Determination of prostate-specific antigen via the assembly of a two-dimensional nanoplateform

Junjie Chen · Xiangqian Li · Xiaoqi Yu · Wei Zhou · Qianming Wang

Received: 8 October 2021 / Accepted: 16 February 2022 / Published online: 18 April 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract Two-dimensional platforms generate considerable interests due to diverse application. We report a “turn-on” fluorescent nanoprobe for prostate-specific antigen (PSA) detection. It is based on cobalt oxyhydroxide nanosheets (CoOOH NSs). Fluorescin amidite (abbreviated as FAM)-labeled aptamer probe (abbreviated as FAM-aptamer) has been adsorbed onto the nanosheets. Energy transfer between substrate and optical species has induced the quenching of FAM-aptamer emission. The strong affinity of FAM-aptamer to the target PSA causes the formation of a rigid aptamer structure. The integration between FAM-aptamer and CoOOH NSs has been drastically affected. The release of the aptamer probe from the nanosheet surface has been realized. The green luminescence has been recovered. The dynamic nanosensor exhibits highly sensitive performance toward PSA with a linear detection range from 0.1 to 5 ng/mL. Its detection limit is measured to be 56.1 pg/mL. Therefore, a simple and efficient sensing platform for the detection of prostate cancer can be established.

Keywords CoOOH nanosheets · Prostate-specific antigen · Fluorescent probe

Introduction

Cancer refers to disease that involves abnormal cell growth and may affect various parts of the body. Prostate-specific antigen (PSA) is a single-chain polypeptide containing 237 amino acids. It is the most sensitive biomarker for prostate cancer (Zhao et al. 2021; Li et al. 2018a; Pei et al. 2015). Therefore, it is necessary to develop biomarkers for detecting prostate cancer with higher sensitivity. A variety of analytical techniques have been used to detect PSA, such as radioimmunoassay, mass spectrometry immunoassay, enzyme-linked immunosorbent assay, colorimetric analysis, electrochemical methods, polymerase
chain reaction, and surface enhancement Raman analysis (Soomro et al. 2021; Chen et al. 2019a; Shao et al. 2018; Bhardwaj et al. 2017; You et al. 2019; Zhao et al. 2019). However, these methods require expensive apparatus and complicated pretreatment procedures. Determination process with facile steps would be warmly welcome. From last decade, fluorescence-based technology has attracted widespread attention due to its high sensitivity and stability (Wen et al. 2021; Wu et al. 2019). As for the structure design, nanomaterials with unique properties have been developed (Salah et al. 2018). Especially 2D nanomaterials have generated significant interests in biological applications (Liaok et al. 2016; Zhou et al. 2016). They possess unique properties including large surface area, bio-compatibility, and low toxicity (Kong et al. 2015). In particular, 2D nanosheets have been provided as the excellent platforms for the detection of DNA sequence. As a result, a variety of 2D nanosheets have been developed to construct nanofluorescence sensor for the DNA detection. Transition metal dichalcogenide, metal oxides, and carbon nanomaterials were reported (Lan et al. 2018; Peng et al. 2019; Wu et al. 2020; Zhou et al. 2017; Zhao et al. 2015). Therefore, a two-dimensional CoOOH nanosheet-based PSA sensor was prepared. The corresponding CoOOH NSs were played as the hosts for the sensing process.

The cobalt oxyhydroxide nanosheet has been developed as a transition metal-based oxide nanomaterial. It has regular hexagon and two-dimensional structure (Liu et al. 2017; Han et al. 2018; Saberi et al. 2018). Therefore, the structure possesses similar features as some reported 2D nanosheets, such as graphene oxide (GO), MoS2, WS2, and MnO2 (Feng et al. 2012; Gu et al. 2019; Dhenadhayalan et al. 2017; Chen et al. 2019b; Zhou et al. 2020). Most of them have been extensively used for biological applications owing to their quantum size properties and surface effects. Some of them were functionalized as powerful quenchers for organic fluorescent dyes. The quenching results would be also effective to fluorescent nanoparticles such as up-conversion nanoparticles and quantum dots (Zhang et al. 2019a; Wang et al. 2020). Because of the quantities of hydroxyls on the CoOOH NS surface, CoOOH NSs gave rise to excellent water solubility, good biocompatibility, and large specific surface area. They would contribute to the potential uses in environmental or biological conditions (Liu et al. 2019; Zhang et al. 2019b). To our knowledge, the employment of CoOOH NSs as the biosensor platform for the detection of PSA has not been reported.

Herein, CoOOH NSs were used as the signal substrate and its microstructure was verified. As for the active species, aptamers are known as short and single-stranded DNA structures. The complementary DNA sequence leads to the recognition. The aptamers possess the ability to selectively bind to a variety of specific targets including low-molecular-weight molecules, proteins, or cells. CoOOH NSs can selectively adsorb fluorescent dye FAM-labeled aptamers. The hybrid structure was formed via self-assembly due to electrostatic adsorption or van der Waals force. In this way, the fluorescent signal of dye-labeled aptamer would be suppressed by the efficient energy transfer process. The aptamer moiety was appended with fluorescent molecule at its terminal unit. Before the encapsulation of PSA, the aptamer might be in the unfolded or loose state. Due to the addition of PSA, the binding of the aptamer to the target PSA induced a rigid and tertiary structure. This result significantly changed the integration process with the CoOOH NSs. The affinity to the two-dimensional substrate became very weak based on the rigid aptamer conformation. Accordingly, such recognition resulted in the release of the FAM-aptamer from the nanosheet surface. The quenched fluorescence was restored (Scheme 1). Therefore, the assay could be considered as suitable for PSA detection. It can be expected that the CoOOH NS nanohost strategy would provide possibility in the field of early clinical diagnosis.

**Experimental**

**Materials**

Cobalt(II) chloride hexahydrate (CoCl2·6H2O) (99%), sodium hydroxide (NaOH) (98%), sodium hypochlorite (NaClO) (99%), and other reagents were obtained from Guangzhou Chemical Reagent Factory (Guangzhou, China). No further purification was employed. CaCl2 (99.5%), MgCl2 (99.5%), ZnCl2 (99.5%), bovine serum albumin (BSA) (>96%), glutathione (GSH) (98%), L-cysteine (Cys) (98%), uric acid (UA) (98%), ascorbic acid (AA) (99.5%), and vitamin B1 (98%) were provided by Aladdin Reagent Company.
(Shanghai, China). Prostate-specific antigen (PSA) (>95%) was obtained from Shanghai Linc-Bio Science Co., Ltd. (Shanghai, China). The stock solutions of oligonucleotides were prepared in Tris–HCl (10 mM, pH 7.4, including 150 mM NaCl, 5 mM KCl, and 5 mM MgCl2). All oligonucleotides were synthesized and purified by Sangon Biotechnology Co., Ltd. (Shanghai, China). The corresponding sequences were as follows:

**PSA aptamer 5′-/FAM/-TTA
TTA
AAG
CTC
GCC
ATC
AAA
TAG
C-3′**

**Apparatus**

Powder X-ray diffraction (PXRD) data were collected on a Bruker D8-ADVANCE X-ray diffractometer with Cu-Kα radiation (λ = 1.5418 Å) (Bruker, Germany). Transmission electron microscopy (TEM) images were obtained with a JEOL JEM-2100HR (Hitachi, Japan). The morphologies and structures of CoOOH NSs were examined by field emission scanning electron microscope (SEM; Sigma 500) equipped with an energy-dispersive X-ray spectrum attachment (EDX Oxford Instruments Isis 300) (Zeiss, Germany). X-ray photoelectron spectroscopy (XPS) measurements were performed on a VG ESCALAB 220iXL surface analysis system (VG Scientific, UK). The zeta potential of CoOOH NSs was determined by Malvern Nano-ZS90 system (Malvern, UK). Fourier transform infrared (FT-IR) spectra were recorded on a Nicolet 6700 (Thermo, USA). Thermogravimetric analysis (TGA) experiments were carried out using a SII EXStar6000 TG/DTA6300 thermal analyzer from room temperature to 800 °C under an air atmosphere at a heating rate of 10 °C·min^{-1} (Seiko, Japan). The UV–Vis spectrum was obtained using a Shimadzu UV-2600 spectrophotometer (Shimadzu, Japan). Fluorescence measurements were conducted using a Hitachi F-7000 fluorescence spectrophotometer with a 150-W xenon lamp as a light source (Hitachi, Japan).

**Synthesis of CoOOH NSs**

The synthesis of CoOOH NSs was based on previous literature with slight changes (Yang et al. 2021). First, 1.25 mL of 1 M NaOH was added into a glass vial with 5 mL of 10 mM CoCl2·6H2O. The mixture was subjected to ultrasonic irradiation at a power of 300 W for 1 min. Then the mixture was mixed with 0.25 mL of 0.9 M NaClO followed by an ultrasound treatment at a power of 300 W for 10 min. Subsequently the mixture was subjected to centrifugation at 10,000 rpm for 15 min and washed with water three times. The product yield could be determined to be 16.5%. Finally, the CoOOH NSs were dispersed in 50 mL of deionized water and stored at 4 °C for further use.

**Fluorescent sensing of PSA**

In a typical PSA detection, the aptamer probe FAM-aptamer (50 nM) in 10 mM Tris–HCl buffer was
incubated with different concentrations of PSA at 37 °C for 30 min. Then, the CoOOH NS suspension (35 μg/mL) was added to the above mixed solution. The sample was incubated at room temperature for 10 min. The final concentration of PSA was adjusted in the range between 0 and 100 ng/mL. Finally, the parallel samples in 10 mm × 10 mm quartz cuvettes were put into a fluorescence spectrometer. The photoluminescence spectra were measured and collected by a fluorescence spectrophotometer excited at 495 nm. The excitation and emission slits were both fixed at 5 nm. The scan speed was set at 125 nm/min. For comparison purpose, control experiments were performed by replacing PSA with other interfering analytes, such as CaCl2, MgCl2, ZnCl2, bovine serum albumin (BSA), glutathione (GSH), L-cysteine (Cys), urea (UA), ascorbic acid (AA), and vitamin B1 (VB1). The concentration of all the above interference species was set as 100 ng/mL.

In vitro studies and analytical applications

Hela cells (human cervical cancer cell) were cultured in RPMI 1640 medium (RPMI refers to Roswell Park Memorial Institute) and DMEM medium (Dulbecco’s Modified Eagle Medium). The above medium was both supplemented with 10% heat-inactivated fetal bovine serum (FBS) and 1% antibiotic penicillin (PS). The cellular system was maintained at 37 °C in a humidified condition of 95% air and 5% CO2. For cell imaging, Hela cells were cultured in Lab-Tek chambered cover glass (4-well, Thermo Scientific, USA) with a density of 5 × 104 cells/well and grown to 70% confluency. The cells were washed with culture medium and incubated in FAM-labeled aptamer (30 nM) for 30 min. In the next step, CoOOH NS (20 μg/mL) was added and incubated for further 30 min. In the case of recovery, the cells were incubated with FAM-labeled aptamer (30 nM) and PSA (50 ng/mL) for 30 min. Then CoOOH NS (20 μg/mL) was incorporated for 1–2 h. The cell images were taken with a Zeiss confocal laser scanning microscope (LSM710, Zeiss, Germany).

To confirm the applicability of the as-developed assay system, FL measurement was conducted on PSA content in human serum of two people (samples 1 and 2) (provided by Local School Hospital of South China Normal University). The aptamer probe FAM-aptamer (50 nM) in 10 mM Tris–HCl buffer was incubated with these two samples at 37 °C for 30 min. Recovery experiments were carried out by spiking 0.5, 1.0, and 2.0 ng/mL PSA into two samples of human serum, separately. Then, the CoOOH NS suspension (35 μg/mL) was added to the above mixed solution and incubated at room temperature for 10 min. Finally, the fluorescence spectra of the samples were detected by a fluorescence spectrophotometer excited at 495 nm.

Results and discussion

Ultrathin nanosheets are regarded as the suitable units that could connect the microscopic property with excellent macroscopic features (Tan and Zhang 2015; Yu et al. 2017). The CoOOH nanosheets have been used as efficient quencher owing to optical absorption and high surface area. As the energy acceptor, ultrathin CoOOH NSs were synthesized by the previously reported method with slight modification. The structures of the CoOOH NSs were evaluated by X-ray powder diffraction (XRD). As is shown in Fig. 1A, the XRD pattern of CoOOH NSs possesses three representative peaks at 20.19, 38.95, and 50.62°; such signals can be indexed as (003), (012), and (015) planes of CoOOH NSs according to the standard JCPDS card (No. 73–0497). The intense and sharp diffraction peaks demonstrate that the product is well crystallized. The full-scan X-ray photoelectron spectroscopy (XPS) of CoOOH NSs has been determined to explore their composition (Fig. 1B). Two peaks at 532.7 eV and 787.3 eV were attributed to O 1s and Co 2p, respectively. TEM images supported the existence of typical hexagon nanosheet morphology of CoOOH NSs (Fig. 1C). In addition, the major elemental analysis was demonstrated by energy-dispersive spectroscopy (EDS). The curve confirmed the presence of Co and O elements. The distribution was given in Fig. 1D. Moreover, SEM images and the energy-dispersive X-ray mapping results proved the presence of Co and O elements (Fig. 2). The FT-IR spectrum of the CoOOH NSs is shown in Fig. S1. The broad band located at 3415 cm−1 is attributed to the vibrations of free O–H from the surface of CoOOH NSs. Meanwhile, the peak at 1635 cm−1 assigned to Co=O double bond has been observed (Zhang et al. 2019b). Therefore, all above results verified that ultrathin CoOOH NSs were successfully fabricated.
The zeta potential of the CoOOH NSs was 21.1 mV, showing that the positive charge was found in the nanosheets (Fig. S2). The TGA curves revealed that the CoOOH NSs were thermally stable; the weight change was less than 2% at lower temperature range (< 100 °C). Such outstanding performance indicated that the inorganic nanosubstrate possessed densely packed structures with enough stabilities. Less than 10% of mass loss was observed even at temperature as high as 290 °C (Fig. S3).
To demonstrate the optical performance of the PSA sensor, the fluorescence quenching and subsequent recovery ability of FAM-aptamer were evaluated in the presence of CoOOH NSs and PSA. The FAM-labeled aptamer was used as a probe to monitor PSA. The fluorescence quenching ability of CoOOH NSs was firstly investigated. As shown in Fig. 3A, with the increasing concentration of CoOOH NSs (from 0 to 35 µg/mL), the emission intensity of FAM-aptamer (50 nM) was gradually suppressed. The signal was completely quenched in the end. Moreover, the fluorescence intensity was maintained stable within only 3 min, indicating the fast quenching of CoOOH NSs toward FAM-aptamer (Fig. S4). When FAM-aptamer was hybridized with excessive PSA, the FAM-aptamer/PSA duplex was formed. The quenched fluorescence of FAM-aptamer was recovered in the presence of CoOOH NSs (Fig. 3B). It is estimated that CoOOH NSs had weaker affinity to dsDNA than to ssDNA.

The UV–Vis absorption spectrum of CoOOH NSs was explored (Fig. 4). The absorption curve covers a wide range of wavelengths from ultraviolet light to visible region. The result suggested that the CoOOH NSs can be considered as an ideal energy acceptor for diverse chromophores. The close distance of the aptamer FAM-aptamer and CoOOH NSs has provided the possibility of the fluorescence resonance energy transfer (FRET) process from the excited FAM dye to the CoOOH NSs. The FRET channel mainly depended on the spectral overlap between the absorption spectrum of the energy acceptor and emission spectrum of the energy donor. Herein, it was seen that the emission signal of FAM-aptamer was highly overlapped with the covering region of CoOOH NSs. The emitted energy was completely absorbed by the nanohost (Fig. 4). Thus, the fluorescence quenching of FAM-aptamer was observed.

Figure 5A records the fluorescence intensity changes of the aptamer FAM-aptamer in the presence of PSA at different concentrations. The curves showed that fluorescence could be improved gradually due to the continuous addition of PSA species. Moreover, the emission changes versus the concentration of PSA were found to give a good linear relationship ($R^2 = 0.9912$) in the range of 0.1 to 5 ng/mL (Fig. 5B). The limit of detection (LOD) was calculated to be 56.1 pg/mL according to the 3SD/slope approach (Li et al. 2018b). SD refers to the standard deviation of the controlled measurements. The denominator is defined as the slope of the linear equation. To explore the potential applications, a series of representative cations, anions, and biomolecules were used to evaluate the sensing properties of CoOOH NSs (Fig. 6). Compared with other interference...
analytes, PSA could be the only target to generate the green light with great selectivity.

With the aim of exploring the feasibility of the proposed method in practical samples, recoveries of PSA in human serum samples are given in Table 1. Under such real biological conditions, numerous interferences including proteins and contaminants were present. During the measurements, the background optical signals were improved. But it was found that PSA-caused signal increase was much stronger than the controlled samples. The results can be analogous to the responses collected in aqueous solution. The determined concentration of PSA was located within the linear range. The recoveries varied from 93 to 105%. RSDs were equal or lower than 0.77%, both of which are within the acceptance criteria. Moreover, the collected confocal image showed very low fluorescent signals in the presence of FAM-labeled aptamer and CoOOH NSs (Fig. S5A). After PSA was encapsulated into the cellular system, the

---

**Fig. 4** Absorption spectrum of CoOOH NSs (35 μg/mL) (blue line) and fluorescence spectrum of FAM-aptamer (50 nM) in pH 7.4 PBS (inset: absorption spectrum of CoOOH NSs (35 μg/mL) in the range of 200–800 nm)

---

**Fig. 5** A Fluorescence spectra for FAM-labeled aptamer (FAM-aptamer, 50 nM) appended CoOOH NSs (35 μg/mL) in the presence of PSA at different concentrations (0, 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 100 ng/mL, respectively). B Linear correlation between the fluorescence intensity change at 519 nm and the concentration of PSA.
green emission was generated after incubation for 1 h. The optical signal became more intensive due to time extension to 2 h (Fig. S5B-C). These data revealed that the incubators of CoOOH NSs and FAM-aptamer had high reliability and practicability for PSA detection.

Conclusion

This work has been established on the exploration of 2D materials in the field of catalysis and energy chemistry. Herein, we developed its potential in the substrate for fluorescent sensing. Understanding and controlling its microstructure would extend its performance in a variety of aspects. We have constructed a novel fluorescence biosensor for the PSA detection by using CoOOH NSs as the fluorescence quencher. Additionally, this CoOOH NSs also possesses several merits including good biocompatibility, easy operation, and low cost. Therefore, it could be applied in the fields of cell imaging and biomedical analysis.

Author contribution

Junjie Chen: writing — original draft.
Xiangqian Li: investigation.
Xiaoqi Yu: assisted with data collection and data analysis.
Wei Zhou: validation.
Qianming Wang: supervision, writing, and reviewing.

Funding

Q. M. appreciates Guangzhou Science and Technology Plan (No. 202002030325); Natural Science Foundation of Guangdong Province, China (No. 2021A1515010324); and Science and Technology Plan of Guangdong Province (No. 2020A0505100055).

**Table 1** Determination of PSA spiked into human serum samples (n = 5)

| Sample | Found (ng/mL) | Added (ng/mL) | Total found (ng/mL) | Recovery (%) | RSD (%), n = 5 |
|--------|---------------|---------------|---------------------|--------------|---------------|
| 1      | 1.21          | 0.5           | 1.71                | 100.0        | 0.30          |
| 1      | 2.18          | 97            | 2.54                | 97           | 0.43          |
| 2      | 3.07          | 93            | 3.90                | 93           | 0.25          |
| 1      | 2.93          | 0.5           | 3.42                | 98           | 0.29          |
| 2      | 3.98          | 105           | 4.93                | 105          | 0.77          |
| 1      | 4.97          | 102           | 5.99                | 102          | 0.35          |

**Fig. 6** Selectivity experiments of FAM-labeled aptamer (FAM-aptamer, 50 nM) appended CoOOH NSs in the presence of PSA (100 ng/mL) or other interfering species: 1 CaCl2, 2 MgCl2, 3 ZnCl2, 4 bovine serum albumin (BSA), 5 glutathione (GSH), 6 cysteine (Cys), 7 uric acid (UA), 8 ascorbic acid (AA), 9 vitamin B1 (VB1), 10 PSA. The concentration of all the interference species was set as 100 ng/mL (F0 and F refer to the emission intensity at 519 nm in the absence or presence of interfering species)
Data availability  All data generated or analyzed during this study are included in this published article.

Code availability  Not applicable.

Declarations

Ethics approval  This manuscript is not currently under consideration, in press, or published elsewhere and is truthful original work without fabrication, fraud, or plagiarism.

Consent to participate  Not applicable.

Consent for publication  Not applicable.

Conflict of interest  The authors declare that they have no conflict of interest.

References

Bhardwaj SK, Sharma AL, Bhardwaj N, Kukkar M, Gill AAS, Kim KH, Deep A (2017) TCNQ-doped Cu-metal organic framework as a novel conductometric immunosensing platform for the quantification of prostate cancer antigen. Sensor Actuat B-Chem 240:10–17

Chen MJ, Ma CB, Yan Y, Zhao H (2019) A label-free fluorescence method based on terminal deoxynucleotidyl transferase and thioflavin T for detecting prostate-specific antigen. Anal Bioanal Chem 411(22):5779–5784

Chen JL, Tong P, Huang LT, Yu ZH, Tang DP (2019) Ti3C2 MXene nanosheet-based capacitance immunoassay with tyramine-enzyme repeats to detect prostate-specific antigen on interdigitated micro-comb electrode. Electrochim Acta 319:375–381

Dhenadhayalan N, Yadav K, Sriram MI, Lee HL, Lin KC (2017) Ultra-sensitive DNA sensing of a prostate-specific antigen based on 2D nanosheets in live cells. Nanoscale 9(33):12087–12095

Feng TT, Feng D, Shi W, Li XH, Ma HM (2012) A graphene oxide-peptide fluorescence sensor for proteolytically active prostate-specific antigen. Mol Biosyst 8(5):1441–1445

Gu JP, Li XQ, Zhou Z, Liu WQ, Li K, Gao JW, Zhao Y, Wang QM (2019) 2D MnO2 nanosheets generated signal transduction with 0D carbon quantum dots: synthesis strategy, dual-mode behavior and glucose detection. Nanoscale 11(27):13058–13068

Han QX, Yang H, Wen ST, Jiang HE, Wang L, Liu WS (2018) Selective and rapid detection of ascorbic acid by a cobalt oxyhydroxide-based two-photon fluorescent nano-platform. Inorg Chem Front 5(4):773–779

Kong RM, Ding L, Wang ZJ, You JM, Qu FL (2015) A novel aptamer-functionalized MoS2 nanosheet fluorescent biosensor for sensitive detection of prostate specific antigen. Anal Bioanal Chem 407(2):369–377

Lan LY, Chen DK, Yao Y, Peng XS, Wu J, Li YB, Ping JF, Ying YB (2018) Phase-dependent fluorescence quenching efficiency of MoS2 nanosheets and their applications in multiplex target biosensing. ACS Appl Mater Inter 10(49):42009–42017

Liakos IL, Abdellatif MH, Innocenti C, Scarpellini A, Carzino R, Brunetti V, Marras S, Brescia R, Drago F, Pompa PP (2016) Antimicrobial lemongrass essential oil—copper ferrite cellulose acetate nanocapsules. Molecules 21:520

Li X, Wei L, Pan L, Yi Z, Wang X, Ye Z, Xiao L, Li H-W, Wang J (2018) Homogeneous immunosorbent assay based on single-particle enumeration using upconversion nanoparticles for the sensitive detection of cancer biomarkers. Anal Chem 90(7):4807–4814

Li XQ, Zhou Z, Zhang CC, Zheng YH, Gao JW, Wang QM (2018b) Ratiometric fluorescence platform based on modified silicon quantum dots and its logic gate performance. Inorg Chem 57:8866–8873

Liu JJ, Tang DS, Chen ZT, Yan XM, Zhong Z, Kang LT, Yao JN (2017) Chemical redox modulated fluorescence of nitrogen-doped graphene quantum dots for probing the activity of alkaline phosphatase. Biosens Bioelectron 94:271–277

Liu SG, Luo D, Han L, Li NB, Luo HQ (2019) A hybrid material composed of guanine-rich single stranded DNA and cobalt(III) oxyhydroxide (CoOOH) nanosheets as a fluorescence probe for ascorbic acid via formation of a complex between G-quadruplex and thioflavin T. Microchim Acta 186(3).

Pei HM, Zhu SY, Yang MH, Kong RM, Zheng YQ, Qu FL (2015) Graphene oxide quantum dots@silver core-shell nanocrystals as turn-on fluorescent nanoprobe for ultra-sensitive detection of prostate specific antigen. Biosens Bioelectron 74:909–914

Peng XY, Zhang YL, Lu DT, Guo YJ, Guo SJ (2019) Ultrathin Ti3C2 nanosheets based “off-on” fluorescent nanoprobe for rapid and sensitive detection of HPV infection. Sensor Actuat B-Chem 286:222–229

Safari Z, Rezaei B, Faroukhpour H, Ensafi AA (2018) A fluorometric aptasensor for methamphetamine based on fluorescence resonance energy transfer using cobalt oxyhydroxide nanosheets and carbon dots. Microchim. Acta 185(6).

Salah LM, Mabied AF, Abdellatif MH (2018) Multiferroic property of Ca1−LaTi1−FeO3 perovskite structure. J Magn Magn Mater 458:1–14

Soomro RA, Jawaid S, Zhang P, Han X, Hallam KR, Karakus S, Kilislioglu A, Xu B, Willander M (2021) NiWO4-induced partial oxidation of MXene for photoelectrochemical sensing of PSA based on MOF/Au/G-quadruplex. Biosens Bioelectron 110:160–166

Tan CL, Zhang H (2015) Two-dimensional transition metal dichalcogenide nanosheet-based composites. Chem Soc Rev 44(9):2713–2731

Wang CX, Pan CW, Wei ZT, Wei XR, Yang F, Mao LQ (2020) Bionanosensor based on N-doped graphene quantum dots coupled with CoOOH nanosheets and their application for in vivo analysis of ascorbic acid. Anal Chim Acta 1100:191–199
Wen Q, Jiang CX, Liu WQ, Zeng Z, Gao JW, Zheng YH (2021) Fluorescence determination of Ni²⁺ ions based on a novel nano-platform derived from silicon quantum dots. SILICON. https://doi.org/10.1007/s12633-020-00814-6

Wu NT, Yu AW, Zhang LB, Liu WQ, Gao JW, Zhang CC, Zheng YH (2019) Biocompatible nanoplatfrom based on mussel adhesive chemistry: effective assembly, dual mode sensing, and cellular imaging performance. Adv Mater Interf 6:1900732

Wu T, Li X, Fu YQ, Ding XL, Li ZJ, Zhu GF, Fan J (2020) A highly sensitive and selective fluorescence biosensor for hepatitis C virus DNA detection based on delta-FeOOH and exonuclease III-assisted signal amplification. Talanta 209.

Yu JF, Wang Q, O’Hare D, Sun LY (2017) Preparation of two dimensional layered double hydroxide nanosheets and their applications. Chem Soc Rev 46(19):5950–5974

You PY, Li FC, Liu MH, Chan YH (2019) Colorimetric and fluorescent dual-mode immunoassay based on plasin-enhanced fluorescence of polymer dots for detection of PSA in whole blood. ACS Appl Mater Inter 11(10):9841–9849

Yang X, Long C, Tan Y, Wang Q (2021) Surface recognition strategy via ascorbic acid-triggered decomposition of boron nitride-loaded cobalt oxyhydroxide nanosheets. Alloy Compd 872.

Zhang H, Wang Z, Yang XQ, Li ZL, Sun LH, Ma JM, Jiang H (2019) The determination of alpha-glucosidase activity through a nano fluorescent sensor of F-PDA-CoOOH. Anal Chim Acta 1080:170–177

Zhao MT, Wang YX, Ma QL, Huang Y, Zhang X, Ping JF, Zhang ZC, Lu QP, Yu YF, Xu H, Zhao YL, Zhang H (2015) Ultrathin 2D metal-organic framework nanosheets. Adv Mater 27(45):7372–7378

Zhou Z, Li B, Shen C, Wu D, Fan H, Zhao J, Li H, Zeng Z, Luo Z, Ma L, Tan C (2020) Metallic 1T phase enabling MoS₂ nanodots as an efficient agent for photoacoustic imaging guided photothermal therapy in the near-infrared-II window. Small 16(43):2004173

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.