
ARTICLES

Spectrophotometric Determination of Putrescine with Boron-Doped Carbon Quantum Dots: Development of a New Sensitive Analytical Method

Zehra O. Erdogan^{a, *} and Cigdem Cicek^b

^a Department of Pharmacy Services, Vocational School, Yuksek Ihtisas University, Ankara, 06291 Turkey

^b Department of Medical Biochemistry, Faculty of Medicine, Yuksek Ihtisas University, Ankara, 06520 Turkey

*e-mail: duruzera@gmail.com

Received May 20, 2025; revised August 25, 2025; accepted August 27, 2025

Abstract—Putrescine, a vital polyamine involved in various cellular functions, particularly cell proliferation, is often associated with health conditions such as cancer. Traditional methods for putrescine determination suffer from limitations such as high detection limits and complexity. Hence, there is a need for sensitive and efficient detection methods. In this research, a novel spectrophotometric method utilizing boron-doped carbon quantum dots (B-CQDs) was developed for the detection of putrescine in artificial blood samples. B-CQDs, being a promising member of semiconductor quantum dots, offer improved optical properties along with enhanced biocompatibility and stability compared to conventional quantum dots. B-CQDs were synthesized *via* a straightforward method using boric acid, citric acid, and urea. The B-CQDs were characterized by Fourier-transform infrared spectroscopy, scanning electron microscopy, dynamic light scattering, and ultraviolet-visible spectroscopy, and the absorbance wavelength of B-CQDs was found to be 204.0 nm. The addition of putrescine to B-CQDs resulted in an increase in absorbance, enabling the quantification of putrescine through absorbance difference measurements. Optimization studies revealed that the developed method exhibits maximum sensitivity at pH 6.0, within the stable putrescine concentration range (1.0 μM). The linear working range of the method was found to be 0.05–0.75 μM with a high correlation coefficient ($R^2 = 0.9975$). The stability of the B-CQDs solution was evaluated, indicating its suitability for at least 20 min of continuous measurements. The applicability of the developed method was validated by analyzing putrescine in artificial blood samples, yielding satisfactory recovery values ($89.5 \pm 0.9\%$ and $98.3 \pm 0.6\%$ for two different concentrations).

Keywords: putrescine, boron-doped carbon quantum dots, spectrophotometric detection, artificial blood

DOI: 10.1134/S1061934825701370

Biogenic amines, particularly polyamines, have been linked to positive impacts on human health because of their anti-inflammatory and antioxidant characteristics [1]. They play a role in basic cellular functions, including cell proliferation and differentiation [2, 3]. Several studies have also pointed to the role of polyamines in glucose utilization, insulin sensitivity, and fat oxidation [4, 5]. However, polyamine concentrations generally decline with aging in most organisms, and this decline has been associated with various age-related health disorders in humans [6]. Polyamines have been suggested to increase lifespan, possibly through stimulation of the autophagic cycle of cytoplasmic organelles or senescent proteins [7]. Polyamines, spermine, spermidine, and their precursor putrescine, are produced by mammals. Putrescine, also known as 1,4-diaminobutane, is formed by the enzyme ornithine decarboxylase, while S-adenosylmethionine decarboxylase produces decarboxylated S-adenosylmethionine. Putrescine is one of the pre-

dominant polyamines in mammalian cells and is widespread in a wide variety of organisms, as it is essential for cell growth and proliferation [8]. Certain types of cancer have been reported to be linked to high putrescine concentrations in tissue. Putrescine has been reported to accumulate in human lung tumors, blood, serum, and mucosa of cancer patients [9]. Therefore, putrescine has been listed as a tumor marker [10, 11]. Detection of putrescine in clinical samples may be important for diagnosing malignancy and monitoring the effectiveness of treatment, such as radiotherapy [12] or chemotherapy [13].

Quantitative determination of putrescine has been reported by different methods; chromatographic methods are the most common. Cation exchange chromatography, capillary electrophoresis [14], reverse-phase high-performance liquid chromatography, and ion chromatography-integrated pulsed amperometric detection [15], ion-spray ionization mass spectrometry [16] are among the methods used.

In addition, enzymatic and immunological methods have also been employed [13]. These techniques offer good separation and low detection limits, but they also require expensive apparatus and sophisticated processing operations. Spectrophotometric methods can be an alternative for the detection of putrescine because of their advantages such as low cost, simple procedure, and ease of use.

Carbon quantum dots (CQDs), a class of semiconductor quantum dots (QDs), are zero-dimensional carbon materials with strong optical properties [17, 18]. CQDs have low toxicity, improved chemical stability, and biocompatibility compared to conventional QDs, as well as being easily functionalized. Despite these advantages, insufficient emission sensitivity and selectivity have limited their use in applications. CQD properties can be improved by functionalization with dopant atoms [19, 20]. Furthermore, one of the most efficient methods for enhancing and controlling the photoluminescence characteristics used to determine quantum efficiency is doping of CQDs [21]. Heteroatom-doped CQDs, including fluorine, phosphorus, nitrogen, and boron, have recently been synthesized and used as dopants in optoelectronic devices. Due to their close proximity in the periodic table and similar atomic diameters, boron is naturally selected for atomic doping [22, 23]. Although studies on doped CQDs are limited, studies so far have shown that the photoluminescence efficiency of CQDs is enhanced after boron doping [24, 25]. Further, B-CQDs have excellent stability with respect to storage, ultraviolet (UV) illumination time, temperature, and pH [26].

In light of previous studies, spectrophotometric determination of putrescine may be possible using B-CQDs. B-CQDs have not been previously used and reported as a putrescine measurement method. In this study, a spectrophotometric measurement method was developed using B-CQDs for in vitro detection of putrescine in artificial blood samples.

EXPERIMENTAL

Reagents and instruments. A Shimadzu UV-1280 UV-Vis spectrophotometer (Japan) was used to make the spectrophotometric measurements. The solutions' pH levels were measured using an Ohaus Starter 2100 pH meter with a combination pH electrode. A phosphate buffer (PB) solution (0.1 M) was used to prepare solutions utilized in the spectrophotometric experiments. Fourier-transform infrared (FTIR) spectra were obtained at the Gulhane Faculty of Pharmacy, University of Health Sciences. Scanning electron microscope (SEM) and dynamic light scattering (DLS) measurements were taken at the Middle East Technical University Central Laboratory for the characterization of B-CQDs. A stock putrescine solution was prepared by dissolving 8.8 mg of putrescine (Sigma-Aldrich, cat. no. 51799) in 10 mL of distilled water. Putrescine solutions used in the experimental

studies were prepared by diluting this stock solution. One milligram of B-CQDs was dissolved in 1 mL of dimethyl sulfoxide (Aromel, cat. no. mf_PRM04). It was then diluted to 1 : 100 in a pH 6.0 PB solution. The diluted B-CQDs solution was used in experiments. Simulated blood plasma was prepared as described below [27]: 0.40 g NaCl (Sigma-Aldrich, 99.5%), 0.02 g NaHCO₃ (Sigma-Aldrich, 99.7%), 0.01 g KCl (Sigma-Aldrich, 99.0%), 0.01 g K₂HPO₄·3H₂O (Merck, 99.0%), 0.015 g MgCl₂·6H₂O (Sigma-Aldrich, 99.0%), 0.014 g CaCl₂ (Merck), 0.004 g Na₂SO₄ (Sigma-Aldrich, 99.0%), 0.303 g Na₃C₆H₅O₇·2H₂O (Sigma-Aldrich, 99.0%) were added and allowed to dissolve on a magnetic stirrer at 36.5°C (each reagent was added only after the previous one was completely dissolved). The pH of the solution was adjusted to 7.4 by titrating with 1 M HCl (Tekkim, 37.0%) solution. The volume was made up to 50 mL with distilled water. The solution was maintained at 4°C throughout the utilization process.

B-CQDs synthesis. Four grams of boric acid, 4 g of citric acid (VWR International, USA, 99.5%), and 4 g of urea (Sigma-Aldrich, 99.0%) were dissolved in 80.0 mL of deionized water and placed in a Teflon-coated stainless steel autoclave [28]. Boric acid was used as a boron source, with urea and citric acid serving as carbon sources. The autoclave was then placed in an oven at 120°C for 12 h to complete the reaction. At the end of the process, the autoclave was cooled down to room temperature, and the solution changed from a clear yellowish color to green-black. The solution was then separated from the solvent by centrifugation at 6000 rpm for 10 min. The solid precipitate was washed three times with distilled water to remove the solvent. It was then dried in an oven at 80°C for 24 h.

RESULTS AND DISCUSSION

Characterization of B-CQDs. A solution of 0.05 µg/mL B-CQDs was measured at a wavelength range of 200–800 nm to determine the absorbance wavelength of B-CQDs. According to UV-Vis spectroscopy, a maximum absorption was detected at 204 nm, with a UV absorption in the range of 200–230 nm (Fig. 1a). The $n-\sigma^*$, $n-\pi^*$, and/or $\pi-\pi^*$ electronic transitions of the hydroxyl and carbonyl groups could be the cause of the maximum absorbance value at 204 nm [29]. The FTIR spectra of B-CQDs are shown in Fig. 1b. The peak at 3191 cm⁻¹ is related to the O–H stretching vibration [30], and the peak at 1408 cm⁻¹ corresponds to B–C [31]. The peaks at 1193 and 703 cm⁻¹ indicate B–OH [31] and B–O–B bending vibrations, respectively [32]. The average hydrodynamic size of B-CQDs was determined to be 8.0 nm using DLS measurements (Fig. 1c). SEM was used to analyze the morphology of the synthesized B-CQDs. The agglomeration of the B-CQDs may account for

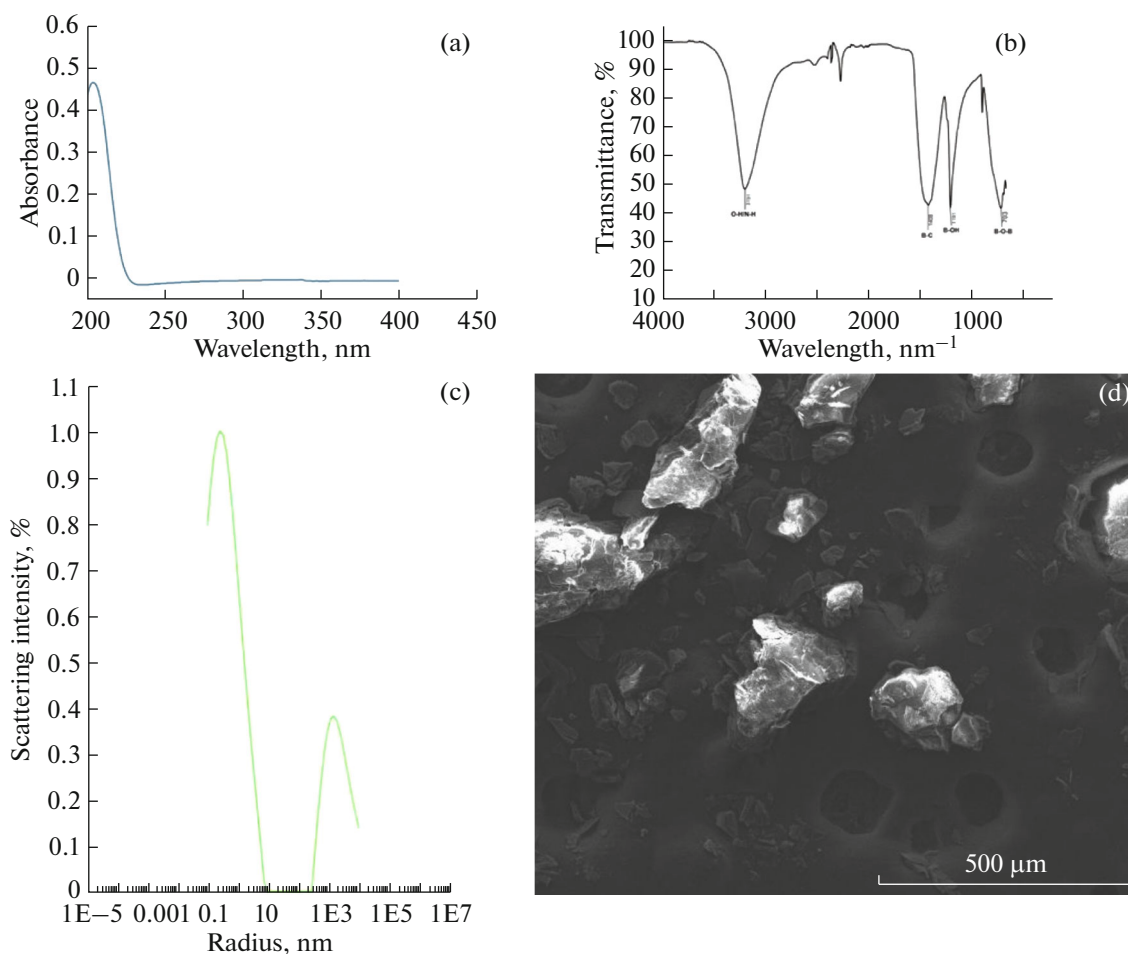


Fig. 1. (a) Spectrophotometric response, (b) FTIR spectrum of B-CQD, (c) DLS, and (d) SEM images of B-CQDs.

the varying sizes observed in the SEM images (Fig. 1d).

Spectrophotometric detection of putrescine. The absorbance value of B-CQDs at 204.0 nm was used for spectrophotometric measurements. Putrescine was indirectly determined using spectrophotometry by monitoring changes in the absorbance value of B-CQDs. Figure 2 shows the spectrophotometric measurement of a B-CQDs solution with and without putrescine. The change in absorbance caused by putrescine was observed by adding 1.0 μM putrescine solution to 0.05 $\mu\text{g/mL}$ B-CQDs solution (Fig. 2). The addition of putrescine increased the absorbance of B-CQDs. The amino groups of putrescine and the oxygen-containing functional groups on the surface of B-CQDs are thought to interact through hydrogen bonds. The electrical environment of B-CQDs may be altered by this interaction, improving their optical characteristics. A schematic illustration of the interaction between B-CQDs and putrescine is presented in Fig. 3. Putrescine determination was performed using the absorbance difference ($A_1 - A_0$) (A_0 : absorbance of B-CQDs, A_1 : absorbance of B-CQDs + putrescine).

Optimization of pH. Establishing the optimum medium pH value for the developed method is crucial since it can impact the spectrophotometric response of B-CQDs. The optimum medium pH for putrescine determination using the B-CQDs-based spectrophotometric technique was determined at a constant putrescine concentration (1.0 μM). In pH optimization, different PB solutions were used in the pH range of 5.0–8.0, and the change in absorbance values of B-CQDs was analyzed. The optimal pH value for the spectrophotometric method was determined to be 6.0, as this was the value at which the highest absorbance difference response was produced (Fig. 4). CQDs exhibit good pH stability and their optical characteristics are strong in the pH range of 5 to 9. Under acidic and/or basic conditions, pH stability is impaired and their optical properties weaken [33, 34].

Performance parameters of the spectrophotometric method. The linear working range of the B-CQD-based spectrophotometric method was determined by adding different concentrations of putrescine solution to 0.05 $\mu\text{g/mL}$ B-CQD solution and calculating the ($A_1 - A_0$) values. ($A_1 - A_0$) values and putrescine con-

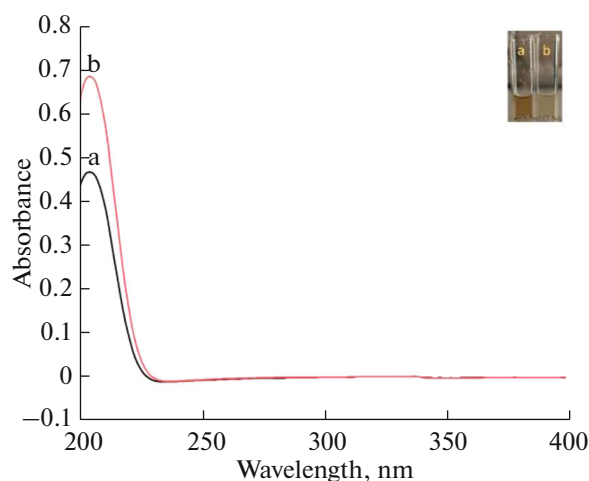


Fig. 2. UV-Vis absorption spectra of (a) B-CQDs and (b) putrescine-B-CQDs (pH 7.0 PB solution, concentration of putrescine: 1.0 μ M, concentration of B-CQDs: 0.05 μ g/mL).

centrations were plotted, and a calibration graph was obtained (Fig. 5). The linear range of the developed method was found to be 0.05–0.75 μ M. The correlation equation of the spectrophotometric method is shown in Eq. (1).

$$(A_1 - A_0) = 0.506[\text{putrescine}] + 0.062 \quad (R^2 = 0.9975). \quad (1)$$

The detection limit (**LOD**) for the B-CQDs-based spectrophotometric method was calculated to be 0.05 μ M ($\text{LOD} = 3.3 \times \text{SD}/m$, where SD is the standard deviation of the responses from ten different 0.05 μ M putrescine solutions and m is the slope of the calibration curve). Furthermore, the quantification limit (**LOQ**) was determined to be 0.15 μ M ($\text{LOQ} = 10 \times \text{SD}/m$, where SD is the standard deviation of the responses from ten different 0.05 μ M putrescine solutions and m is the slope of the calibration curve). The LOD of the B-CQDs-based spectrophotometric method is lower than 0.33 μ g/mL for the SDS-

AgNPS-based colorimetric method [35], 10 ppm of the ninhydrin-based colorimetric method [36], 1.9 μ M for the N,S-CDs@CdTe QDs-based fluorescent sensor [37], and 68 nM for the thiazole-based fluorescent sensor [38].

The measurement stability of the B-CQDs solution, which was employed as a nanomaterial in the development of the method for the determination of putrescine, was investigated both in the absence and presence of putrescine by taking measurements every five minutes for 20 min. The standard deviation of the measurement results was calculated as 0.03, and the relative standard deviation (**RSD**) was calculated as 3.52% (Table 1). According to calculations, the B-CQDs solution is stable for at least 20 min both in the absence and presence of putrescine.

To evaluate the performance of the developed spectrophotometric method using B-CQDs, a comparison with different methods for putrescine determination reported in the literature was presented in Table 2. The results summarized in Table 2 show that the B-CQDs-based spectrophotometric method is equal or superior to the other methods reported so far.

Analytical applicability. The applicability of the B-CQDs-based spectrophotometric method was investigated by determining putrescine in artificial blood samples. The laboratory-prepared artificial blood sample, as detailed in the experimental section, was diluted to 1 : 7 before being utilized in the experiments. Putrescine measurement was performed using B-CQDs based on the standard calibration curve. In the first sample, 0.35 μ M putrescine was added, and the three replicate measurements yielded 0.310 ± 0.003 μ M. In the second sample, 0.45 μ M putrescine was added, and the three replicate measurements resulted in 0.440 ± 0.003 μ M. (Table 3). The recovery values, calculated as $89.5 \pm 0.9\%$ and $98.4 \pm 0.6\%$ for two different concentrations, show the applicability of the developed method in sample analyses. The absorbance spectra of the artificial blood sample with and without the analyte are shown in Fig. 6.

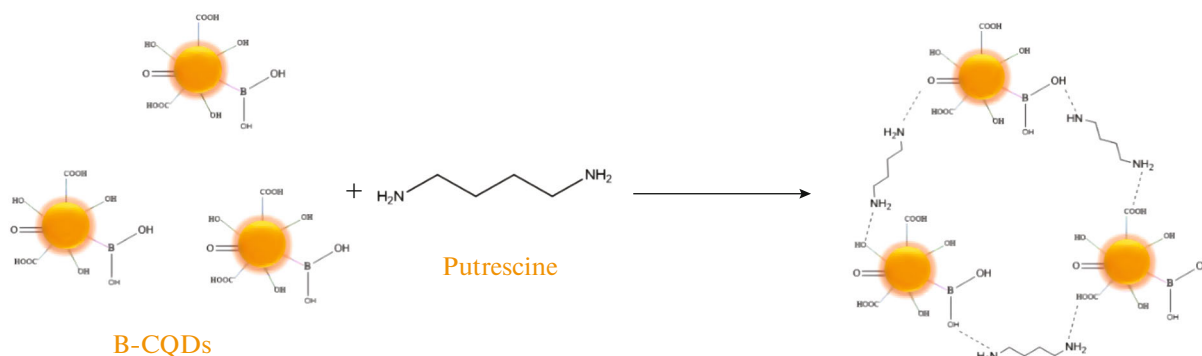


Fig. 3. Schematic representation of spectrophotometric detection of putrescine using B-CQDs plasmonic nanoparticles.

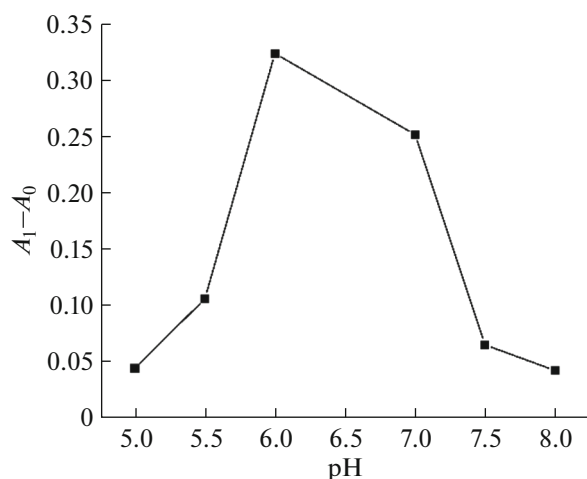


Fig. 4. Optimization of pH (concentration of putrescine: 1.0 μ M, concentration of B-CQDs: 0.05 μ g/mL).

Evaluation of greenness of the proposed spectrophotometric method. Green analytical chemistry deals with measuring various environmental impacts of analytical processes. The greenness of the proposed spectrophotometric method was evaluated using the analytical greenness metric (AGREE) and the analytical greenness metric for sample preparation (AGREEprep) tools. Greenness is assessed using 12 criteria by AGREE and 10 criteria by AGREEprep, which are then converted into a score ranging from 0 to 1 [48]. The AGREE and AGREEprep pictograms for the proposed method are shown in Fig. 7. The yellow, green, and red colors in the pictograms indicate the performance of the method in each criterion. The closer the overall score obtained as a result of the evaluation is to 1, the greener the method becomes. The AGREE and AGREEprep scores for the method are 0.69 and 0.7, respectively. The scores close to 1 indicate that the proposed spectrophotometric method

Table 1. Stability study for the spectrophotometric method based on B-CQDs

Time, min	A_0	A_1
0	0.99	1.08
5	0.99	1.31
10	0.92	1.18
15	0.93	1.08
20	0.94	1.05
Mean	0.95	1.15
SD	0.03	0.11
RSD, %	3.52	9.38
CI	1.05 ± 0.16	1.04 ± 1.24

SD—standard deviation, RSD—relative standard deviation, CI—confidence interval.

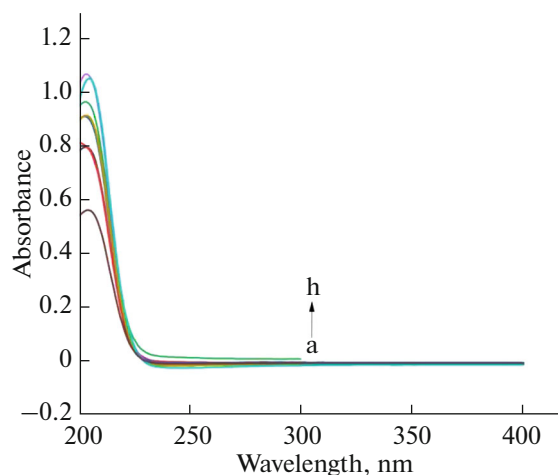


Fig. 5. Spectrophotometric response (0.1 M, pH 6.0 PB solution, concentration of B-CQDs: 0.05 μ g/mL, a–h: 0.05–0.75 μ M, error bars from three different measurements).

has a green character. Moreover, the close scores obtained with the two tools indicate that the advantages and disadvantages obtained with AGREE and AGREEprep are consistent.

CONCLUSIONS

In the present work, B-CQDs were employed to create a spectrophotometric method for putrescine that is quick, simple, and sensitive. The synthesized B-CQDs were characterized by SEM, DLS, FTIR, and UV-Vis absorbance measurements. B-CQDs-based spectrophotometric method demonstrated a wide working range (0.05–0.75 μ M), low LOD (0.05 μ M), and good stability in pH 6.0 PB solution. The analytical usability of the spectrophotometric method was investigated by determining putrescine in artificial blood samples. The recovery results (89.5 ± 0.9 and $98.4 \pm 0.6\%$) indicated that B-CQDs can be a useful nanomaterial in the development of a spectrophotometric method for the determination of putrescine. In conclusion, the proposed spectrophotometric method utilizing B-CQDs offers a sensitive-and reliable approach for the determination of putrescine in artificial blood samples, thus holding potential for clinical diagnostics and biomedical research.

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

Table 2. Putrescine quantitative measurement methods

Method	LOD	Reference
Ion chromatography-integrated pulsed amperometric detection method	1.25 ng/25 mL	[15]
Capillary electrophoresis	1–40 μ M	[14]
Ion spray ionization-mass spectrometry	5.0 μ M	[16]
Amperometric biosensor (in vitro measurement)	50 nM	[39]
Voltammetric sensors	0.34 μ M	[40]
Amperometry	0.11 μ M	[41]
Multiwall carbon nanotube-based electrochemical biosensors	0.50 μ M	[42]
Amperometric biosensor	5.0 μ M	[43]
Enzymatic nanointerfaced biosensor	0.65 nM	[44]
Ion-pair facilitated non-enzymatic electrochemical sensing	0.25 μ M	[45]
Liquid-liquid microextraction coupled with gas chromatography-mass spectrometry method	0.5 μ g/L	[46]
N, S-CDs@CdTe QDs-based fluorescent sensor	1.9 μ M	[37]
Thiazole-based fluorescent sensor (4CTP)	68 nM	[38]
Ninhydrin-based colorimetric method	10 ppm	[36]
Colorimetric method using OPA derivatization	0.44 μ M	[47]
Sodium dodecyl sulfate-protected silver nanoparticles-based colorimetric method	0.33 μ g/mL	[35]
B-CQDs-based spectrophotometric method	0.05 μ M	This study

4CTP – (E)-4-chloro-2-((thiazol-2-ylimino)methyl)phenol, OPA- *o*-phthalaldehyde.

Table 3. Recovery results of putrescine in artificial blood samples

Putrescine added, μ M	Found, μ M	Recovery, %
0.35	0.310 ± 0.003	89.5 ± 0.9
0.45	0.440 ± 0.003	98.4 ± 0.6

$\pm$ SD calculated from three different absorbance measurements.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

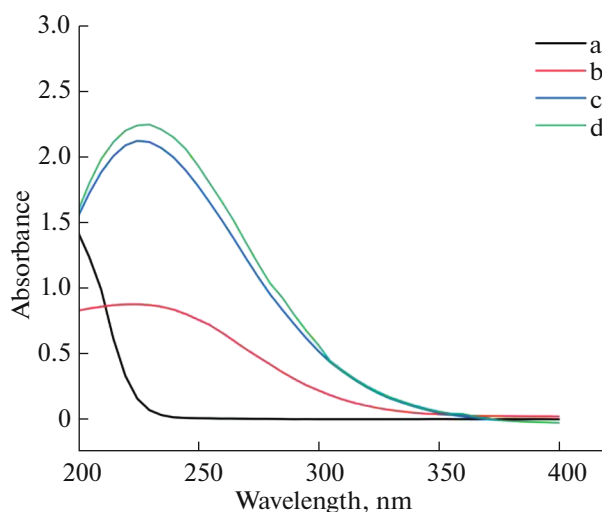


Fig. 6. Absorbance spectra of (a) artificial blood sample, (b) artificial blood sample + B-CQDs, (c) artificial blood sample + B-CQDs in the presence of 0.35 μ M putrescine, and (d) artificial blood sample + B-CQDs in the presence of 0.45 μ M putrescine (0.1 M, pH 6.0 PB solution, concentration of B-CQDs: 0.05 μ g/mL).

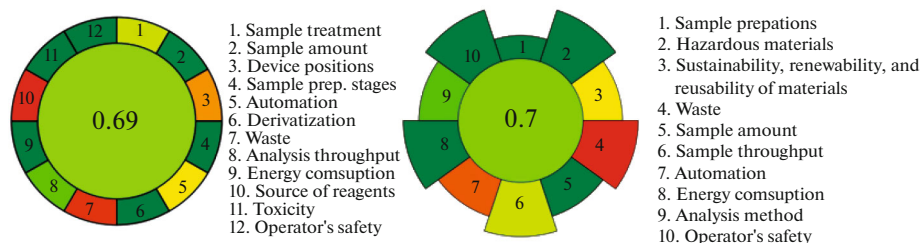


Fig. 7. Pictograms of AGREE and AGREEprep for the proposed B-CQDs-based spectrophotometric method.

REFERENCES

- Lagishetty, C.V. and Naik, S.R., *Indian J. Pharmacol.*, 2008, vol. 40, p. 121.
<https://doi.org/10.4103/0253-7613.42305>
- Kalac, P. and Krausová, P., *Food Chem.*, 2005, vol. 90, p. 219.
<https://doi.org/10.1016/j.foodchem.2004.03.044>
- Vuohelainen, S., Pirinen, E., Cerrada-Gimenez, M., Keinänen, T.A., Uimari, A., Pietilä, M., Khomutov, A.R., Janne, J., and Alhonen, L., *J. Cell. Mol. Med.*, 2010, vol. 14, p. 1683.
<https://doi.org/10.1111/j.1582-4934.2009.00808.x>
- Lockwood, D.H. and East, L.E., *J. Biol. Chem.*, 1974, vol. 249, p. 7717.
[https://doi.org/10.1016/S0021-9258\(19\)42026-7](https://doi.org/10.1016/S0021-9258(19)42026-7)
- Sadasivan, S.K., Vasamsetti, B., Singh, J., Marikunte, V.V., Oommen, A.M., Jagannath, M.R., and Rao, R.P., *Eur. J. Pharmacol.*, 2014, vol. 729, p. 94.
<https://doi.org/10.1016/j.ejphar.2014.01.073>
- Handa, A.K., Fatima, T., and Mattoo, A.K., *Front. Chem.*, 2018, vol. 6, p. 10.
<https://doi.org/10.3389/fchem.2018.00010>
- Madeo, F., Eisenberg, T., Büttner, S., Ruckenstein, C., and Kroemer, G., *Autophagy*, 2010, vol. 6, p. 160.
<https://doi.org/10.4161/auto.6.1.10600>
- Pegg, A.E., *J. Biol. Chem.*, 2016, vol. 291, p. 14904.
<https://doi.org/10.1074/jbc.R116.731661>
- Hoet, P.H.M., Dinsdale, D., Verbeken, E.K., Demedts, M., and Nemery B., *Br. J. Cancer*, 1996, vol. 73, p. 96.
<https://doi.org/10.1038/bjc.1996.17>
- Harik, S.I. and Sutton, C.H., *Cancer Res.*, 1979, vol. 39, p. 5010.
- Fu, S., Xiao, C., Zhao, W., and Yu, X., *Front. Biosci. (Elite Ed.)*, 2012, vol. 4, p. 1795.
- Khuawar, M., Memon, A.A., Jaipal, P.D., and Bhangar, M.I., *J. Chromatogr. B: Biomed. Sci. Appl.*, 1999, vol. 723, p. 17.
[https://doi.org/10.1016/S0378-4347\(98\)00478-2](https://doi.org/10.1016/S0378-4347(98)00478-2)
- Seiler, N., *Clin. Chem.*, 1977, vol. 23, p. 1519.
- Kovács, Á., Simon-Sarkadi, L., and Ganzler, K., *J. Chromatogr. A*, 1999, vol. 836, p. 305.
[https://doi.org/10.1016/S0021-9673\(98\)00912-1](https://doi.org/10.1016/S0021-9673(98)00912-1)
- Draisci, R., Gianetti, L., Boria, P., Lucentini, L., Palleschi, L., and Cavalli, S., *J. Chromatogr. A*, 1998, vol. 798, p. 109.
[https://doi.org/10.1016/S0021-9673\(97\)01198-9](https://doi.org/10.1016/S0021-9673(97)01198-9)
- Furuumi, N., Amano, D., Xu, Y.J., Samejima, K., Niitsu, M., and Shirahata, A., *Anal. Biochem.*, 1998, vol. 265, p. 253.
<https://doi.org/10.1006/abio.1998.2934>
- Wang, X., Feng, Y., Dong, P., and Huang, J., *Front. Chem.*, 2019, vol. 7, p. 671.
<https://doi.org/10.3389/fchem.2019.00671>
- Molaei, M.J., *Sol. Energy*, 2020, vol. 196, p. 549.
<https://doi.org/10.1016/j.solener.2019.12.036>
- Kandasamy, G., *J. Carbon Res.*, 2019, vol. 5, p. 24.
<https://doi.org/10.3390/c5020024>
- Jana, J. and Pal, T., *Nat. Resour. Eng.*, 2017, vol. 2, p. 5.
<https://doi.org/10.1080/23802693.2017.1421506>
- Atabaev, T.S., *Nanomaterials*, 2018, vol. 8, p. 342.
<https://doi.org/10.3390/nano8050342>
- Liu, Y., Li, W., Wu, P., Ma, C., Wu, X., Xu, M., Luo, S., Xu, Z., and Liu, S., *Sens. Actuators, B*, 2019, vol. 281, p. 34.
<https://doi.org/10.1016/j.snb.2018.10.075>
- Pu, Z.F., Wen, Q.L., Yang, J.Y., Cui, X.M., Ling, J., Liu, P., and Cao, Q.E., *Spectrochim. Acta, Part A*, 2020, vol. 229, p. 117944.
<https://doi.org/10.1016/j.saa.2019.117944>
- Jia, Y., Hu, Y., Li, Y., Zeng, Q., Jiang, X., and Cheng, Z., *Microchim. Acta*, 2019, vol. 186, p. 84.
<https://doi.org/10.1007/s00604-018-3196-5>
- Shan, X., Chai, L., Ma, J., Qian, Z., Chen, J., and Feng, H., *Analyst*, 2014, vol. 139, p. 2322.
<https://doi.org/10.1039/C3AN02222F>
- Ma, Y., Chen, A.Y., Huang, Y.Y., He, X., Xie, X.F., He, B., Yang, J.H., and Wang, X.Y., *Carbon*, 2020, vol. 162, p. 234.
<https://doi.org/10.1016/j.carbon.2020.02.048>
- Sharma, D.K., Sood, S., and Raj, P., *Anal. Chem. Lett.*, 2019, vol. 9, p. 345.
<https://doi.org/10.1080/22297928.2019.1644194>
- Bourlinos, A.B., Trivizas, G., Karakassides, M.A., Baikousi, M., Kouloumpis, A., Gournis, D., Bakkas, A., Hala, K., Kozak, O., Zboril, R., Papagiannouli, I., Aloukos, P., and Couris, S., *Carbon*, 2015, vol. 83, p. 173.
- Zhang, X., Ren, Y., Ji, Z., and Fan, J., *J. Mol. Liq.*, 2020, vol. 311, p. 113278.
<https://doi.org/10.1016/j.molliq.2020.113278>
- Cam, V., Olgac, A., Kilic, M., Erel, O., Neselioglu, S., and Kasapkara, C.S., *J. Coll. Physicians Surg. Pak.*, 2021, vol. 31, p. 663.
<https://doi.org/10.29271/jcpsp.2021.06.663>

31. Shen, P. and Xia, Y., *Anal. Chem.*, 2014, vol. 86, p. 5323.
<https://doi.org/10.1021/acsami.4c04739>
32. Salman, B.I., Hassan, A.I., Hassan, Y.F., and Saraya, R.E., *BMC Chem.*, 2022, vol. 16, p. 58.
<https://doi.org/10.1186/s13065-022-00849-3>
33. Yang, Z., Xu, M., Liu, Y., He, F., Gao, F., Su, Y., Wei, H., and Zhang, Y., *Nanoscale*, 2014, vol. 6, p. 1890.
<https://doi.org/10.1039/C3NR05380F>
34. Ustun, O., Karadag, S.N., Mazlumoglu, H., Yilmaz, A., and Yilmaz, M., *Coatings*, 2023, vol. 13, p. 456.
<https://doi.org/10.3390/coatings13020456>
35. Ghoto, S.A. and Khuhawar, M.Y., *Anal. Sci.*, 2021, vol. 37, p. 267.
<https://doi.org/10.2116/analsci.20P153>
36. Sudalaimani, S., Esokkiya, A., Hansda, S., Suresh, C., Tamilarasan, P., and Giribabu, K., *Food Anal. Methods*, 2020, vol. 13, p. 629.
<https://doi.org/10.1007/s12161-019-01671-9>
37. Yan, J., Fu, Q., Zhang, S., Liu, Y., Shi, X., Hou, J., Duan, J., and Ai, S., *Spectrochim. Acta, Part A*, 2022, vol. 282, p. 121706.
<https://doi.org/10.1016/j.saa.2022.121706>
38. Raja, L., Venkatesan, S., Mingchang, L., and Veditappan, P., *J. Photochem. Photobiol., A*, 2023, vol. 438, p. 114546.
<https://doi.org/10.1016/j.jphotochem.2023.114546>
39. Nagy, L., Nagy, G., Gyurcsanyi, R.E., Neuman, M.R., and Lindne, E., *J. Biochem. Biophys. Methods*, 2020, vol. 53, p. 165.
40. Apetrei, I.M. and Apetrei, C., *Sens. Actuators, B*, 2016, vol. 234, p. 371.
<https://doi.org/10.1016/j.snb.2016.05.005>
41. Lin, M.S., Chen, C.H., and Chen, Z., *Electrochim. Acta*, 2011, vol. 56, p. 1069.
<https://doi.org/10.1016/j.electacta.2010.10.083>
42. Luong, J.H.T., Hrapovic, S., and Wang, D., *Electroanalysis*, 2005, vol. 17, p. 47.
<https://doi.org/10.1002/elan.200403117>
43. Bóka, B., Adányi, N., Szamos, J., Virág, A., and Kiss, A., *Enzyme Microb. Technol.*, 2012, vol. 51, p. 258.
<https://doi.org/10.1016/j.enzmictec.2012.07.006>
44. Shanmugam, S., Thandavan, K., Gandhi, S., Sethuraman, S., Rayappan, J.B.B., and Krishan, U.M., *Analyst*, 2021, vol. 136, p. 5234.
<https://doi.org/10.1039/C1AN15637C>
45. Kumar, S., Arockiaraj, M., Esokkiya, A., Sudalaimani, S., Hansda, S., Sivakumar, C., Sulaiman, Y., Khan, M.M., and Giribabu, K., *J. Electrochem. Soc.*, 2021, vol. 168, p. 047505.
<https://doi.org/10.1149/1945-7111/abf263>
46. Almeida, C., Fernandes, J.O., and Cunha, S.C., *Food Control*, 2012, vol. 25, p. 380.
<https://doi.org/10.1016/j.foodcont.2011.10.052>
47. Qi, X., Wang, W.F., Wang, J., Yang, J.F., and Shi, Y.P., *Food Chem.*, 2018, vol. 259, p. 245.
<https://doi.org/10.1016/j.foodchem.2018.03.131>
48. Pena-Pereira, F., Wojnowski, W., and Tobiszewski, M., *Anal. Chem.*, 2020, vol. 92, p. 10076.
<https://doi.org/10.1021/acs.analchem.0c01887>

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. AI tools may have been used in the translation or editing of this article.