induced sample are $x = 0.21875$ and $y = 0.1888$ whereas it is found to be $x = 0.15504$ and $y = 0.1344$ in the pure sensor material. Such dramatic quenching makes this fluorometric probe (FCD) a potential Cr (VI) sensor.

Alternatively, a quantitative quenching experiment has been conducted to determine the amount of chromium contamination in water. In this experiment, the varying concentration of hexavalent chromium has been added to the fluorometric probe (FCD) separately and the corresponding fluorescence intensities have been measured. It is found that the fluorescence intensity has been gradually quenched upon Cr (VI) addition. Further, the fluorescence intensities

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**Fig. 3** Fluorescence stability experiments of the sensing probe varying the a temperature, b pH and c time respectively

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at higher concentrations follow an exponential decay which is quite significant in this type of sensing probe evident in Fig. 5. The concentration-dependent fluorescence intensities have been plotted and further fitted with linear and exponential Stern–Volmer equations [37, 38].

The Stern Volmer plot (S-V) was used to estimate the limit of detection (LOD) and limit of quantitation (LOQ) using the following expressions,

\[ \frac{I_0}{I} = 1 + K_{SV}[M] \] \hspace{1cm} (1)

\[ \frac{I_0}{I} = A \exp(K_{SV}[M]) \] \hspace{1cm} (2)

where \( I_0 \) and \( I \) are taken as fluorescent intensities of the probe before and after the Cr (VI) addition, \([M]\) stands for the concentration of respective ions, \( A \) is a constant term and \( K_{SV} \) is the Stern–Volmer constant. The linearity of the plot was found up to 10 µM concentration beyond this concentration of Cr (VI) exponential decay of the fluorescence occurred.

The LOD and LOQ of the probe have been estimated using Eqs. 3 and 4 and found to be 81 nM and 269.73 nM respectively.

\[ \text{LOD} = \frac{3 \sigma}{K_{SV}} \] \hspace{1cm} (3)

\[ \text{LOD} = \frac{10 \sigma}{K_{SV}} \] \hspace{1cm} (4)

where \( \sigma \) and \( K_{SV} \) are the calculated normalized standard deviation of the fluorescence of the sensing probe without

Fig. 4  a Selectivity study of the sensor probe against an array of different ions; b CIE-1931 plot showing colorimetric analysis of the sensor material

Fig. 5  a Concentration-dependent quenching experiment; b linear and c exponential S-V Plots of the sensing probe upon Cr (VI) addition
any quencher (taking at least ten separate experiments) and S-V quenching constant respectively. Such a competent selectivity and low detection limit (LOD 81 nM) with moderately high $K_{SV}$ values suggest the fluorescent FCD is an effective sensing probe for hexavalent chromium in the aqueous medium (Table S2).

**Detection Mechanism of the Sensing Probe**

The fluorometric detection of hexavalent chromium is ascertained by using the S-V plots and the fluorescence lifetime data of the sensor material. The simultaneous decay of the steady-state fluorescence (from S-V plots) and fluorescence lifetime upon chromium addition suggests that the fluorescence quenching mechanism takes place in the excited state of the fluorophores. The linear S-V plot (up to 10 µM concentration) in Fig. 5 of the sensor material also validates the photoinduced electron transfer from the fluorophores to the quencher moiety [38–40]. Such electron transfer definitely restricts the radiative transition during the emission of the fluorophore molecule (precisely carbon dot). Thus, no emission occurs during the LUMO–HOMO transition of the fluorophores due to an insufficient number of electrons. This phenomenon has been reported by various other groups in their recent papers [11].

Moreover, at higher quencher concentrations (> 10 µM concentration), the fluorophores are surrounded by the quencher ions, which block the radiative path of the fluorophores causing rapid fluorometric quenching. Such a phenomenon is known as the inner filter effect [41–43]. Herein, the simultaneous occurrence of the photoinduced electron transfer and inner filter effect is obtained at higher Cr (VI) concentrations, which justifies the exponential S-V plot.

**Application of Sensor in Real-life Water Samples**

The efficacy of the synthesized probe was analyzed for an array of water samples collected from different sources. Potable drinking water was taken from a water purifier, pond water was collected from a nearby small pond within the Jadavpur University campus and the wastewater was collected from drainage near the Jadavpur area, Kolkata. The water samples were collected in fresh sterile tubes and were further passed through 0.45 µm membrane filters and divided into two parts. One part is treated with 50 µM Cr(VI) and the other remained untreated. The physical parameters of the collected freshwater samples have been assessed using a Hanna-HI991300 portable pH/TDS/Temperature meter prior to the fluorescence assay (Table S3). The fluorescence intensity in all the cases is recorded and depicted in Fig. 6. It is found that the fluorescence intensity of the Cr (VI) treated water samples get quenched irrespective of their source. Such sensing characteristics of the sensing probe in various real-life water samples certainly reveal the real-life applicability of the probe.

The sensing efficacy of the synthesized probe was further tested against real-life tannery wastewater, which was collected from a canal adjacent to a tannery factory. Initially, the elemental analysis was performed by employing an inductively coupled plasma atomic absorption spectroscopy (ICP-AES) showing an alarming amount of chromium (16.53 ppm) (Table S4) besides other toxic heavy metals. Further, the fluorescence intensity of this wastewater sample

![Fig. 6](image-url) (a) Detection of hexavalent chromium in different water samples (b); Real-life sensing of Cr (VI) in tannery wastewater

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has been experimented with using the synthesized sensing probe (FCD). The fluorescence intensity is found to decrease rapidly after the addition of the wastewater sample into the probe solution. This proves the fact that our synthesized nano-probe can detect Cr (VI) in real-life industrial wastewater samples.

**In-Vitro Biosensing of Cr (VI) using the Probe**

Hexavalent chromium Cr (VI) enters into the cells via an array of enzyme mediating reactions with the generation of intermediates and free radicals like hydroxyl and peroxide ultimately culminating in the production of Cr (III). This reduction of chromium can be extracellular or intracellular, the latter piles up ultimately in the cell to give rise to genotoxicity, its intercalation within the DNA through Fenton’s reaction, causing oxidative stress via p53 generation [44–50]. Thus, it is necessary to detect hexavalent chromium in living cells in order to assess the rate of contamination.

Herein, the experimental verification of the biosensing efficacy of our probe (FCD) has been performed using a simple fluorescence microscopy technique [51–54]. HeLa cells have been used to determine such activity of the sensing probe. Initially, HeLa cells were segregated into two segments. One segment is treated with hexavalent chromium and the other one remained untreated. Both the treated and untreated cells were additionally treated with the sensor material prior to the Cr(VI) treatment. Finally, the cells are seen using a fluorescence microscope and the images are depicted in Fig. 7. The fluorescence microscopy images show a promising blue emission in the untreated sample under UV excitation. This suggests the permeability of the nano-sensor (FCD) through the cell membrane. Whereas, the Cr(VI) treated samples do not show any fluorescence under the UV excitation energy. Such drastic quenching of fluorescence suggests the successful sensing efficacy of Cr(VI) in living cells. In order to validate such biosensing activity, a theoretical molecular docking study was performed involving the probe (FCD) with that of cytochrome-b₅ (cyt b₅) and cytochrome-P450 (cyt P450) as shown in Fig. 8. There is a total of nine poses obtained for both cyt b₅ and cyt P450 separately, among which the initial poses have been selected as they are providing the lowest binding energies. In the case of cyt b₅, there was weak hydrogen bonding resulting from C=O and N–H interaction between the glycine residue and the OH-group of the carbon dot moiety of the sensing probe. Additionally, the tyrosine moiety of the enzyme is well attached to the probe resulting in a binding affinity of -7.8 kcal/mol between the sensor and cyt b₅.

**Fig. 7** Bio-imaging of pure and Cr (VI) contained He La cells using the synthesized sensor material
On the other hand, the carbon dot moiety of the fluorescent probe is attached to the crevices of the cyt P450 by weak hydrogen bonding. This interaction with amino acids like threonine and alanine resulted in a binding affinity of -8.0 kcal/mol between the sensing probe and the enzyme. The terminal nitrogen of the sensor moiety in this case forms weak hydrogen bonds with both the carboxylic groups of the hydrophobic threonine (Thr 309) and aliphatic alanine (Ala 305) for interaction.
Conclusions

In this work, a fluorescent carbon quantum dot incorporated biocompatible α-FeOOH nanoparticle has been synthesized through a facile hydrothermal method. The x-ray crystallographic studies coupled with elemental and morphological analyses infers the successful synthesis of the hybrid nanoparticle. The synthesized nanosystem acts as a selective and sensitive probe for hexavalent chromium ions in wastewater with a pronounced sensitivity (LOD 81 nm). It can be presumed that the fluorescence quenching is taking place at an excited state, which is a case of photoinduced electron transfer, where with the addition of Cr (VI) quenches the fluorophores rapidly. In higher Cr (VI) concentrations, the fluorescence intensity seems to decrease a way faster and can be attributed to the simultaneous possessions of the inner filter effect and photoinduced electron transfer. The efficacy of the probe has been validated by using various types of Cr (VI) contained waters showing uninterrupted sensing efficiency of the probe in all water types. Additionally, a sensing experiment has been conducted in chromium-containing industrial tannery wastewater, which also depicts the successful detection of hexavalent chromium irrespective of other heavy metals present in the sample. Such an efficient and rapid fluorometric probe has been employed in biosensing studies to detect Cr(VI) in living cells. The sensor material shows an excellent blue fluorescence in cells, whereas it gets quenched upon chromium addition. Such sensing activity has been theoretically demonstrated using molecular docking simulations showing that the cyt b2 and cyt p450 are primarily responsible for such sensing phenomenon in HeLa cells. Such excellent bioimaging capability, especially in the cancer cell line confirms the potentiality of the sensor in early-stage cancer detection. Such natural mineral-based cost-effective but efficient sensor can have the immense possibility as a tumor marker and in biopsy applications as an alternative to the expensive medical techniques. Moreover, this sensor can be useful for tracing the pathway for biomagnification and in bioaccumulation studies. Hence, this fluorosensor is a promising candidate in wastewater monitoring systems but also creates an opportunity to evaluate chromium toxicity in living systems.

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Data Availability Statement The data will be available at the reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare that they have no competing interests.

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