

Gold Nanoparticles Functionalized with Mercaptosuccinic Acid as a Means for Detecting Fe(III) ions [†]

Nadezhda S. Komova, Ksenya V. Serebrennikova, Anna N. Berlina, Svetlana M. Pridvorova, Anatoly V. Zherdev and Boris B. Dzantiev *

A.N. Bach Institute of Biochemistry, Research Center of Biotechnology of the Russian Academy of Sciences, Leninsky prospect 33, Moscow 119071, Russia; nad4883@yandex.ru (N.S.K.); anberlina@yandex.ru (A.N.B.); zherdev@inbi.ras.ru (A.V.Z.);

* Correspondence: dzantiev@inbi.ras.ru, Tel.: +7-495-954-31-42

[†] Presented at the 1st International Electronic Conference on Chemical Sensors and Analytical Chemistry, 01–15 July 2021; Available online: <https://csac2021.sciforum.net/>.

Abstract: The application of mercaptosuccinic acid-capped gold nanoparticles as a sensing probe for the colorimetric detection of Fe(III) is reported. The well-dispersed gold nanoparticles (AuNPs) with a diameter of around 20 nm were obtained by a one-step reaction of tetrachloroauric acid with mercaptosuccinic acid (MSA) as a reducing and capping agent, respectively. Fe(III) reportedly causes the aggregation of prepared MSA-capped AuNPs followed by a change in color and a shift to long wavelengths in the absorbance spectra. The resulting method allows for a visual and spectrophotometric Fe(III) determination with detection limits of 30 ng/mL and 23 ng/mL, respectively. MSA-capped AuNPs have been used as sensing probes for the detection of Fe(III) in drinking water samples with a detection limit that is much lower than the maximum permissible level of Fe(III) specified by official regulations (300 ng/mL).

Keywords: mercaptosuccinic acid; gold nanoparticles; Fe(III) ions; colorimetry; aggregation; drinking water

Citation: Komova, N.; Serebrennikova, K.; Berlina, A.; Zherdev, A.; Dzantiev, B. Gold nanoparticles functionalized with mercaptosuccinic acid as a means for detecting Fe(III) ions. *Chem. Proc.* **2021**, *3*, x. <https://doi.org/10.3390/xxxxx>

Published: 01 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Currently, the control of the quality and composition of consumed drinking water has become extremely important. One of the main problems with a centralized water supply is the almost ubiquitous increased concentration of heavy metals in water, the main of which is iron. This is primarily due to the widespread occurrence of this chemical element in various soils [1]; however, significant amounts of Fe(III) can also come from wastewater from the metallurgical, metalworking, textile, paint, and varnish industries and from agricultural wastewater. Because a high consumption of Fe(III) can cause toxic effects, the determination of Fe(III) content in water resources is of great importance for human life.

Various analytical methods, such as atomic absorption spectrometry [2], inductively coupled plasma mass spectrometry [3], liquid chromatography [4], spectrophotometric [5], and fluorescent [6] methods, are successfully applied for Fe(III) determination. Despite the high sensitivity of these methods, they are complex and time-consuming and usually require expensive equipment operated by skilled personnel. On the contrary, colorimetric systems offer a promising approach for the detection of various metal ions, largely due to their simplicity and rapidity as well as to the opportunity to estimate results visually. To date, a number of colorimetric sensors based on the aggregation of nanomaterials induced by metal ions and the registration of color changes (visually) and a shift of the plasmon resonance peak (spectrophotometrically) has been reported [7]. A widespread approach used to increase the selectivity of these techniques is the functionalization of the surface

of nanomaterials with various ligands [8]. Among these, pyrophosphate [9], hydroxamic acid [10], oxamic and p-aminobenzoic acids [11], casein [12], and (glycol)chitosan [13, 14] have been employed for the colorimetric detection of Fe(III) in various environmental and biological samples.

A colorimetric system based on gold nanoparticles (AuNPs) functionalized with mercaptosuccinic acid (MSA) for the simple, rapid, selective, and cost-effective detection of trace Fe(III) ions in water was developed. The choice of the functionalizing agent was determined by previously described binding properties of mercaptosuccinic acid [15-17]. Moreover, the one-step preparation and functionalization of the proposed AuNPs greatly simplifies and accelerates the preparation of the sensor system. To the best of our knowledge, this is the first report of using mercaptosuccinic acid-functionalized AuNPs as a colorimetric sensor for the detection of trace levels of Fe(III) in aqueous media.

2. Experimental.

2.1. Chemicals and Materials

An aqueous solution of Fe(III) (1 g/L) was obtained from the Center of Standardization of Samples and High-Purity Substances (St. Petersburg, Russia). Salts of Cd²⁺, As³⁺, Cu²⁺, Zn²⁺, Pb²⁺, Sn²⁺, and Cr³⁺ were also obtained from the Center of Standardization of Samples and High-Purity Substances. 2-Mercaptosuccinic acid (MSA) and tetrachloroauric acid (HAuCl₄) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Milli-Q-purified water was obtained using a Milli-Q Simplicity system from Millipore (Bedford, MA, USA) and was used to prepare all aqueous solutions.

2.2. Synthesis of MSA-functionalized AuNPs

Gold nanoparticles were synthesized through the reduction of HAuCl₄ by mercaptosuccinic acid [18]. First, 100 mL of the 0.01% HAuCl₄ solution was heated to boiling temperature and stirred using a magnet stirrer. After that, 12.5 mL of the 1 mM aqueous solution of MSA was added to the reaction mixture. The MSA solution was preliminarily neutralized with a sodium hydroxide in a stoichiometric ratio 1:2. Thereafter, the reaction mixture was incubated with continuous stirring for 15 min and cooled to room temperature. The synthesized MSA-functionalized AuNPs were concentrated 10 times by centrifugation, resuspended in Milli-Q water with an adjustment to pH 3-4, and stored at 4-6 °C until analysis.

2.3. Transmission Electron Microscopy

The prepared MSA-functionalized AuNPs were applied to 300-mesh grids (Pelco International, Redding, CA, USA) coated with a support film of polyvinyl formal deposited from chloroform. A JEM CX-100 electron microscope (JEOL, Tokyo, Japan) operating at 80 kV was used to obtain the images. The digital images were analyzed using Image Tool software (University of Texas Health Science Center, San Antonio, TX, USA).

2.4. Detection of Fe(III) ions

To determine the Fe(III) ions, 5 µL of a concentrated MSA-AuNP colloidal solution was added to an aqueous solution (pH 5) containing various amounts of analyte. After 5 min, the absorption spectra were measured by the EnSpire Multi-mode Plate Reader (PerkinElmer, USA). When applying this technique for real water samples, a preliminary dilution (2-15 times depending on the water source) of the samples was used. To test the selectivity of the developed technique and the interference from other heavy metal ions, the solutions containing Hg²⁺, Cd²⁺, As³⁺, Cu²⁺, Zn²⁺, Pb²⁺, Sn²⁺, or Cr³⁺ (100 ng/mL) were examined.

3. Results and Discussion

3.1. Synthesis and Characterization of MSA-capped AuNPs

Mercaptosuccinic acid was chosen as a reducing agent due to the presence of two carboxyl groups providing functionalization by a chelate structure (Figure 1). The procedure of the MSA-capped AuNPs synthesis includes mixing a HAuCl_4 and MSA solution at an optimized molar ratio of 2:1, which ensures a spherical form of particles with a size distribution within 20–25 nm [18]. Figure 2A,B shows the TEM image of MSA-functionalized AuNPs and the size distribution of the nanoparticles. The obtained nanoparticles have a spherical morphology with an average diameter of 19.9 ± 7.1 nm (number of particles was 195). In addition, the protection layer on the gold particles was observed in a TEM image. The obtained absorbance spectra of the MSA-AuNPs in the presence and absence of Fe(III) are given at Figure 2C. A strong peak at 530 nm was observed for MSA-AuNPs.

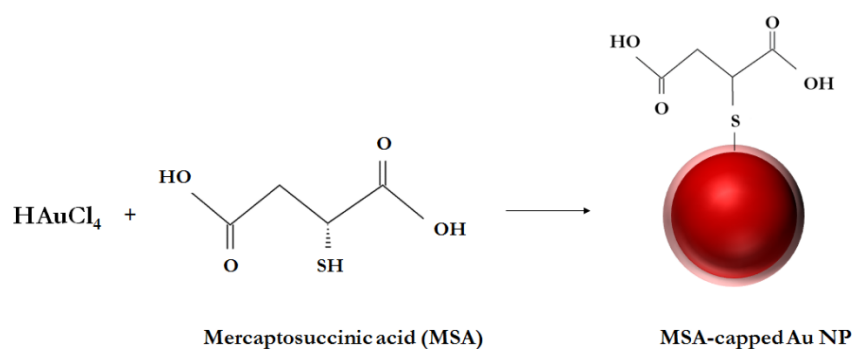


Figure 1. Scheme of MSA-functionalized AuNPs synthesis.

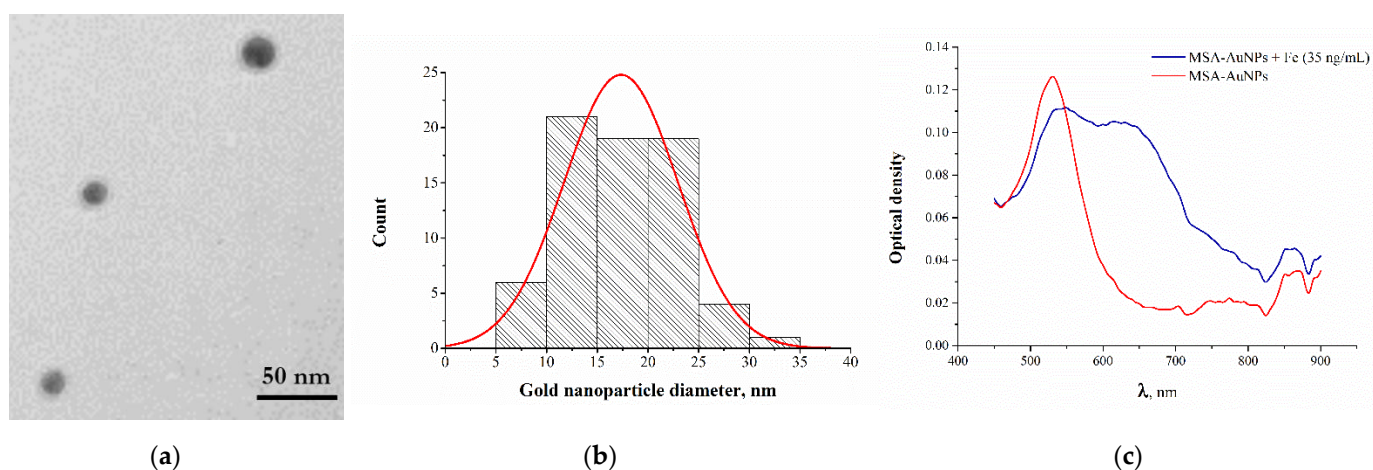


Figure 2. (a) TEM image of MSA-capped AuNPs; (b) Histogram of MSA-AuNPs particles diameter distribution; (c) Absorption spectrum of MSA-AuNPs before (red) and after (blue) the addition of Fe(III) ions.

3.2. Colorimetric Determination of Fe(III) ions

The proposed assay scheme is illustrated in Figure 3. In the presence of Fe(III), the coordination of MSA on the particle surface induces the critical convergence and loss of stability of the colloidal solution, resulting in a color change from red to blue. When the Fe(III) concentration reaches 20 ng/mL, particle aggregation occurs registered by a decrease in the absorption peak at 530 nm and an increase in the peak at 660 nm. Consequently, the A_{530}/A_{660} ratio was selected as an analytical signal.

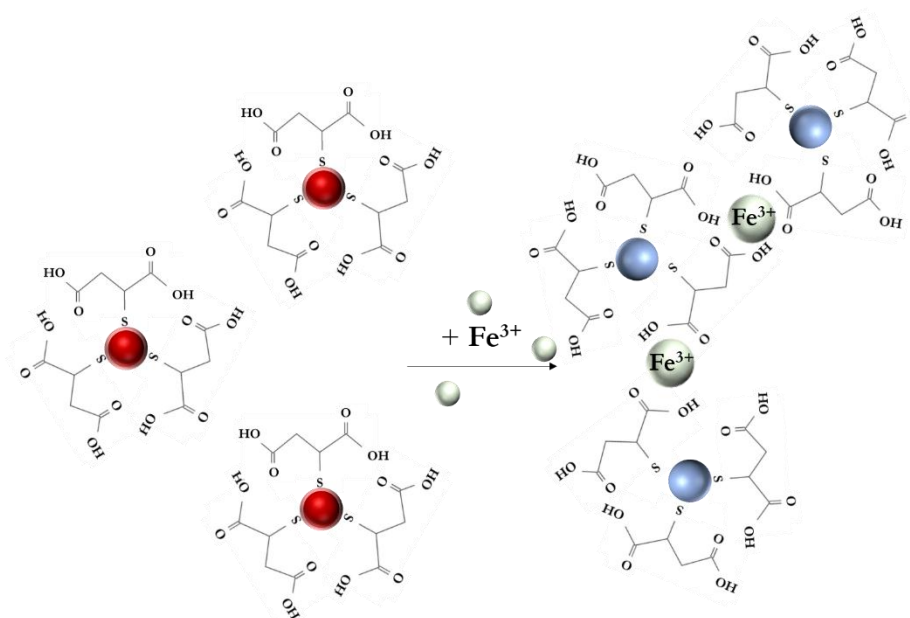


Figure 3. Scheme of colorimetric detection of Fe(III) ions using MSA-capped gold nanoparticles.

To find the optimal conditions for the determination of Fe(III) ions, we studied some factors affecting the analytical signal, such as the pH of the medium and the volume ratio of the reacting components (MSA-AuNPs and Fe(III)). The effect of pH on the changes in the analytical signal in the presence of Fe(III) ions was studied; the maximum detection sensitivity was achieved at pH 4.5.

To investigate the optimum volume ratio of reaction components (MSA-AuNPs and Fe(III) solution), various ratios of the volumes of MSA-AuNPs and Fe(III) ion-containing solutions (1:1, 1:3, 1:30) were tested. The best sensitivity of the analysis was achieved with the volume ratio of MSA-AuNPs / Fe(III) ion solutions equal to 1:30.

The aggregation of MSA-AuNPs in the presence of Fe(III) proceeded by complexation with the chelating ligands of mercaptosuccinic acid, which was accompanied by a blue shift in the absorption spectrum. The detection limit using MSA-AuNPs as the sensing probe was 23 ng/mL, at least 10 times lower than the maximum permissible concentration of Fe(III) for drinking water, which is 300 ng/mL by official regulations. The linear range of the calibration curve was 20–30 ng/mL with an approximation factor of R^2 0.98 (Figure 4). In addition, the developed sensing system allowed for the detection of Fe(III) by the naked eye at a concentration from 30 ng/mL, which corresponds to the blue color of the reaction mixture. The effectiveness of the developed system for the analysis of real samples was confirmed by the determination of Fe(III) ions in water samples without a matrix influence.

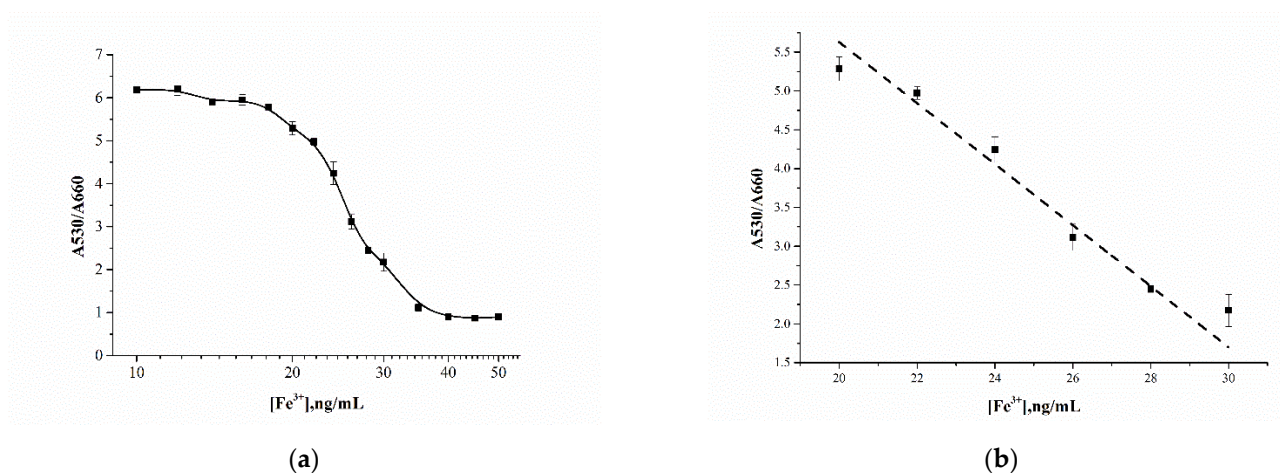


Figure 4. (a) Calibration curve for Fe(III) ion detection using AuNP-MSA; (b) Linear range of the calibration curve.

3.3. Selectivity of Fe(III) ions Detection

To check for the possible influence of other metal ions on analytical signals for the detection of Fe(III) ions, solutions of Hg(II), Cd(II), As(II), Cu(II), Zn(II), Pb(II), Sn(II), and Cr(II) were tested under the chosen optimal conditions. It was found that the tested ions do not influence the analytical signal; the color change was achieved only for Fe(III) ions. The experimental data showed that the analytical signal (A_{530}/A_{660}) induced by Fe(III) significantly exceeded signals for other metal ions.

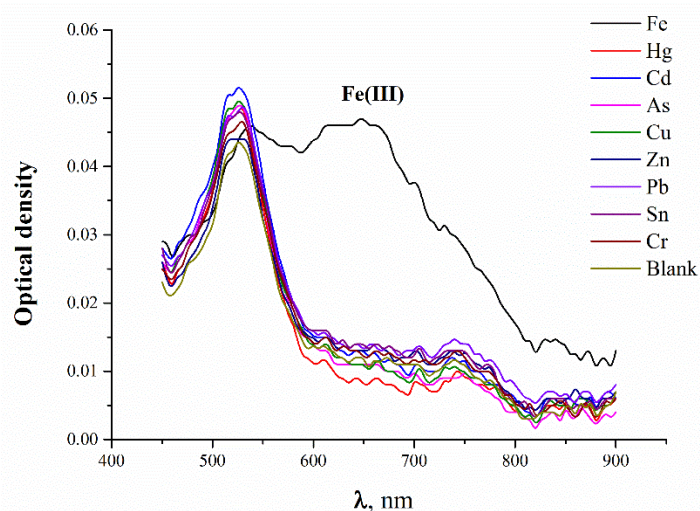


Figure 5. Absorbance spectra of MSA-capped Au NPs after the addition of 100 ng/mL metal ions.

4. Conclusion

A highly sensitive and selective colorimetric system for Fe(III) ion detection based on mercaptosuccinic acid functionalized gold nanoparticles was developed. The sensing mechanism is the aggregation of gold nanoparticles due to the selective complexation of mercaptosuccinic acid with Fe(III), resulting in a change in color and in the absorbance spectrum. Under optimal conditions, this system showed a good linear correlation between Fe (III) concentrations and the colorimetric signal, with visual and instrumental detection limits of 30 and 23 ng/mL, respectively. The system demonstrated high selectivity against other metal ions. The assay combined simple fabrication and operation with the possibility of sensitive on-site monitoring. The effectiveness of the developed system

was confirmed by the determination of Fe(III) ions in the water samples without a matrix influence.

Author Contributions: Conceptualization, A.N.B. and A.V.Z.; methodology, A.N.B., N.S.K. and K.V.S.; software, N.S.K.; validation, N.S.K., K.V.S. and A.N.B.; formal analysis, N.S.K., K.V.S., S.M.P.; investigation, A.N.B., K.V.S.; resources, S.M.P.; data curation, A.V.Z. and B.B.D.; writing—original draft preparation, N.S.K., K.V.S. and A.N.B.; writing—review and editing, A.V.Z., B.B.D.; visualization, N.S.K.; supervision, A.V.Z. and B.B.D.; project administration, A.V.Z.; funding acquisition, A.N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Russian Science Foundation (project # 19-44-02020, assay development) and the Ministry of Science and Higher Education of the Russian Federation (study of assay selectivity).

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: This work was financially supported by the Russian Science Foundation (project # 19-44-02020, assay development) and the Ministry of Science and Higher Education of the Russian Federation (study of assay selectivity).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xu, T.T.; Yang, J.X.; Song, J.M.; Chen, J.S.; Niu, H.L.; Mao, C.J.; et al. Synthesis of high fluorescence graphene quantum dots and their selective detection for Fe³⁺ in aqueous solution. *Sens. Actuators B: Chem.* **2017**, *243*, 863–72.
2. Bagheri, H.; Afkhami, A.; Saber-Tehrani, M.; Khoshafar, H. Preparation and characterization of magnetic nanocomposite of Schiff base/silica/magnetite as a preconcentration phase for the trace determination of heavy metal ions in water, food and biological samples using atomic absorption spectrometry. *Talanta* **2012**, *97*, 87–95.
3. Wu, J.; Boyle, E.A. Determination of iron in seawater by high-resolution isotope dilution inductively coupled plasma mass spectrometry after Mg(OH)₂ coprecipitation. *Anal. Chim. Acta* **1998**, *367*, 183–91.
4. Ariga, T.; Ito, K.; Imura, Y.; Yoshimura, E. High-performance liquid chromatography method for ferric iron chelators using a post-column reaction with Calcein Blue. *J. Chromatogr. B* **2015**, *985*, 48–53.
5. Kuljanin, J.; Janković, I.; Nedeljković, J.; Prstojević, D.; Marinković, V. Spectrophotometric determination of alendronate in pharmaceutical formulations via complex formation with Fe(III) ions. *J. Pharm. Biomed. Anal.* **2002**, *28*, 1215–20.
6. Hirayama, T. Fluorescent probes for the detection of catalytic Fe(II) ion. *Free Radic. Biol. Med.* **2019**, *133*, 38–45.
7. Piriya, V.S.A.; Joseph, P.; Daniel, S.C.G.K.; Lakshmanan, S.; Kinoshita, T.; Muthusamy, S. Colorimetric sensors for rapid detection of various analytes. *Mater. Sci. Eng. C* **2017**, *78*, 1231–45.
8. Alex, S.; Tiwari, A. Functionalized Gold Nanoparticles: Synthesis, Properties and Applications. A Review. *J. Nanosci. Nanotechnol.* **2015**, *15*, 1869–94.
9. Wu, S.P.; Chen, Y.P.; Sung, Y.M. Colorimetric detection of Fe³⁺ ions using pyrophosphate functionalized gold nanoparticles. *Analyst* **2011**, *136*, 1887–91.
10. Karami, C.; Alizadeh, A.; Taher, M.A.; Hamidi, Z.; Bahrami, B. UV-Visible Spectroscopy Detection of Iron(III) Ion on Modified Gold Nanoparticles With a Hydroxamic Acid. *J. Appl. Spectrosc.* **2016**, *83*, 687–93.
11. Buduru, P.; Reddy, B.C.S.R. Oxamic acid and p-aminobenzoic acid functionalized gold nanoparticles as a probe for colorimetric detection of Fe³⁺ ion. *Sens. Actuators B: Chem.* **2016**, *237*, 935–43.
12. Kim, D.Y.; Shinde, S.; Saratale, R.; Syed, A.; Ameen, F.; Ghodake, G. Spectrophotometric determination of Fe(III) by using casein-functionalized gold nanoparticles. *Microchim. Acta* **2017**, *184*, 4695–704.
13. Li, J.; Wang, X.; Huo, D.; Hou, C.; Fa, H.; Yang, M. et al. Colorimetric measurement of Fe³⁺ using a functional paper-based sensor based on catalytic oxidation of gold nanoparticles. *Sens. Actuators B: Chem.* **2017**, *242*, 1265–71.
14. Kim, K.; Nam, Y.S.; Lee, Y.; Lee, K.B. Highly Sensitive Colorimetric Assay for Determining Fe³⁺ Based on Gold Nanoparticles Conjugated with Glycol Chitosan. *J. Anal. Methods Chem.* **2017**, *2017*, 3648564.
15. Cheney, G.E.; Fernando, Q.; Freiser, H. Some Metal Chelates of Mercaptosuccinic Acid. *J. Phys. Chem.* **1959**, *63*, 2055–7.
16. Larkworthy, L.F.; Sattari, D. Some complexes of thiomalate with bivalent transition metal ions and gold (I). *J. Inorg. Nucl. Chem.* **1980**, *42*, 551–9.
17. Pawelec, M.; Stochel, G.; Eldik, R. Mechanistic information on the copper-catalysed autoxidation of mercaptosuccinic acid in aqueous solution. *Dalton Trans.* **2004**, *2*, 292–8.
18. Vasilev, K.; Zhu, T.; Glasser, G.; Knoll, W.; Kreiter, M. Preparation of gold nanoparticles in an aqueous medium using 2-mercaptosuccinic acid as both reduction and capping agent. *J. Nanosci. Nanotechnol.* **2008**, *8*, 2062–8.