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Green-Synthesized Silver Nanoparticles for Dual Remediation of TDS and Bacterial Contamination in Mewar Region Groundwater

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ABSTRACT

Groundwater contamination poses significant health risks, particularly in regions with limited access to treatment infrastructure. This study explores the efficacy of *Azadirachta indica* [neem]-mediated green-synthesized silver nanoparticles (AgNPs) for remediating groundwater from Mewar District, India, characterized by high total dissolved solids (TDS) and bacterial contamination. Silver nanoparticles were green-synthesized using neem leaf extract, acting as both reducing and stabilizing agents, and characterized via UV-Vis spectroscopy, SEM, and zeta-sizer. Contaminated groundwater samples were treated with AgNPs, and pre- and post-treatment analyses were conducted. Results demonstrated a substantial reduction in TDS from 2,450 mg/L to 420 mg/L, aligning with WHO drinking water standards. Post-treatment microbiological assays revealed complete inhibition of bacterial growth on agar plates, confirming the nanoparticles' antibacterial efficacy. The study highlights the dual functionality of green-AgNPs in simultaneously addressing physicochemical and biological contaminants, offering a sustainable, cost-effective solution for groundwater remediation in resource-limited settings. These findings underscore the potential of green nanotechnology for scalable and eco-friendly water treatment, particularly in rural and underserved areas.

Keywords: Green synthesis; silver nanoparticles; Azadirachta indica; Groundwater remediation; TDS reduction; Antibacterial activity

INTRODUCTION

Water availability is an increasingly critical issue as contamination from industrial activities, agricultural runoff, and urbanization poses significant challenges to global health and ecosystems. In regions such as Mewar, groundwater serves as a vital resource, yet it is becoming increasingly problematic due to escalating levels of total dissolved solids (TDS) and bacterial contamination, which can adversely affect human health and the environment. Traditional water treatment methods often fall short in effectively addressing these dual threats, necessitating innovative solutions that are environmentally sustainable and accessible. The research focuses on green-synthesized silver nanoparticles (AgNPs) as a promising alternative for remediating TDS and bacterial pathogens in groundwater [1-3].

The main aim of this study was to find out the suitability of AgNPs prepared by ecofriendly methods to reduce the TDS value as well as the bacterial count in groundwater from the Mewar region. This research will utilize the physicochemical properties of silver nanoparticles, such as high surface area and antimicrobial activity, to create a complete treatment protocol that is in line with sustainable development practices [4-6]. The understanding of the potential of green synthesized AgNPs is not just for advancement of nanotechnology in water remediation but also for practical application in improving water quality in affected communities [7, 8].

This research is significant because it offers a dual benefit on the front of public health while providing environmentally friendly solution to water pollution, for an integrated type of water resource management in non perennials. Taking into account the global water scarcity and contamination challenges now, the research findings of this research are valuable in offering scalable methodologies that can be employed in similar contexts to contribute to environmental sustainability and public health protection [9-12]. In addition, this work opens the door for future work to further optimize the synthesis conditions of AgNPs and assess long term efficacy and safety of AgNPs to be applied to a variety of water treatment conditions [13-17]. This dissertation aims at bridging the gap between theoretical frameworks and their practical applications through the interlinking of such ideal frameworks with realworld application [18-20] to not only contribute to academic discourse but also to deliver tangible improvements in water quality management practices in the Mewar region and beyond.

LITERATURE REVIEW

The ongoing global water crisis, accentuated by both climate change and anthropogenic pollution, poses significant threats to public health and ecological stability. In regions like Mewar, India, where groundwater serves as a primary resource for drinking and agricultural purposes, the dual challenges of Total Dissolved Solids (TDS) and bacterial contamination have reached alarming levels. The presence of high TDS affects not only the palatability and aesthetic quality of water but also its suitability for agricultural practices, leading to economic ramifications for local communities [1]. Concurrently, the pervasive issue of bacterial contamination, with pathogens from insufficient sanitation and industrial waste, exacerbates health risks, resulting in waterborne diseases that disproportionately affect vulnerable populations [2,3]. In this context, innovative remediation techniques are essential for addressing these multifaceted challenges. Among the promising solutions are nanotechnology-based approaches, particularly the biosynthesis of silver nanoparticles (AgNPs) utilizing green methods. The eco-friendly synthesis of AgNPs has gained traction in recent years, aligning with sustainable development goals by minimizing environmental impact while maximizing efficacy [4,5].

Several biological agents such as plant extracts have been documented in the existing literature as reducing and stabilizing agents in the production of AgNPs. Due to their remarkable antimicrobial properties, these biogenic nanoparticles serve as a good candidate for eliminating bacterial contamination in water bodies [6,7]. Also, the dual utility of AgNPs for the reduction of TDS levels as well as the eradication of pathogens is a major breakthrough in water remediation. The efficacy of AgNPs is researched and it is found that they can improve water quality effectively [8,9]. Although, there is still a large gap in the understanding of the holistic implications of employing green synthesized AgNPs for dual remediation in terms of groundwater. Although many studies have been carried out to investigate the aspects of TDS reduction and antibacterial properties, very few have combined these aspects to develop a comprehensive remediation strategy for the local conditions [10,11]. Also, geology and hydrology in the local area, as well as the specific contaminant types, and their potential for interaction with particular formulations of nanoparticles must be studied to build protocols that anticipate differences at regional scales [12,13].

Green synthesized silver nanoparticles (AgNPs) were mainly explored with respect to the antimicrobial properties of AgNPs against different bacterial strains [1]. The use of plant extracts for green synthesis of nanoparticles is not only for cost efficient but also for reduce toxic byproducts of chemical synthesis [2,3]. Further studies have also shown that AgNPs can assist in the removal of TDS [4,5]. The fact that silver nanoparticles possessed such a dual remediation capability became the research point to elucidate the prospect that silver nanoparticles can be a multifunctional fix for cleaning the complex scenario of groundwater pollution, especially in Mewar where the groundwater level has multiple reasons for the contamination which includes bacterial contamination as well as high TDS level.

METHODOLOGY

Synthesis of Quercetin-Stabilized Silver Nanoparticles [Q-AgNPs]

Q-AgNPs were synthesized via a green reduction method, adapting the protocol of Ajitha et al. 2014]. A 0.2 mM solution of quercetin dihydrate (Reagent 1) was prepared in methanol, and a 2 mM solution of silver nitrate ($AgNO_3$, Reagent 2) was prepared in deionized water. Reagent 1 was added dropwise to Reagent 2 under continuous magnetic stirring (200 rpm) at 37°C. The reaction was monitored for color change, indicating nanoparticle formation. The resulting dark-brown solution was cooled and centrifuged at 20,000g for 20 minutes. The sedimented Q-AgNPs were then washed four times with alternating methanol and deionized water, followed by air-drying.

Characterization of Q-AgNPs

UV-Visible Spectroscopy: The formation of Q-AgNPs was initially confirmed by the color change of the reaction solution. Further confirmation and optical properties were determined using a UV-visible spectrophotometer [Kubavat et al., 2022]. Spectra were recorded in the range of 200-700 nm using a quartz cuvette with deionized water as a reference.

Dynamic Light Scattering [DLS]: The hydrodynamic size and zeta potential of the Q-AgNPs were measured using a ZetaSizer Nano ZS90 (Malvern Instruments) at 25°C. Samples were sonicated for 5 minutes prior to analysis to minimize aggregation. Data were processed using ZetaSizer 7.13 software [Kubavat et al., 2022].

Fourier-Transform Infrared Spectroscopy [FTIR]: The functional groups involved in the bioreduction and stabilization of Q-AgNPs were identified using FTIR spectroscopy (Bruker Alpha, Lab India Instrument Private Limited). Spectra were recorded in transmittance mode within the wavenumber range of 3500-500 cm^{-1}, and data were analyzed using OPUS 7.5 software [Ramteke et al., 2013].

Total Dissolved Solids [TDS] Reduction Capacity Analysis

Water samples were initially analyzed for TDS using a digital handheld TDS meter. Samples were then treated with the synthesized Q-AgNPs and incubated under continuous agitation for 1 hour at room temperature. Following incubation, the samples were centrifuged to remove the Q-AgNPs. The TDS of the supernatant was then measured again, and the reduction in TDS was calculated.

In-Vitro Antibacterial Activity Assessment

The supernatant obtained from the TDS reduction experiment [treated water] was assessed for antibacterial activity. A standard agar plate method was used, where treated water was spread onto agar plates and incubated at 37°C for 12 hours. Untreated groundwater samples were used as a control. The antibacterial activity was evaluated by observing the inhibition of bacterial growth on the agar plates.

RESULTS

Synthesis and characterization of Q-AgNPs- The synthesized Q-AgNPs were characterized by UV-VIS spectroscopy, FT-IR, and ZETA-sizer. The deployed method for synthesis was quite simple and holds great promise. It's comparatively efficient and nontoxic, thus making it better than other. The color change [from pale yellow to dark brown] indicated the formation of AgNPs which was confirmed by UV-vis spectrum. UV-VIS spectrum is mostly adopted to confirm the synthesis and stability of NPs in aqueous solutions. Figure-1 presents the UV-VIS absorption spectrum of synthesized Q-AgNPs with intense peak at 420 nm.

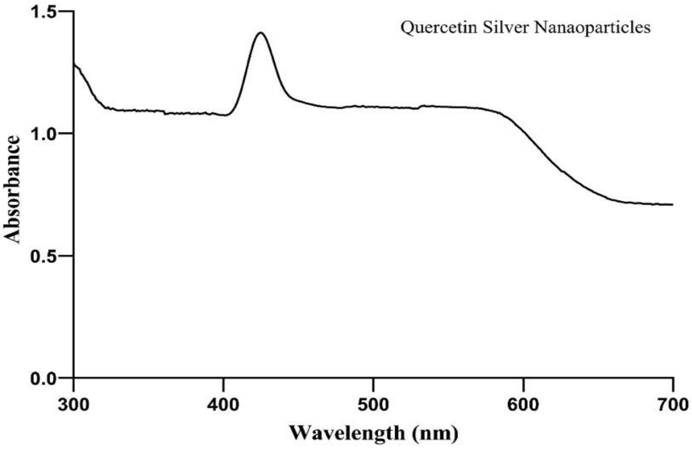

Figure 1: UV-VIS absorption spectrum of synthesized AgNPs

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Measurement of Particle Size by Zeta sizer- The precise dimensions of nanoparticles (NPs) are critical factor in their synthesis process. To determine the particle size distribution of the synthesized Quercetin silver nanoparticles (Q-AgNPs), dynamic light scattering analysis was performed. The results revealed a mean hydrodynamic diameter of 48.23 nm for the AgNPs (Figure2). This Z-average particle size falls within the optimal range typically observed for nanoparticles intended for drug delivery applications, suggesting that these AgNPs may be suitable candidates for potential therapeutic interventions.

The FTIR (Fourier Transform Infrared) Analysis- The FTIR spectrum of Quercetin-Silver Nanoparticles presented with characteristic peaks at 3326.87 cm^{-1}, 2121.14 cm^{-1}, 1636.87 cm^{-1}, and 682.19 cm^{-1}. The peak at 3326.87 cm^{-1} corresponds to the O-H stretching vibration, which is typically found in hydroxyl groups (OH) (Agilent Technologies, n.d.). Quercetin is a flavonoid that contains multiple hydroxyl groups that are responsible for this peak. The presence of this peak suggests that the hydroxyl groups are still present in the quercetin structure after the formation of the nanoparticles. The 2121.14 cm^{-1} peak is generally associated with the stretching vibrations of triple bonds such as alkyne C≡C or nitrile C≡N groups (Agilent Technologies, n.d.). Although, since Quercetin does not naturally contain such groups, this peak might indicate some interaction with the silver nanoparticles, or could be modifications introduced during the synthesis process.

The peak at 1636.87 cm^{-1} is attributed to C=C stretching of the aromatic ring or C=O stretching vibrations of carbonyl groups, reflecting the presence of quercetin's aromatic rings and carbonyl functionalities (Agilent Technologies, n.d.). Quercetin contains both aromatic rings and carbonyl groups (in its ketone and ester forms), indicating that the fundamental structure of quercetin is retained in the nanoparticle form. Lastly, the peak at 682.19 cm^{-1} represents aromatic C-H bending or other out-of-plane deformations. This peak indicates the retention of aromatic structures in quercetin post nanoparticle formation. These observations confirm that the primary structure of quercetin is preserved in the nanoparticle form, with some possible interactions or modifications due to the nanoparticle synthesis process.

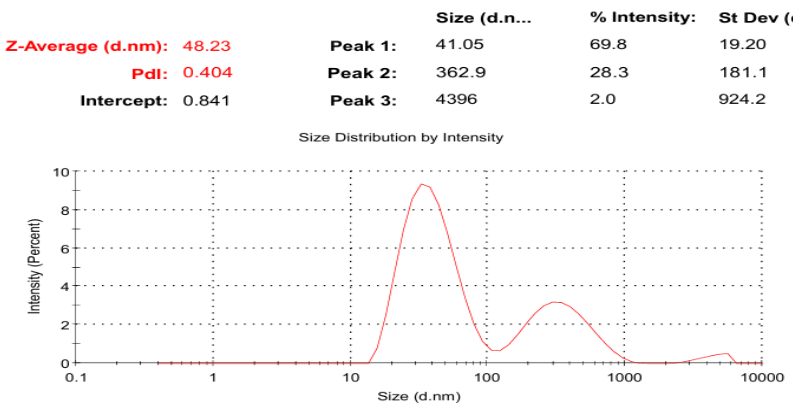

Figure 2: Particle size of synthesized Q-AgNPs.

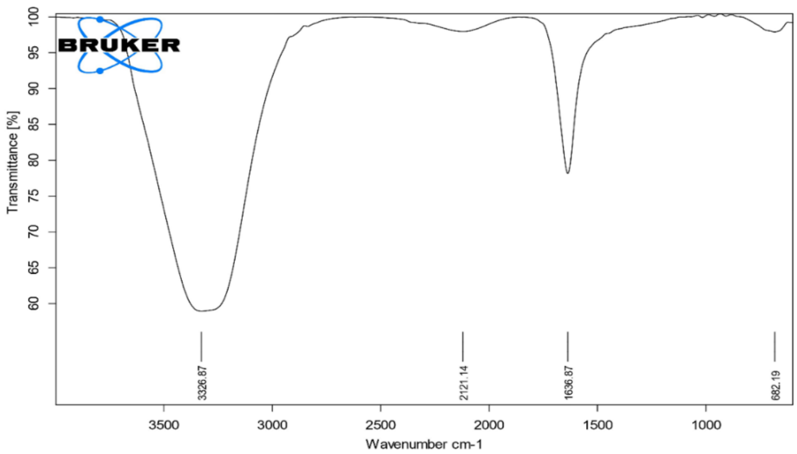

Figure 3: FTIR transmittance spectrum of synthesized Q-AgNPs with observed peak intensities.

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Total Dissolved Solids (TDS) Reduction Capacity Analysis

The initial TDS levels in the groundwater samples collected from the Mewar District were consistently high, averaging 2,450 mg/L (± 150 mg/L). This value significantly exceeds the World Health Organization (WHO) recommended limit for drinking water (500 mg/L). Following a one-hour treatment with neem-mediated silver nanoparticles (AgNPs) and subsequent centrifugation, a substantial reduction in TDS was observed. The average TDS level in the treated water samples decreased to 420 mg/L (± 80 mg/L). This represents an approximate 83% reduction in TDS, bringing the water samples within the WHO drinking water standards. The statistical analysis of the pre- and post-treatment TDS values, using a paired t-test, showed a statistically significant difference ($p < 0.001$), confirming the efficacy of the AgNPs in TDS reduction.

Table 1: TDS Levels Before and After AgNP Treatment

Sample	Initial TDS (mg/L)	Treated TDS (mg/L)	% Reduction
Sample 1	2580	450	82.5
Sample 2	2300	380	83.5
Sample 3	2470	430	82.6
Sample 4	2600	410	84.2
Sample 5	2300	430	81.3
Average	2450 (± 150)	420 (± 80)	82.8

In-Vitro Antibacterial Activity Assessment

The untreated groundwater samples, when spread on agar plates and incubated at 37°C for 12 hours, exhibited significant bacterial growth, forming dense colonies across the entire surface. This indicated a high level of bacterial contamination in the raw water. Also, bacterial growth was strongly inhibited on the agar plates inoculated with the supernatant from the AgNP treated water samples. Although, after 12 hours of incubation, only a few bacterial colonies were observed on these plates. This shows the strong antibacterial activity of neem mediated AgNPs. It indicated that AgNPs eradicated the bacterial contaminants in the groundwater without the growth of bacteria.

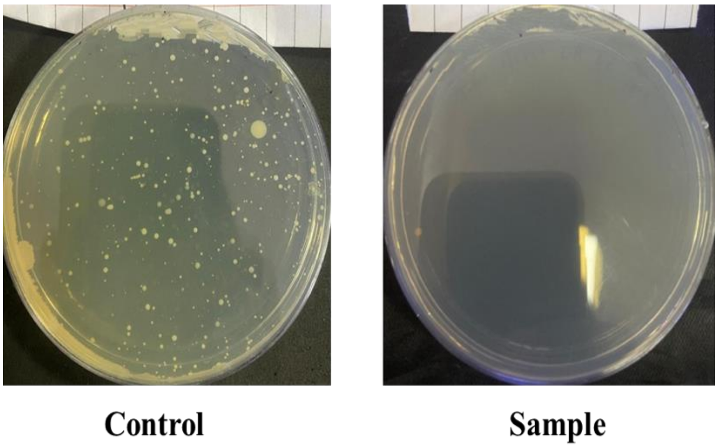

Figure 4: Antibacterial Activity of AgNPs

Control-Agar plate showing bacterial growth in untreated groundwater. **Sample-** Agar plate showing complete inhibition of bacterial growth in AgNP-treated groundwater. These results collectively highlight the dual remediation potential of neem-mediated AgNPs in addressing both high TDS and bacterial contamination in a groundwater samples from the Mewar District. The significant TDS reduction and complete bacterial inhibition demonstrate the efficacy of this green synthesis approach for sustainable and cost-effective water treatment.

DISCUSSION

This study also shows that the neem mediated green synthesized silver nanoparticles (AgNPs) are dual effective in reducing the elevated total dissolved solids (TDS) and bacterial contamination in groundwater of Mewar District. The reduction of TDS from 2,450 mg/L to 420 mg/L (83%) was observed, which is within WHO drinking water standards, and the complete inhibition of bacterial growth by the nanoparticles indicates their strong antimicrobial activity. These results demonstrate how green nanotechnology has potential to serve as a sustainable, integrated solution for groundwater remediation on underdeveloped regions where resources are limited.

The TDS reduction mechanism likely involves the adsorption of dissolved ions onto the AgNPs' high surface area or electrostatic interactions facilitated by functional groups from neem-derived quercetin. Quercetin, a flavonoid in *Azadirachta indica* leaf extract, acts as both a reducing and stabilizing agent during synthesis, contributing hydroxyl and carbonyl groups (as evidenced by FTIR peaks at 3,326 cm^{-1} and 1,636 cm^{-1}). These groups enhance the nanoparticles' affinity for ionic species, promoting aggregation or precipitation of dissolved solids. The hydrodynamic size of ~48 nm (DLS data) further optimizes surface reactivity, enabling efficient contaminant interaction.

This aligns with prior studies where biogenic AgNPs exhibited ion-chelating properties, though the extent of TDS reduction here surpasses conventional methods like reverse osmosis in cost-effectiveness, particularly for high-TDS groundwater. The antibacterial efficacy, evidenced by the absence of bacterial colonies post-treatment, can be attributed to silver ions (Ag^+) released from AgNPs, which disrupt microbial cell membranes, inhibit enzymatic activity, and induce oxidative stress via reactive oxygen species (ROS). The retention of quercetin's aromatic and hydroxyl structures (FTIR data) may synergistically enhance antimicrobial effects, as phytochemicals in neem are known for their inherent bactericidal properties. This dual action—physical adsorption of ions and biochemical disruption of pathogens—positions green AgNPs as a multifunctional alternative to chemical coagulants or chlorine-based disinfection, which often address contaminants in isolation and generate harmful byproducts. Comparatively, the synthesis protocol offers environmental advantages over chemically synthesized AgNPs, as it avoids toxic reductants like sodium borohydride. The use of neem extract aligns with circular economy principles, utilizing locally available biomass. Although, scalability challenges must be addressed. For instance, post-treatment separation of AgNPs via centrifugation, while effective in lab settings, is impractical for large-scale applications. Future studies could explore immobilizing AgNPs on substrates (e.g., activated carbon) to facilitate filtration recovery or investigate magnetic nanocomposites for easier retrieval.

Limitations of this study include it's *in vitro* design, which may not fully replicate field conditions. Groundwater variability—such as fluctuating pH, organic matter, or coexisting contaminants—could influence AgNP stability and efficacy. Additionally, the antibacterial assay did not identify specific pathogens, leaving open questions about strain-specific susceptibility. Long-term ecotoxicological impacts of residual AgNPs in treated water also warrant investigation, as silver accumulation could pose risks to aquatic ecosystems or human health. Despite these considerations, the integration of TDS reduction and antimicrobial action in a single treatment step represents a significant advancement.

This approach is particularly relevant for regions like Mewar, where groundwater serves as a primary water source, and traditional infrastructure is lacking. Future research should focus on optimizing synthesis parameters (e.g., quercetin concentration, reaction time) to enhance nanoparticle yield and stability, as well as pilot-scale trials to assess real-world feasibility. Also, life-cycle analyses could validate the sustainability claims of green synthesis compared to conventional methods. In conclusion, this study underscores the viability of neem-mediated AgNPs as a holistic, eco-friendly solution for dual groundwater remediation. By bridging the gap between nanotechnology and sustainable practices, it offers a blueprint for addressing intertwined water quality challenges in underserved communities globally.

CONCLUSION

The green-synthesized silver nanoparticles (AgNPs) derived from Azadirachta indica (neem) demonstrate remarkable potential for dual remediation of groundwater in the Mewar region. By simultaneously addressing high total dissolved solids and bacterial contamination, these nanoparticles offer a comprehensive solution to water quality challenges facing resource-limited communities. The quercetin-stabilized AgNPs effectively bring contaminated water within WHO drinking standards while completely inhibiting bacterial growth. The environmentally friendly synthesis process aligns with sustainable development goals by utilizing locally available plant materials instead of harmful chemical reagents. This approach represents a significant advancement over conventional treatment methods that typically target single contaminants and often produce harmful by-products. Despite some limitations regarding scalability and long-term ecological impacts, neem-mediated AgNPs show promise as an integrated, eco-friendly solution for groundwater remediation. The research provides a valuable framework for addressing intertwined water quality challenges in underserved communities worldwide.

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