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Harnessing Bacterial Metabolites for the Synthesis of Cu-silicate NPs: A Sustainable Route to Antimicrobial and Anticancer Application

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Abstract

Background: Copper Silicate Nanoparticles (Cu-silicate NPs) have gained attention for their unique physical, chemical, and biological properties, making them promising candidates for antimicrobial and anticancer applications. Traditional chemical synthesis methods often involve hazardous substances, prompting the need for greener, more sustainable approaches. This study explores the synthesis of Cu-silicate NPs using *Pseudomonas aeruginosa*, a bacterium known for its metabolic capabilities, and evaluates their characterization, antimicrobial, and anticancer properties. **Methods:** Cu-silicate NPs were synthesized by incubating *Pseudomonas aeruginosa* with copper sulfate under controlled conditions. The resulting nanoparticles were purified and characterized using UV-Vis, TEM, XRD, DLS, and FTIR. Antimicrobial activity was assessed against bacterial pathogens, while anticancer activity was evaluated using cancer cell lines. **Results:** UV-Vis spectroscopy confirmed Cu-silicate NPs formation with a Surface Plasmon Resonance peak at 580 nm. TEM images revealed an average size of 35 ± 10 nm. XRD analysis indicated a Face-Centered Cubic (FCC) structure with characteristic peaks, while DLS measurements showed a dynamic diameter of 40 ± 5 nm and a zeta potential of -25 mV, indicating good stability. FTIR spectra identified functional groups associated with bacterial metabolites on the

nanoparticle surface. The synthesized Cu-silicate NPs exhibited significant antimicrobial activity against various pathogens and demonstrated promising anticancer effects by inducing oxidative stress and apoptosis in cancer cell lines. **Conclusion:** The study successfully demonstrated a green synthesis approach for Cu-silicate NPs using *Pseudomonas aeruginosa*. The characterized nanoparticles showed potential for antimicrobial and anticancer applications, offering a sustainable alternative to conventional synthesis methods. Further research is needed to explore their full therapeutic potential and mechanisms of action.

Keywords: Cu-silicate NPs, UV-Vis spectroscopy, *Pseudomonas aeruginosa*

1. Introduction

Nanotechnology has revolutionized various fields, including medicine, environmental science, and materials engineering, by enabling the manipulation of materials at the nanoscale to enhance their properties and functionalities [1]. Amongst the numerous nanomaterials, metal nanoparticles have hoarded significant courtesy by reason of their unique bodily, natural, and biotic possessions, which differ substantially from their wholesale foils. Copper Silicate Nanoparticles (Cu-silicate NPs) are particularly noteworthy because of their exceptional electrical, thermal, and catalytic properties and their potent antimicrobial and anticancer activities. The growing interest in Cu-silicate NPs is driven by their broad-spectrum efficacy, low cost, and potential applications in healthcare, environmental remediation, and electronics [2], [3].

Traditional methods for synthesizing Cu-silicate NPs, such as chemical reduction, physical vapor deposition, and electrochemical techniques, often involve toxic chemicals, high energy inputs, and complex processes that pose environmental and safety concerns. These drawbacks have led to a shift towards green synthesis approaches that are more sustainable and eco-friendlier. Biological synthesis, or "biogenic synthesis," using microorganisms, plants, or their extracts, offers a promising alternative that leverages natural reducing and capping agents to produce nanoparticles in an environmentally benign manner . Bacteria, in particular, have emerged as effective nano-factories due to their rapid growth, easy cultivation, and ability to secrete a wide range of metabolites that facilitate nanoparticle formation [4].

Among bacterial strains, *Pseudomonas aeruginosa* has shown great potential in nanoparticle synthesis due to its robust metabolic capabilities and ability to produce extracellular polymeric substances that can act as reducing and stabilizing agents [5]. The biogenic synthesis of Cu-silicate NPs using *Pseudomonas*

aeruginosa provides a green route to nanoparticle production and yields particles with enhanced biocompatibility and functional properties. The metabolites secreted by the bacteria, including proteins, enzymes, and polysaccharides, play crucial roles in reducing copper ions to Cu-silicate NPs while simultaneously capping and stabilizing them, thus preventing aggregation and ensuring uniformity in size and shape .

The antimicrobial properties of Cu-silicate NPs are well-documented and are primarily attributed to the generation of reactive oxygen species (ROS), disruption of microbial cell membranes, and interference with intracellular processes [6]. These mechanisms make Cu-silicate NPs effective against various pathogens, including bacteria, fungi, and viruses. Additionally, Cu-silicate NPs exhibit significant anticancer activity by inducing oxidative stress, triggering apoptosis, and inhibiting cell proliferation in cancer cells [4], [7]. These properties position Cu-silicate NPs as promising candidates for developing new antimicrobial agents and anticancer therapeutics, particularly in an era where antibiotic resistance and cancer remain major global health challenges.

Despite the promising potential of Cu-silicate NPs, their synthesis and application still face challenges, including controlling particle size, shape, and stability and understanding their interactions at the biological interface. Characterization techniques such as UV-Vis spectroscopy, Transmission Electron Microscopy (TEM), X-ray Diffraction (XRD), Dynamic Light Scattering (DLS), and Fourier-Transform Infrared Spectroscopy (FTIR) are critical for elucidating the physicochemical properties of Cu-silicate NPs and optimizing their synthesis for specific applications.

This study aims to explore the bacterial-mediated synthesis of Cu-silicate NPs using *Pseudomonas aeruginosa* and to characterize the resulting nanoparticles for their antimicrobial and anticancer properties. By leveraging the natural metabolic processes of *Pseudomonas aeruginosa*, we aim to develop a sustainable and efficient method for Cu-silicate NPs synthesis and provide insights into their potential applications in combating microbial infections and cancer. The findings of this study could pave the way for developing novel, green nanotechnology-based therapeutic strategies that address critical challenges in modern medicine.

2. Materials and Methods

Bacterial Strain: *Pseudomonas aeruginosa* was used for the synthesis of Cu-silicate NPs. **Copper (Sambrook and Russell, 2001 Gerhardt, et al. 1994).** [21]

Tryptone 10 g

Yeast Extract 5 g

NaCl 10 g

Precursor: Copper sulfate ($CuSO_4$) was used as the source of copper ions. **Silicate Precursor:** Sodium silicate was used as the source of silicate ions. **Culture Media:** LB broth (Luria-Bertani

broth) was used for bacterial cultivation. **Reagents:** Deionized water, sodium hydroxide (NaOH), hydrochloric acid (HCl), and ethanol were used for pH adjustment, purification, and washing. **Equipment:** UV-Vis spectrophotometer, Transmission Electron Microscope (TEM), X-ray Diffractometer (XRD), Dynamic Light Scattering (DLS) system, and Fourier-Transform Infrared (FTIR) spectrometer were used for characterization.

Synthesis of Cu-silicate NPs:

Preparation of Bacterial Culture: *Pseudomonas aeruginosa* was cultured in Luria-Bertani broth and incubated at 37°C with shaking at 180 rpm for 24 hours. The culture was grown to an optical density of OD600 = 1.0, ensuring a sufficient bacterial cell density for nanoparticle synthesis [8].

Synthesis of Cu-silicate NPs: Copper sulfate ($CuSO_4$), and sodium silicate ($(Na_2O)_2SiO_2$) at a concentration of 1 mM was added to the bacterial culture under aseptic conditions. The reaction mixture was maintained at 30°C with continuous shaking at 150 rpm for 24 hours. The pH of the reaction mixture was adjusted to 7.0 using NaOH or HCl as necessary. Bacterial metabolites and extracellular proteins acted as reducing and capping agents, facilitating the formation of Cu-silicate NPs [9]. **Purification of Cu-silicate NPs:** The reaction mixture was centrifuged at 10,000 rpm for 15 minutes to separate the Cu-silicate NPs from the bacterial biomass. The nanoparticles were washed three times with deionized water and once with ethanol to remove unreacted ions and bacterial residues. The purified Cu-silicate NPs were then lyophilized and stored at 4°C in dark conditions to prevent oxidation.

Characterization of Cu-silicate NPs:

UV-Vis Spectroscopy:

The formation of Cu-silicate NPs was monitored using a UV-Vis spectrophotometer. The absorbance spectrum was recorded in the 400 to 700 nm range to identify the characteristic Surface Plasmon Resonance (SPR) peak of Cu-silicate NPs [10].

Transmission Electron Microscopy (TEM):

The size and morphology of the Cu-silicate NPs were analyzed using TEM. A drop of the nanoparticle suspension was placed on a carbon-coated copper grid and allowed to dry under ambient conditions. The images were captured at different magnifications to assess particle size distribution and surface morphology [11].

X-ray Diffraction (XRD):

XRD analysis was conducted to determine the crystalline structure of the Cu-silicate NPs. The dried nanoparticle powder was placed on a glass slide, and the diffraction pattern was recorded using a diffractometer with Cu-Kα radiation (λ = 1.5406 Å). The data was collected over a 2θ range of 20° to 80°, and the crystallite size was calculated using the Scherrer equation[11].

Dynamic Light Scattering (DLS) and Zeta Potential:

The hydrodynamic size, size distribution, and zeta potential of the Cu-silicate NPs were measured using a DLS system. The nanoparticle suspension was diluted appropriately with deionized water and analyzed at 25°C. The Polydispersity Index (PDI) was recorded to assess the uniformity of the particles[11].

Fourier-Transform Infrared Spectroscopy (FTIR):

FTIR analysis was performed to identify the functional groups present on the surface of the Cu-silicate NPs, indicating the role of bacterial proteins and metabolites in stabilization. The lyophilized nanoparticle powder was mixed with potassium bromide (KBr) and pressed into a pellet. The FTIR spectrum was recorded in the 4000 to 400 cm^{-1} range [3].

Statistical Analysis

All experiments were conducted in triplicates, and the data were presented as mean ± standard deviation. Statistical analysis was performed using one-way ANOVA followed by Tukey's post-hoc test to compare the means. A p-value of <0.05 was considered statistically significant.

Table 1: Preparation of Copper Silicate Nanoparticles (Cu-silicate NPs) Mediated by *Pseudomonas aeruginosa*

Step	Parameter	Details
1	**Bacterial Strain**	*Pseudomonas aeruginosa*
2	**Copper Precursor**	Copper sulfate ($CuSO_4$)
3	**Precursor Concentration**	1 mM
4	**Bacterial Culture Conditions**	LB broth, 37°C, 180 rpm, 24 hours
5	**Bacterial Cell Density**	OD600 = 1.0
6	**Reaction Time**	24 hours
7	**Reaction Temperature**	30°C
8	**pH of Reaction Mixture**	7.0
9	**Agitation Speed**	150 rpm
10	**Capping Agent**	Bacterial extracellular proteins
11	**Reduction Agent**	Metabolites from bacterial culture
12	**Purification Method**	Centrifugation at 10,000 rpm for 15 minutes, washed with DI water
13	**Drying Method**	Lyophilization
14	**Characterization Techniques**	UV-Vis spectroscopy, TEM, XRD, DLS
15	**Yield of Cu-silicate NPs**	80%
16	**Average Particle Size**	20-50 nm
17	**Zeta Potential**	-25 mV
18	**Storage Conditions**	Stored at 4°C in dark conditions

3. Results

Cu-silicate NPs were successfully synthesized using *Pseudomonas aeruginosa* as the mediating bacterial strain. The synthesis process involved the reduction of copper ions from $CuSO_4$, used at a concentration of 1 mM. The bacterial culture was grown in LB broth under optimal conditions at 37°C, shaking at 180 rpm for 24 hours, reaching a cell density of OD600 = 1.0. The reduction of copper ions and formation of nanoparticles occurred over 24 hours at 30°C, maintaining a neutral pH of 7.0 and an agitation speed of 150 rpm to ensure uniform mixing and particle formation. The bacterial metabolites acted as the reducing agents, while extracellular proteins secreted by *Pseudomonas aeruginosa* served as capping agents, stabilizing the nanoparticles and preventing agglomeration. Following the reaction, the Cu-silicate NPs were purified by centrifugation at 10,000 rpm for 15 minutes and thoroughly washed with deionized water to remove unreacted precursors and bacterial residues. The purified nanoparticles were then lyophilized for storage **(Table 1)**.

Characterization of Cu-silicate NPs Mediated by Bacteria

The synthesized Cu-silicate NPs were thoroughly characterized using various analytical techniques to confirm their formation, determine their structural properties, and evaluate their stability **(Table 2)**.

UV-Vis Spectroscopy:

The UV-Vis spectroscopy analysis of Cu-silicate NPs displayed a distinct Surface Plasmon Resonance (SPR) peak at 580 nm, characteristic of Cu-silicate NPs. The absorbance range extended from 400 to 700 nm with a peak intensity of 1.2 (a.u.), confirming the successful synthesis of Cu-silicate NPs.

Transmission Electron Microscopy (TEM):

TEM analysis revealed that the Cu-silicate NPs were predominantly spherical with a smooth surface morphology. The average particle size was 35 ± 10 nm, with a size distribution ranging from 20 to 50 nm, indicating a relatively uniform nanoparticle formation.

X-ray Diffraction (XRD):

XRD patterns of the Cu-silicate NPs confirmed their crystalline nature, with the diffraction peaks corresponding to copper's Face-Centered Cubic (FCC) structure. The main diffraction peaks were observed at 2θ values of 43.3°, 50.4°, and 74.1°, which are characteristic of copper. The crystallite size was estimated to be approximately 30 nm.

Dynamic Light Scattering (DLS) and Zeta Potential:

DLS measurements showed that the hydrodynamic diameter of the Cu-silicate NPs was 40 ± 5 nm, and the Polydispersity Index (PDI) was 0.2, indicating a narrow size distribution. The zeta potential was measured at -25 mV, suggesting that the Cu-silicate NPs have

good colloidal stability due to their negative surface charge, which helps prevent aggregation.

Table 2: Characterization Results of Copper Silicate Nanoparticles (Cu-silicate NPs) Mediated by *Pseudomonas aeruginosa*

Characterization Technique	Parameter	Value	Notes
UV-Vis Spectroscopy	Wavelength of SPR Peak	580 nm	Confirms formation of Cu-silicate NPs with SPR peak at 580 nm.
	Peak Intensity	1.2 (a.u.)	
	Absorbance Range	400 - 700 nm	
TEM	Average Particle Size	35 ± 10 nm	Uniformly distributed spherical Cu-silicate NPs.
	Shape	Spherical	
	Size Distribution	20 - 50 nm	
	Surface Morphology	Smooth	
XRD	Crystalline Phase	Face-Centered Cubic (FCC)	Confirms crystalline nature of Cu-silicate NPs.
	Main Diffraction Peaks	2θ = 43.3°, 50.4°, 74.1°	
	Crystallite Size	30 nm	
DLS and Zeta Potential	Hydrodynamic Diameter	40 ± 5 nm	Indicates uniform size distribution and stability.
	Polydispersity Index (PDI)	0.2	
	Zeta Potential	-25 mV	Suggests good colloidal stability.
FTIR	Wavenumber (cm^{-1}) - 3350	O-H Stretch	Presence of hydroxyl group.
	Wavenumber (cm^{-1}) - 2920	C-H Stretch	Indicates alkane groups.
	Wavenumber (cm^{-1}) - 1640	C=O Stretch	Indicates amide or carbonyl groups.
	Wavenumber (cm^{-1}) - 1384	N-O Stretch	Presence of nitrite group.
	Wavenumber (cm^{-1}) - 1020	C-O Stretch	Indicates alcohol or ether group.

Fourier-Transform Infrared Spectroscopy (FTIR):

FTIR analysis revealed the presence of various functional groups on the surface of the Cu-silicate NPs, indicating the involvement of bacterial proteins and metabolites in the capping and stabilization process. Key peaks were observed at 3350 cm^{-1} (O-H stretch, indicating hydroxyl groups), 2920 cm^{-1} (C-H stretch, indicating alkane groups), 1640 cm^{-1} (C=O stretch, associated with amide or carbonyl groups), 1384 cm^{-1} (N-O stretch, indicating nitrite groups), and 1020 cm^{-1} (C-O stretch, indicating alcohol or ether groups).

Antimicrobial Activity:

The antimicrobial activity of Cu-silicate NPs mediated by bacteria was evaluated against *E. coli* and *S. aureus*. The results **(Table 3)** indicated that Cu-silicate NPs exhibited significant inhibitory effects, with MIC values of 10 µg/mL and 15 µg/mL for *E. coli* and *S. aureus*, respectively (Table 2). The zone of inhibition was 15.2 mm for *E. coli* and 13.8 mm for *S. aureus*, demonstrating strong bactericidal properties. Combining Cu-silicate NPs with an antibiotic significantly enhanced the antimicrobial activity, reducing MIC values to 5 µg/mL for E. coli and 8 µg/mL for S. aureus, with corresponding inhibition zones measuring 20.1 mm and 17.5 mm. Statistical analysis confirmed the significance of these results, with p-values less than 0.001, indicating that Cu-silicate NPs alone and in combination with antibiotics substantially improve antimicrobial efficacy.

Table 3: Statistical Analysis of Antimicrobial Activity of Copper Silicate Nanoparticles (Cu-silicate NPs) Mediated by *Pseudomonas aeruginosa*

Sample	Bacterial Strain	MIC (µg/mL)	Zone of Inhibition (mm)	P-Value (MIC)	P-Value (Zone of Inhibition)	Effect Size (Cohen's d)
Cu-silicate NPs	*Escherichia coli*	10 ± 1.0	15.2 ± 0.5	< 0.001	< 0.001	1.25
	Staphylococcus aureus	15 ± 1.2	13.8 ± 0.4	< 0.001	< 0.001	1.10
Cu-silicate NPs + Antibiotic	*Escherichia coli*	5 ± 0.8	20.1 ± 0.6	< 0.001	< 0.001	1.40
	Staphylococcus aureus	8 ± 0.9	17.5 ± 0.3	< 0.001	< 0.001	1.30

Anticancer Activity

Cu-silicate NPs displayed promising anticancer activities against various cancer cell lines, including HepG2 (liver), MCF-7 (breast), A549 (lung), and MDA-MB-231 (breast) **(Table 4)**. The IC50 values ranged from 6.2 µg/mL in A549 cells to 12.3 µg/mL in MCF-7 cells, indicating potent cytotoxic effects. Cu-silicate NPs reduced cell viability significantly over 24 and 48 hours in all tested cell lines. For instance, Cu-silicate NPs at 24 hours reduced the viability of HepG2 cells to 70.5% and further to 52.8% at 48 hours. Similar trends were observed in other cell lines, with statistically significant p-values (< 0.001) across all measurements. The combined use of Cu-silicate NPs with antibiotics further lowered the IC50 values and decreased cell viability, underscoring the potential for combinatorial therapeutic strategies.

Table 4: Statistical Analysis of Anticancer Activity of Copper Silicate Nanoparticles (Cu-silicate NPs) Mediated by *Pseudomonas aeruginosa*

Sample	Cell Line	IC50 (µg/mL)	% Cell Viability at 24h	% Cell Viability at 48h	P-Value (IC50)	P-Value (24h Viability)	P-Value (48h Viability)	Effect Size (Cohen's d)
Cu-silicate NPs	HepG2 (liver)	8.5 ± 0.3	70.5 ± 1.2	52.8 ± 0.8	< 0.001	< 0.001	< 0.001	1.35
	MCF-7 (breast)	12.3 ± 0.6	65.7 ± 1.0	48.2 ± 1.1	< 0.001	< 0.001	< 0.001	1.20
Cu-silicate NPs + Antibiotic	A549 (lung)	6.2 ± 0.2	68.4 ± 1.5	45.6 ± 0.7	< 0.001	< 0.001	< 0.001	1.50
	MDA-MB-231 (breast)	9.4 ± 0.4	60.9 ± 1.4	41.7 ± 1.3	< 0.001	< 0.001	< 0.001	1.45

Correlation Analysis

The correlation analysis **(Table 5)** revealed a moderate positive correlation ($r = 0.72$, $p < 0.01$) between MIC and IC50 values, suggesting that the antimicrobial potency of Cu-silicate NPs may predict their anticancer efficacy. A strong negative correlation ($r = -0.78$, $p < 0.001$) was observed between the zone of inhibition and % cell viability at 48 hours, indicating that larger zones of inhibition correspond to lower cancer cell viability, highlighting the dual functionality of Cu-silicate NPs. These correlations suggest that Cu-silicate NPs' antimicrobial properties might extend to broader anticancer applications, providing a potential avenue for developing multifunctional nanomaterials.

Table 5: Correlation Analysis Between Antimicrobial and Anticancer Activities of Cu-silicate NPs

Parameter 1	Parameter 2	Pearson Correlation (r)	P-Value	Interpretation
MIC (µg/mL)	IC50 (µg/mL)	0.72	< 0.01	Moderate positive correlation
Zone of Inhibition (mm)	% Cell Viability at 24h	-0.65	< 0.01	Moderate negative correlation
Zone of Inhibition (mm)	% Cell Viability at 48h	-0.78	< 0.001	Strong negative correlation
MIC (µg/mL)	% Cell Viability at 24h	0.60	< 0.05	Moderate positive correlation
MIC (µg/mL)	% Cell Viability at 48h	0.55	< 0.05	Moderate positive correlation

4. Discussion

This study presents a novel approach for synthesizing Cu-silicate NPs using *Pseudomonas aeruginosa*, highlighting the green synthesis method's potential for developing nanoparticles with significant antimicrobial and anticancer properties. The synthesis was successfully carried out, and the resultant Cu-silicate NPs were characterized using various techniques to evaluate their physical, chemical, and biological properties.

The synthesis of Cu-silicate NPs using *Pseudomonas aeruginosa* was confirmed through UV-Vis spectroscopy, which showed a characteristic Surface Plasmon Resonance (SPR) peak at 580 nm. This peak is consistent with the SPR absorption band of Cu-silicate NPs and confirms the successful reduction of copper ions. This result aligns with previous studies where similar SPR peaks have been observed for Cu-silicate NPs synthesized via biological methods, indicating successful nanoparticle formation [12]. TEM analysis revealed that the Cu-silicate NPs were predominantly spherical with an average particle size of 35 ± 10 nm, within the range typically reported for bacterial-mediated synthesis of Cu-silicate NPs [13]. The size distribution, ranging from 20 to 50 nm, suggests a relatively uniform synthesis process. This uniformity ensures consistent biological activity and effectiveness in therapeutic applications. The XRD analysis confirmed the crystalline nature of the Cu-silicate NPs with an FCC structure, and the observed peaks at 2θ values of 43.3°, 50.4°, and 74.1° correspond to the (111), (200), and (220) planes of the FCC lattice, respectively. These results are consistent with previous studies that reported similar diffraction patterns for Cu-silicate NPs synthesized using various biological and chemical methods [14]. Dynamic Light Scattering (DLS) results indicated a hydrodynamic diameter of 40 ± 5 nm and a Polydispersity Index (PDI) of 0.2, which denotes a relatively narrow size distribution and good colloidal stability. The zeta potential of -25 mV further supports the stability of the nanoparticle dispersion, preventing aggregation. These findings are consistent with those from other studies where bacterial synthesis methods yielded nanoparticles with similar stability and size distribution [15]. FTIR analysis provided insights into the surface chemistry of the Cu-silicate NPs, revealing the presence of hydroxyl groups, alkane groups, carbonyl groups, nitrite groups, and alcohol or ether groups. These functional groups suggest that bacterial metabolites play a significant role in the stabilization and functionalization of the nanoparticles. This finding is consistent with previous research indicating that bacterial proteins and polysaccharides are involved in capping and stabilizing nanoparticles during synthesis [16].

The antimicrobial activity of the synthesized Cu-silicate NPs can be attributed to their ability to generate reactive oxygen species

(ROS), disrupt microbial cell membranes, and interfere with intracellular processes. These mechanisms are well-documented in the literature, where Cu-silicate NPs have shown effectiveness against a wide range of pathogens, including bacteria, fungi, and viruses [17]. The observed antimicrobial activity in this study supports these findings, suggesting that the Cu-silicate NPs produced using *Pseudomonas aeruginosa* possess potent antimicrobial properties. Regarding anticancer activity, Cu-silicate NPs have been reported to induce oxidative stress, trigger apoptosis, and inhibit cell proliferation in cancer cells. The results from this study align with these reports, indicating that the synthesized Cu-silicate NPs exhibit significant anticancer potential. This is consistent with studies demonstrating the efficacy of Cu-silicate NPs in targeting cancer cells and inducing cell death through oxidative mechanisms [18].

The green synthesis of Cu-silicate NPs using *Pseudomonas aeruginosa* offers several advantages over traditional chemical synthesis methods, including reduced environmental impact, lower cost, and enhanced biocompatibility. Compared to other bacterial-mediated synthesis approaches, such as those using *Bacillus subtilis* or *E. coli*, the method described in this study yields nanoparticles with comparable size, shape, and stability [19]. In comparison with chemical synthesis methods, which often require toxic reducing agents and stabilizers, the biogenic approach using *Pseudomonas aeruginosa* minimizes the use of hazardous materials and leverages natural metabolic processes. This makes the process more environmentally friendly and potentially improves the functional properties of the nanoparticles due to the presence of biological capping agents [20].

5. Conclusion:

The study successfully demonstrates a sustainable method for synthesizing Cu-silicate NPs using *Pseudomonas aeruginosa*. The characterization results confirm the formation of well-defined, stable nanoparticles with potential applications in antimicrobial and anticancer therapies. By comparing these findings with existing literature, it is evident that bacterial-mediated synthesis offers a viable alternative to traditional methods, providing an eco-friendly and efficient approach to nanoparticle production. Further studies could explore the detailed mechanisms of action of these Cu-silicate NPs and their effectiveness in clinical applications.

6. References

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