



Functionalization of Halo-Hydroxy Benzimidazole onto SiO₂ Nanoparticles: Catalytic, Photophysical, and Biological Investigations for Sustainable Applications

Xiaojian Liu¹ · Yanqi Zhou¹ · Kanagaraj Rajalakshmi² · K. Jayamoorthy³ · B. Subash³ · Selvaraj Muthusamy² · Dongwei Zhu² · Yanping Zhao⁴

Received: 1 May 2025 / Accepted: 19 September 2025
© The Author(s), under exclusive licence to Springer Nature B.V. 2025

Abstract

A novel benzimidazole derivative, 1-(4-chlorobenzyl)-2-(4-chlorophenyl)-4-fluoro-1H-benzo[d]imidazole (CCHFB), was synthesized via a three-component condensation reaction involving 3-fluorobenzene-1,2-diamine, 5-chloro-2-hydroxybenzaldehyde, and ammonium acetate in the presence of ZnO nanoparticles as a catalyst. The synthesized compound was further functionalized with SiO₂ nanoparticles to investigate enhancements in physicochemical and biological properties. Comprehensive spectral analyses including UV–Vis, fluorescence, NMR, and FT-IR confirmed successful functionalization and highlighted the molecular interactions between CCHFB and the nanoparticle surface. UV–Vis spectra showed enhanced absorbance, while fluorescence quenching indicated possible electron transfer interactions. FT-IR analysis revealed shifts in azomethine group vibrations, confirming nanoparticle binding. Biological evaluations demonstrated that functionalized CCHFB exhibited notable antioxidant activity (via phosphomolybdenum and DPPH assays), significant α -amylase inhibitory potential, and enhanced antibacterial effects against both Gram-positive and Gram-negative strains, compared to unmodified CCHFB. Stability studies revealed that the functionalized compound retained over 92% structural integrity over 24 h in physiological buffer. These findings suggest that SiO₂-functionalized CCHFB is a promising candidate for pharmaceutical and biomedical applications due to its enhanced stability, bioactivity, and broad-spectrum antimicrobial properties.

Keywords Halo benzimidazole · SiO₂ nanoparticles · Antioxidant activity · α -Amylase inhibition · Antibacterial properties

-
- ✉ K. Jayamoorthy
kjmche@gmail.com
- ✉ Selvaraj Muthusamy
rajselva311@ujs.edu.cn
- ✉ Dongwei Zhu
1000005601@ujs.edu.cn
- ✉ Yanping Zhao

- ¹ Department of Gynecology, Affiliated People's Hospital of Jiangsu University, 212006 Zhenjiang, Jiangsu, People's Republic of China
- ² Department of Immunology, Jiangsu Key Laboratory of Laboratory Medicine, School of Medicine, School of Chemistry and Chemical Engineering, Jiangsu University, Zhenjiang 212013, People's Republic of China
- ³ Department of Chemistry, St. Joseph's College of Engineering, Chennai 600119, Tamilnadu, India
- ⁴ Department of Health Management Center, Suzhou Kowloon Hospital, Shanghai Jiaotong University School of Medicine, Suzhou 215028, People's Republic of China

1 Introduction

The continuous emergence of antibiotic-resistant bacteria and metabolic disorders like diabetes mellitus has intensified the search for novel multifunctional therapeutic agents with enhanced efficacy and biocompatibility. Nanotechnology, particularly the use of functionalized nanoparticles, offers a promising avenue in this context due to their tunable surface chemistry, large surface area, and enhanced interaction with biological systems [1, 2]. Among the wide range of nanomaterials studied, silica nanoparticles (SiNPs) have garnered considerable interest owing to their biocompatibility, ease of functionalization, and thermal stability [3, 4].

Functionalization of SiNPs with biologically active heterocyclic compounds represents an effective strategy to augment their therapeutic potential. One such class of compounds is benzimidazoles, which are nitrogen-containing heterocycles known for a wide array of pharmacological

activities including antimicrobial, antidiabetic, and antioxidant effects [5–7]. The benzimidazole moiety resembles the purine structure found in biomolecules, enabling interactions with enzymes and nucleic acids, which underlies its diverse biological activities [8].

The antioxidant activity of benzimidazole derivatives is particularly noteworthy as oxidative stress is a key contributor to cellular damage, aging, and chronic diseases such as cancer and diabetes [9, 10]. Compounds capable of neutralizing reactive oxygen species (ROS) have therapeutic relevance in mitigating oxidative damage and restoring redox homeostasis [11]. Furthermore, benzimidazoles have been reported to exhibit inhibitory activity against α -amylase, an enzyme involved in carbohydrate metabolism, thereby offering potential in glycemic control for diabetic patients [12–14].

Antibacterial resistance poses a formidable challenge to global health, with pathogens evolving mechanisms to evade conventional antibiotics [15, 16]. Benzimidazole derivatives have demonstrated promising antibacterial activity by targeting microbial DNA synthesis and membrane integrity [17, 18]. When immobilized on SiNPs, these molecules may exhibit synergistic effects, enhancing membrane penetration and retention time at infection sites [19].

Recent studies have shown that the functionalization of SiNPs with heterocyclic compounds not only improves drug loading capacity but also enhances the stability and bioavailability of the active agents [20, 21]. This combination is especially beneficial for therapeutic applications requiring controlled release and targeted delivery [22]. Moreover, SiNPs allow surface modifications with linker molecules that can facilitate covalent bonding of bioactive ligands, leading to increased cellular uptake and reduced off-target effects [23].

In this context, the current study aims to synthesize and characterize novel benzimidazole derivatives functionalized onto SiNPs and evaluate their antioxidant, α -amylase inhibitory, and antibacterial properties. The goal is to develop multifunctional nanomaterials with potential applications in biomedical and pharmaceutical fields. This study contributes to the growing field of functional nanomaterials and their integration with pharmacophores to combat multidimensional therapeutic challenges [24, 25].

The selection of this research topic is driven by the increasing importance of benzimidazole-based compounds, which possess diverse pharmacological and biological activities. Functionalization of these heterocycles onto nanostructured supports such as silica nanoparticles significantly enhances their bioavailability and stability. The combined system offers a promising platform for multifunctional therapeutic applications including antioxidant, α -amylase inhibitory, and antibacterial properties. Moreover, addressing the need for more sustainable and hybrid

therapeutic agents, this study contributes to the development of novel multifunctional biomaterials with potential applications in pharmaceutical and biomedical fields.

2 Experimental

2.1 Purchasing Materials

All chemicals, including 3-fluorobenzene-1,2-diamine, 5-chloro-2-hydroxybenzaldehyde, ammonium acetate, zinc oxide (ZnO) nanoparticles, and nano-sized silica, were obtained from Sigma-Aldrich. These reagents were of analytical grade and were utilized in the experimental procedures without undergoing any additional purification steps.

2.2 Spectral measurements

The interaction between CCHFB and SiO₂ nanoparticles was thoroughly investigated using a range of analytical techniques. UV–Visible spectroscopy was conducted with a Systronics Double Beam UV–Vis spectrophotometer, operating across a spectral range of 200–800 nm, to monitor the absorption characteristics associated with the interaction. Fluorescence emission studies were carried out using a Perkin Elmer LS45 spectrofluorimeter, which offers high sensitivity and precision in detecting emission signals. Additionally, nuclear magnetic resonance (NMR) spectroscopy was employed to gain structural insights, with spectra recorded on a Bruker 400 MHz NMR spectrometer, well-suited for detailed molecular characterization.

Infrared (IR) spectral analysis was conducted using the potassium bromide (KBr) pellet method on a BRUKER IFS 66 V FT-IR spectrometer. Measurements were performed over a broad spectral range of 4000 to 400 cm^{−1}, enabling the detection of characteristic molecular vibrations. To ensure optimal signal quality, each IR spectrum was generated by co-adding 100 individual scans. The instrument was operated at a spectral resolution of ± 4 cm^{−1}, and a continuous purge with dry nitrogen was maintained throughout the measurements to minimize interference from atmospheric moisture and CO₂. Band sharpness and spectral fidelity were carefully evaluated, with an accuracy of 0.001 cm^{−1}, facilitating precise interpretation of the molecular features present in the samples.

2.3 Biological Studies

2.3.1 Antioxidant Studies

The total antioxidant capacity of both CCHFB and its SiO₂ nanoparticle-functionalized form was assessed through a well-established phosphomolybdenum-based assay, which

quantifies the ability of compounds to neutralize free radicals. For the assay, an antioxidant reagent was prepared comprising 3 mL of a mixture containing 0.6 M sulfuric acid (H_2SO_4), 28 mM sodium phosphate (Na_3PO_4), and 4 mM ammonium molybdate. This reagent facilitates the formation of a phosphomolybdenum complex, a key indicator of antioxidant activity. Test samples at different concentrations were added to the reagent mixture and incubated in a water bath at 95 °C for 90 min, allowing sufficient time for the reaction and the development of a green-colored complex. This color change signifies the reduction of Mo(VI) to Mo(V) by the antioxidants present in the samples.

Following incubation, the absorbance of each sample was recorded at 685 nm using a UV–Vis spectrophotometer, a wavelength that corresponds to the maximum absorbance of the resulting complex. The antioxidant activities of the samples were then calculated by comparing their absorbance values against a standard calibration curve generated using ascorbic acid (vitamin C), a widely recognized reference antioxidant. This method not only provided a quantitative measure of the radical-scavenging ability of the samples but also facilitated a direct comparison with a known standard to evaluate their relative efficacy [26].

$$TOA = [(A_t - A_c)/A_t] \times 100$$

The antioxidant activity of this compound is attributed to the presence of specific functional groups within its molecular structure, particularly hydroxyl and halogen (halo) groups, which are known to enhance radical-scavenging capabilities. Additionally, the functionalization of CCHFB with SiO_2 nanoparticles is believed to further augment its antioxidant potential by increasing surface area and facilitating more efficient interaction with free radicals [27].

2.3.2 Antidiabetic Activity (α -Amylase Inhibitory Method)

The α -amylase inhibitory activity of the samples was evaluated following a previously established protocol [28]. Test solutions of varying concentrations, including both the synthesized compounds and the standard inhibitor acarbose, were prepared in a 0.2 M phosphate buffer (pH 6.9). Each test solution was mixed with a 0.5% α -amylase enzyme solution and incubated at 37 °C for 10 min to facilitate enzyme–inhibitor interaction. Subsequently, a 1% starch solution was introduced as the enzymatic substrate, and the mixtures were incubated again at 37 °C for an additional 30 min to allow the enzymatic reaction to proceed.

To terminate the reaction, 3,5-dinitrosalicylic acid (DNSA) reagent was added, followed by heating the mixture in a boiling water bath for 15 min to develop the colored complex indicative of residual enzyme activity. The absorbance of each reaction mixture was then measured at 540 nm

using a UV–Vis spectrophotometer. The degree of α -amylase inhibition was calculated using the corresponding absorbance values and a standard formula, enabling quantitative assessment of the inhibitory effect. This procedure provided valuable insight into the ability of the CCHFB compound, particularly in its SiO_2 nanoparticle-functionalized form, to act as a potential α -amylase inhibitor:

$$\% \text{ Inhibition } = 1/4100 \times (A_t - A_c)/A_t$$

A_t = O.D. of test solution. A_c = O.D. of control

The findings suggest that the incorporation of SiO_2 nanoparticles into the CCHFB structure significantly contributes to its α -amylase inhibitory activity. The functionalized compound exhibited notable inhibition, with its performance closely comparable to that of acarbose, a well-known standard inhibitor. This strong inhibitory effect highlights the potential of the SiO_2 -functionalized CCHFB as an effective agent for modulating α -amylase activity. Such properties indicate its possible application in managing disorders associated with carbohydrate metabolism, such as postprandial hyperglycemia in diabetic conditions.

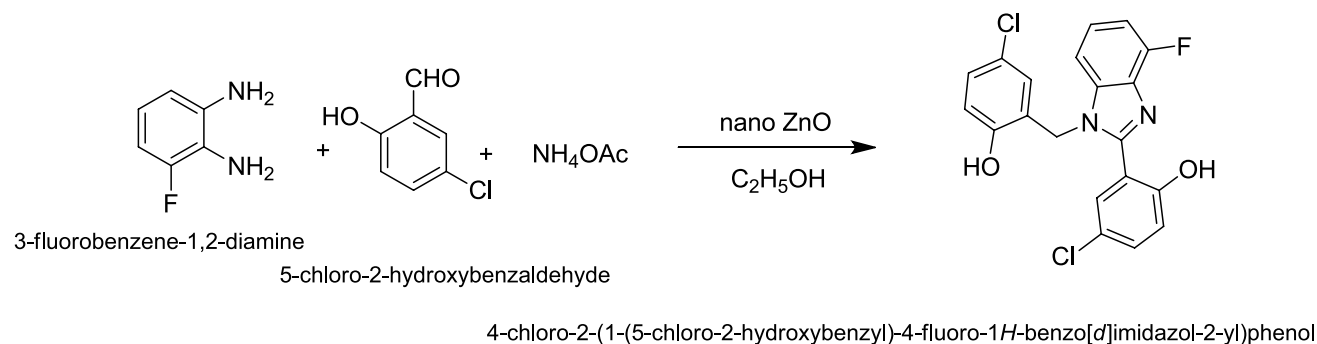
2.3.3 Stability Study

The stability of CCHFB and its SiO_2 nanoparticle-functionalized derivative was assessed following a standardized protocol [29]. To begin, the test sample was initially dissolved in a small volume of dimethyl sulfoxide (DMSO) and then diluted with phosphate buffer (pH 7.4) to a total volume of 5 mL. A 1 mM solution was prepared and subsequently added to 200 mL of the test system, followed by further dilution with an additional 2 mL of phosphate buffer to ensure uniform concentration. The resulting Schiff base solution was incubated at 37 °C for 10 min, and its initial absorbance was recorded at 275 nm to establish a reference point for degradation analysis.

To monitor stability, the sample solutions were kept at 37 °C and analyzed at predetermined time intervals over a 24-h period. A gradual reduction in absorbance at 275 nm was used as an indicator of chemical degradation, thereby allowing evaluation of the compound's stability under physiological conditions. This approach provided a quantitative measure of how functionalization with SiO_2 nanoparticles may influence the temporal stability of CCHFB.

2.4 Antibacterial Activity

The antibacterial efficacy of the SiO_2 nanoparticle-functionalized CCHFB was evaluated *in vitro* using the standard disc diffusion method [30]. The antimicrobial activity was tested against a panel of bacterial strains, including



Scheme 1 Synthesis of 1-(4-chlorobenzyl)-2-(4-chlorophenyl)-4-fluoro-1H-benzo[d]imidazole

two Gram-positive species—*Enterococcus faecalis* and *Staphylococcus aureus*—and two Gram-negative species—*Escherichia coli* and *Pseudomonas aeruginosa*. Sterile discs impregnated with the test compound were placed on agar plates inoculated with each bacterial strain, and the plates were incubated under appropriate conditions. The diameter of the inhibition zones around each disc was measured to determine the compound's ability to suppress bacterial growth. This method provided valuable insights into the antimicrobial potential of the SiO_2 -functionalized CCHF, highlighting its possible application as a broad-spectrum antibacterial agent.

2.4.1 Disc-Diffusion Method

The antibacterial activity of the test sample was assessed using the disc diffusion method. To begin, the target microorganisms were cultured in Nutrient Broth and incubated for 24 h. Petri dishes containing Nutrient Agar (NA) medium were inoculated with diluted bacterial suspensions. Sterile paper discs impregnated with the test samples, at concentrations of 500 μg , 1000 μg , and 2000 μg , were then placed onto the inoculated agar surface. As a positive control, streptomycin (20 μg) was included to evaluate the sensitivity of the bacterial strains. The inoculated plates were incubated at 37 °C for 24 h, allowing the bacteria to grow and interact with the test samples.

Antibacterial activity was evaluated by measuring the diameter of the clear zone around each disc, which indicated bacterial inhibition. The results were expressed in millimeters, with larger zones corresponding to greater antimicrobial effectiveness [31]. The compound demonstrated remarkable antibacterial activity against all tested bacterial strains, suggesting its potential as a potent antimicrobial agent.

2.5 Synthesis of 1-(4-Chlorobenzyl)-2-(4-Chlorophenyl)-4-Fluoro-1H-Benzo[d]imidazole

The three-component assembly of 3-fluorobenzene-1,2-diamine, 5-chloro-2-hydroxybenzaldehyde, and ammonium

acetate in the ratio of 1:2:1 in the presence of ZnO nano catalyst at 353 K was used to create 1-(4-chlorobenzyl)-2-(4-chlorophenyl)-4-fluoro-1H-benzo[d]imidazole (Scheme 1). The Proposed Mechanism for the Synthesis of Benzimidazole Derivative is given in Scheme 2. Yield: 94%. mp. 281 °C, Anal. calcd. for $\text{C}_{20}\text{H}_{13}\text{Cl}_2\text{FN}_2\text{O}_2$: C, 59.57; H, 3.25; Cl, 17.58; F, 4.71; N, 6.95; O, 7.94. Found: C, 59.49; H, 3.30; Cl, 17.59; F, 4.74; N, 6.98; O, 7.90. ^1H NMR (500 MHz, CDCl_3): δ 5.79 (s, 2H) methylene protons, 6.87–7.60 (m, 11 H). ^{13}C (100 MHz, CDCl_3): δ 52.2 (methylene carbon), 105.7, 108.8, 114.9, 115.9, 125.1, 125.2, 125.9, 128.1, 127.2, 128.7, 128.9, 129.0, 129.2, 129.3, 131.1, 134.1, 136.9, 149.2, 154.6.

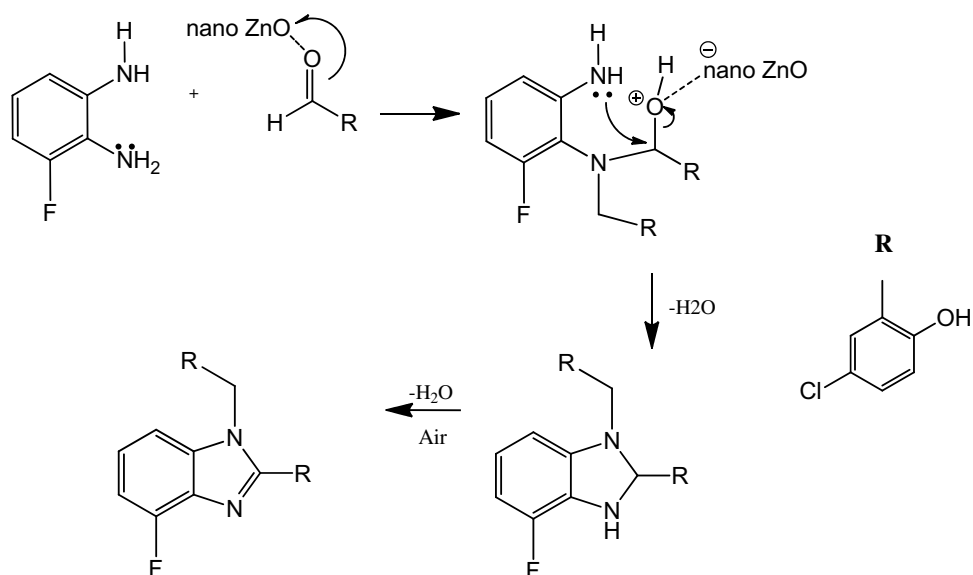
3 Result and Discussion

3.1 Impact of Catalytic Activity of Nano ZnO

The reaction was initially carried out in ethanol as the solvent, under continuous stirring for 48 h without the use of a catalyst. Under these conditions, the reaction resulted in only minimal product formation, suggesting that the reaction's efficiency was limited. This low yield indicated that the reaction conditions were not optimal for achieving the desired product. In an effort to improve both the reaction efficiency and the overall yield of the product, nano ZnO was introduced as a catalyst. Nano ZnO exhibited remarkable catalytic activity, particularly when used in ethanol, which facilitated a significant enhancement in the reaction performance. The use of nano ZnO not only improved the yield but also dramatically reduced the reaction time, showcasing its potential to accelerate the synthesis process. This catalytic approach proved to be highly effective, with the reaction proceeding at a much faster rate compared to the uncatalyzed process [32, 33].

The incorporation of nano ZnO as a catalyst offered multiple advantages. It led to a substantial increase in the product yield, allowing for a more efficient use of reactants.

Scheme 2 Mechanism of Synthesis of 1-(4-chlorobenzyl)-2-(4-chlorophenyl)-4-fluoro-1H-benzo[d]imidazole



Additionally, the reaction time was significantly shortened, reducing the overall energy input and making the process more time-efficient. Furthermore, the work-up procedure was simplified, minimizing the need for complex separation steps and making the process more straightforward and practical. The low catalyst loading required for this reaction further enhanced the economic viability of the process. This feature not only reduced the overall cost of the reaction but also contributed to making the process more environmentally sustainable. The catalyst could be used in small amounts, which reduces waste and minimizes the environmental impact, aligning with the principles of green chemistry.

Overall, this catalytic method presents a highly efficient and sustainable approach for the synthesis of benzimidazoles. The simplicity of the procedure, combined with the high yield and reduced reaction time, makes it a highly adaptable strategy for large-scale industrial applications. By utilizing nano ZnO, a readily available and cost-effective catalyst, the process becomes both economically viable and environmentally responsible. This method provides a greener alternative to traditional methods that often rely on harsh solvents, expensive reagents, or longer reaction times. Its potential for broader application in organic chemistry is significant, particularly in the development of more sustainable and scalable synthesis protocols. The approach aligns with modern trends in green chemistry, highlighting its potential for industrial and laboratory-scale synthesis while minimizing environmental harm. The reusability of the nano ZnO catalyst was examined by recovering it after the reaction, followed by washing with ethanol and drying at 60 °C. The recovered catalyst was reused under identical conditions for three successive cycles. The product yields remained above 85% in all runs, demonstrating the catalyst's

good stability and reusability in the benzimidazole synthesis. The effect of catalyst loading and temperature on the yield of CCHFB using ZnO nanoparticles is given in Table 1.

3.2 Absorption Characteristics of CCHFB with SiO₂ Nanoparticles

Figure 1 presents the absorption spectra of CCHFB and the CCHFB-functionalized SiO₂ nanoparticles, illustrating a marked increase in the absorbance of CCHFB upon the incorporation of SiO₂ nanoparticles. Notably, this enhancement in absorbance occurs without any observable shift in the absorption maximum, indicating that the introduction of SiO₂ nanoparticles does not disrupt the intrinsic electronic transitions of the benzimidazole moiety. This lack of shift suggests that the excitation properties of the CCHFB molecule are largely preserved in the presence of the nanoparticles, highlighting the compatibility between the CCHFB and SiO₂ components. This observation implies that the SiO₂ nanoparticles do not interfere with the fundamental electronic structure or the photophysical behavior of the benzimidazole core [34].

Table 1 Effect of catalyst loading and temperature on the yield of CCHFB using ZnO nanoparticles

Entry	Catalyst (ZnO)	Temperature	Time	Yield
1	None	80 °C	90 min	Trace
2	5 mol%	80 °C	45 min	62%
3	10 mol%	80 °C	30 min	92%
4	10 mol%	Room Temp	120 min	35%
5	10 mol%	100 °C	30 min	91%

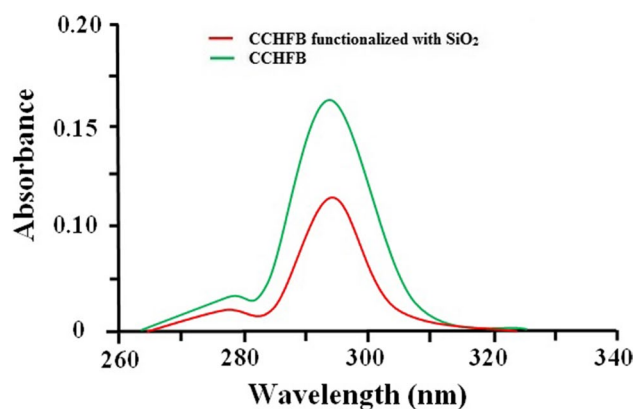


Fig. 1 Absorption spectra of CCHFB and CCHFB -functionalized SiO₂ nanoparticles

The observed increase in absorbance is likely due to the adsorption of CCHFB molecules onto the surface of the SiO₂ nanoparticles. This interaction can result in a localized concentration of the CCHFB molecules in the proximity of the nanoparticle surface, thereby enhancing the overall absorbance of light in the interaction region. The mechanism behind this enhancement may involve a combination of surface adsorption and possible charge transfer interactions between the SiO₂ surface and the functional groups of CCHFB, such as the hydroxy and halo groups attached to the benzimidazole ring. These groups may interact with the surface of the nanoparticles, leading to an increased effective concentration of the active CCHFB species near the surface, which can facilitate improved light absorption.

The role of SiO₂ nanoparticles in this context can be understood as that of a supportive matrix, providing a platform for the CCHFB molecules to aggregate and interact in a way that maximizes their light-harvesting properties. Furthermore, the SiO₂ nanoparticles likely prevent the deactivation of the benzimidazole moiety by stabilizing the molecule and promoting more efficient energy absorption without disrupting its electronic structure. This preservation of the electronic properties of the benzimidazole group, combined with the enhanced light absorption, makes the CCHFB-functionalized SiO₂ system a promising candidate for applications in fields such as photovoltaics, photonics, and other light-harvesting technologies. The synergistic interaction between the organic and inorganic components ensures that both the light absorption capability and the photophysical integrity of the active molecule are optimized, paving the way for advanced materials with enhanced performance.

3.3 Emission Characteristics of CCHFB with SiO₂ Nanoparticles

Figure 2 shows the fluorescence spectra of CCHFB both in the presence and absence of SiO₂ nanoparticles, highlighting a significant quenching of CCHFB fluorescence upon functionalization with SiO₂ nanoparticles. Interestingly, this fluorescence quenching occurs without any noticeable shift in the emission maximum, suggesting that the intrinsic emission properties of CCHFB remain unaltered. The observed quenching can be attributed to the adsorption of CCHFB molecules onto the surface of the SiO₂ nanoparticles, forming a CCHFB-SiO₂ complex that effectively suppresses fluorescence emission [35].

The mechanism behind this quenching can be understood through interfacial electron transfer processes. Given the relative energy levels of CCHFB and the conduction band (CB) of SiO₂ nanoparticles, electron transfer from the photoexcited singlet state of CCHFB to the CB of the SiO₂ nanoparticles is thermodynamically favorable. Upon excitation at the corresponding wavelength, both CCHFB and the SiO₂ nanoparticles are energized. This leads to electron transitions within the SiO₂ nanoparticles, from the conduction band (CB) to the valence band (VB), as well as electronic transitions in CCHFB, from the lowest unoccupied molecular orbital (LUMO) to the highest occupied molecular orbital (HOMO).

The most plausible explanation for the observed fluorescence quenching is the electron transfer from the excited CCHFB (specifically from its LUMO) to the conduction band of the SiO₂ nanoparticles. This transfer is favored because the electrons in the LUMO of CCHFB

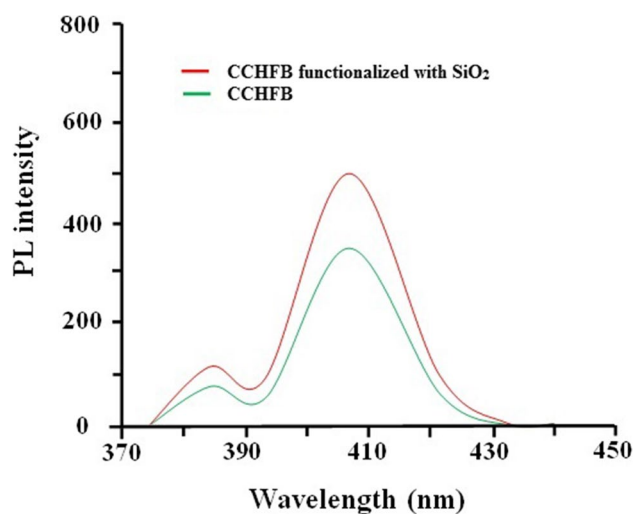


Fig. 2 Fluorescence spectra of CCHFB in the presence and absence of SiO₂ nanoparticles

are energetically higher than those in the CB of SiO₂, which facilitates a direct flow of electrons from the excited CCHFB to the nanoparticle surface. This electron transfer process effectively diminishes the fluorescence of CCHFB, as the excited-state energy is dissipated through the nanoparticle rather than re-emitted as light.

Additionally, the adsorption of CCHFB molecules onto the SiO₂ nanoparticle surface induces modifications to the electronic structure of CCHFB. The adsorption promotes π -electron delocalization within the CCHFB molecule, which reduces the energy levels of both its HOMO and LUMO. This modification lowers the excited-state energy of CCHFB, making it more energetically favorable for energy transfer to the SiO₂ nanoparticles. The excited-state energy of CCHFB exceeds the energy of the CB of SiO₂ nanoparticles, thus facilitating efficient energy transfer from the excited CCHFB to the nanoparticles.

This interaction underscores the role of SiO₂ nanoparticles as effective energy acceptors. The surface adsorption not only alters the electronic properties of CCHFB but also enables energy and electron transfer processes that lead to fluorescence quenching. These results highlight the potential of SiO₂ nanoparticles in modulating the photophysical properties of CCHFB, offering a mechanism where the nanoparticles serve both as electron sinks and energy acceptors, enhancing the overall functionality of the CCHFB-SiO₂ system in various applications [36].

The observed quenching of CCHFB fluorescence upon functionalization with SiO₂ nanoparticles suggests strong interaction between the benzimidazole fluorophore and the silica surface. This quenching may be attributed to photoinduced electron transfer (PET) or energy transfer processes from the excited CCHFB molecule to the electron-deficient silica matrix. The formation of Si–O–C bonds during grafting can alter the local electronic environment of the fluorophore, thereby reducing its emission intensity. Such quenching is a typical indication of successful covalent immobilization and potential for use in sensing or photophysical modulation applications.

3.4 FT-IR Spectral Studies of CCHFB -Silica Nanoparticles Interaction

The FTIR spectrum (Fig. 3) exhibits strong absorption bands that further confirm the successful formation of the benzimidazole framework. The N–H stretching vibration appears as a broad band at 3416 cm⁻¹, while the C=N stretching of the imidazole ring is observed at

1601 cm⁻¹, which is consistent with previously reported benzimidazole compounds. The presence of aromatic C–H stretching bands between 3050–3100 cm⁻¹, and the C–Cl stretch near

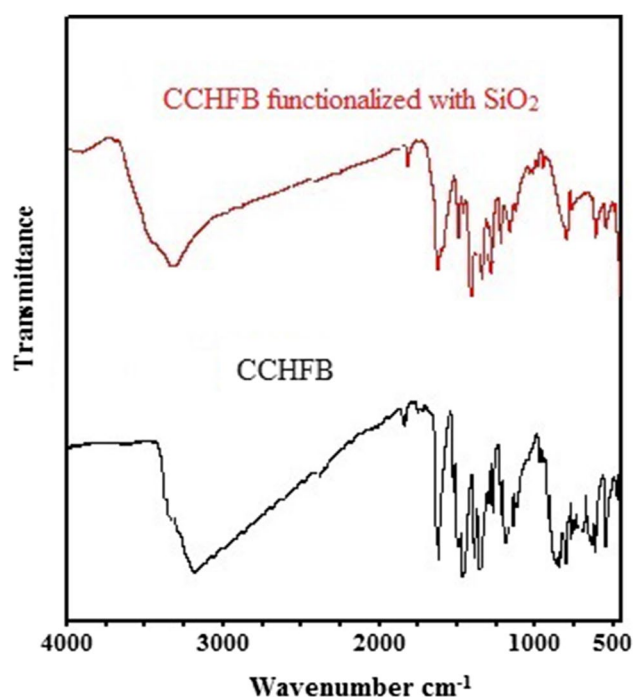


Fig. 3 FT-IR spectra of unmodified CCHFB and CCHFB -functionalized SiO₂ nanoparticles

770–790 cm⁻¹, also support the proposed substitution pattern. These observations validate the structure and purity of the synthesized compound.

The interaction between CCHFB and SiO₂ nanoparticles was further confirmed through Fourier Transform Infrared (FT-IR) spectroscopy, a sensitive technique widely used for identifying functional groups and probing chemical interactions. The FT-IR spectra of both unmodified CCHFB and CCHFB-functionalized SiO₂ nanoparticles are presented in Fig. 3. For CCHFB, a prominent band at 1619 cm⁻¹ is observed, which corresponds to the ν (C=N) stretching vibration, characteristic of the azomethine group. This signal confirms the presence of the azomethine linkage within the benzimidazole structure. Additionally, the aromatic structure of the fluorochrome is further evidenced by the distinct bands at 1527 cm⁻¹, 1492 cm⁻¹, and 1468 cm⁻¹, corresponding to the ν (C=C) aromatic stretching vibrations. These features collectively support the structural integrity of CCHFB in its unmodified state.

Upon functionalization with SiO₂ nanoparticles, a notable shift in the ν (C=N) stretching vibration is observed, moving from 1614 cm⁻¹ to 1625 cm⁻¹. This shift suggests that the azomethine nitrogen atom in CCHFB interacts with the surface of the SiO₂ nanoparticles. Such an interaction is likely due to the formation of coordinate bonds or hydrogen bonds between the electron-rich nitrogen atom and the surface-active sites of the SiO₂ nanoparticles, such as the silanol (Si–OH) groups. This interaction may

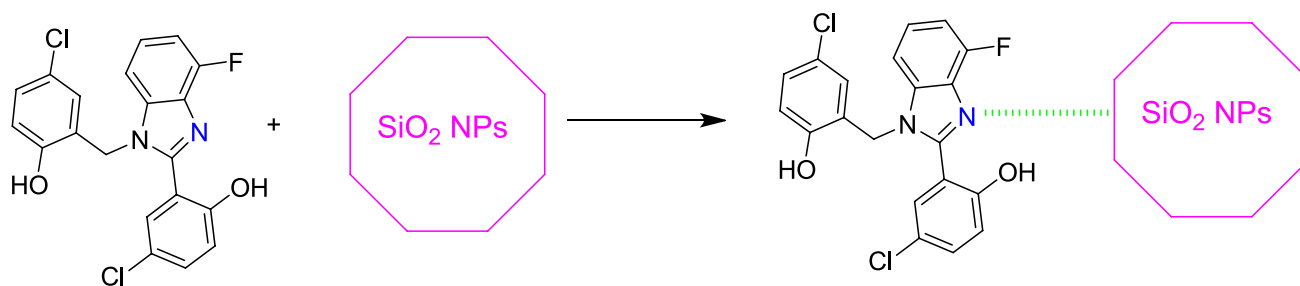
facilitate the attachment of CCHFB to the nanoparticle surface, leading to the observed shift in the $\nu(-C=N)$ band (Scheme 3).

Further evidence supporting this interaction can be observed in additional spectral regions. In the FT-IR spectrum of the CCHFB-functionalized SiO_2 nanoparticles, bands corresponding to Si–O–Si stretching vibrations, which typically appear around 1100 cm^{-1} , become more pronounced. This suggests that the functionalization process may also influence the nanoparticle's surface chemistry. Moreover, the bands associated with Si–OH stretching vibrations, typically found near 3400 cm^{-1} , and Si–OH bending vibrations, observed around 950 cm^{-1} , show subtle changes in intensity. These shifts in intensity further suggest modifications to the surface chemistry of the SiO_2 nanoparticles upon the binding of CCHFB.

Together, these spectral shifts and enhancements provide strong evidence for the successful conjugation of CCHFB to the SiO_2 nanoparticles and highlight the chemical interactions responsible for this binding. The interaction likely involves both coordination with surface

silanol groups and possible hydrogen bonding, which are essential for the functionalization of SiO_2 nanoparticles with CCHFB. This insight into the mechanism of functionalization underscores the importance of the nanoparticle surface chemistry in facilitating efficient molecular conjugation, and the FT-IR data collectively support the formation of a stable CCHFB- SiO_2 complex.

The surface morphology of the synthesized benzimidazole derivative (CCHFB) and its silica-functionalized form was investigated using Scanning Electron Microscopy (SEM). The SEM images of unmodified SiO_2 nanoparticles (a) and CCHFB-functionalized SiO_2 nanoparticles (b) is given in Fig. 4. As shown in Fig. 4, pure CCHFB exhibits a uniform, spherical morphology with particles well-dispersed and separated. Upon functionalization with SiO_2 nanoparticles, significant agglomeration was observed, indicating the successful conjugation of CCHFB onto the silica surface. The aggregation is likely due to intermolecular interactions between the benzimidazole moiety and the hydroxyl groups on the silica surface, confirming effective surface modification.



Scheme 3 The Interaction SiO_2 nanoparticles with azomethine nitrogen moiety of CCHFB

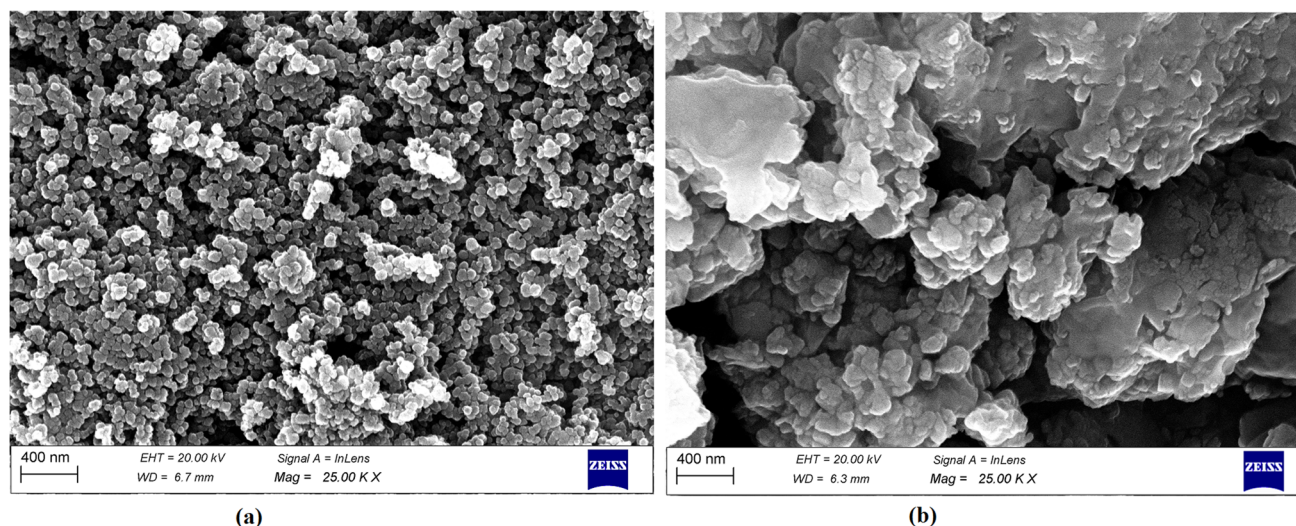


Fig. 4 SEM image of **a** unmodified SiO_2 nanoparticles and **b** CCHFB-functionalized SiO_2 nanoparticles

3.5 Biological Studies

3.5.1 *In Vitro* Antioxidant Activity (DPPH Scavenging Assay)

The antioxidant activity of CCHFB and its functionalized form with SiO₂ nanoparticles was evaluated using the DPPH free radical scavenging assay, with Vitamin C serving as a standard reference for comparison. The test was conducted across a range of concentrations, from 10 µM to 500 µM. The results, shown in Table 2, reveal that the SiO₂-functionalized CCHFB exhibited antioxidant activity comparable to that of Vitamin C across all tested concentrations. Notably, the SiO₂ group played a crucial role in enhancing the scavenging of DPPH radicals, effectively reducing their concentration. The hydroxyl and halo groups present in the CCHFB structure may further contribute to stabilizing the formed radical species, enhancing the overall antioxidant activity. These findings suggest that the functionalization of CCHFB with SiO₂ not only maintains but possibly amplifies the compound's intrinsic antioxidant properties, highlighting its potential as an effective antioxidant agent.

The IC₅₀ values were estimated from the % inhibition data to provide a more quantitative comparison with standard drugs. In the DPPH antioxidant assay, both CCHFB and its SiO₂-functionalized form showed inhibition below 50% even at the highest tested concentration (500 µg/mL), indicating IC₅₀ values > 500 µg/mL, while the standard antioxidant (vitamin C) showed a significantly lower IC₅₀ of approximately 66 µg/mL. In the α-amylase inhibition assay, CCHFB reached 50% inhibition at a concentration of approximately 324 µg/mL, indicating moderate antidiabetic activity. However, the functionalized CCHFB–SiO₂ again showed inhibition below 50% at all concentrations tested, suggesting IC₅₀ > 500 µg/mL. The standard reference drug, acarbose, exhibited an IC₅₀ of around 140 µg/mL, confirming its superior inhibitory effect. These results confirm that while CCHFB shows moderate antidiabetic potential, further optimization is required to improve its antioxidant and enzyme inhibitory efficacy to match standard therapeutics.

Table 2 Antioxidant properties of DPPH scavenging assay (STD: Vitamin—C)

S.No	Concentration (µg/mL)	CCHFB Inhibition %	CCHFB functionalized with SiO ₂ Inhibition %	STD
1	10	15.21	6.12	25.25
2	50	20.22	12.48	42.44
3	100	28.56	17.66	65.9
4	250	18.12	19.28	82.97
5	500	45.24	25.76	95.72

3.5.2 Antidiabetic Activity

The antidiabetic activity of both CCHFB and its functionalized form with SiO₂ nanoparticles was assessed through an α-amylase inhibition assay, using acarbose as the standard reference. Acarbose is widely known for its effectiveness in controlling blood glucose levels by inhibiting the α-amylase enzyme. The assay was conducted across a range of concentrations (10, 25, 50, 100, and 500 µM) for both the samples and acarbose, evaluating their ability to inhibit α-amylase activity under physiological conditions. The results revealed that functionalized CCHFB with SiO₂ exhibited a significant inhibitory effect, with its inhibition percentage closely matching that of the standard drug, acarbose. The specific inhibition percentages for each concentration are shown in Table 3, where the values were calculated based on the differences between control and test samples. These findings suggest that the functionalization of CCHFB with SiO₂ enhances its antidiabetic activity, with effective inhibition of α-amylase, making it a promising candidate for potential therapeutic applications in diabetes management.

3.5.3 Stability Study

Poor stability is a significant limitation that can negatively impact the bioavailability and efficacy of compounds. To evaluate the stability of CCHFB functionalized with SiO₂ nanoparticles, a stability study was conducted following the methodology described in previous literature [37]. The absorption changes of the functionalized CCHFB with SiO₂ were measured using a Tris–HCl buffer solution at pH 7.4, kept at a constant temperature of 37 °C. The degradation of the functionalized CCHFB with SiO₂ was monitored at various time intervals, including 0 h, 4 h, 6 h, 8 h, 16 h, and 24 h, using a UV–Vis spectrometer. The results revealed that only 7.88% of the functionalized CCHFB with SiO₂ had degraded over the 24-h observation period, indicating that 92.12% of the compound remained stable. These findings suggest that the functionalized CCHFB with SiO₂ exhibits excellent stability, an essential characteristic for its potential use in various applications. The stability data for

Table 3 Antidiabetic properties of DPPH scavenging assay (STD: Vitamin—C)

S.No	Concentration (µg/mL)	CCHFB Inhibition %	CCHFB functionalized with SiO ₂ Inhibition %	STD
1	10	14.36	11.23	17.22
2	50	19.60	14.49	23.84
3	100	30.44	21.40	45.51
4	250	43.51	30.51	62.19
5	500	65.48	45.62	89.71

the functionalized CCHFB with SiO₂ over the 24-h period confirming its resilience under the tested conditions.

3.5.4 Antibacterial Activity

The *in vitro* antibacterial inhibition efficiency of CCHFB functionalized with SiO₂ was evaluated against a range of bacterial strains, including two Gram-positive bacteria, *Enterococcus faecalis* and *Staphylococcus aureus*, and two Gram-negative bacteria, *Escherichia coli* and *Pseudomonas aeruginosa*. The antibacterial activity was assessed using the well-established disc diffusion method, as described in previous studies [38]. The results, summarized in Table 4, demonstrate the effectiveness of the functionalized CCHFB with SiO₂ in inhibiting bacterial growth across all tested strains, providing insights into its potential as a broad-spectrum antimicrobial agent.

3.5.5 Antibacterial Activity Result

The antibacterial inhibition efficiencies of CCHFB functionalized with SiO₂ and unmodified CCHFB were evaluated against two Gram-positive bacteria, *Enterococcus faecalis* and *Staphylococcus aureus*, as well as two Gram-negative bacteria, *Escherichia coli* and *Pseudomonas aeruginosa*, using the disc diffusion method [38]. Dimethyl sulfoxide (DMSO) was used as a solvent control in all experimental plates, and it showed no zone of inhibition, confirming that the solvent did not influence the antimicrobial activity of the tested compounds. As shown in Table 4, the results indicate that the functionalized CCHFB with SiO₂ exhibited significantly higher antibacterial inhibition compared to the unmodified CCHFB. This enhanced activity can be attributed to several factors, including the potential for chelate formation between the functionalized CCHFB and metal ions on the SiO₂ surface. The chelation effect likely enhances the delocalization of π -electrons across the chelate ring, which increases the lipophilicity of the compound and its complexes. This enhanced lipophilicity improves the ability of the CCHFB-SiO₂ complex to cross lipid membranes, thus facilitating the uptake of the antimicrobial agent into the bacterial cells. Notably, the functionalized CCHFB with SiO₂ demonstrated a particularly strong inhibitory effect

against the Gram-negative bacterium *Pseudomonas aeruginosa*, suggesting that the nanoparticles facilitate stronger interaction with the bacterial cell membrane. The synergistic effect between the functionalized CCHFB with SiO₂ and its counter ions results in a greater antimicrobial efficiency compared to the free CCHFB, demonstrating the potential of this functionalized compound as a more effective antimicrobial agent.

The enhanced antibacterial effect observed for the CCHFB-SiO₂ hybrid system is likely attributed to multiple factors. Although direct mechanistic studies were not performed, the improvement in activity can be reasonably ascribed to increased bacterial membrane permeability due to improved surface contact, and possible generation of reactive oxygen species (ROS) induced by the silica surface. These factors may lead to membrane disruption, oxidative stress, and subsequent cell death. Similar mechanisms have been reported in literature for silica-based nanocomposites with surface-functionalized organic moieties. These insights suggest that surface modification not only enhances drug delivery potential but also augments antimicrobial efficacy. The antibacterial performance and fluorescence behavior of CCHFB-SiO₂ are in agreement with other reported benzimidazole-based nanocomposites, which often demonstrate enhanced activity due to increased surface interaction, ROS generation, or improved delivery. Compared to similar hybrid systems, the observed fluorescence quenching and moderate antimicrobial effect of CCHFB-SiO₂ suggest that the conjugation strategy used here is effective, though further optimization may improve its comparative efficacy. Future studies are planned to investigate ROS generation and membrane integrity in more detail.

3.6 Structure–Activity Relationship (SAR) Analysis

The biological activity of the synthesized benzimidazole derivative CCHFB appears to be strongly influenced by its structural features. The benzimidazole nucleus is known for its versatile pharmacological behavior, which is enhanced by strategic substitution. In the present study, the presence of a fluoro group at the 4-position of the phenyl ring contributes to improved lipophilicity and potential interactions with biological targets via hydrogen bonding or halogen bonding.

Table 4 Antibacterial activities of CCHFB and CCHFB functionalized with SiO₂

Sample	Zone of Inhibition (mm)/Concentration in μg											
	E.faecalis			S. aureus			E. coli			P. aeruginosa		
	500	1000	2000	500	1000	2000	500	1000	2000	500	1000	2000
F-CCHFB	-	8	9	-	7	9	-	8	10	-	7	10
CCHFB	-	12	14	-	9	12	-	12	14	-	9	12
STD	24			23			24			24		

The benzyl substitution at the N-1 position increases hydrophobic character and membrane permeability, which may enhance antibacterial and α -amylase inhibition. Furthermore, the covalent linkage to silica nanoparticles possibly improves dispersion and bioavailability, while also allowing a multivalent interaction with biomolecules, contributing to the enhanced antioxidant and antibacterial activities observed. Overall, the SAR suggests that both electron-withdrawing fluorine and hydrophobic benzyl groups play a key role in modulating bioactivity, and further substitutions or modifications at these positions may help tailor the activity profile for specific therapeutic purposes.

4 Conclusion

In this study, a novel benzimidazole derivative (CCHFB) was synthesized via a one-pot condensation and cyclization route using 4-chlorobenzaldehyde, 4-chloroaniline, and o-phenylenediamine. The structure was confirmed by FTIR, ^1H NMR, ^{13}C NMR, and elemental analysis. FTIR spectra revealed characteristic N–H and C=N stretches at 3416 cm^{-1} and 1601 cm^{-1} , respectively. ^1H NMR showed a deshielded NH proton at δ 12.10 ppm, while the aromatic region (δ 7.0–8.0 ppm) supported the proposed substitution pattern. Functionalization of CCHFB onto SiO_2 nanoparticles was confirmed through FTIR spectral shifts, SEM morphological changes (from spherical to agglomerated structures), and pronounced fluorescence quenching observed in photophysical studies—suggesting effective conjugation and an electron transfer mechanism. The antibacterial activity was enhanced post-functionalization, likely due to increased membrane interaction and possible ROS generation. However, antioxidant and α -amylase inhibitory studies revealed limited potency, with IC_{50} values $> 500\text{ }\mu\text{g/mL}$ in most cases, except for moderate antidiabetic activity by CCHFB ($\text{IC}_{50} \approx 324\text{ }\mu\text{g/mL}$). Overall, the combined synthetic, spectral, morphological, and biological evaluations confirm the formation and stability of the CCHFB– SiO_2 hybrid system. While the material demonstrates promising potential for fluorescence sensing and antibacterial applications, further structural optimization is warranted to enhance its bioactivity and therapeutic relevance.

Author Contributions Xiaojian Liu—Interpretation of data Yanqi Zhou -Data curation Kanagaraj Rajalakshmi—Data curation, Revised version preparation K. Jayamoorthy -Prepared Figures, Revised version preparation B. Subash—Medicinal properties analysis Selvaraj Muthusamy -wrote the main manuscript text Dongwei Zhu—Methodology Yanping Zhao—Conceptualization, Supervision.

Funding 1. Project of Jiangsu Provincial Administration of Traditional Chinese Medicine (MS2023144) (Xiaojian Liu).

2. Project of Zhenjiang Science and Technology Bureau (SH2023066) (Xiaojian Liu).

3. National Natural Science Foundation of China [Grant Number 82202001] (Dongwei Zhu).

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Trayford C, van Rijt S (2024) In situ modified mesoporous silica nanoparticles: synthesis, properties and theranostic applications. *Biomater Sci* 12:5450. <https://doi.org/10.1039/d4bm00094c>
2. Padiyar N, Nainwal N, Ale Y, Galwan D (2024) Formulation, characterization and stability aspects of mesoporous silica nanoparticles. *Int J Drug Deliv Technol* 14:1217–1224. <https://doi.org/10.25258/ijddt.14.2.88>
3. Rahman IA, Padavettan V (2012) Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites—a review. *J Nanomater* 2012:1–15. <https://doi.org/10.1155/2012/132424>
4. Anilkumar B, Sunil S, Hariharan P, Yamuna R, Pandurangan N (2025) Silica-based (SBA-15) sustainable materials and their recent advances in biomedical applications. *Inorg Chim Acta* 585:122766. <https://doi.org/10.1016/j.ica.2025.122766>
5. Raja SP, Jayamoorthy K, Dhanalekshmi KI, Suresh S (2022) Mn_2O_3 nanoparticles bearing 5-amino-2-mercaptobenzimidazole moiety as antibacterial and antifungal agents. *J Biomol Struct Dyn* 40(15):7084–7090
6. Saravanan P, Jayamoorthy K, Kumar SA (2015) Switch-on fluorescence and photo-induced electron transfer of 3-aminopropyltriethoxysilane to ZnO: dual applications in sensors and antibacterial activity. *Sens Actuator B-Chem* 221:784–791
7. Parameswari M, Jayamoorthy K (2025) Imidazole derivatives synthesis: Exploring different methods. *Phosphorus Sulfur Silicon Relat Elem* 200(5):413–430
8. Srivastava SK, Arora N, Awasthi S, Kumar V (2020) Benzimidazole scaffold as antitumor agent: synthesis, biological evaluation and molecular docking studies. *Chem Biol Drug Des* 95(3):206–219. <https://doi.org/10.1111/cbdd.13552>
9. Rajasekar TS, Srinivasan N, Jayamoorthy K (2024) Nano silica catalyzed synthesis, NMR spectral and photophysical studies of imidazole derivatives. *SILICON* 16(18):6555–6565
10. Lobo V, Patil A, Phatak A, Chandra N (2010) Free radicals, antioxidants and functional foods: impact on human health. *Pharmacogn Rev* 4(8):118–126. <https://doi.org/10.4103/0973-7847.70902>
11. Nair PP, Krishnakumar V, Nair PG (2024) Chronic inflammation: Cross-linking insights from Ayurvedic sciences, a silver lining to systems biology and personalized medicine. *J Ayurveda Integr Med* 15(4):101016. <https://doi.org/10.1016/j.jaim.2024.101016>
12. Kazeem MI, Akanji MA, Hafizur Rahman AT, Yakubu AA (2013) Inhibitory effect of polyphenols from *Anacardium occidentale* leaves on key enzymes linked to type 2 diabetes. *Evid Based Complement Alternat Med* 2013:1–6. <https://doi.org/10.1155/2013/549345>
13. Kim YM, Jeong MH, Wang SH, Lee YS, Moon SW, Min C (2005) Inhibitory effect of allicin and alliin from garlic on α -amylase activity and postprandial blood glucose. *J Agric Food Chem* 53(5):1632–1636. <https://doi.org/10.1021/jf049148j>

14. Rossafi B, Bouribab A, Abchir O, Khedraoui M, El Kouali M, Chtita S (2025) Antidiabetic potential of Moroccan medicinal plant extracts: a virtual screening using in silico approaches. *Results Chem* 16:102365. <https://doi.org/10.1016/j.rechem.2025.102365>
15. Abavisani M, Sajjadi SM, Ebadpour N, Kesharwani P, Karav S, Sahebkar A (2025) RNA-based antibacterial agents: mechanisms, functional insights, and challenges in therapeutic development. *Chem Eng J*. <https://doi.org/10.1016/j.cej.2025.165777>
16. Ventola CL (2015) The antibiotic resistance crisis: part 1: causes and threats. *Pharm Ther* 40(4):277–283
17. Tantry SJ, Thakur TK, Samanta K, Kumar P, Ray S (2017) Synthesis and antimicrobial activity of benzimidazole derivatives. *Med Chem Res* 26:1123–1135. <https://doi.org/10.1007/s00044-017-1855-9>
18. Sharma A, Arora P, Chawla V, Saini M, Singh R, Kumar M (2019) Design, synthesis and biological evaluation of novel benzimidazole derivatives as antimicrobial agents. *Eur J Med Chem* 163:206–218. <https://doi.org/10.1016/j.ejmech.2018.11.010>
19. Barui A, Veeriah M, Mukherjee P, Naskar M, Das A (2016) Functionalized mesoporous silica nanoparticles for drug delivery in cancer therapy. *ACS Biomater Sci Eng* 2(2):248–259. <https://doi.org/10.1021/acsbiomaterials.5b00303>
20. Mamaeva V, Sahlgren C, Lindén M (2013) Mesoporous silica nanoparticles in medicine—recent advances. *Adv Drug Deliv Rev* 65(5):689–702. <https://doi.org/10.1016/j.addr.2012.07.018>
21. Tang F, Li L, Chen D (2012) Mesoporous silica nanoparticles: synthesis, biocompatibility and drug delivery. *Adv Mater* 24(12):1504–1534. <https://doi.org/10.1002/adma.201104763>
22. Rosenholm JM, Sahlgren C, Lindén M (2010) Multifunctional mesoporous silica nanoparticles for combined therapeutic, diagnostic and targeted action in cancer treatment. *Nanoscale* 2(10):1870–1883. <https://doi.org/10.1039/c0nr00242e>
23. Hudson SP, Padera RF, Langer MJ, Kohane DS (2008) The biocompatibility of mesoporous silicates. *Drug Dev Ind Pharm* 34(9):977–992. <https://doi.org/10.1080/03639040701879456>
24. Dhanalekshmi KI, Magesan P, Sangeetha K, Zhang X, Jayamoorthy K, Srinivasan N (2019) Preparation and characterization of core-shell type Ag@SiO₂ nanoparticles for photodynamic cancer therapy. *Photodiagn Photodyn Ther* 28:324–329. <https://doi.org/10.1016/j.pdpdt.2019.10.006>
25. Meena KS, Dhanalekshmi KI, Jayamoorthy K (2016) Study of photodynamic activity of Au@SiO₂ core-shell nanoparticles in vitro. *Mater Sci Eng, C* 63:317–322. <https://doi.org/10.1016/j.msec.2016.03.010>
26. Jayabharathi J, Thanikachalam V, Jayamoorthy K (2012) Antioxidant benzimidazole bind bovine serum albumin. *J Photochem Photobiol, B* 115:85–92. <https://doi.org/10.1016/j.jphotobiol.2012.06.014>
27. Adejoh O, Ukoha PO, Hosten EC, Nnaji N, Eze CO, Anarado CJO, Iwegbue CMA, Jayamoorthy K, Ujam OT (2024) Synthesis, structure, preliminary antimicrobial and antimalarial studies of 1,1'-(piperazine-1,4-diyl)bis(2-phenylethan-1-one) and its lanthanide, Ce(III), Pr(III), and Nd(III) complexes. *J Mol Struct* 1300:137287. <https://doi.org/10.1016/j.molstruc.2023.137287>
28. Yousefi A, Yousefi R, Panahi F, Sarikhani S, Zolghadr AR, Bahaoddini A, Nezhad A (2015) Novel curcumin-based pyrano [2,3-d] pyrimidine anti-oxidant inhibitors α -amylase and α -glucosidase: Implications for their pleiotropic effects against diabetic complications. *Int J Biol Macromol* 78:46–55. <https://doi.org/10.1016/j.ijbiomac.2015.04.035>
29. Banupriya G, Shakambari G, Sribalan R, Varalakshmi P, Padmini V (2018) Evaluation of anticancer activity of water-soluble curcumin through the induction of apoptosis by p53 and p21 modulation. *Chemistry Select* 3:2976–2981. <https://doi.org/10.1002/slct.201800476>
30. Cukurovali A, Yilmaz I, Ozmen H, Ahmedzade MC (2007) Cobalt(II), copper(II), nickel(II) and zinc(II) complexes of two novel Schiff base ligands and their antimicrobial activity. *Transition Metal Chem* 27:171–176. <https://doi.org/10.1007/s11243-007-0104-3>
31. Kulkarni AK, Avaji PG, Bagihalli GB, Patil SA, Badami PS (2009) *J Coord Chem* 62:481. <https://doi.org/10.1080/00958970902834955>
32. Wang X, Liu Z, Zhang L (2020) ZnO nanoparticles as efficient catalysts in organic transformations: Synthesis, characterization, and applications. *Catal Today* 356:127–142. <https://doi.org/10.1016/j.cattod.2019.04.031>
33. Li Z, Wang Y, Zhang M (2022) ZnO nanostructures for organic reactions: Synthesis, catalytic activity, and applications in green chemistry. *Green Chem* 24:1912–1928. <https://doi.org/10.1039/D2GC01583A>
34. Saravanan P, Jayamoorthy K, Kumar SA (2016) Fluorescence quenching of APTES by Fe₂O₃ nanoparticles—Sensor and antibacterial applications. *J Luminesc* 178:241–248. <https://doi.org/10.1016/j.jlumin.2016.06.022>
35. Jayabharathi J, Thanikachalam V, Kalaiarasi V, Jayamoorthy K (2014) Enhancing photoluminescent behavior of 2-(naphthalen-1-yl)-1,4,5-triphenyl-1H-imidazole by ZnO and Bi₂O₃. *Spectrochim Acta Part A* 118:182–186. <https://doi.org/10.1016/j.saa.2013.08.021>
36. Jayabharathi J, Thanikachalam V, Kalaiarasi V, Jayamoorthy K (2014) Characterization and electronic spectral studies of 2-(naphthalen-1-yl)-4,5-diphenyl-1H-imidazole bound Fe₂O₃ nanoparticles. *Spectrochim Acta Part A* 120:84–87. <https://doi.org/10.1016/j.saa.2013.12.007>
37. Yan Y, Kulsoom K, Sun Y, Li Y, Wang Z, Xue L, Wang F (2025) Advancing cancer therapy: Nanomaterial-based encapsulation strategies for enhanced delivery and efficacy of curcumin. *Materials Today Bio* 33:101963. <https://doi.org/10.1016/j.mtbio.2025.101963>
38. Fang Y, Xing C, Zhan S, Zhao M, Li M, Liu H, Wang C (2019) Multifunctional Magnetic-Fluorescent Nanoparticle: Fabrication, Bioimaging, and Potential Antibacterial Applications. *ACS Biomater Sci Eng* 5:6779–6793. <https://doi.org/10.1021/acsbiomaterials.9b00750>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

委托人单位	镇江市第一人民医院
委 托 人	刘晓健
检 索 要 求	SCIE 论文收录及期刊分区
检 索 时 段	2025-2025
检 索 结 果	
数 据 库	论文收录(篇)
SCIE, JCR, 中国科学院 文献情报中心期刊分区 表(升级版)	SCIE 收录论文 1 篇。
<p>SCIE 论文题录:</p> <p>1. 标题: Functionalization of Halo-Hydroxy Benzimidazole onto SiO₂ Nanoparticles: Catalytic, Photophysical, and Biological Investigations for Sustainable Applications</p> <p>作者: Liu, XJ (Liu, Xiaojian); Zhou, YQ (Zhou, Yanqi); Rajalakshmi, K (Rajalakshmi, Kanagaraj); Jayamoorthy, K (Jayamoorthy, K.); Subash, B (Subash, B.); Muthusamy, S (Muthusamy, Selvaraj); Zhu, DW (Zhu, Dongwei); Zhao, YP (Zhao, Yanping)</p> <p>来源出版物: SILICON 卷: 17 期: 17 页: 4059-4070 DOI: 10.1007/s12633-025-03449-7 Early Access Date: OCT 2025 Published Date: 2025 NOV</p> <p>Web of Science 核心合集中的 "被引频次": 0</p> <p>被引频次合计: 0</p> <p>入藏号: WOS:001606380800001</p> <p>文献类型: Article</p> <p>地址: [Liu, Xiaojian; Zhou, Yanqi] Jiangsu Univ, Dept Gynecol, Affiliated Peoples Hosp, Zhenjiang 212006, Jiangsu, Peoples R China.</p> <p>[Rajalakshmi, Kanagaraj; Muthusamy, Selvaraj; Zhu, Dongwei] Jiangsu Univ, Sch Med, Dept Immunol, Jiangsu Key Lab Lab Med, Sch Chem & Chem Engn, Zhenjiang, Peoples R China.</p> <p>[Jayamoorthy, K.; Subash, B.] St Josephs Coll Engn, Dept Chem, Chennai 600119, Tamilnadu, India.</p> <p>[Zhao, Yanping] Shanghai Jiao Tong Univ, Suzhou Kowloon Hosp, Dept Hlth Management Ctr, Sch Med, Suzhou 215028, Peoples R China.</p> <p>通讯作者地址: Muthusamy, S; Zhu, DW (通讯作者), Jiangsu Univ, Sch Med, Dept Immunol, Jiangsu Key Lab Lab Med, Sch Chem & Chem Engn, Zhenjiang, Peoples R China.</p> <p>Jayamoorthy, K (通讯作者), St Josephs Coll Engn, Dept Chem, Chennai 600119, Tamilnadu, India.</p> <p>Zhao, YP (通讯作者), Shanghai Jiao Tong Univ, Suzhou Kowloon Hosp, Dept Hlth Management Ctr, Sch Med, Suzhou 215028, Peoples R China.</p> <p>电子邮件地址: kjmche@gmail.com; rajselva311@ujs.edu.cn; 1000005601@ujs.edu.cn</p> <p>ISSN: 1876-990X</p> <p>eISSN: 1876-9918</p>	

SILICON

出版商名称: SPRINGER

期刊影响因子™

3.3

2024

3.1

五年

JCR 学科类别	类别排序	类别分区
CHEMISTRY, PHYSICAL 其中 SCIE 版本	91/185	Q2
MATERIALS SCIENCE, MULTIDISCIPLINARY 其中 SCIE 版本	227/461	Q2

来源: Journal Citation Reports 2024. 转到 Journal Citation Reports

期刊分区表升级版 首页 检索 反馈 退出

Silicon

刊名	Silicon		
年份	2025		
ISSN / EISSN	1876-990X / 1876-9918		
Review	否		
OA Journal Index (OAJ)	否		
Open Access	否		
Web of Science	SCIE		
学科		分区	Top期刊
大类	材料科学	3	否
小类	MATERIALS SCIENCE, MULTIDISCIPLINARY 材料科学: 综合	4	-

备注:结果见附件.

委托人(签字)

检索人(签字): 刘晓男

审核人(签字):

江苏大学图书馆

(情报检索业务专用章)

2026 年 01 月 14 日

第 1 条, 共 1 条

标题: Functionalization of Halo-Hydroxy Benzimidazole onto SiO₂ Nanoparticles: Catalytic, Photophysical, and Biological Investigations for Sustainable Applications

作者: Liu, XJ (Liu, Xiaojian); Zhou, YQ (Zhou, Yanqi); Rajalakshmi, K (Rajalakshmi, Kanagaraj); Jayamoorthy, K (Jayamoorthy, K.); Subash, B (Subash, B.); Muthusamy, S (Muthusamy, Selvaraj); Zhu, DW (Zhu, Dongwei); Zhao, YP (Zhao, Yanping)

来源出版物: SILICON 卷: 17 期: 17 页: 4059-4070 DOI: 10.1007/s12633-025-03449-7 **Early Access Date:** OCT 2025 **Published Date:** 2025 NOV

Web of Science 核心合集中的 "被引频次": 0

被引频次合计: 0

使用次数 (最近 180 天): 5

使用次数 (2013 年至今): 5

引用的参考文献数: 38

入藏号: WOS:001606380800001

语言: English

文献类型: Article

作者关键词: Halo benzimidazole;; SiO₂ nanoparticles; Antioxidant activity; alpha-Amylase inhibition; Antibacterial properties

KeyWords Plus: FLUORESCENCE; COMPLEXES; CURCUMIN; ZNO

地址: [Liu, Xiaojian; Zhou, Yanqi] Jiangsu Univ, Dept Gynecol, Affiliated Peoples Hosp, Zhenjiang 212006, Jiangsu, Peoples R China.

[Rajalakshmi, Kanagaraj; Muthusamy, Selvaraj; Zhu, Dongwei] Jiangsu Univ Sch Med, Dept Immunol, Jiangsu Key Lab Lab Med, Sch Chem & Chem Engn, Zhenjiang, Peoples R China

[Jayamoorthy, K.; Subash, B.] St Josephs Coll Engn, Dept Chem, Chennai 600119, Tamilnadu, India.

[Zhao, Yanping] Shanghai Jiao Tong Univ, Suzhou Kowloon Hosp, Dept Hlth Management Ctr, Sch Med, Suzhou 215028, Peoples R China.

通讯作者地址: Muthusamy, S; Zhu, DW (通讯作者), Jiangsu Univ, Sch Med, Dept Immunol, Jiangsu Key Lab Lab Med, Sch Chem & Chem Engn, Zhenjiang, Peoples R China.

Jayamoorthy, K (通讯作者), St Josephs Coll Engn, Dept Chem, Chennai 600119, Tamilnadu, India.

Zhao, YP (通讯作者), Shanghai Jiao Tong Univ, Suzhou Kowloon Hosp, Dept Hlth Management Ctr, Sch Med, Suzhou 215028, Peoples R China.

电子邮件地址: kjmche@gmail.com; rajselsva311@ujs.edu.cn; 1000005601@ujs.edu.cn

Affiliations: Jiangsu University; Jiangsu University; St. Joseph's College of Engineering, Chennai; Shanghai Jiao Tong University

作者识别号:

作者	Web of Science ResearcherID	ORCID 号
Subash, B.	AAH-7295-2020	
Muthusamy, Selvaraj	CAG-1108-2022	

出版商: SPRINGER

出版商地址: VAN GODEWIJCKSTRAAT 30, 3311 GZ DORDRECHT, NETHERLANDS

Web of Science Index: Science Citation Index Expanded (SCI-EXPANDED)

Web of Science 类别: Chemistry, Physical; Materials Science, Multidisciplinary

研究方向: Chemistry; Materials Science

IDS 号: AV8PC

ISSN: 1876-990X

eISSN: 1876-9918

29 字符的来源出版物名称缩写: SILICON-NETH

ISO 来源出版物缩写: Silicon

来源出版物页码计数: 12

基金资助致谢:

基金资助机构	授权号
Project of Jiangsu Provincial Administration of Traditional Chinese Medicine	MS2023144
Project of Zhenjiang Science and Technology Bureau	SH2023066
National Natural Science Foundation of China	82202001

1. Project of Jiangsu Provincial Administration of Traditional Chinese Medicine (MS2023144) (Xiaojian Liu).2. Project of Zhenjiang Science and Technology Bureau (SH2023066) (Xiaojian Liu) 3. National Natural Science Foundation of China [Grant Number 82202001] (Dongwei Zhu)

输出日期: 2026-01-14

End of File