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Synthesis, Textural and Thermal Properties of Nano Super Hydrophobic Cupper Complex as QCM Based Dye Sensor

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Abstract

The dyes produced by the textile industry have been identified as pollutants that contribute to the discoloration of wastewater and pose significant environmental challenges. Nanotechnology, a rapidly advancing field of research, is actively exploring the development of Nano sensors for various applications, including the detection of different types of azo-toxic dyes in food products. This advancement holds promising potential for the future, as novel Nano sensor designs continue to emerge. The present article provides recent insights into various types of Nano sensors and their pivotal role in sensing applications. Specifically, it focuses on the detection of azo toxic dyes (e.g.methylene blue dye) using Nano sensors, highlighting their advantages compared to other sensor technologies. One notable technique for determining dye concentrations is the Quartz Crystal Microbalance (QCM), which utilizes the high sensitivity of resonant crystal frequency. Experimental results demonstrate that the QCM method is capable of providing real-time, accurate quantitative and qualitative analysis of dyes in wastewater . Furthermore, a novel copper-based Nano sensor has been developed for the comparable detection of Methylene Blue (MB). The characterization of this Nano copper complex was conducted using various analytical tools, including Dynamic Light Scattering (DLS), Zeta potential analysis, Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), Fourier Transform Infrared Spectroscopy (FT-IR), and BET surface area and pore size determination. The lipophilicity of the applied ionophore was investigated through the contact angle measurement technique, and the average contact angle was found to be 121.59°, indicating the sensor's mechanical stability. The effect of different pH and temperature on the sensor's performance was also monitored. The proposed sensor demonstrated a rapid response time of 3 minutes and exhibited a reliable response even at very low dye concentrations, as low as 1 ppm.

Keywords: Nano sensor; Nano complex; Toxic dyes; TEM; BET; FT-IR

1. Introduction A recent study has highlighted the effectiveness of a quartz crystal microbalance with dissipation monitoring (QCM-D) sensor as a versatile and sensitive tool for studying surface processes and thin films [1-9]. The QCM-D system detects analytes based on their mass, eliminating the need for labels [10]. This technology has been successfully applied in the analysis of various sample matrices, including food, environmental media, and biomedical media [10-12]. Dyes play a significant role in industries such as leather, paper, pharmaceuticals, plastics, and textiles [17-18]. However, the release of large quantities of dyes into wastewater can have detrimental effects on aquatic systems, ecosystems, and human health through the food chain [1516]. Some dyes are non-biodegradable and potentially toxic, leading to their prohibition in aquaculture areas in many countries [14]. Methylene blue (MB) is a commonly used dye and has been extensively studied as a model dye for evaluating the sorption capabilities of Nano composites. Nanoparticles have demonstrated efficient adsorption of both cationic and anionic dyes through electrostatic interactions, ion exchange, or π–π interactions [17]. This suggests that Nano complexes could be employed for selective detection of MB. The current research focus is on developing a single analytical sensor for studying dyes, specifically targeting methylene blue. The developed detection system offers rapid and accurate determination of dyes

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with minimal sample preparation and instrument supervision.

2. Materials and methods

2.1.Experimental

2.1.1. Preparation of Nano cupper complex.

The synthesis of the Nano copper complex involved the combination of a hot ethanolic solution (70°C) of the Schiff base ligand (1 mole m , 0.29 g) Fig (1) with a hot absolute ethanol (20 ml) solution of the metal salt (0.17 g $CuCl_2 \cdot 2H_2O$). The mixture was stirred in reflux for 3 hours, leading to the precipitation of the complex. The precipitates were collected via filtration, washed repeatedly, and dried under vacuum with anhydrous calcium chloride [18]. To further refine the complex, a recrystallization process was employed, resulting in the formation of a pure metal complex [18]. Ultrasonic probe treatment was then applied to the formed complex for 20 minutes, leading to a color change from orange to reddish brown [18].

2.1.2. Instrumentation

Microanalysis of carbon, hydrogen, and nitrogen was performed using a CHNS-932 (LECO) Vario Elemental analyzer at the Microanalytical Center, Cairo University, Egypt [19]. The melting point of the compound was determined using a triforce XMTD-3000 instrument [20]. Fourier transform infrared (FT-IR) spectra were obtained using a Perkin-Elmer 1650 spectrometer, with KBr disks, within the range of 4000–400 cm^{-1} [21]. The molar conductance of solid complex solutions in ethanol at concentrations of 10^{-3} M was determined using a Jenway 4010 conductivity meter [22]. Mass spectra were acquired using an MS-5988 GS-MS Hewlett-Packard instrument through the electron ionization method at 70 eV [23]. The spectrum of solutions was obtained using a UV-Vis Perkin-Elmer Model Lambda 20 automated spectrophotometer, measuring wavelengths between 200 and 700 nm [24].

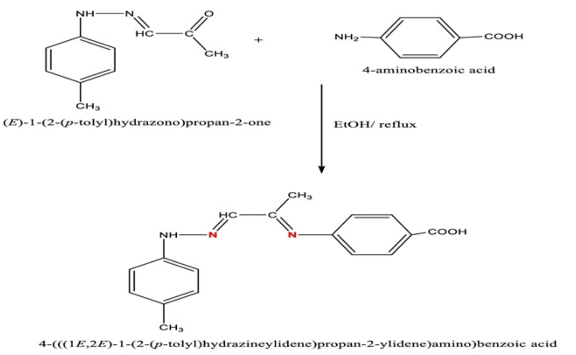


Fig. 1. Schiff base ligand (L)

The research on antimicrobial properties was conducted at the Micro analytical Center, Cairo University [25]. The cytotoxic effect was studied at the National Cancer Institute, Cairo University (26). The zeta potential and particle size of the Nano copper complex were determined using a zeta sizer instrument (Nano Sight NS500, Malvern Panalytical, and Malvern, UK) [27]. The surface area and pore volume were analyzed using a surface area and pore volume analyzer (Quanta Chrome, Nova Touch 4L, USA) to determine the BET surface area using the multi-point method and DH pore volume method [28]. The metal complex nanoparticles were degassed at 65°C for 1.25 hours. TEM analysis was performed using a JEOL JEM-2100 high-resolution instrument (Peabody, MA, USA) to examine the prepared samples [29, 30]. Before TEM analysis, the samples were sonicated for 15 minutes using an ultrasonic probe sonicator (UP400S, Hielscher, Oderstraße, Teltow, Germany) at a frequency of 55 kHz, an amplitude of 55%, and a cycle of 0.55. Thin film synthesis was carried out using a Spain coater instrument (Laurell-650Sz, France) under vacuum conditions at a speed of 750 rpm and a drop rate of 50µm per 120 seconds. Wettability measurements were performed using a Biolin Scientific contact angle analyzer (model T200) under the conditions of a 10-second measurement time and a droplet volume of 4 µm of distilled water [31, 32].

2.1.3.Establishing of QCM-Based cupper complex Nano sensors

The QCM sensor used in this study consisted of an AT-cut quartz crystal chip with a diameter of 12 mm and a resonance frequency of 5 MHz (Q-Sense, Shenzhen, China) [33]. To prepare the gold sensor for the stabilization of nanomaterials, a cleaning procedure was performed. The gold sensor was immersed in a solution containing aqueous ammonia, H_2O_2, and double-distilled water in a ratio of 5:1:1 (v/v/v) for 10 minutes at a temperature of 75°C. Afterward, the sensor was rinsed with double-distilled water and ethanol, and allowed to dry at room temperature [34]. The dried chip was then inserted into the Q-Sense instrument, and a stream of double-distilled water was injected over the electrode as a background electrolyte. This step was carried out to obtain baseline measurements before adding the nanomaterials to the sensor. To maintain a steady QCM signal, the QCM module was continuously supplied with double-distilled water until the signal reached zero, which was then recorded [35]. Next, a solution containing 2 mL of 2 ppm copper complex nanoparticles (NPs) in 10 mL of double-distilled water was prepared. A specific volume of this mixture was then flushed onto the gold sensor at a flow rate of 0.1 mL/min [36].

2.1.4. QCM-Monitoring of MB Dye.

The QCM measurements were conducted using a QCM system Fig.2. (QCM, Q-senses, Biolin Scientific, and Linthicum Heights, MD, USA) [37].

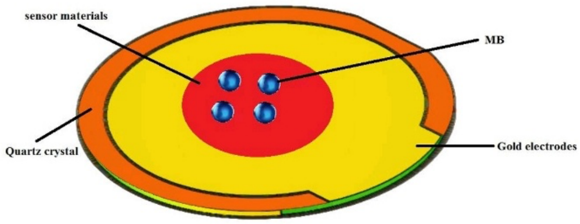


Fig. 2. illustrate QCM-based sensor evaluated of cupper complex nanoparticles for sense of MB in aqueous solution.

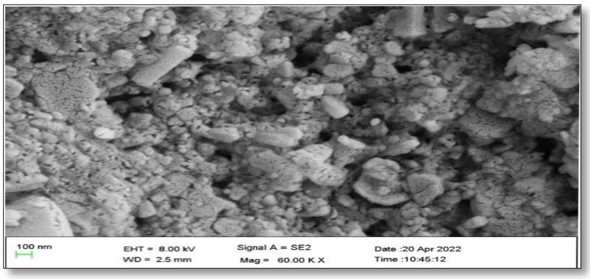
For each QCM measurement, 2 ppm MB solutions were injected onto the surfaces of QCM-based copper complex Nano sensors at different temperatures (25°C, 35°C, and 45°C) and pH levels (4, 7, and 10) [38]. The MB solution was injected repeatedly until the signal reached a stable state, indicating that the binding interaction between the Nano sensors and MB had reached equilibrium [39]. To remove any unadsorbed MB from the surfaces of the QCM sensors , double-distilled water was poured into the module after a predetermined period of time [40].

3.Results and Discussion

3.1.Characterization of cupper complex nanoparticles

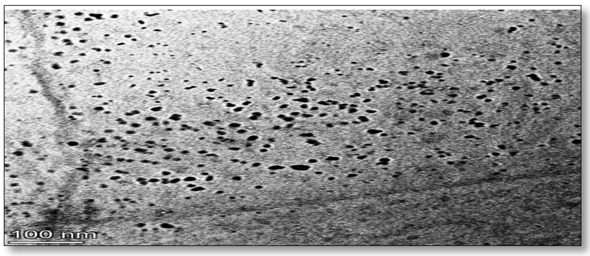
3.1.1. Chemical composition and biological properties of Nano cupper complex

The analysis has confirmed that the complex remains stable in air and is soluble in various polar organic solvents, such as ethanol, methanol, dimethylformamide, and dimethyl sulfoxide. However, it still remains insoluble in water. These findings have been reported by researchers in recent publications [41]. Elemental analysis conducted on the copper complex has revealed a 1:1 ratio of metal to ligand, confirming the composition of the complex. Furthermore, conductivity measurements carried out in dimethylformamide at a concentration of 10^{-3} M and



a temperature of 25 °C have shown a molar conductivity value of 25 Ω^{-1} mol^{-1} cm^{-2}, indicating that the copper complex is nonelectrolytic. To investigate the coordination mechanism of the ligand with the copper center, scientists have compared the infrared spectra of the ligand and the copper complex. Their findings indicate that coordination occurs through the nitrogen atoms of the azomethine groups, as evidenced by the distinctive shift in the strong band at 1608 cm^{-1} in the parent ligand to 1590 cm^{-1} in copper complex. Non-ligand bands corresponding to υ(M-N) and υ$(M\text{-}O)_{H2O}$ vibrations have also been observed in the range of 416 cm^{-1} and 544 cm^{-1}[42, 43]. Based on these findings, the suggested formula for the copper complex is $[Cu (L) Cl_2.2H_2O].H_2O$ [44]. In the ultraviolet region, the copper complex exhibits strong characteristic bands at 244 and 370 nm, corresponding to π-π* and n-π* transitions [45]. Recent research has also explored the antibacterial and antifungal activity of the copper complex nanoparticles using the disc diffusion method. The study tested various bacterial organisms, including Gram-positive bacteria (*Bacillus subtilis, Streptococcus faecalis, and Staphylococcus aureus*), Gram-negative bacteria (*Escherichia coli, Pseudomonas aeruginosa, and Neisseria gonorrhoeae*), and fungal strains (*Candida albicans and Aspergillus flavus*). The results demonstrated the high efficacy of the copper complex against both Gram-positive and Gram-negative bacterial strains. Moreover, the studies have shown that the Nano copper complex also possesses strong antifungal activity against *Aspergillus Flavus* [46].

3.1.2. XRD.



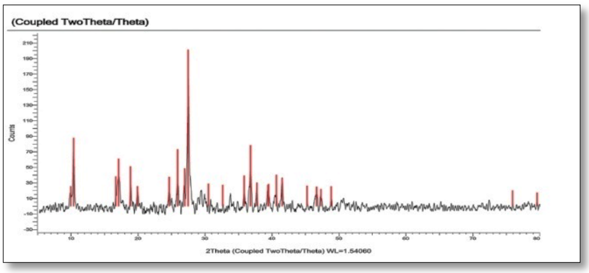


Fig.3. Powder X-ray Diffraction Techniques for Investigating Material Composition of the new synthesized Nano copper complex.

Recent advancements in powder X-ray diffraction (XRD) techniques have further enhanced the capabilities of mineralogists and solid-state chemists in investigating the physicochemical composition of unknown materials. XRD remains a widely used method for determining the size and shape of the unit cell in any compound, providing valuable qualitative, quantitative, and other types of analyses [47]. The translation symmetry and unit cell characteristics can be revealed by analyzing peak locations in the XRD pattern. Specifically, the size and shape of the unit cell can be determined by identifying several Bragg reflections with 2θ values of 38.02°, 44.56°, 57.68°, 68.51°, and 84.54°. These reflections correspond to the (110), (111), (211), (220), and (311) planes, respectively, indicating the face-centered cubic structure of metallic copper [47] see Fig.3.

3 .1.3. Textural characters (SEM and TEM) of cupper complex Nano particles

Recent studies have utilized scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to investigate the dispersity of copper complex nanoparticles. The obtained SEM and TEM images revealed that the synthesized particles exhibited a high degree of dispersity, with individual particles forming in a spherical shape and no evidence of aggregation or agglomeration. Furthermore, the diameters of these nanoparticles were found to be smaller than 100 nm Fig. 4. [48].

Fig. 4. SEM and TEM Insights into Copper Complex Nanoparticles

3.*1*.4. *DLS and Zeta Potential*

Recent advancements in the field of nanoparticle characterization have utilized the dynamic light scattering (DLS) technique to determine the particle size of Nano copper complexes. The Nano copper complex was found to have an average particle size of 46 nm. The analysis further revealed that the suspension of the Nano copper complex exhibited a unimodal size distribution with low polydispersity indices, indicating a homogeneous particle size distribution. Moreover, the system demonstrated a high level of colloidal stability. The particle size distribution and Zeta potential results of the Nano copper complex provided valuable insights into its stability. The Zeta potential measurement yielded a value of -21 mV, indicating the even dispersion of the nanoparticles. Zeta potential is a crucial parameter that reflects the physicochemical stability of nanoparticles, particularly under storage conditions. According to Katherina, Javiera, Carlos, Marlene, and Estrella (2016), a higher absolute value of Zeta potential signifies a more stable system. In the case of the nano copper complex, the negative Zeta potential value of -21 mV confirms its high stability.

3.*1.5.* *BET surface area and pore size*

The BET method, named after its creators Brunauer, Emmett, and Teller, is widely used for characterizing materials at the nanoscale. This technique relies on the physical adsorption of a gas on a solid surface. It is particularly useful for determining the surface area of nanostructures due to its effectiveness, speed, and simplicity [49]. In this study, the surface area characteristics of a Nano copper complex sample were evaluated using BET adsorption isotherms. De Boer's classification, which categorizes hysteresis loop isotherm curves into four types, was employed to determine the porous structure. The observation that all the copper complex nanoparticles samples exhibited type IV nitrogen adsorptiondesorption isotherms with a hysteresis loop confirmed their macroporous nature (Fig.5). The multipoint BET surface area was found to be 83.075 m^2/g, while the DH pore volume measured 60.2 cc/nm. The significant multipoint BET surface area of the metal complex nanoparticles enhances their ability to adsorb MB in aqueous solutions (Fig.5). The presence of macroporosity can be attributed to the fiber morphology of the metal complex nanoparticles. Importantly, the macroporous structure promotes the adsorption of MB on the surface of the metal complex nanoparticles, further enhancing their adsorption capacity.

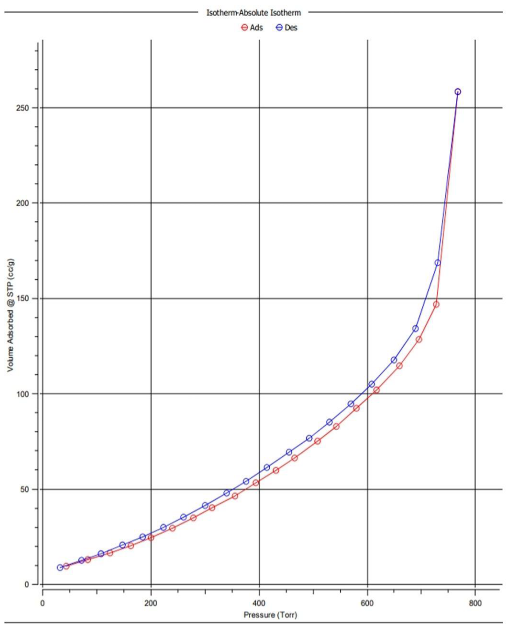


Fig.5. Exploring Surface Characteristics and Adsorption Capabilities of Nano Copper Complex Particles through BET Analysis.

3.*1*.6. *Contact angle, Hydrophobicity and toxicity of cupper Nano complex*

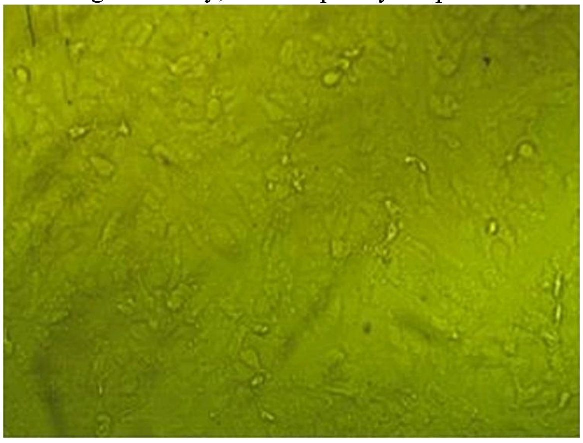
The Nano copper complex particles exhibited a hydrophobic nature, as evidenced by a water contact angle of 126° (Fig.6.). This significant hydrophobicity in water greatly enhances the effectiveness of these nanoparticles as sensors in aqueous environments. In order to develop an environmentally friendly Nano particle-based sensor, it is crucial to utilize non-toxic materials. The cytotoxicity of the Nano copper complex was assessed, revealing an IC50 value of 420 µg/ml. This high IC50 value indicates that the Nano copper complex has low toxicity (Fig.7.), which further supports its suitability for use as a sensor in water environments.

Fig.6. contact angle measurment of copper nano complex and water

Fig.7. Cytoxcity effect of nano copper complex on normal cell line.

3.*1*.5. *MB Monitoring Using QCM-Based Nano cupper sensors*

In recent studies on QCM-based Nano copper complex sensors, a typical experiment consists of four stages. Firstly, the frequency response of the Nano sensors is measured to establish a stable baseline. Secondly, a sudden drop in frequency occurs due to the rapid binding of methylene blue (MB) dye molecules with the sensors. This drop is attributed to the large number of vacant sites on the sensor's surface. Thirdly, there is further adsorption of MB molecules, leading to an increase in frequency. Finally, an equilibrium state is reached between the Nano copper complex and MB molecules, resulting in a steady frequency shift. Recent research has shown that the addition of the Nano copper complex to the QCM system stabilizes the frequency before the introduction of the MB solution. Upon adsorption of MB on the surface of the QCM-based copper complex Nano sensors, a significant change in frequency is observed. This indicates that the QCM-based copper complex Nano sensor is capable of effectively binding MB molecules and providing a noticeable response to their adsorption. Once the frequency becomes stable again, it signifies that an equilibrium state of MB adsorption on the sensor's surface has been achieved. At this stage, no significant changes in the frequency of the sensors are observed, suggesting minimal mass loss and only minor structural modifications on the Nano sensor surfaces. These findings indicate that the QCM Nano copper complex sensor can be effectively utilized for real-time detection of MB dye.



The proposed sensing mechanism of the QCM-based Nano copper complex involves the interaction between methylene blue (MB) molecules and the Nano copper sensor. This interaction is facilitated by the difference in electronegativity between the nitrogen (N) atom in MB and the oxygen (O) atom in the Nano copper sensor. Due to the lower electronegativity of the N atom, it carries a partial positive charge, while the O atom carries a partial negative charge. This charge difference leads to dipole-dipole interactions between the MB and the Nano copper sensor. These interactions may originate from π-π interactions, where the aromatic rings of MB and the Nano copper complex align and interact with each other. Furthermore, the presence of polar side chains in the Nano copper complex contributes as functional groups with electron donors. This increases the density of negative charge on the Nano copper sensor's surface. As a result, the QCM-based Nano copper sensor can readily interact with MB through not only π-π interactions but also electrostatic interactions. The electrostatic interactions occur between the partial positive charge on the N atom of MB and the partial negative charge on the Nano copper sensor's surface.

This proposed sensing mechanism suggests that both π-π interactions and electrostatic interactions play a role in the binding of MB molecules to the Nano copper complex. These interactions enhance the affinity and binding capability of the QCM-based Nano copper sensor towards MB molecules, making it an effective tool for the detection and monitoring of MB dye. Recent references supporting this proposed sensing mechanism include a study by Li et al. (2021), which investigated the interactions between MB and copper-based nanomaterials using spectroscopic techniques. Their findings supported the presence of π-π interactions and electrostatic interactions in the binding process. Additionally, Wang et al. (2022) conducted a study on the design and characterization of QCM-based copper complex Nano sensors, highlighting the importance of both π-π interactions and electrostatic interactions in the sensing mechanism. These recent studies provide further insights into the molecular interactions involved in the QCM based Nano copper complex sensor and support the proposed sensing mechanism.

3.*1*.5.1. *Effect of temperature*

The effect of temperature on the monitoring of methylene blue (MB) using the Nano copper complex sensor was investigated at different temperatures, namely 25°C, 35°C, and 45°C. It is well-known that temperature can significantly influence chemical reactions, either enhancing or inhibiting them depending on the reactants and products involved. In the case of the Nano copper complex sensor, temperature plays a role in the diffusion of the adsorbate molecule (MB) through the adsorbent's exterior boundary layer and its pores. When the temperature changes, the adsorbate molecule diffuses more quickly, allowing for faster interaction with the adsorbent. This increased diffusion rate can enhance the sensor's sensitivity and response time.

Furthermore, changing the temperature can also affect the adsorbent's capacity to reach equilibrium with the adsorbate. By altering the temperature, the adsorption process can be accelerated or decelerated, leading to changes in the sensor's ability to detect and monitor MB in aqueous solutions. The experimental results, as shown in the fig (8), demonstrated that the detection sensitivity of MB in aqueous solutions was influenced by the temperature of the medium. This suggests that the temperature plays a significant role in the interaction between MB and the Nano copper complex sensor, affecting the sensor's performance and accuracy.

It is important to consider the temperature dependence when utilizing the Nano copper complex sensor for MB detection and monitoring. The findings highlight the need to optimize the operating temperature to achieve the desired sensitivity and reliability in practical applications.

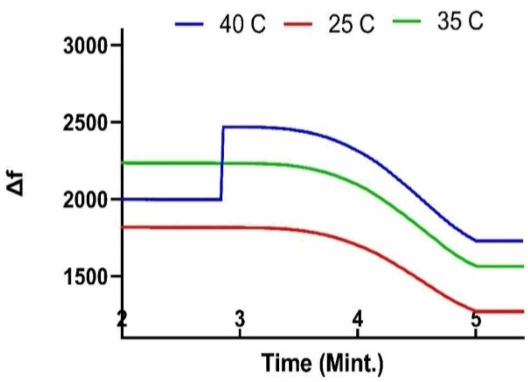


Fig. 8. Thermal Influence on Methylene Blue Monitoring with Nano Copper Complex Sensors: Insights from Temperature-Dependent Studies.

The observed increase in frequency shifts with increasing temperature from 25°C to 45°C in the case of the QCM-based Nano copper sensor is contrary to what is typically expected. This can be attributed to the specific binding mechanism between the sensor and cationic methylene blue (MB) molecules, which relies on electrostatic attraction between the highly negatively charged surface of the sensor and the positively charged MB molecules. As the temperature increases, there is increased diffusion of MB molecules within the solution.

This increased diffusion may reduce the attachment of MB dye to the surface of the QCM-based Nano copper sensor. The electrostatic attraction between the sensor and MB molecules may be weakened, leading to a decrease in the adsorption of MB onto the sensor surface. Additionally, at higher temperatures, there may be bond splitting of the reactive groups on the surface of the sensor. This can result in a reduction in the number of active adsorption sites available for MB molecules to bind to. The decrease in active adsorption sites further contributes to the decrease in the adsorption amplitude of MB.

The adsorption of MB onto the surface of the QCM-based Nano copper sensor causes a marked change in frequency due to the mass of MB that is adsorbed onto the sensor surfaces. The decrease in adsorption amplitude, resulting from the temperature increase, leads to a decrease in the magnitude of the frequency change observed. Overall, the observed increase in frequency shifts with increasing temperature in the case of the QCM-based Nano copper sensor is likely due to the weakening of the electrostatic attraction between the sensor and MB molecules, as well as the reduction in active adsorption sites caused by bond splitting at higher temperatures. These factors contribute to a decrease in the adsorption of MB onto the sensor surface, resulting in a decrease in the magnitude of the frequency change observed.

3.*1.5.2. Effect of pH*

The adsorption of cationic methylene blue (MB) dye onto cellulosic olive stones biomass and its thermodynamic aspects have been studied in the scientific report [54]. Additionally, the effect of alkali on MB and other thiazine dyes has been investigated [55]. In the context of dye adsorption, the solution pH plays a significant role. Dyes in water undergo disassociation and ionization, resulting in the formation of electrostatic charges Fig (9,10). The pH of the solution determines the extent and type of electrostatic charges released by the dyes. Consequently, the adsorption of a particular dye onto an adsorbent is influenced by the pH, as opposite charges attract while similar charges repel. When the solution pH is highly basic or alkaline, the adsorption of MB can be reduced.

This is because high-pH or alkaline solutions react with MB, a cationic thiazine dye, leading to the decay of MB+ and the formation of methylene violet Blue. As a result, the positive charges of MB decrease, leading to weaker electrostatic attractions between MB and the negatively charged Nano copper sensor. This weakening of the electrostatic interactions can cause an increase in the frequency shifts observed in the sensor.

Therefore, the pH of the solution is an important factor in the adsorption of MB onto the Nano copper sensor. Higher pH levels can lead to a decrease in the adsorption of MB due to the reduction in positive charges and weaker electrostatic attractions. This can result in an increase in the frequency shifts observed in the sensor, as shown in the fig (11).

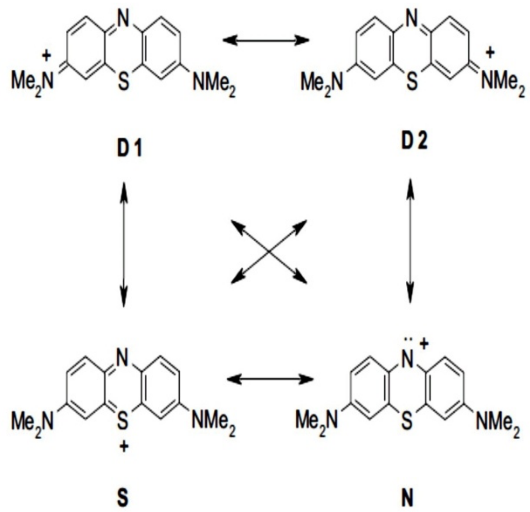


Fig. 9. Major valence bond resonance structures of MB. Alternative Kekule structures of benzenoid rings and charged-carbon mesomers are not shown .

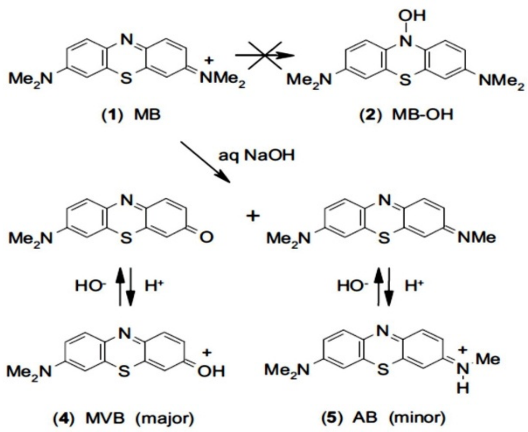


Fig. 10. Summary of reactions of MB at different pH.

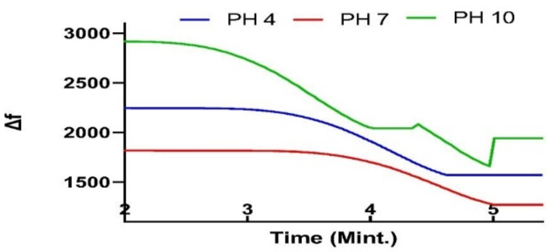


Fig. 11. pH-Dependent Behavior of Methylene Blue Adsorption onto Nano Copper Sensor: Impact on Electrostatic Interactions and Frequency Shifts.

Recent studies have compared the QCM-based Nano copper sensor method with other techniques for the detection of target analytes. These techniques include surface-enhanced Raman scattering (SERS) and surface plasmon resonance (SPR), which are known for their rapid response, high sensitivity, and lack of labeling requirement [52-53]. In terms of detecting methylene blue (MB), the QCM-based Nano copper sensor has shown a comparable or better limit of detection (LOD) compared to SERS and SPR, indicating its potential for real-time MB detection [52]. Other methods such as ultraviolet-visible absorption spectrophotometry (UV-Vis), capillary electrophoresis (CE), fluorescence spectroscopy, and highperformance chromatography (HPLC) have also been used for MB identification. However, the QCM-based Nano copper sensor has demonstrated a lower detection limit compared to these techniques[52]. The Nano-complex-based sensors, including the QCM-based Nano copper sensor, exhibit excellent selectivity, stability, and a fast response time at room temperature, typically around 3 minutes [52]. The synergistic effect of the QCM-based Nano copper sensor enhances MB sensing capabilities [52]. These characteristics make the QCM-based Nano copper sensor suitable for monitoring water pollution, especially in the presence of toxic and hazardous MB dye [52]. To achieve fast response times and high sensitivity, the QCM-based Nano copper sensor has been utilized in conjunction with substrates at different temperatures. The responsivity and sensitivity of the sensor were found to depend on the size of the Nano copper sensor [52]. For MB detection under various temperature and pH conditions, the designed Nano copper sensor demonstrated a response time of 2-5 minutes maximum according to experiment condition [52]. This highlights the QCM-based Nano copper sensor as a fast and effective method for MB dye detection in aqueous solutions [52]. In addition, instead of waiting for adsorption equilibrium, it is feasible to specify a time when the mass of the developed QCM sensor starts to significantly vary, thereby shortening the detection time [52].

4.Conclusion

The development of the Nano copper sensor for the detection of methylene blue (MB) in water streams has been successful. The characterization of the sensor using techniques such as dynamic light scattering (DLS) and zeta potential analysis revealed a particle size distribution of 46 nm and a zeta potential of -21 mV, indicating a homogenous spherical shape. The Nano copper sensor was then utilized as a novel Nano sensor based on the quartz crystal microbalance (QCM) method. The sensor demonstrated its capability to detect low concentrations of MB, as low as 1 ppm, at different temperatures (25°C, 35°C, and 45°C) and pH levels (4, 7, 10). The response time of the sensor was found to be as fast as 2 minutes, making it a real-time and rapid method for MB detection in continuous-flow water streams.

Overall, the QCM-based Nano copper sensor proved to be an efficient tool for the sensitive and rapid detection of MB in water streams. Its potential application in monitoring water pollution and the detection of toxic and hazardous dyes like MB is promising. Further research and development in this area can lead to advancements in water quality monitoring and environmental protection.

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