



Colorimetric detection of sulfamethazine based on target resolved calixarene derivative stabilized gold nanoparticles aggregation

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Abstract

Sulfamethazine (SMZ) is one of the most used broad-spectrum antibiotics owing to its low cost and high efficacy towards bacterial diseases. This work reports a novel label-free SMZ sensor based on *para*-sulfonatocalix[4]arene (pSC₄) capped gold nanoparticles (pSC₄-AuNPs) for colorimetric detection through the host–guest interaction. The existence of SMZ resulted in the aggregation of pSC₄-AuNPs and can be observed through colorimetric assay. A good linear relationship in the range 2.5–20 nM was obtained with a correlation coefficient of 0.9908. The limit of detection for SMZ was 1.39 nM. High recoveries (90.18–107.06%) were obtained, and RSD ranged from 1.21 to 2.05%. The color changes can be observed from red to gray within 10 min. Combining the supermolecule's recognition and AuNP's optical performance, the method paves a new, easy, and rapid way for small target sensing.

Highlights

- Supermolecule-modified AuNPs were prepared by using one-step method.
- Quantitative detection for SMZ was achieved by simple visual and colorimetric detection.
- The highly sensitive determination is attributed for the host-guest recognition with a low detection limit of 1.39 nM.

Keywords *Para*-sulfonatocalix[4]arene capped AuNPs · Host–guest recognition · Sulfamethazine · Colorimetric sensor

Zhijuan Niu and Yawen Liu has the same contributions.

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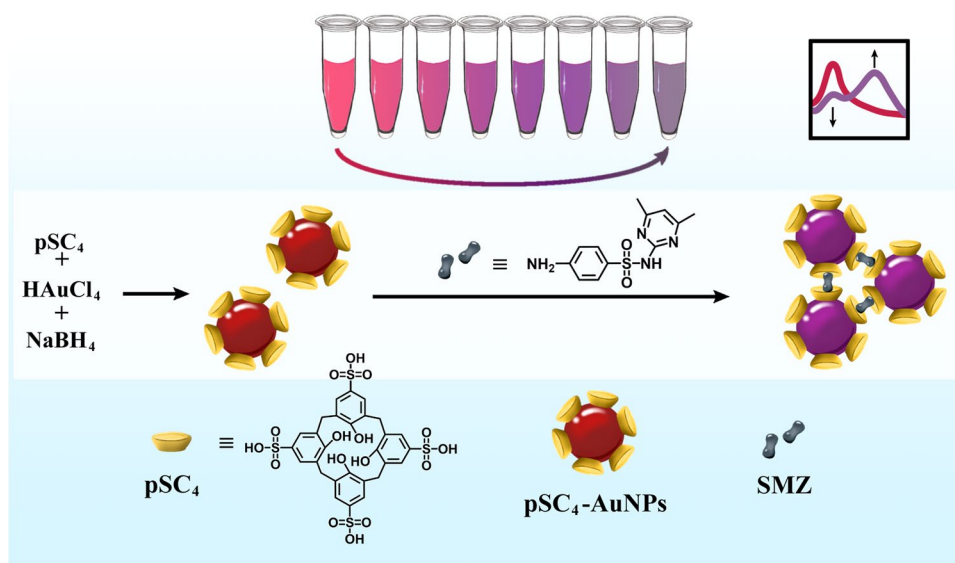
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Introduction

Sulfamethazine (4-amino-N-(4, 6-dimethyl-2-pyrimidinyl) benzene sulfonamide, SMZ), as one of the common antibiotics, was utilized in human and veterinary medicine [1–3]. It is reported that SMZ is widely presented in groundwater, surface water, and soil sediments [4]. The content of SMZ in the environment is generally between nanograms per liter and micrograms per liter. Although EU countries have stopped using sulfamethazine in agriculture since 2006 [5], however, sulfonamide antibiotics were still widely used in feed additives to improve livestock and poultry growth [6]. Overdosing or chronic abuse of SMZ may cause the accumulation in the human body [7]. EU, USA, and China have established the maximum residue limit of SMZ as 89.8 nM in milk [8]. In order to measure SMZ sensitively and quantitatively, the development of an efficient and simple detection system is still necessary.

Scheme 1 Schematic illustration of ultrasensitive UV visualization of SMZ based on host–guest recognition



At present, the fluorescence/chirality [9], enzyme-linked immunosorbent assay (ELISA) [10], electrochemical immunosensor [11], and ultra-high-performance liquid chromatography spectrometry-mass spectrometry (UHPLC-MS/MS) [12] have been developed for detection of SMZ. Consequently, it is necessary to develop a high-selectivity and low-cost-effective sensors for the detection of SMZ. In recent years, gold nanoparticles (AuNPs) have been considered for applications in different fields such as medicinal coverings [13], catalysis [14], and electrode materials [15] due to their good significant optical, high electrical conductivity, suitable redox property, and stability [16]. Among them, AuNP-based colorimetric analysis has been developed widely due to its rapidity and convenience. The macrocyclic supramolecules, such as cyclodextrin (CD), crown ether, and calixarene, possess unique and size-tunable cavity structures and exhibit special recognition properties [17]. Due to their great chemical stability, facile synthesis, and easy functionalization, the hybrid nanomaterial and macrocyclic supramolecules have been extensively studied [18–26]. *Para*-sulfonated calix[n]arene (pSCn) has open, rigid cavities and is water-soluble, which was widely used as recognition molecule.

In this work, we designed a label-free colorimetric sensor platform based on pSC₄-AuNPs. *Para*-sulfonatocalix[4]arene (pSC₄) capped gold nanoparticles (pSC₄-AuNPs) were synthesized using one-pot methods [27]. The pSC₄ has been confirmed to bind with the -NH₂ group selectively, which has the ability to recognize the amine group containing molecules. SMZ contains -NH₂ and sulfonamide groups at both ends of molecule, which is possible to bind two pSC₄ through host–guest interaction [28]. Here, pSC₄ was used as SMZ's potential recognition host for developing simple, ultrasensitive, and rapid colorimetric detection approaches

towards SMZ. Due to the specific binding between SMZ and pSC₄, gold nanoparticles aggregate in the presence of SMZ and result in the color changes. As shown in Scheme 1, the SMZ binds to pSC₄-AuNPs via host–guest recognition between the -NH₂ and sulfonamide groups of SMZ and the macrocyclic cavity of pSC₄. With the existence of target molecule, the aggregation of pSC₄-AuNPs will be observed. Therefore, combining the properties of gold nanostructures and supramolecular chemistry, the fabricated colorimetric sensor has good specificity and sensitivity.

Experimental

Chemicals and materials

Para-sulfonatocalix [4] arene (pSC₄) was obtained from TCI Development Co., Ltd. (Shanghai, China). Sodium borohydride (NaBH₄), potassium chloride (KCl), disodium hydrogen orthophosphate (Na₂HPO₄), and hydrogen tetrachloroaurate trihydrate (HAuCl₄·3H₂O) were obtained from Sigma-Aldrich, Inc. (St. Louis, USA). Sulfamethazine (SMZ), tetracycline (TC), enrofloxacin (ENR), norfloxacin (NOR), oxytetracycline (OTC), sulfamoxole (SMX), and levofloxacin (LEV) were purchased from Sangon Biotech Co., Ltd. (Shanghai, China). All the aqueous solutions were prepared with ultrapure water (18.2 MΩ cm) from a Millipore Milli-Q purification system (Barnstead, USA).

Apparatus

The UV–vis spectra were carried out with a Shimadzu UV-2450 spectrophotometer (Japan), using a quartz cuvette having a volume of 50 μL and a path length of 10 mm.

Transmission electron microscopy (TEM) image was obtained with the JEM-2010F instrument (Japan). Fourier transform infrared (FT-IR) spectra were recorded by using a spectrum FTIR 6300 spectroscopy system (JASCO, Japan). Dynamic light scattering (DLS) and zeta-potential experiments were obtained by a Malvern Zetasizer 3000 HS system (Malvern Instruments, UK). SPR measurements were performed by the MP-SPR Navi 210A VASA instrument (BioNavis Ltd, Tampere, Finland).

Preparation of the pSC₄-AuNPs and recognition of SMZ by pSC₄-AuNPs

Typically, the pSC₄-AuNPs were prepared according to previous research [29]. SMZ is almost insoluble in water and easily soluble in dilute hydrochloric acid, sodium hydroxide, or an ammonia solution. To make the stock solution, a quantity of 2.85 mg of SMZ was dissolved into 1 mL of 0.25 M diluted sulfuric acid solution and stored at 4 °C for subsequent experiments. Subsequently, pSC₄-AuNPs (90 μL) were prepared by dropping 10 μL of SMZ into a glass beaker at room temperature. The solution was continuously mixed with a vortex mixer for 2 min and measured with UV–vis spectra.

Selectivity detection of SMZ

To demonstrate that the proposed detection method had good selectivity of SMZ, the ENR, NOR, LEV, SMX OTC, TC, and SMZ as known to be the present substances in environmental water were added into the reaction system. Various antibiotics solutions (10 μL, 10 nM) were mixed with 90 μL nanoparticle solution in range of 2.5–80 nM. All determines were recorded by the UV absorption spectrum at 520 nm and 675 nm. The equilibrium dissociation constant of pSC₄-AuNPs to SMZ was determined using an SPR binding experiment. Different concentrations of SMZ were flowed and reacted on the pSC₄-AuNPs modified gold chip for about 40 min for the detection process (1 nM, 10 nM, 100 nM, 1 μM, 10 μM, 100 μM).

Real-sample detection of SMZ

To validate the practicability of this established method, the sensing of SMZ was accomplished in real samples. The determination of SMZ in deionized, tap, and lake water were investigated using the standard addition method. The tap water and lake water were filtered through a 0.22 μm PTFE syringe filter before sensing, samples (deionized, tap, and lake water) do not contain sulfamethazine. The 20 nM concentration of SMZ was added to deionized, tap and river water solutions which added 80 μL of pSC₄-AuNPs and 20 μL SMZ mixed buffer. Therefore, the final concentration of

sulfamethazine in the samples is 20 nM after spiking. The 675 nm UV–vis absorbance value was used for further actual sample analysis. All of the experiments mentioned above were repeated three times. Under optimal experimental conditions, the determination of SMZ in deionized, tap and river water was investigated using the standard addition method.

Results and discussion

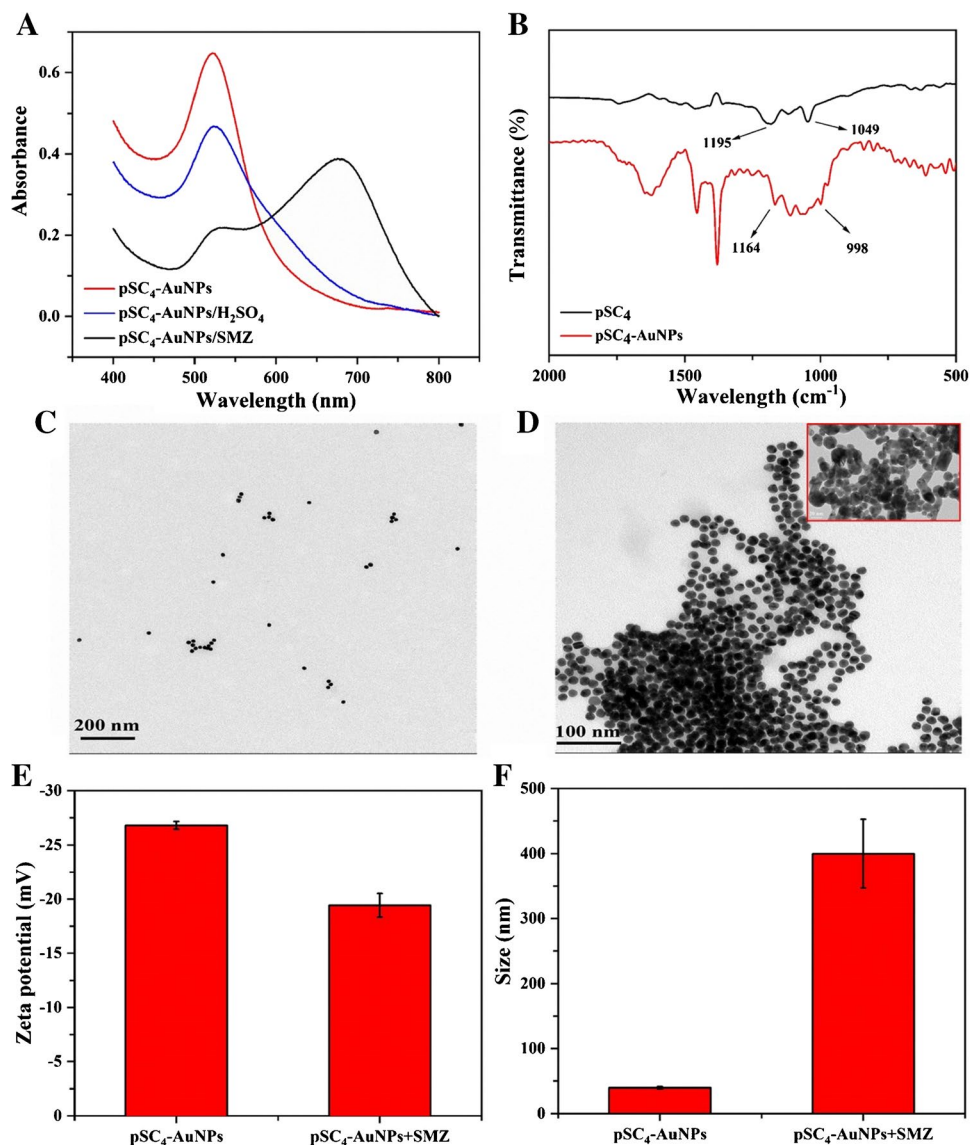
Characterization of the synthesized pSC₄-AuNPs and pSC₄-AuNPs/SMZ aggregates

The pSC₄-AuNPs were prepared via a simple and efficient one-step synthesis procedure. To prove the principle of the detection system, the host–guest recognition and electrostatic interaction between SMZ and pSC₄-AuNPs were measured by UV–vis spectroscopy. As shown in Fig. 1A, the UV–vis absorption spectrum of pSC₄-AuNPs was observed at 520 nm. After adding the SMZ, the peak at 520 nm was decreased and a new peak at 675 nm appeared. These results indicate that the SMZ can successfully make the aggregation of gold nanoparticles via host–guest recognition between the -NH₂ and sulfonamide groups of SMZ and the macrocyclic cavity of pSC₄ [30]. In the Fourier transform infrared spectroscopy (FT-IR) spectra of pure pSC₄ and AuNPs modified with pSC₄ (Fig. 1B), the stretching vibration peaks of -SO₃⁻ were found at 1195 and 1049 cm⁻¹, which shifted to 1164 and 998 cm⁻¹ after being modified to AuNPs, indicating that the -SO₃⁻ groups coordinate with the gold atoms on the surface interaction of the AuNPs [31]. To further study the SMZ controlled aggregation of pSC₄-AuNPs, the TEM was used to characterize pSC₄-AuNPs samples before and after the addition of SMZ. As shown in Fig. 1C, uniform gold nanoparticles with a diameter of 14 nm are observed. TEM images of Fig. 1D showed the aggregation structure of pSC₄-AuNPs clearly and the inset of Fig. 1D shows the higher magnifier. These results indicate that the SMZ can successfully regulate the aggregation of gold nanoparticles. Figure 1E shows that the zeta-potential of pSC₄-AuNPs changes from -26.8 to -19.4 mV after interaction with SMZ. Also shown in Fig. 1F, the particle diameter of pSC₄-AuNPs/SMZ was 399.8 nm, which is larger than that of pSC₄-AuNPs (39.6 nm). Above of all, the pSC₄ on the surface of AuNPs can recognize SMZ that leads to the obvious aggregation of the pSC₄-AuNPs.

The feasibility and condition optimization

The effects of the reaction time of SMZ and the pSC₄-AuNPs were investigated using UV–vis absorption spectroscopy. The absorption peak of UV–vis at 520 nm represents the dispersed pSC₄-AuNPs, while the absorbance value at

Fig. 1 **A** UV–vis spectra of the pSC₄-AuNPs (red trace), pSC₄-AuNPs/SMZ (black trace), and pSC₄-AuNPs/H₂SO₄ (blue trace). **B** FT-IR spectra of pSC₄ and the pSC₄-AuNPs. **C** TEM images of pSC₄-AuNPs. **D** TEM images of pSC₄-AuNPs aggregation. **E** Zeta-potential profile spectra (E) and size of pSC₄-AuNPs (F) before and after in the presence of SMZ



675 nm showed the aggregation peak [32]. Therefore, the conjugation of pSC₄-AuNPs and SMZ was measured based on UV–vis absorption spectra (Fig. S2 A). The absorbance ratio of A_{675}/A_{520} was used to quantify SMZ-induced aggregation (Fig. S2 B). The results showed that the host–guest reaction of pSC₄ and SMZ on the surface of AuNPs resulted in a gradual aggregation process. The A_{675}/A_{520} value rises rapidly at the first stage of 10 min and then remains almost constant, indicating that SMZ and pSC₄-AuNPs have completely reacted after 10 min. Therefore, the reaction time of 10 min was chosen as the reaction conditions for the subsequent study.

Performance of the constructed colorimetric sensor

Colorimetric investigation for detection of SMZ was carried out under the room temperature. As shown in Fig. 2A, with

the concentration of SMZ increases, the gradual aggregation of nanocomposites causes the color of the pSC₄-AuNPs solution to gradually change from red to gray. Figure 2B reveals linear relation between SMZ concentrations and UV–vis signals. The values following a linear behavior were observed for concentration range of 2.5 ~ 20 nM by the regression equation $y = 1.5 \times 10^{-2} [\text{SMZ}] + 8.7 \times 10^{-2}$ with $r^2 = 0.9908$ (inset of Fig. 2B). The limit of detection (LOD) can be calculated from the equation $\text{LOD} = 3\sigma/s$, where σ is the standard deviation of blank signal and s is the slope of regression equation. The LOD was found to be 1.39 nM. The performance of SMZ colorimetric sensors was compared with the reported sensors (Table 1). Compared with those sensors, such as LC–MS, enzyme-linked aptamer or fluorescence methods, the fabricated method has a narrow detection window and higher LOD. However, the synthesis of pSC₄-AuNPs was very simple, which avoids expensive

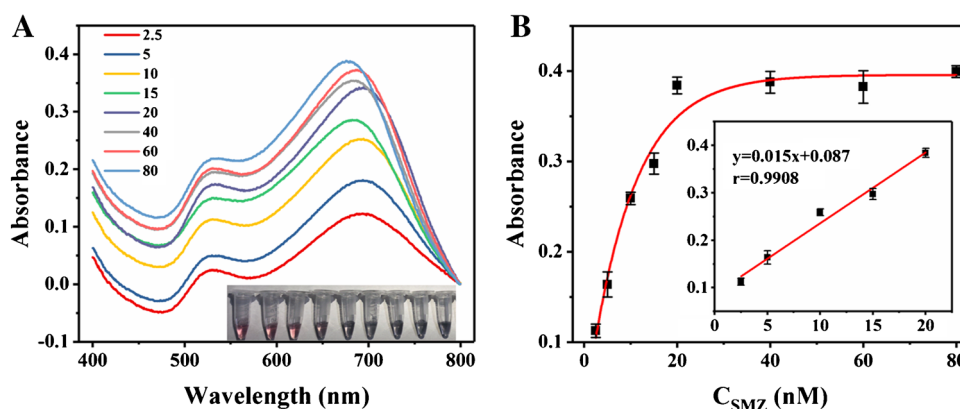


Fig. 2 **A** Visible spectra with the different concentrations of SMZ. The color change on the bottom from left to right represents SMZ at the concentrations of 0, 2.5, 5.0, 10, 15, 20, 40, 60, 80 nM, respectively (inset: pSC₄-AuNPs solution before (left) and after (right) add-

ing of SMZ with different concentrations). **B** Calibration curve representing absorption A_{675} versus concentration of SMZ in 10 nM (Inset: linear range with 2.5, 5, 10, 15, 20 nM for SMZ detection)

Table 1 Comparison of LOD value for SMZ detection performance of pSC₄-AuNPs with other methods

Method	Materials	Linear range (nM)	LOD	Ref
Fluorescence /Chirality	Au@Ag@AuNPs	0.36–360/3.6–360	0.072 /2.7	[9]
LC–MS / MS	Acetate-buffered	1.8–180	0.54	[12]
CG-ICA	Colloidal gold nanoparticles	0.36–346	0.37	[22]
Fluorescence	AgNCs	0.5–258	0.18	[24]
Chemiluminescence resonance energy transfer	QD	0.036–180	0.032	[25]
Enzyme-linked aptamer assay	Aptamer	0.36–36	0.18	[33]
Fluorescent aptamer	GO-SELEX	7.2–360	1.26	[34]
LC/EIS-MS	MoS ₂	1.8–36	Not given	[4]
Colorimetric	pSC ₄ -AuNPs	2.5–20	1.39	this study

antibody costs. Also, the detection limit reached the national maximum residue limit and the detection process was also very fast. Therefore, this colorimetric on-site detection method is still competitive in terms of rapid detection and simple fabrication.

Specificity detection and stability of the pSC₄-AuNPs

To assess the sensor selectivity, the same concentrations of tetracycline (TC), enrofloxacin (ENR), norfloxacin (NOR), oxytetracycline (OTC), sulfamoxole (SMX), and levofloxacin (LEV) were added in the colorimetric sensor. From Fig. 3A, we can observe that the binding of pSC₄-AuNPs to SMZ is significantly different from others. In the ultraviolet spectrum of the pSC₄-AuNPs system, there is no obvious change when introducing other antibiotics except the SMZ. In addition, the result of Fig. S1 also showed that the equilibrium dissociation constant of SMZ and pSC₄-AuNPs was 98.9 nM. It is indicated that pSC₄-AuNPs has higher affinity toward sulfamethazine. With the addition of SMZ,

the ratio of the absorbance intensity at A_{520} nm and A_{675} nm (A_{675}/A_{520}) was proportionally increased, suggesting an excellent selectivity to SMZ. The results showed that all of the presented coexisting substances have no interference in the detection of SMZ for the reported pSC₄-AuNPs system, which demonstrates the constructed colorimetric sensor has a good selectivity and specificity. The stability of the SMZ sensor was evaluated by UV–vis absorbance of pSC₄-AuNPs for 14 weeks. As shown in Fig. 3B, the absorbance of pSC₄-AuNPs did not significantly change after 14 weeks of storage, which indicated the good stability of pSC₄-AuNPs.

Detection in tap and lake water samples

The feasibility and reliability of colorimetric sensor for the determination of SMZ in deionized, tap, and river water was investigated using the standard addition method. The 20 nM concentrations of SMZ were added into real samples. Each analysis was conducted in triplicate to reduce the experimental error. As shown in Table 2, the high recoveries

Fig. 3 **A** The variations in the absorbance ratio A_{675}/A_{520} colorimetric pSC₄-AuNPs detection system in the presence of ENR, NOR, LEV, SMX, OTC, TC, SMZ. Blank means pure water only. **B** Stability of pSC₄-AuNPs for long term storage

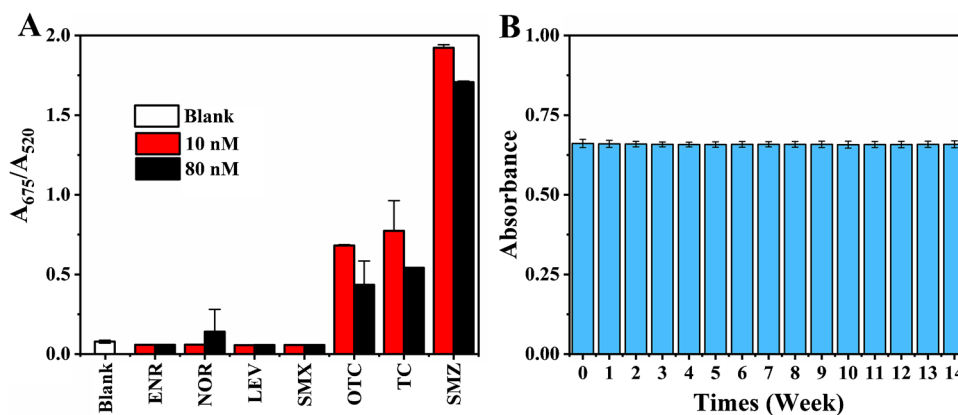


Table 2 Analysis results of water samples spiked with SMZ by the proposed sensor ($n=3$)

Samples	Added (nM)	SMZ determined (nM)	Recovery (%)	RSD (%)
Deionized water	20	18.07 ± 0.27	90.18 ± 1.09	1.21
Tap water	20	19.22 ± 0.27	96.99 ± 1.34	1.38
River water	20	21.41 ± 0.54	107.06 ± 2.19	2.05

(90.18–107.06%) were obtained, and RSD ranged from 1.21 to 2.05%. For river or lakes samples, the results indicated that this SMZ sensor can be applied in real samples determination even though the water environment is complicated.

Conclusions

In this work, a sensitive and facile method was developed based on the host–guest interaction for aqueous determination of SMZ. SMZ mediates the aggregation of pSC₄-AuNPs through the host–guest recognition, which can be used as a simple and on-site colorimetric SMZ assay. Compared with other sensors, it has a small disadvantage in terms of versatility, which has low specificity and a narrow detection window. Take into account of the simple synthesis of pSC₄-AuNPs and fast detection of SMZ, the proposed strategy paves the way for the development of a simple and sensitive platform for the rapid detection of interactions between small molecules and macrocycles.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00604-022-05176-x>.

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Declarations

Conflict of interest The authors declare no competing interests.

References

- Guo XY, Shen XF, Zhang M et al (2017) Sorption mechanisms of sulfamethazine to soil humin and its subfractions after sequential treatments. *Environ Pollut* 221:266–275
- Fry H, Mietle K, Mahner E et al (2017) Interlaboratory validation of an LC-MS/MS method for the determination of melamine and cyanuric acid in animal feed. *Food Addit Contam: Part A* 34(8):1320–1332
- Kowalski P, Plenis A, Oledzka I et al (2011) Optimization and validation of the micellar electrokinetic capillary chromatographic method for simultaneous determination of sulfonamide and amphenicol-type drugs in poultry tissue. *J Pharmaceut Biomed* 54:160–167
- Zhao YJ, Tang MM, Liao QB et al (2018) Disposable MoS₂ arrayed MALDI MS Chip for high-throughput and rapid quantification of sulfonamides in multiple real samples. *ACS Sensor* 3(4):806–814
- Kivits T, Broers H P, Beeltje H, et al (2018) Presence and fate of veterinary antibiotics in age-dated groundwater in areas with intensive livestock farming. *Environ Pollut* 241:988–998
- Heuer H, Schmitt H, Smalla K (2011) Antibiotic resistance gene spread due to manure application on agricultural fields. *Curr Opin Microbiol* 14(3):236–243
- Cui EP, Gao F, Liu Y et al (2018) Amendment soil with biochar to control antibiotic resistance genes under unconventional water resources irrigation: Proceed with caution. *Environ Pollut* 240:475–484
- Wang S, Wang Z, Zhang L et al (2022) Adsorption and convenient ELISA detection of sulfamethazine in milk based on MOFs pretreatment. *Food Chem* 374:131712

9. Chen YN, Liu LQ, Xu LG et al (2017) Gold immunochromatographic sensor for the rapid detection of twenty-six sulfonamides in foods. *Nano Res* 10(8):2833–2844
10. Shelver WL, Shappell et al (2008) ELISA for sulfonamides and its application for screening in water contamination. *J Agric Food Chem* 56(15):6609–6615
11. Pollap A, Kochana J (2019) Electrochemical immunosensors for antibiotic detection. *Biosensors* 9(2):61
12. Yu LM, Song C, Zhang C et al (2018) Occurrence of sulfonamides in fish in the lower reaches of yangtze river, China and estimated daily intake for understanding human dietary exposure. *Aquaculture* 495:538–544
13. Attar F, Shahpar MG, Rasti B et al (2019) Nanozymes with intrinsic peroxidase-like activities. *J Mol Liq* 278:130–144
14. Ren JS, Qu XG (2019) Nanozymes: classification, catalytic mechanisms, activity regulation, and applications. *Chem Rev* 119(6):4357–4412
15. Wu JJX, Wang XY, Wang Q et al (2019) Nanomaterials with enzyme-like characteristics (nanozymes): next-generation artificial enzymes (II). *Chem Soc Rev* 48(4):1004–1076
16. Singh M, Singh S, Prasad S et al (2008) Nanotechnology in medicine and antibacterial effect of silver nanoparticles. *Dig J Nanomater Bios* 3(3):115–122
17. Zhao Y, Huang YC, Zhu H et al (2016) Three-in-One: sensing, self-assembly, and cascade catalysis of cyclodextrin modified gold nanoparticles. *J Am Chem Soc* 138(51):16645–16654
18. Bassanetti I, Comotti A, Sozzani P et al (2014) Porous molecular crystals by macrocyclic coordination supramolecules. *J Am Chem Soc* 136(42):14883–14895
19. Qu DH, Wang QC, Zhang QW et al (2015) Photoresponsive host-guest functional systems. *Chem Rev* 115:7543–7588
20. Yang YW, Sun YL, Song N (2014) Switchable host-guest systems on surfaces. *Acc Chem Res* 47:1950–1960
21. Hu JJ, Zhao JL, Zhu H et al (2021) AuNPs network structures as a plasmonic matrix for ultrasensitive immunoassay based on surface plasmon resonance spectroscopy. *Sens Actuators B: Chem* 340:129948
22. Liu NM, Xing KY, Wang C et al (2018) Matrix effect of five kinds of meat on colloidal gold immunochromatographic assay for sulfamethazine detection. *Anal Methods* 10(37):4505–4510
23. Zhang P, Shao CL, Zhang ZY et al (2011) In situ assembly of well-dispersed Ag nanoparticles (AgNPs) on electrospun carbon nanofibers (CNFs) for catalytic reduction of 4-nitrophenol. *Nanoscale* 3(8):3357–3363
24. Zhu NF, Zhu YQ, Wang J et al (2019) A novel fluorescence immunoassay based on AgNCs and ALP for ultrasensitive detection of sulfamethazine (SMZ) in environmental and biological samples. *Talanta* 199:72–79
25. Ma MF, Wen K, Beier RC et al (2016) Chemiluminescence resonance energy transfer competitive immunoassay employing hapten-functionalized quantum dots for the detection of sulfamethazine. *ACS Appl Mater Interfaces* 8(28):17745–17750
26. Hoskins, C., Papachristou, A., Ho, T. M. H et al (2016) Investigation into drug solubilisation potential of sulfonated calix [4] resorcinarenes. *J Nanomed Nanotechnol* 7(2)
27. Wang XX, Du DS, Dong HB et al (2018) para-sulfonatocalix[4]arene stabilized gold nanoparticles multilayers interfaced to electrodes through host-guest interaction for sensitive ErbB2 detection. *Biosens Bioelectron* 99:375–381
28. Zou F, Wang XX, Qi FJ et al (2017) Magneto-plasmonic nanoparticles enhanced surface plasmon resonance TB sensor based on recombinant gold binding antibody. *Sens Actuators B: Chem* 25:356–363
29. Dong HB, Zou F, Hu XJ et al (2018) Analyte induced AuNPs aggregation enhanced surface plasmon resonance for sensitive detection of Paraquat. *Biosens Bioelectron* 117:605–612
30. Wang X, Koh K, Chen H (2017) Colorimetric assay of butyrylcholinesterase activity based on para-sulfonatocalix [4] arene-modified gold nanoparticles. *Sens Actuators B: Chem* 251:869–876
31. Xiong DJ, Chen ML, Li HB (2008) Synthesis of para-sulfonatocalix[4]arene-modified silver nanoparticles as colorimetric histidine probes. *Chem Commun* 7:880–882
32. Dong HB, Hu XJ, Zhao JL et al (2018) Sensitive detection of fractalkine based on AuNPs and metal-organic frameworks composite at para-sulfonatocalix[4]arene-AuNPs assembled multilayer interface. *Sens Actuators B: Chem* 276:150–157
33. Yang MY, Wu XY, Hu XL et al (2019) Electrochemical immunosensor based on Ag⁺-dependent CTAB-AuNPs for ultrasensitive detection of sulfamethazine. *Biosens Bioelectron* 144:111643
34. Kou QM, Wu P, Sun Q et al (2021) Selection and truncation of aptamers for ultrasensitive detection of sulfamethazine using a fluorescent biosensor based on graphene oxide. *Anal Bioanal Chem* 413(3):901–909

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