A glassy carbon electrode modified with $\gamma$-Ce$_2$S$_3$-decorated CNT nanocomposites for uric acid sensor development: a real sample analysis†

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$\gamma$-Ce$_2$S$_3$-decorated multi-walled carbon nanotube nanocomposite (Ce$_2$S$_3$-CNT NC) was synthesized by a wet chemical method in basic phase. Characterization of the resulting Ce$_2$S$_3$-CNT NCs was performed in detail by field emission scanning electron microscopy (FE-SEM) attached with energy dispersive spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), UV/vis spectroscopy, FT-IR spectroscopy, and X-ray diffraction (XRD). A glassy carbon electrode (GCE) was fabricated using the Ce$_2$S$_3$-CNT NCs and then it was utilized to develop a biological sensor for the detection of uric acid (UA) via a simple electrochemical approach. With the selectivity study, UA was selected as a target since it exhibited a fast electrochemical response towards the Ce$_2$S$_3$-CNT NC-fabricated GCE sensor in the I–V method. The fabricated sensor also displayed an excellent sensitivity, very low detection limit, long-term stability, and reproducibility. In the diagnostic study, a linear calibration plot ($r^2 = 0.9972$) was obtained for 0.1 nM to 1.0 mM aqueous UA solution, with the sensitivity value of 1.5822 $\mu$A nM$^{-1}$ m$^{-2}$ and an extremely low detection limit LOD $= 60.0 \pm 0.05$ pM (S/N = 3). Potentials of the Ce$_2$S$_3$-CNT NCs in terms of biological sensing were also investigated via real serum and urine sample analyses. This approach is emerging as an effective technique in the development of an efficient biological sensor for the detection of biochemicals in broad scales.

1. Introduction

Uric acid (UA) is an important biomolecule that is often present in blood serum, urine, or biological fluids and is excreted from the human body. 1,2 UA is a product of the metabolism of purine nucleotides, nucleic acids, and nucleoproteins. 3 Due to its poor solubility in water (approximately 60 mg L$^{-1}$), UA can easily accumulate in human body. Moreover, UA when present in excess in the body fluid can also solidify as a urate, which may cause gout or kidney stones. 4 High uric acid concentration in the blood may lead to deterioration of the renal function and also causes several diseases such as gout, myocardial infarction, hyperuricemia, physiological disorders, and Lesch–Nyhan syndrome. 5–7 Therefore, monitoring the uric acid level in the body fluid is sometimes considered as a key factor for the evaluation of a health condition. 8 Therefore, detection of UA is essential for diagnosis as well as public health monitoring. Various enzyme-based sensors have already been reported for UA detection. However, enzymes can properly work only under appropriate conditions and hence these sensors cannot be used for a wide range of applications. On the other hand, non-enzymatic biosensors are more versatile. 9 Electrochemical sensors always offer fast, profound, and cost-effective methods in UA detection and quantification. 10 However, the electrochemical response of UA at a bare electrode is kinetically slow and often associated with high overpotential. Consequently, searching for new materials for the modification of electrodes to enhance the rate of electron transfer and reduce the overpotential is required. 11 Carbonaceous materials such as CNT, graphene oxides, carbon black, fullerenes, etc. exhibit promising electrocatalytic properties. 12–15 Liu et al. proposed a CNT composite-based sensor for electrically conductive strain sensing, conductive thermoplastic polyurethane–graphene nanocomposite-based organic vapor sensing, and a strain sensor based on conductive thermoplastic elastomer–graphene nanocomposites. 16–18 Several redox mediators such as pristine graphene, 1 gold nanocluster, 2 Au–Pt bimetallic nanoclusters decorated on graphene oxide, 19 mesoporous nickel oxide, 20 polypyrrole films doped with ferrocyanide ions onto an iron substrate, 21 reduced graphene oxide/zinc sulfide nanocomposite, 22 calixarene-modified glassy carbon electrode, 23 flexible graphene fibers, 24 poly(glyoxal-bis(2-hydroxyanil))-functionalized GCE, 24 CeO$_2$ nanoparticle-fabricated glassy carbon paste electrode, 25 iron nanoparticle-fabricated MWNT enriched carbon paste electrode, 26 carbon nanohorns/poly(glycine)-modified glassy carbon electrode 27 etc. have been developed to date for the modification of the electrode in UA

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These nanocomposites are deposited in and around the CNT. An important benefit of these nanocomposites is that nanostructured cerium sulphides have been prepared; etc. However, the real indoor environment is much more convoluted than experimental scenarios. Sometimes the vision of a robot can hardly offer enough information for successfully executing some challenging tasks such as picking, placing or assembling some small targeting objects. In these circumstances, if two objects are too close to each other, it is difficult to correctly segment them; moreover, some occlusion cases often occur in the real indoor environment. Thus, a tele-operative demonstration method is an efficient way to overcome these problems. These demonstration techniques have already been implemented on industrial robots for several years.

Recently, nanostructured transition metal sulfo-des show important roles as electrocatalysts among all other transition metal sulfo-des. To date, core–shell structured Ce₂S₃ on ZnO, Ce₂S₃ on SiO₂, undoped and sodium-doped γ-Ce₂S₃ amorphous cerium sulfides, cerium sulfide/graphene nanocomposites, etc. have been prepared; however, these efforts have become unsuccessful in improving the electrochemical properties of cerium sulfides because of ineffective external interaction between cerium sulfides and carbonaceous substances. This ineffective communication among redox active entities and charge-transfer materials will only allow the fractional cerium sulfide molecules to join in the electron transfer process. Hence, unexpected electrochemical properties of cerium sulfides achieved slower charge-transfer than that of carbonaceous materials. To overcome these complications, herein, we proposed a facile wet-chemical method to prepare Ce₂S₃-CNT NCs in the form of interconnected three dimensional conductive links where Ce₂S₃ nanostructures are attached in and around CNT. Dispersed CNT solution plays a role as a precursor in these attachments, where γ-Ce₂S₃ nanoparticles are deposited in and around the CNT. An important benefit of these nanocomposites is that nanostructured cerium sulfo-des are firmly attached to the CNT and these two different entities are rigidly joined together. The as-grown nanocomposite Ce₂S₃-CNT NC exhibits unprecedented electrochemical performance. Since the improvement of the electrochemical properties of CNT, by making them nanocomposites, is cost-effective and quick relative to that of others reported in the literature, herein, we proposed an electrochemical sensor for the detection and quantification of UA in aqueous solutions (even at pico molar level) using Ce₂S₃-CNT NC-fabricated GCE. To the best of our knowledge, a Ce₂S₃-CNT NC-fabricated GCE sensor has not been reported to date, and herein, this sensor displays the lowest detection limit (LOD = 60.0 ± 0.05 PM) for the detection of UA than any other reported sensor.

2. Experimental
2.1. Materials and methods

Ce(III)chloride heptahydrate (CeCl₃·7H₂O), hydrated sodium sulphide (Na₂S·9H₂O), ethanol, disodium phosphate, monosodium phosphate, multi-walled CNT, creatinine, cystine, glycine, leucine, thionin acetate, tyrosine, uric acid, Nafion (5% ethanolic solution), and acetone were used without any further purification and were purchased from the Sigma-Aldrich Company. Ce₂S₃-CNT NCs was investigated via UV/vis spectroscopy (Evolution 300 UV/visible spectrophotometer, Thermo scientific). An FT-IR spectrum was obtained for the Ce₂S₃-CNT NCs using a spectrophotometer (NICOLET iS50 FTIR spectrometer, Thermo scientific.) in the range from 400 to 4000 cm⁻¹. The XPS measurements were carried out to estimate the binding energies in eV for C, Ce, and S using a MgKα₁, spectrometer (Thermo scientific, Kz 1066, USA) with an excitation radiation source (Al Kz, beam spot size = 300.0 μm, pass energy = 200.0 eV, and pressure ~ 10⁻⁸ torr). The powdered XRD spectrum was obtained by an X-ray diffractometer (XRD, Thermo scientific, ARL XTRA diffractometer) with Cu Kα₁ radiation (λ = 1.5406 nm) using the generator voltage of 40 kV and current of 35 mA measured for the measurement. Morphologies of the Ce₂S₃-CNT NCs were investigated by FESEM (JEOL, JSM-7600F, Japan). Elemental analysis was carried out by EDS (JEOL, Japan). I-V measurements were performed by the Keithley, 6517A Electrometer, USA, at 25.0 °C.

2.2. Synthesis of the Ce₂S₃-CNT NCs

A simple wet-chemical method was used to synthesize Ce₂S₃-CNT NCs in an alkaline medium using cerium(III)chloride heptahydrate (CoCl₃·7H₂O), sodium sulphide (Na₂S·9H₂O), and CNT. In the synthesis process, 50.0 mL of CeCl₃ solution (0.1 M) and 50.0 mL of Na₂S solution (0.1 M) were separately prepared in deionized (DI) water. Then, 1.0 mg of CNT was added to 50.0 mL of cerium(III)chloride solution in a conical flask and heated up to 85 °C for 30 minutes under continuous stirring. Later, 50.0 mL of the Na₂S solution was added dropwise to the abovementioned mixture under constant stirring. After 6 hours of continuous stirring at 85.0 °C, the reaction mixture was cooled down to room temperature and yielded black precipitate of the Ce₂S₃-CNT NCs. The black precipitate was washed by DI water and alcohol to remove any organic or inorganic impurities present and dried at room temperature. Then, the collected
black powdered sample was dried at 65.0 °C using an oven for 6 h and finally the as-grown Ce2S3-CNT NCs were obtained.

The reaction scheme of Ce2S3-CNT NCs formation first depends on the slow release of Ce3+ and S2− ions within the solution and second on the precipitation of these ions as CeS3 in and around the CNT. Formation of Ce2S3 depends on the fact that the ionic product of Ce3+ and S2− ions is greater than the solubility product of Ce2S3. Ce3+ and S2− ions are provided by the hydrolysis reactions of CeCl3 and Na2S, respectively. The proposed mechanism may be described as follows: 

CeCl3 gets ionized in water (eqn (i)) and dispersed in and around the CNT. Na2S also gets ionized (eqn (ii)) and S2− ions will also diffuse into the solution.

\[
\text{CeCl}_3 \rightarrow \text{Ce}^{3+} + 3\text{Cl}^{-} \quad (i)
\]

\[
\text{Na}_2\text{S} \rightarrow 2\text{Na}^{+} + \text{S}^{2-} \quad (ii)
\]

Effective collisions between Ce3+ and S2− ions cause nucleation followed by aggregation and finally the formation of Ce2S3-CNT NCs in the presence of dispersed CNTs (eqn (iii)).

\[
\text{CNT}_{(\text{disp})} + 2\text{Ce}^{3+} + 3\text{S}^{2-} \rightarrow \text{Ce}_2\text{S}_3\text{-CNT}_{(s)} \quad (iii)
\]

The overall reaction can be written as follows (eqn (iv)):

\[
2\text{CeCl}_3_{(aq)} + 3\text{Na}_2\text{S}_{(aq)} + \text{CNT}_{(\text{disp})} \rightarrow \text{Ce}_2\text{S}_3\text{-CNT}_{(s)} + 6\text{Na}^{+} + 6\text{Cl}^{-}_{(aq)} \quad (iv)
\]

Finally, the as-grown Ce2S3-CNT NCs were washed by DI water and alcohol to remove any impurities present and dried at 65.0 °C using an oven. As-obtained Ce2S3-CNT NCs were characterized in detail for crystallinity, morphology, structural, electrochemical properties etc. and later used as a fabricating material on the GCE for the UA sensor in the simple I-V technique. In the Ce2S3-CNT NCs growth mechanism, at the beginning, growth of the Ce2S3 nucleus occurs by itself with mutual aggregation. As described by the Ostwald ripening method, later, nanocrystals re-aggregate to form combined γ-Ce2S3 nano-crystals.31-38 In the presence of dispersed CNTs, γ-Ce2S3 nanocrystals crystallize and re-aggregate with one another and are deposited in and around CNT using van der Waals forces, which result in the porous morphology of the Ce2S3-CNT NCs, which is presented in Scheme 1.

2.3. Fabrication of GCE using Ce2S3-CNT NCs and detection of UA

Fabrication of GCE was carried out by the as-grown Ce2S3-CNT NCs using 5% ethanolic Nafton solution as the conducting binder. It was then heated in an oven at 65 °C for 2 h to obtain a dry film on GCE. In the electrochemical cell, a working electrode (WE) was made of the Ce2S3-CNT NC-coated GCE, whereas the counter electrode was made by a platinum (Pt) wire and aqueous UA in the buffer solution was the electrolyte. To use as target analytes, aqueous UA solution (0.1 M) was diluted to different concentrations (from 1.0 mM to 0.01 mM) using deionized water. All I–V measurements were carried out in 5.0 mL of phosphate buffer solution (PBS; 0.1 M; pH 7.0). From the slope of the current vs. voltage plot, the sensitivity of the proposed UA sensor was estimated.23 Using an electrometer, I–V method was applied to UA solutions with Ce2S3-CNT NCs/GCE as the WE. Real samples were obtained from the medical center (KAU medical center). Initially, the rabbit serum was isolated from the blood. After dilution in PBS buffer, real serum and urine samples were analyzed via the fabricated Ce2S3-CNT NCs/GCE sensor using the I–V method under ambient conditions.

3. Results and discussion

3.1. Optical and structural evaluation

We analyzed the UV/vis spectrum (300–600 nm) of the as-grown Ce2S3-CNT NCs to obtain the band-gap energy (Ebg) of Ce2S3-CNT NCs. The broad peak at 493 nm was attributed to the characteristic peak of the Ce2S3, which is shown in Fig. 1(a). Using the UV/vis spectral data in the Tauc’s equation, the Ebg for the Ce2S3-CNT NCs was calculated.39-40 Tauc’s equation (eqn (v)) can be represented as

\[
a hv = (h v - E_{bg})^n
\]

where \( n = 1/2 \) or 2 for a direct or indirect electronic transition, respectively. From the \((ahv)^2 \) vs. \((hv)\) plot (Fig. 1(b)), the \( E_{bg} \) for the as-grown Ce2S3-CNT NCs was estimated as \(~2.31\) eV, which is consistent with those of the previously reported Ce2S3-CNT NCs.

The FTIR spectrum of the as-grown Ce2S3-CNT NCs is shown in Fig. 1(c). Broad peaks at 3105 and 1475 cm\(^{-1}\) are due to the stretching and bending mode of vibration of water, respectively.41 The stretching vibration of Ce2S3 gives a peak at 579 cm\(^{-1}\). Peaks at 1159 and 980 cm\(^{-1}\) can be attributed to C-O single bond vibrations. The peak at 1730 cm\(^{-1}\) might be due to C=O. The C=S and C–S vibrational peaks occur at 1032 cm\(^{-1}\) and 627 cm\(^{-1}\), respectively.42 The XRD pattern, as shown in Fig. 1(d), matched JCPDS # 50-0851 for the γ-Ce2S3 orthorhombic phase.23 Peaks at 25.8° and 42.7° indicate the presence of CNT.43-46 The more intense (211) peak at 23.2° implies that the (211) plane of the orthorhombic structure is slanted towards the experimental system. Overall, the whole XRD spectrum resembled that of the orthorhombic phase structure of γ-Ce2S3.

3.2. Morphological and elemental evaluation

The morphology and structure of the Ce2S3-CNT NCs were investigated by FESEM. Typical morphological information of the as-grown Ce2S3-CNT NCs is presented in Fig. 2(a)–(d). As-grown Ce2S3-CNT NCs exhibit interconnected networks of carbon nanotubes and Ce2S3 nanoparticles are adsorbed onto the CNT (white spots). This exceptional structure with self-assembled orthorhombic Ce2S3 nanoparticles provides a large surface area and increases the electron transport.

The chemical compositions were determined by the EDS analysis (Fig. 2(e) and (f)) of the as-grown Ce2S3-CNT NCs, which confirmed the presence of C, S, and Ce. Composition (wt%) of
carbon, sulphur, and cerium in the as-grown Ce₂S₃-CNT NCs was 84.20%, 15.57%, and 0.23%, respectively. The absence of any other extra peak(s) (Fig. 2(f)) confirms the purity of the Ce₂S₃-CNT NCs.

3.3. Evaluation of binding energy

XPS was used for further investigation of the purity and nanostructure of the Ce₂S₃-CNT NCs. From the full scan spectrum (Fig. 3(a)), it can be deduced that the surface of the Ce₂S₃-CNT NCs consisted of cerium, sulfur, carbon, and oxygen atoms. Oxygen atoms present in the Ce₂S₃-CNT NCs may attach to carbon atoms by a carbon-oxygen single or double covalent bond or as C=O. Obtained binding energy values of C1s and O1s of the as-grown Ce₂S₃-CNT NCs are 284.9 eV and 532.4 eV, respectively (Fig. 3(b) and (c)), which are very close to the reported values. The Ce3d spectra consist of three well-resolved peaks (Fig. 3(d)) located at 933.6, 923.4, and 918.7 eV, corresponding to Ce3d₅/₂, Ce3d₃/₂, and Ce3d₁/₂, respectively, which are also in good agreement with the binding energy of cerium in Ce₂S₃. As shown in Fig. 3(e), the two photoelectron signals at 164.2 and 169.4 eV can be attributed to S2p₁/₂ and S2p₃/₂, respectively, and the photoelectron signals at 228.4 eV, as shown in Fig. 3(f), can be attributed to S2s. Main peaks in the XPS spectra (Fig. 3(a)–(f)) are consistent with those of previously reported Ce₂S₃.

4. Applications

4.1. Detection of UA using the Ce₂S₃-CNT NCs/GCE

UA in an aqueous solution was detected and the content was measured using the Ce₂S₃-CNT NC-fabricated GCE as the chemical sensor. Non-toxic nature, chemical stability, and
electrochemical activity make the Ce$_2$S$_3$-CNT NCs one of the best sensing materials for UA. UA provided a remarkable response upon contact with the Ce$_2$S$_3$-CNT NCs in the $I$–$V$ measurement. Fig. 4(a) shows the Ce$_2$S$_3$-CNT NCs/GCE electrode surface prepared in 5% ethanolic Nafion solution. The possible reduction scheme on the Ce$_2$S$_3$-CNT NCs/GCE is

Fig. 2 Morphological and elemental evaluation. (a–d) Low to high-resolution FE-SEM images and (e and f) EDS spectrum for the as-grown Ce$_2$S$_3$-CNT NCs.

Fig. 3 Binding energy evaluation: XPS spectrum of (a) as-prepared Ce$_2$S$_3$-CNT NCs, (b) C1s, (c) O1s, (d) Ce3d, (e) S2p, and (f) S2s orbital acquired using MgK$_\alpha$ radiation.
generalized in Fig. 4(b), where UA gets reduced by gaining electrons from the conduction band of the Ce₂S₃-CNT NCs/GCE sensor surface during the I-V measurements, which decreases the current intensity with the increasing concentration at room temperature.⁵¹-⁵³ Fig. 4(c) shows the theoretical outcome, whereas Fig. 4(d) shows the practical I-V response with UA and without UA on the Ce₂S₃-CNT NCs/GCE working electrode at the delay time of 1.0 second in the electrometer, where a higher current response to the increasing voltage is clearly demonstrated.

### 4.2. Optimization and application of the UA biosensor

The electrochemical behavior of the Ce₂S₃-CNT NCs depends on the pH value. The pH dependence of the Ce₂S₃-CNT NCs was examined in PBS with different pH values (5.7 to 8.0), as shown in Fig. 5(a). These results demonstrate that the Ce₂S₃-CNT NCs show good electrochemical performance at various pH values. It can be well observed that on changing the pH value of the PBS, the electrocatalytic activity of the Ce₂S₃ CNT NCs changed, which is reflected by a variety of current responses. During the pH optimization using PBS (without using UA), the highest current response was obtained at pH 7.0. Therefore, pH 7.0 was kept constant throughout this study during the UA detection using the Ce₂S₃-CNT NCs/GCE assembly.

Current intensities in PBS (pH = 7.0) without UA for the bare GCE (blue dotted) and Ce₂S₃-CNT NCs/GCE (red dotted) are given in Fig. 5(b). With the Ce₂S₃-CNT NCs/GCE, the current intensity is much higher as compared to that with the bare GCE for UA detection, which demonstrates the excellent electrochemical properties of the Ce₂S₃-CNT NCs. Fig. 5(c) demonstrates the current responses to seven biological analytes, where (1.0 μM; 25.0 μL) UA solution (red dotted) in PBS (pH = 7.0) gave the best response with the Ce₂S₃-CNT NCs/GCE surface. Fig. 5(d) represents I-V responses of the Ce₂S₃-CNT NCs/GCE without UA (blue dotted) and with UA (red dotted; 1.0 μM; 25.0 μL) in 5.0 mL of PBS solution. In the presence of UA in PBS, a noticeable decrease in the current response implies the UA sensing ability of the developed Ce₂S₃-CNT NCs/GCE sensor. UA solution (25.0 μL) of different concentrations (from 0.1 nM to 0.1 M) was sequentially injected into 5.0 mL of PBS from the stock solutions and variations of surface current were investigated after every injection using the Ce₂S₃-CNT NCs/GCE as the WE, which is given in Fig. 5(e). It clearly demonstrates that the current response gradually decreases with the increasing concentration of UA at room temperature for the Ce₂S₃-CNT NCs/GCE sensor. Aqueous solutions of UA (from 0.01 nM to 1.0 mM) were obtained to investigate the detection limit of the proposed sensor. Fig. 5(f) represents the magnification of the concentration variation plot (Fig. 5(e)) from +0.6 to +1.5 V.

The calibration plot current vs. concentration (at +0.8 V) in the full concentration range is given in Fig. 6(a). A very high sensitivity value (1.5822 μA nM⁻¹ m⁻²) was calculated from the calibration plot at +0.8 V. The LDR of the proposed sensor was obtained from 0.1 nM to 1.0 mM (r² = 0.9972) and the LOD was calculated as 60.0 ± 0.05 pM [3 x noise (N)/slope (S)]. Fig. 6(b) represents the repeatability of the I-V responses with the as-grown Ce₂S₃-CNT NC-coated CNT NCs/GCE using 25.0 μL of 0.1 μM UA solutions with nine different working electrodes in Run 1 - Run 9 under identical conditions. Almost the same current response in nine repeated experiments confirmed the excellent repeatability of the sensor (RSD = 3.52%; n = 9). This small % RSD may be due to the mass variation of the coating materials Ce₂S₃-CNT NCs in the working electrodes. When the same working...
electrode was used in different solutions of the same concentration, even under identical conditions, current response slightly decreased. This is because after each run, the number of the active sites of the $\text{Ce}_2\text{S}_3$-CNT NCs slightly decreases.

4.3. Application to real samples

To confirm the validity of the $I-V$ method, the $\text{Ce}_2\text{S}_3$-CNT NCs/GCE was used to quantify UA in two real aqueous UA solutions. For this purpose, we used the standard addition method to check the precision of the UA detection in aqueous samples (human urine and rabbit serum; Diluted 10 times in the buffer).

A fixed amount (~25.0 $\mu$L) of real water sample was mixed and analyzed in PBS (5.0 mL) by the $\text{Ce}_2\text{S}_3$-CNT NCs/GCE working electrodes. Table 1 shows the results, which demonstrated that the amount of UA in the rabbit serum is higher than that in the urine sample. Based on the results, therefore, we can conclude that the $I-V$ method is suitable, consistent, and appropriate in real sample analysis with the $\text{Ce}_2\text{S}_3$-CNT NCs/GCE system.

The resistance of the fabricated nanocomposites sensor decreases with the increasing electron communication, characteristics that are important features of the nanomaterial at RTP and vice versa. During the reduction of UA, the number

Fig. 5  $I-V$ responses with a delay time of 1.0 s for (a) pH optimization of the $\text{Ce}_2\text{S}_3$-CNT NC-coated GCE, (b) bare and $\text{Ce}_2\text{S}_3$-CNT NC-coated GCE in PBS with UA, (c) selectivity study with various interferences (7 analytes) (d) in the absence and presence of UA (1.0 $\mu$M; 25.0 $\mu$L) in 5.0 mL of PBS solution, (e) current variations for different concentrations (from 0.01 nM to 1.0 mM) of aqueous UA solution in the full voltage range, and (f) magnified view of concentration variation (+0.6 to +1.5 V).

Fig. 6  (a) Calibration plot of $\text{Ce}_2\text{S}_3$-CNT NC-fabricated GCE surfaces. Potential range from 0.0 to +1.5 V and (b) repeatability using different WE (25.0 $\mu$L; 0.1 $\mu$M UA).
of electrons in the conduction band decreases and hence it increases the resistance of the Ce$_2$S$_3$-CNT NCs. Reduction of UA on the Ce$_2$S$_3$-CNT NCs surface is the main phenomenon involved in this proposed UA sensor. Due to its mesoporous structure, Ce$_2$S$_3$-CNT NCs have a large surface area that may be responsible for this sensitive reduction at room temperature. The rate of the UA reduction in Ce$_2$S$_3$-CNT NCs was higher than that of other analytes, even under identical conditions, as shown in Fig. 5(b). When UA is reduced on the Ce$_2$S$_3$-CNT NCs, it removes electrons from the conduction band of the nanocomposites, which increases the resistance of the coating material Ce$_2$S$_3$-CNT NCs.$^{59}$

Current response in the I–V method during uric acid detection largely depends on the dimensions, morphology, and nanoporosity of the nanocomposites. When Ce$_2$S$_3$-CNT NCs surface is exposed to the oxidizing UA, a surface-mediated reduction reaction takes place. Removal of the conducting electrons from the Ce$_2$S$_3$-CNT NCs/GCE decreases the surface conductance of the electrode. This removal of electrons quickly decreases the conductance of the Ce$_2$S$_3$-CNT NCs coating.

Massive deposition of the γ-Ce$_2$S$_3$ NPs on the CNT (white-spots in Fig. 2(a) and (b)) with porous morphology will increase the reducing power of the Ce$_2$S$_3$-CNT NCs. The Ce$_2$S$_3$-CNT NCs/GCE sensor requires approximately 10 s to achieve a constant current in the I–V measurements. It was practical to measure the response time, and the I–t plot is presented in the ESI (ESM, Fig. S1†). This excellent sensitivity and high electrochemical performance of the Ce$_2$S$_3$-CNT NCs is due to the mesoporous surface that enhances the reduction of UA. The Ce$_2$S$_3$-CNT NCs/GCE sensor is more sensitive and has a lower detection limit than other sensors already reported for UA detection,$^{1-3,16-20,58}$ as given in Table 2. Having a large surface area, the Ce$_2$S$_3$-CNT NCs offered a positive nanoenvironment during the detection and quantification of UA. The Ce$_2$S$_3$-CNT NCs/GCE sensor has also shown better reliability and stability. Despite these developments, there are still numerous important apprehensions that must be investigated before the commercial production of this sensor.

5. Conclusions

In conclusion, we successfully fabricated GCE by the as-grown Ce$_2$S$_3$-CNT NCs with 5% ethanolic Nafion as the conducting coating binder for the first time to act as a selective chemical sensor for the detection of uric acid. Facile Ce$_2$S$_3$-CNT NCs were prepared by a wet-chemical method at low temperature, which is considered as the simplest, convenient, and economical method for the metal-sulphide nanocomposites preparation. The UA biological sensor was studied with Ce$_2$S$_3$-CNT NCs/Nafion/GCE by the simple I–V technique at room conditions. The analytical parameters were thoroughly investigated in terms of sensitivity, limit of detection, and storage ability as well as reproducibility. Significant research activities including synthesis, structural and optical characterization, and chemical-sensing application of the Ce$_2$S$_3$-CNT NCs towards the UA have been included in this study. Crystallinity, morphology, optical properties, band-gap, and binding energies were investigated by XRD, FESEM, FTIR, UV/vis spectroscopy, and XPS methods, respectively. The proposed Ce$_2$S$_3$-CNT NCs/GCE-based UA sensor exhibits the higher-sensitivity (1.5822 µA nM$^{-1}$ m$^{-2}$) and very low detection limit (LOD = 60.0 ± 0.05 pM) with excellent linear response ($r^2$ = 0.9972) in a wide range of concentrations (from 0.1 nM to 1.0 mM) within a short response time. This noble approach is a well-organized and reliable technique of an effective biological sensor development for the detection of biological samples as well as biomolecules in the health care field.

### Table 1 Quantification of uric acid in real samples

<table>
<thead>
<tr>
<th>Real samples</th>
<th>Measured current (µA)</th>
<th>Respective concentration (nM)</th>
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<tbody>
<tr>
<td>Human urine (10 times diluted)</td>
<td>60.4</td>
<td>1.50 ± 0.02</td>
</tr>
<tr>
<td>Rabbit serum (10 times diluted)</td>
<td>78.3</td>
<td>2.12 ± 0.02</td>
</tr>
</tbody>
</table>

### Table 2 Analytical performance comparison of different detection methods for uric acid using various nanocomposites or nanomaterials on conventional electrodes

<table>
<thead>
<tr>
<th>Electrode fabrication</th>
<th>Technique/method</th>
<th>Linear dynamic range (LDR)</th>
<th>Lower detection limit (LOD)</th>
<th>Sensitivity</th>
<th>pH</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine graphene</td>
<td>CV + amperometry</td>
<td>6.00–1330 µM</td>
<td>4.82 µM</td>
<td>0.1029 µA µM$^{-1}$</td>
<td>7.0</td>
<td>1</td>
</tr>
<tr>
<td>Mesoporous NiO</td>
<td>CV</td>
<td>Up to 0.374 mM</td>
<td>0.005 µM</td>
<td>0.7562 µA µM$^{-1}$ cm$^{-2}$</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Gold nanocluster</td>
<td>Fluorescence</td>
<td>7.0 × 10$^{-7}$ to 8.0 × 10$^{-3}$ M</td>
<td>1.2 × 10$^{-7}$ M</td>
<td>—</td>
<td>7.0</td>
<td>3</td>
</tr>
<tr>
<td>Au–Pt bimetallic</td>
<td>CV</td>
<td>0.125 µM to 8.28 × 10$^{-2}$ M</td>
<td>4.07 × 10$^{-2}$ µM</td>
<td>—</td>
<td>7.0</td>
<td>16</td>
</tr>
<tr>
<td>nanoclusters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypyrrole films/</td>
<td>CV</td>
<td>100–5000 µM</td>
<td>23.0 µM</td>
<td>0.0046 µA µM$^{-1}$</td>
<td>7.0</td>
<td>17</td>
</tr>
<tr>
<td>Fe-substrate</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>rGO/ZnS nanocomposites</td>
<td>DPV</td>
<td>1.0–500 µM</td>
<td>0.4 µM</td>
<td>—</td>
<td>7.0</td>
<td>18</td>
</tr>
<tr>
<td>Calixarene film</td>
<td>CV</td>
<td>0.4–40 µM</td>
<td>0.08 µM</td>
<td>—</td>
<td>—</td>
<td>19</td>
</tr>
<tr>
<td>Flexible graphene fibers</td>
<td>CV</td>
<td>10–26 µM</td>
<td>0.2 µM</td>
<td>—</td>
<td>7.0</td>
<td>20</td>
</tr>
<tr>
<td>Silver nanoprism</td>
<td>Colorimetry</td>
<td>1.0–40 µM</td>
<td>0.7 µM</td>
<td>—</td>
<td>—</td>
<td>60</td>
</tr>
<tr>
<td>Ce$_2$S$_3$/CNT NCs/Nafion/GCE</td>
<td>I–V</td>
<td>0.1 nM to 1.0 mM</td>
<td>60.0 ± 0.05 pM</td>
<td>1.5822 µA nM$^{-1}$ m$^{-2}$</td>
<td>7.0</td>
<td>This work</td>
</tr>
</tbody>
</table>
Acknowledgements

This project was funded by the Center of Excellence for Advanced Materials Research (CEAMR), King Abdulaziz University, Jeddah, under grant no. (CEAMR-SG-3-438).

References


50 Z. Li, W. Li, H. Xue, W. Kang, X. Yang, M. Sun, Y. Tang and C. S. Lee, Facile fabrication and electrochemical properties of high-quality reduced graphene oxide/cobalt sulphide composite as anode material for lithium-ion batteries, *RSC Adv.*, 2014, **4**, 37180.


