Malaysian Journal of Analytical Sciences
(MJAS)
Published by Malaysian Analytical Sciences Society

CHARACTERIZATION OF SILICON QUANTUM DOTS SYNTHESIZED VIA HYDROTHERMAL METHOD AND ITS APPLICATION FOR GLUCOSE DETECTION

(Pencirian Titik Kuantum Silikon Sintesis Melalui Kaedah Hidroterma dan Penggunaannya untuk Pengesanan Glukosa)

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Received: 27 October 2023; Accepted: 14 August 2024; Published: 29 December 2024

Abstract

Recent interest has been directed towards developing new nanomaterials with diverse properties. Among these, silicon quantum dots (SiQDs) have gained popularity in biological applications due to their excellent biocompatibility and optical features. This study describes the synthesis of fluorescence water-soluble silicon quantum dots using a one-pot hydrothermal process specifically for glucose detection. The synthesis involved reacting 3-aminopropyltriethoxysilane (APTES) as a precursor, with ethylenediamine as a capping agent and sodium citrate as a reducing agent. The optical features of the SiQDs, including their absorption and emission characteristics, were investigated using UV-Vis and fluorescence spectroscopy. The measurements displayed an absorption pattern from 200 to 400 nm with a prominent shoulder at 329 nm and a maximum emission peak at 382 nm with an excitation of 305 nm. The structural characteristics of the synthesized SiQDs were examined using FTIR. It was found that surface functionalization and bonding composition exhibited strong absorbance at 1101 cm^{-1} and 1001 cm^{-1} due to the Si–O bending vibrations. This observation confirms the successful preparation of SiQDs. TEM analysis revealed a surface morphology characterized by a uniform, near-spherical shape, with sizes ranging from 11.81 nm to 12.95 nm. The XRD analysis indicates the amorphous nature of the SiQDs. Subsequently, the performance of the SiQDs in glucose detection was evaluated, revealing linearity in the range of 0.1 to 0.8 mg/ml with a regression equation of $y = 20249x - 1682.4$ ($R^2 = 0.9804$) and limit of detection (LOD) of 0.03 mg/mL. The findings suggest promising prospects for utilizing SiQDs as sensitive and reliable probes for glucose-sensing applications.

Keywords: Silicon quantum dots, fluorescence, functionalization, APTES, hydrothermal

Abstrak

Kini, penyelidikan pembangunan bahan nano baharu menyediakan pelbagai pilihan bahan nano berasaskan sifat yang diingini adalah menarik. Titik kuantum silikon (SiQDs) telah menjadi salah satu bahan nano yang paling popular dalam aplikasi biologi untuk bioserasi dan sifat optik yang sangat baik. Dalam kajian ini, titik kuantum silikon larut air berpendarfluor telah disintesis menggunakan proses hidroterma satu periuk untuk pengesanan glukos telah diterangkan. Sintesis ini melibatkan tindak balas 3-aminopropiltrietoksisilana (APTES) sebagai bahan pemula, etilenadiamina sebagai agen penukup dan natrium sitrat sebagai agen penurunan. Ciri optik SiQDs, termasuk ciri serapan dan pancaran telah dikaji menggunakan spektroskopi UL-cahaya nampak dan pendarfluor. Ia memaparkan corak penyerapan dari 200 hingga 400 nm dengan bahu yang menonjol sekitar 329 nm dan puncak pancaran maksimum pada 382 nm dengan pengujaan pada 305 nm. Ciri-ciri struktur SiQDs yang disintesis telah dikaji menggunakan FTIR menunjukkan fungsian permukaan dan komposisi ikatan mempunyai penyerapan yang kuat pada 1101 cm−1 dan 1001 cm−1 menunjukkan getaran lenturan Si-O yang terbukti berjaya disediakan bagi SiQDs. Morfologi permukaan oleh TEM menunjukkan keseragaman, bentuk hampir sfera, dan julat saiz dari 11.81 nm hingga 12.95 nm. Analisis XRD menunjukkan sifat SiQDs yang amorfus. Seterusnya, prestasi SiQDs dalam pengesanan glukosa dinilai menunjukkan kelinearan dalam julat 0.1 hingga 0.8 mg/ml dengan persamaan regresi y = 20249*x* - 1682.4 (R^2 = 0.9804) dan had pengesanan (LOD) 0.03 mg/mL. Penemuan ini mencadangkan prospek yang menjanjikan untuk menggunakan SiQDs sebagai prob sensitif dan boleh dipercayai untuk aplikasi penderiaan glukosa.

Kata kunci: Titik kuantum silikon, pendarfluor, kefungsian, APTES, hidroterma

Introduction

Nanocrystals or nanoparticles that exhibit a size range of 2 to 12 nm and are typically constituted by several hundred to thousands of atoms are referred to as quantum dots. The distinct optoelectronic properties of these particles can be primarily attributed to their remarkably high surface-to-volume ratio, which is contingent upon their respective dimensions. In 1823, Berzelius successfully obtained silicon, the second most abundant constituent of the Earth's crust, in its pure form. With the progression of nanotechnology, silicon nanoparticles have been utilized in diverse disciplines, including biology, chemistry, and medicine. Notably, among these applications, photoluminescent (fluorescent) silicon nanoparticles are remarkable due to their exceptional optical endurance and ability to degrade in physiological surroundings [1].

The study of silicon quantum dots (SiQDs) and nanoparticles (SiNPs) has received considerable attention from the scientific community in the past twenty years. This interest has been fueled by their unique properties in optics, mechanics, electronics, and catalysis. There is a significant level of interest in applying quantum dots (QDs) within various fields, including but not limited to detection, therapeutic applications, cellular imaging, drug delivery, biosensing, and the utilization of optical markers in the biomedical field. This increased interest can be primarily attributed to their exceptional qualities, which include remarkable photostability, a narrow emission band with strong luminescence, and a high fluorescent quantum yield [2,3].

With the progression of silicon nanotechnology, SiQDs have emerged as a prevalent form of quantum dot that is utilized extensively for sensing and biosensing applications. In contrast to silicon in its bulk state, which possesses an indirect bandgap leading to suboptimal photoluminescence, SiQDs, benefiting from the quantum confinement effect, exhibit effective fluorescence emission with a high quantum yield, a noteworthy aspect that deserves emphasis. Zero-dimensional SiQDs have attracted considerable interest as possible substitutes for semiconductor quantum dots and traditional organic dyes in the fields of sensing and bioimaging. It is important to highlight that silicon quantum dots derived from silane not only showcase comparable photoluminescent characteristics to other fluorescent nanomaterials but also present several supplementary advantages, including minimal or non-existent toxicity, enduring photostability, substantial biocompatibility, and abundant availability [4,5].

SiQDs hold significant importance as emerging fluorescent biomarkers because of their beneficial characteristics. These include their ability to easily modify their surface, their inert properties, the abundant availability of silicon, remarkable luminescence efficiency, long-lasting photostability, exceptional compatibility with biological systems, and relatively low toxicity [3]. The primary benefit of SiQDs is their non-toxic nature, as they can undergo in vivo metabolism to produce biodegradable orthosilicic acid that can be readily eliminated from the human body through urine [6].

On the other hand, SiQDs can be a suitable alternative to traditional quantum dots due to their inert, low-toxic, abundant, and affordable features. Up till now, SiQDs have been widely used in chemical analysis [7], fluorescent bioimaging [8,9], and biomedicine [10,11]. However, the prevailing consensus is that synthetic SiQDs are predominantly terminated with hydrogen, rendering them susceptible to oxidation [12]. The fabrication of H-Si-terminated SiQDs soluble in water requires the introduction of hydrophilic ligands, a process that, although essential, is time-consuming and burdensome. Surprisingly, limited attention has been given to efficiently detecting biological substances using label-free silicon nanodots, including undoped ones [13].

SiQDs provide a diverse array of applications in the field of fluorescence imaging and detection due to their advantageous properties. An indirect bandgap in silicon's bulk leads to diminished photoluminescence. Nevertheless, the quantum confinement effect exhibited by SiQDs allows for effective fluorescence emission with a substantial quantum yield [14]. According to previous studies, these quantum dots are commonly made via hydrothermal [13,14,5], electrochemical [15], UV irradiation [16] and, microwave methods [17] either in their original configurations or after acceptable modifications [18]. However, these approaches face obstacles, including complexity and cost, limited scalability, and difficulty in controlling size and properties. High temperature or pressure requirements, potential toxicity, limited functionalization options, batch-to-batch variability, and longer synthesis times compared to hydrothermal methods present significant challenges [19] Hydrothermal synthesis offers advantages such as precise control over reaction conditions, a homogeneous environment, and adherence to green chemistry principles by utilizing water as a solvent. Additionally, it exhibits versatility in producing a wide range of high-quality materials, making it a preferred method for tailored material synthesis across various applications. This method facilitates the creation of easily attainable, safe, affordable, water-soluble materials with remarkable biocompatibility and vibrant photoluminescent properties. On top of that, SiQDs can be readily synthesized using a hydrothermal method [20].

Diabetes mellitus is a multifaceted hormonal and metabolic condition resulting from insufficient insulin production. Insulin is crucial in metabolizing sugars and starches into the energy needed for daily activities. However, in diabetes, insulin is either partially or entirely lacking. This global health concern affects numerous individuals and is primarily characterized by consistently elevated glucose levels. Effective management of glucose levels can mitigate the risk of enduring complications like microangiopathy, kidney dysfunction, and nerve impairment associated with diabetes. Thus, maintaining glucose levels within a normal range is paramount for effective diabetes treatment [21]. The World Health Organization reported that over 150 million individuals worldwide had diabetes in 2004, a number projected to escalate to 366 million by 2030. Diabetic individuals face heightened susceptibility to conditions such as heart attacks, strokes, hypertension, and vision impairment. Moreover, early detection of glucose abnormalities holds significant practical value in diabetes prevention efforts [13]. As such, strict regulation of blood glucose levels is imperative to avert the onset of chronic ailments over the long term, including neurological disorders, cardiovascular conditions, and color vision deficiencies.

Presently, glucose detection primarily relies on electrochemical principles, spectrophotometry, capillary electrophoresis, and high-performance liquid chromatography (HPLC). Recently, enzymatic biosensors have garnered increasing attention due to their notable attributes of heightened sensitivity, selectivity, and operational simplicity. Nonetheless, enzymes are prone to fragility and susceptibility to factors such as temperature variations and external influences, resulting in compromised reproducibility of glucose sensing accuracy. Furthermore, enzyme-based sensors have relatively high costs and a limited shelf life [22].

Due to their numerous advantages over existing photoluminescent nanoparticles, including their broad absorption spectrum, low toxicity, sustained photoluminescence, strong biocompatibility, and good solubility in water, SiQDs have garnered attention from researchers in recent years. These benefits have led to the widespread usage of this type of quantum dots in fluorescence imaging and detection. According to the literature review, the most common methods used to produce SiQDs include electrochemical, hydrothermal, microwave, and UV irradiation. These techniques are employed to synthesize either unmodified or modified quantum dots [20].

This study explores the development of a SiQDs probe for glucose detection based on the fluorescence quenching of NH_2@SiQDs in response to glucose. NH_2@SiQDs offer notable advantages, including high sensitivity, simplicity, rapid analysis, and cost-effectiveness [22,18]. Building on this phenomenon, SiQDs doped with ethylenediamine (EDA) have been synthesized using APTES as the silicon source and sodium citrate as a reducing agent. This approach enables the quantitative detection of glucose, offering a quick and straightforward solution for sensing applications.

Materials and Methods

Reagents and solutions

3-Aminopropyltriethoxysilane (APTES, 99%), sodium citrate tribasic dihydrate (≥99.0%), and ethylenediamine (EDA 90%) were purchased from Sigma–Aldrich (USA), deionized water was used for the whole experiment was from Millipore Alpha Q (18.2 MΩ. cm). The SnakeSkinTM dialysis tubing (3500 MWCO, 22 mm) was utilized for the dialysis solution of SiQDs.

Synthesis of silicon quantum dots

The synthesis of water-soluble fluorescent SiQDs was performed using a hydrothermal technique. The process began with 1.104 grams of sodium citrate dissolved in 25 ml of deionized water previously saturated with nitrogen gas to remove oxygen. Next, 6 ml of APTES and 200 µl of EDA were introduced as a capping agent. The mixture was covered with aluminum foil and stirred thoroughly for 10 minutes using a magnetic stirrer. The resulting precursor solution was then transferred into a stainless-steel autoclave and heated at 200 °C for 7 hours. Upon cooling to room temperature, the transparent solution underwent 48 hours of dialysis against ultrapure water to remove impurities such as APTES molecules and sodium citrate. The purified, clear, colorless liquid was dried in an oven at 40 °C. Finally, the synthesized and purified SiQDs solution was stored at 4 °C for future use.

Characterization of the As-prepared silicon quantum dots

The UV-vis absorption spectra were determined using a UV-visible spectrophotometer (Thermo ScientificTM MultiskanTM GO) at ambient temperature within the wavelength range of 200-800 nm. In contrast, fluorescence spectra were acquired using a Tecan instrument equipped with Tecan black 96-well plates and operated with SPARKCONTROL Magellan software. An FT-IR spectrometer (Brucker, ATR FTIR Alpha) was utilized to ascertain and analyze the molecular composition of the molecules attached to the surfaces of the nanoparticles. The morphology and elemental composition of the synthesized SiQDs were examined using a High-Resolution Transmission Electron Microscope coupled with an Energy-Dispersive X-ray (HRTEM-EDX) (JEOL-JEM 2100F). In addition, X-ray Diffraction (XRD) (Shimadzu XRD 6000 Diffractometer cu–K & copper radiation) was employed to assess the crystallography of the crystals.

Optimization parameters

Various phosphate buffer solutions at different pH (7 to 8.5) were tested to determine the optimal pH for glucose detection. For each experiment, 200 µL of the chosen buffer was added to a Tecan black 96-well plate, followed by 50 µL of prepared glucose solution (1 mg/mL) and 50 µL of SiQD. After a 15-minute incubation period at room temperature, fluorescence intensity was measured using a microplate reader at excitation and emission wavelengths of 305 and 438 nm, respectively.

To establish the possible reaction time between 0.5 mg/ml SiQDs and glucose, a fresh 1 mg/mL glucose solution was prepared in a 0.1 M phosphate buffer solution with pH 7.2. Following the same steps as previously outlined, fluorescence intensity was observed at intervals of 0, 5, 10, 15, 20, 25, 30, 35, and 40 minutes. Fluorescence readings were conducted using a microplate reader with excitation and emission wavelengths of 305 and 438 nm, respectively.

A series of glucose concentrations spanning from 0.1 to 1 mg/mL was investigated to assess the analytical performance of the developed sensing system. In a Tecan black 96-well plate, 250 µL of pH 7.2 phosphate buffer solution was mixed with 50 µl of a 0.5 mg/ml SiQDs solution as a control. Additionally, 200 µL of phosphate buffer solution, 50 µL of a predetermined glucose concentration, and 50 µl of the 0.5 mg/ml SiQD solution were pipetted and mixed in five separate wells. After a 15-minute incubation at room temperature, the fluorescence intensity was measured. Fluorescence measurements were taken at excitation and emission wavelengths of 305 nm and 438 nm, respectively.

Results and Discussion

Earlier research explored different silicon sources, like bulk silicon and SiO_2, for the synthesis of SiQD [23]. In this investigation, SiQDs were synthesized through a simple hydrothermal method using APTES as a precursor, capped with EDA, and employing sodium citrate as a reducing agent. APTES, a water-soluble silicon source, readily reacts with trisodium citrate for oxidoreduction. In this procedure, siloxane molecules undergo reduction by trisodium citrate at elevated temperatures to generate silicon nuclei. The synthesized SiQDs have good solubility in aqueous solution and photostability with the increasing surface coating of SiQDs. In this work, EDA was employed as a capping agent to enhance the stability and solubility of the resulting SiQDs in an aqueous solution. This strategy also aimed to improve photostability by increasing surface coverage, potentially benefiting their applications [23]. The use of sodium citrate as a reducing agent also affects the optical properties of SiQDs, as it has been shown to increase the quantum yield and stability of SiQDs synthesized via a hydrothermal process [24].

EDA is a pivotal capping agent in the hydrothermal synthesis of SiQDs due to its multifunctional roles.. Acting as a regulator of quantum dot growth, it ensures uniform size distribution and desired morphology while passivating their surfaces to prevent defects and oxidation, thereby enhancing optical and electronic properties. Furthermore, EDA enables tuning quantum dots' optical characteristics by modulating growth conditions and interactions with precursors. Its stabilizing effect prevents aggregation and maintains dispersion in solution for seamless integration into nanocomposites or devices. Overall, EDA's presence during synthesis facilitates precise control over quantum dots' properties to ensure optimal performance for diverse applications [25].

The optical characteristics of the fabricated SiQDs were assessed using UV–Vis spectrophotometer and fluorescence methods. The synthesized colloidal solution of SiQDs, as demonstrated in Figure 1, exhibited a light-yellow transparent appearance under natural light. However, when exposed to a portable UV lamp, it emitted blue fluorescence (as shown in the inset of Figure 1). A previous investigation also observed this emission of blue fluorescence upon exposure to a UV lamp [26]. The optical properties of SiQDs were examined by recording the UV-Vis spectrum, as depicted in Figure 1(a). This spectrum displays a continuous pattern of absorption within the range of 200 to 400 nm, with a noticeable peak occurring at approximately 329 nm. The SiQDs exhibit a broad absorption band in the UV region, featuring two distinct absorption peaks at 250 and 350 nm. These peaks correspond to the π – p* and n – p* transitions of the SiQDs, respectively. When subjected to UV light, the SiQDs selectively absorb light at two specific wavelengths, namely 250 nm and 350 nm. These wavelengths correspond to different categories of electronic transitions. The π - p* transitions involve the elevation of electrons from π orbitals to p* orbitals, while the n - p* transitions entail the elevation of electrons from non-bonding orbitals to p* orbitals [27]. Another study demonstrated the presence of a conventional absorption band in the UV-Vis absorption spectrum, characterized by two absorption peaks at wavelengths of 280 and 350 nm [18]. The emission properties of the SiQDs are displayed in Figure 1(b). The highest emission peak of the SiQDs observed at 382 nm can be achieved when excited at 305 nm. This wavelength serves as the most optimal excitation wavelength for subsequent experimental investigations [5].

Surface groups and bonding composition analysis of SiQDs were conducted using FTIR spectroscopy (Figure 2). The FTIR spectrum of SiQDs illustrated various absorption peaks. At 3443 cm^{-1}, an absorption peak was observed due to O-H stretching vibrations [28]. Another peak at 1301 cm^{-1} indicated the vibrational motion of the C-N bond, while the peak at 2910 cm^{-1} resulted from unsaturated stretching vibrations of the C-H bond. The stretching vibration of the C-O bond was responsible for the signal at 1566 cm^{-1} [23]. Notably, Si-O bending vibrations were observed at 1109 cm^{-1} and 1012 cm^{-1}, signifying successful SiQD preparation [29]. These results suggested the presence of hydroxyl and amino groups on the SiQD surface, indicating excellent water solubility.

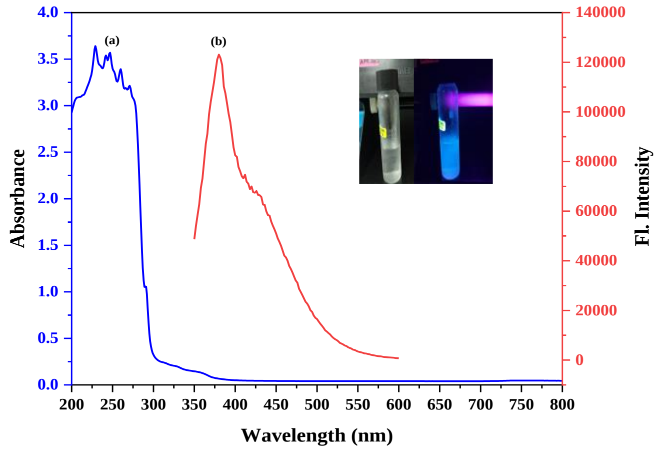

Figure 1. UV/Vis spectrum (a) and fluorescence emission (b) of SiQDs

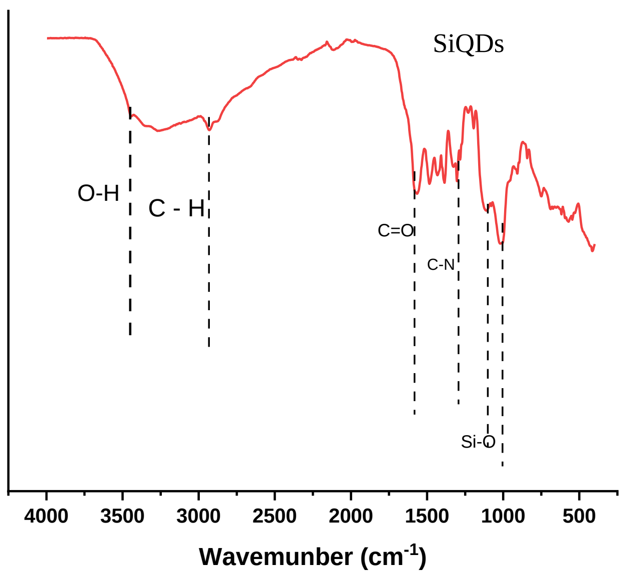

Figure 2. FTIR spectrum of SiQDs

The HRTEM was used to examine the morphology and size distribution of the SiQDs. As depicted in Figure 3(a), the SiQDs exhibited a pleasing uniformity, excellent dispersion, and a nearly spherical shape with sizes ranging from 11.81 nm to 12.95 nm. A prior study also reported that the prepared SiQDs had a spherical shape and a nearly uniform size distribution [18]. The elemental composition of SiQDs was analyzed using EDX (Figure 3b), and the results reveal the presence of silicon, oxygen, sodium, and sulfur elements. The corresponding contents were 59.9% (O), 19.4% (Si), 19.8% (Na), and 0.9% (S), respectively. In short, the findings prove the successful synthesis of the SiQDs. Figure 4 shows the XRD measurement in the range of 10° to 60°. It can be noted that the SiQDs were in the amorphous phase with only one peak at $2\theta = 21.05$ [30].

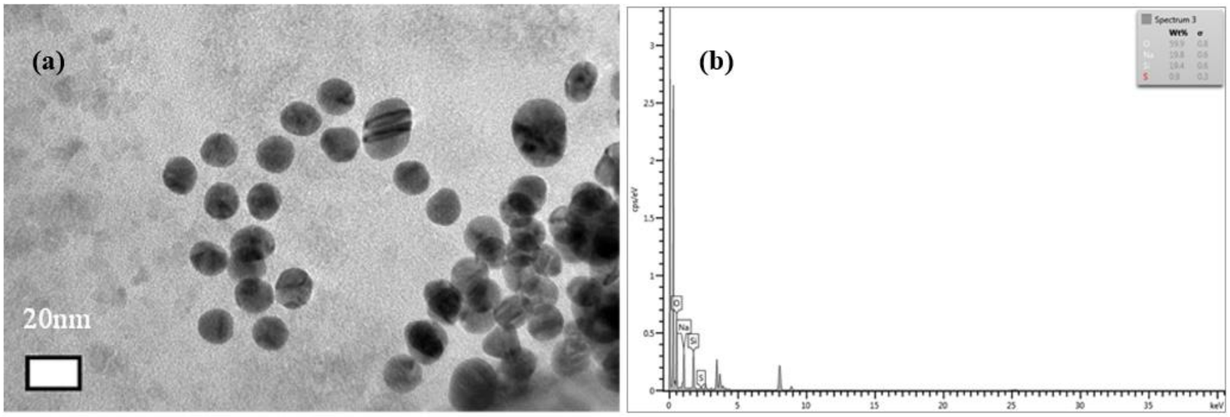

Figure 3. shows the HRTEM image at a 20 nm scale (a), EDX spectra (b) of SiQDs

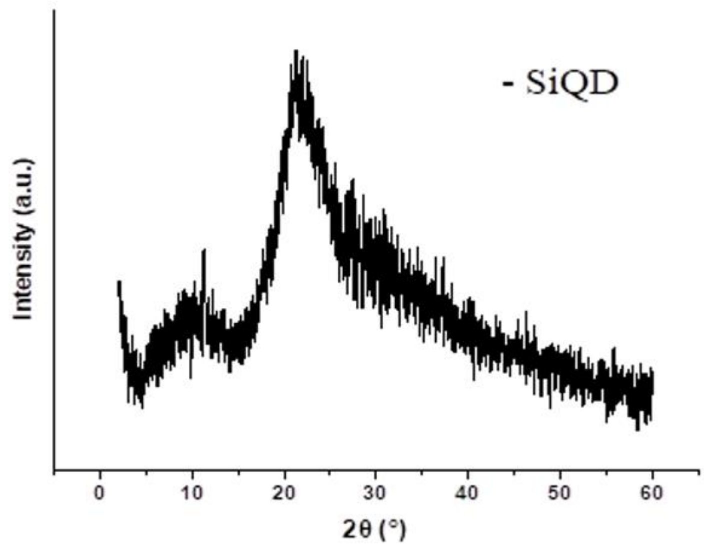

Figure 4. X-ray pattern of the prepared SiQDs

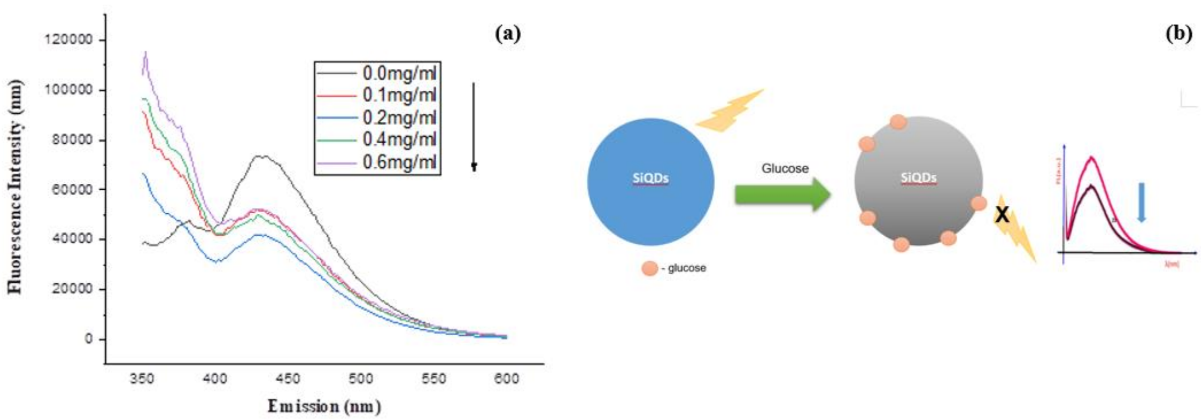

Figure 5. (a) Fluorescence response of SiQDs in a phosphate buffer solution containing different concentrations of glucose, (b) Schematic illustration of the NH_2@SiQDs for glucose detection

Fluorescence behavior of SiQDs towards glucose

Various concentrations of glucose were introduced alongside colloidal SiQDs to evaluate the sensitivity of this method to glucose. The fluorescence spectra of SiQDs, depicted in Figure 5(a), reveal a decrease in intensity as glucose concentrations increase. Hence, a non-enzymatic assay for SiQDs that is centered on the fluorescence quenching of NH_2@SiQDs in response to glucose is proposed. This quenching mechanism is attributed to glucose molecules binding to NH_2@SiQDs via H-bonding and hydrophobic interactions, inducing self-aggregation of SiQDs and subsequent fluorescence quenching, as illustrated in Figure 5b [22]. The fluorescence intensity inversely correlates with glucose concentrations. NH_2@SiQDs offer notable advantages, including high sensitivity, simplicity, rapid analysis, and cost-effectiveness.

Optimization of parameters

The fluorescence intensity was examined across different pH levels using a 0.1 mg/mL glucose concentration with excitation at 305 nm, resulting in a maximum emission peak at a wavelength of 350 nm. As shown in Figure 6(a), as the pH buffer increased, the fluorescence intensity increased, and the highest intensity was observed at pH 7.2. Above pH 7.2, the intensity started to decrease, which might be due to a shift in the conformational state of the fluorescent molecule, which led to quenching of the fluorescence signal. Consequently, a buffer solution of pH 7.2 was determined to be optimum for glucose detection. Notably, most of the optimum pH values selected for glucose determination were in the pH 7.0 to 7.4 [22,31].

Time plays a crucial role in many biochemical reactions and significantly influences their outcomes. Hence, the effect of reaction time at various time intervals (0−40 min) was investigated. As illustrated in Figure 6(b), the reaction initiated promptly, reaching its maximum intensity at 15 min, then gradually decreasing. Therefore, a reaction time of 15 min was selected for further study.

Analytical performance of the developed sensing system

Figure 7 illustrates the dynamic response of the SiQDs system upon introducing different glucose concentrations ranging from 0.1 to 1 mg/mL. As the glucose concentration increased, there was a gradual increase in the net fluorescence intensity of the SiQDs due to their quenching effect. A linear correlation within the range of glucose concentration from 0.1 to 0.8 mg/mL was observed with the equation y =20249*x*-1682.4, R^2 = 0.9804), and the detection limit of 0.03 mg/mL was determined

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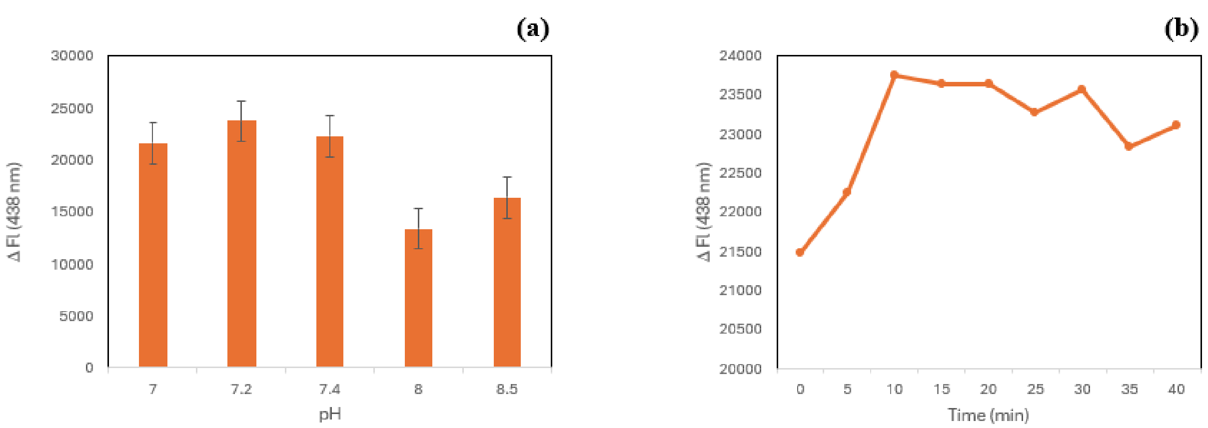

Figure 6. Influence of different pH of phosphate buffer (a) and reaction time (b) towards SiQD (0.5 mg/mL) in the presence of glucose (1 mg/mL)

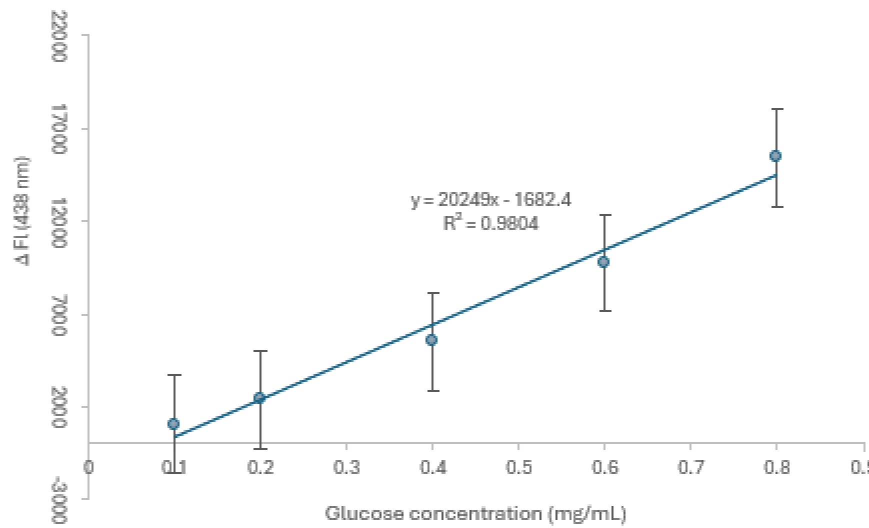

Figure 7. The linearity of the system towards different concentrations of glucose concentration (0.1 to 0.8 mg/mL)

Conclusion

The present study successfully synthesized fluorescent SiQDs via a one-pot hydrothermal process by utilizing APTES as the silicon source and employing EDA and sodium citrate as capping and reducing agents, respectively. Analysis revealed a continuous absorption pattern within the 200 to 400 nm wavelength range, with a prominent shoulder observed around 329 nm. The SiQDs exhibited a maximum emission peak at 382 nm when excited at 305 nm, and their surface morphology displayed satisfactory uniformity, appearing as near-spherical shapes ranging in size from 11.81 nm to 12.95 nm. Additionally, a glucose detection system using water-soluble SiQDs was explored, where the findings demonstrated exceptional sensitivity and specificity. In brief, this system allowed for glucose detection within the range of 0.1 to 0.8 mg/mL, with a limit of detection of 0.03 mg/mL. Furthermore, SiQD-based detection proved to be simple, rapid, cost-effective, and minimally toxic, making it suitable for various biological analyses. The resulting SiQDs exhibited excellent fluorescence properties, suggesting their potential applications in diverse fields such as optoelectronics and biosensing.

Acknowledgement

The authors would like to express gratitude to Universiti Putra Malaysia for providing sponsorship under the Putra Grant (GP-IPS/2023/9746800).

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