



Bioengineered Keratin-PVA/ZnO Nanogel: A Sustainable Approach for Antimicrobial and Arsenic Adsorption

Ashish Dadsena,¹ Snehal Narkhede,¹ Enosh Philips,¹ Akansha Singhai,¹ Varaprasad Kolla,¹ Reecha Sahu,^{2,*} Tanvir Arfin,³

¹Amity Institute of Biotechnology, Amity University, Raipur 493225, India

²Chhattisgarh Swami Vivekanand Technical University (CSVTU),

³Air Resource, Environmental Resource Planning and Management, CSIR-National Environmental Engineering Research Institute (NEERI), Nehru Marg, Nagpur 440020, India

(Received: 14 March 2025

Revised: 16 March 2025

Accepted: 24 March 2025)

KEYWORDS

Keratin-based nanogel; ZnO nanoparticles; Antimicrobial activity, Arsenic adsorption; Biodegradable biomaterial

ABSTRACT:

This study presents the development of a novel keratin-polyvinyl alcohol (PVA) nanogel incorporating zinc oxide (ZnO) nanoparticles for antimicrobial and environmental applications. Keratin was extracted from poultry feathers using a controlled degradation process, followed by the synthesis of ZnO nanoparticles via a green chemistry approach utilizing Aprajita flower extract. The nanogel was fabricated by blending keratin and PVA with ZnO NPs and crosslinking with glutaraldehyde to achieve a stable gel matrix. Characterization techniques, as well as X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), and Fourier transform infrared spectroscopy (FTIR), confirmed the successful integration of keratin, PVA, and ZnO NPs, validating the structural integrity and functional properties of the nanogel. Disc diffusion assays evaluated antimicrobial efficacy against *Pseudomonas*, *Staphylococcus aureus*, *Escherichia coli*, and *Enterobacter*. Results demonstrated enhanced bacterial inhibition, particularly in ZnO-enhanced formulations, confirming their potential in biomedical applications. Additionally, an arsenic uptake study using a Merquant test kit highlighted the nanogel's remarkable adsorption capacity, with significant reductions in arsenic concentration. The findings establish the keratin-PVA/ZnO nanogel as a sustainable biomaterial with multifunctional applications in healthcare and environmental remediation. Future research should focus on large-scale production and further optimization for commercial viability.

1. Introduction

The ecosystem consists of diverse natural components, each playing a crucial role in sustaining the environment [1]. These components are intricately interconnected, working to maintain ecological balance and stability [2]. Heavy metals are naturally occurring elements that various environmental factors can influence [3]. One pressing example is arsenic contamination in groundwater, a critical issue that impacts millions of people worldwide [4]. In India, the state of Chhattisgarh faces significant challenges from arsenic pollution, which threatens the health and well-being of local communities [5]. To address this global concern, the World Health Organization has set a guideline limit of 10 micrograms per litre ($\mu\text{g/L}$) for arsenic in drinking water, emphasizing the urgent need for safe water access [6]. However, even long-term exposure to arsenic at levels

below this threshold can lead to serious health problems, including skin disorders, cardiovascular diseases, and several types of cancer [7]. Traditional methods for reducing arsenic, such as coagulation-filtration, adsorption on activated carbon, and ion exchange, often come with serious challenges [8]. These include high costs, heavy reliance on chemicals, and the risk of causing secondary pollution [9]. These drawbacks highlight the urgent need for innovative, sustainable, and cost-effective solutions to tackle arsenic contamination in groundwater [10]. Researchers are exploring new approaches to repurposing waste materials and adopting environmentally friendly synthesis methods to address this issue [11]. One fascinating idea involves utilizing keratin extracted from the massive amounts of chicken feathers discarded by the poultry industry [12].



Keratin, a fibrous protein found in feathers, holds great promise for environmental remediation [13]. By sustainably extracting keratin from this waste, we can reduce an environmental burden and create a valuable resource [14]. This innovative approach has the potential to combat arsenic pollution effectively while facilitate for a healthier and cleaner ultimate for communities affected by this crisis. Nanotechnology provides innovative solutions to some of the most pressing environmental challenges [15]. It enables the development of nanoparticles with exceptional physical and chemical properties, enhancing their efficiency and versatility [16]. These advanced materials efficiently detect and remove pollutants from air, water, and soil, addressing critical environmental contamination issues [17]. Furthermore, nanoparticles play a pivotal role in renewable energy technologies, such as improving the efficiency of energy storage systems [18]. Integrating nanotechnology into environmental management can create sustainable and scalable solutions to combat ecological degradation [19].

Among various nanomaterials, zinc oxide nanoparticles (ZnO NPs) are particularly notable for their versatility and superior adsorption and pollutant detection capabilities [20]. Green synthesis methods use organic materials and eco-friendly conditions to produce ZnO NPs with minimal environmental impact [21]. These techniques also permit accurate hold under the size, shape, and surface characteristics of ZnO NPs, tailoring them for specific environmental and industrial applications [22].

This study aims to develop an innovative approach by extracting keratin from waste chicken feathers and utilizing it as a sustainable template for the green synthesis of ZnO NPs. These synthesized nanoparticles will then be incorporated into nanogels specially designed to remediate arsenic contamination in groundwater, tackling a critical environmental issue. The research focuses on four primary objectives: extracting keratin from discarded chicken feathers [23], synthesizing eco-friendly ZnO NPs using keratin as a template, developing nanogels infused with these NPs, and systematically evaluating their efficiency in adsorbing arsenic from contaminated water. By addressing the limitations of existing remediation strategies and utilizing waste materials through sustainable synthesis [24], this study aims to deliver

effective and eco-friendly solutions for arsenic contamination in groundwater, both in Chhattisgarh and globally. It provides a detailed analysis of the processes involved, including keratin extraction, the green synthesis of ZnO NPs, the preparation of nanogels, and their effectiveness in arsenic remediation. This research seeks to advance the understanding of sustainable material development and environmental cleanup techniques through an interdisciplinary approach. Furthermore, it aims to establish a framework for tackling other pressing pollution challenges in the future.

2. Experimental

2.1 Materials

Feathers were sourced from local poultry farms in Baloda-Bazar, Chhattisgarh, India. The chemicals used for keratin extraction were of analytical grade and included sodium lauryl sulphate, Tris HCl, urea, 2-mercaptoethanol, and distilled water, all procured from Himedia. Analytic-grade polyvinyl alcohol (PVA) from Himedia synthesised the keratin-PVA nonaogel.

2.2 Methodology

2.2.1 Fabrication of Keratin

Feathers collected from poultry were carefully handled to ensure cleanliness and prevent contamination. After collection, they were thoroughly washed with a mild detergent and rinsed with clean water to remove dirt or residues. The cleaned feathers were then air-dried in a well-ventilated area to ensure they were completely moisture-free. Once dried, the feathers were cut into small, uniform pieces for easier processing. Exactly 10 grams of these prepared feather pieces were weighed for subsequent experimental procedures. A degradation solution was carefully prepared using precise amounts of sodium lauryl sulphate, Tris HCl, urea, 2-mercaptoethanol, and distilled water to extract keratin. Ten grams of cut feather samples were added to the solution and swirled continuously for 24 hours. After this initial breattaking, the compound was left undisturbed for another four days to allow the feathers to break down completely. Throughout the extraction process, detailed observations were made regarding any changes in colour, texture, or degradation of the feathers. The temperature and pH of the degradation solution were closely monitored to ensure optimal conditions for keratin



extraction. The Stepwise process of feather degradation for keratin extraction has been shown in The Fig.1.

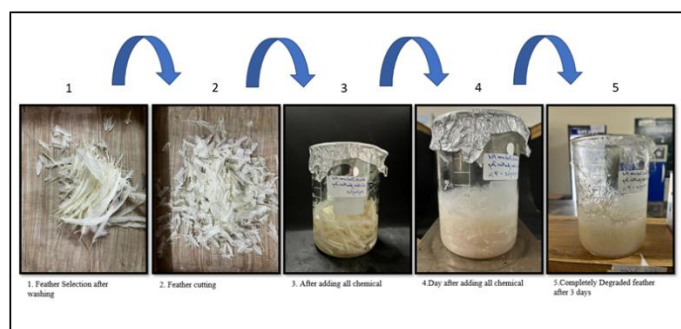


Fig. 1 Stepwise process of feather degradation for keratin extraction

2.2.2 Fabrication of ZnO NPs

In this study, we optimized the green synthesis method from our previous work to produce of ZnO NPs [25]. The process utilized an extract from the Aprajita flower, a natural facilitator for nanoparticle formation. This approach efficiently extracted bioactive compounds while creating an alkaline environment necessary for ZnO nanoparticle synthesis. After the reaction, the nanoparticles were allowed to settle, thoroughly washed, and dried to obtain the final product.

2.2.3. Fabrication of Keratin- PVA/ZnO nanogel

A systematic method was followed to prepare nanogel solutions with varying concentrations. The process began by placing 10 mL of keratin extracted from chicken feathers into a beaker. In a separate beaker, 0.5 mg of PVA was mixed in 10 mL of distilled water and gently agitated to 35- 40 °C using a magnetic stirrer. Once the PVA had fully dissolved, the solution was slowly added to the keratin solution with continuous stirring. Next, ZnO nanoparticles, prepared at a concentration of 1 mg/mL, were incorporated into the mixture. To adjust the pH, a 1N sodium hydroxide (NaOH) solution was added drop by drop until the pH reached between 12 and 13. To solidify the nanogel, 6 mL of a 25% glutaraldehyde solution was gradually introduced while stirring continuously. After 25 minutes of stirring, the solution was poured into a Petri plate and desiccated overnight in a hot air oven set at 60 °C.

This carefully controlled process ensures the formation of nanogel solutions at different concentrations, which can be further studied and applied in various fields.

2.2.4 Characterization

2.2.4.1 Field Emission Scanning Electron Microscopy (FESEM)

FESEM was applied to analyze the surface morphology and structural properties of the nanogel [26]. This technique provided high-resolution images, revealing intricate details of the nanogel's microstructure. Through FESEM, we could observe the surface texture, pore distribution, and overall morphology. These insights are essential for understanding the nanogel's physical characteristics and evaluating its potential in various applications.

2.2.4.2 X-Ray Diffraction (XRD)

XRD was applied to analyse the crystalline structure of the nanogel. This technique offered valuable insights into the material's molecular arrangement and phase composition [27]. Through XRD, we identified the presence of crystalline phases, assessed the degree of crystallinity, and detected any amorphous regions within the nanogel. Understanding these structural properties is essential for predicting the material's stability, mechanical behaviour, and interactions with other substances.

2.2.4.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR was applied to identify the functional moieties and confirm the chemical structure of the nanogel [28]. This technique detected specific chemical bonds, verifying the incorporation of keratin and PVA into the nanogel matrix. The FTIR spectra revealed characteristic absorption bands corresponding to various functional groups,



confirming that the intended chemical modifications were successfully achieved.

2.2.5 Antimicrobial Investigation

The experimental methodology evaluated the antimicrobial efficacy of four samples against four microbial strains: *Staphylococcus aureus* (*S. aureus*), *Pseudomonas*, *Escherichia coli* (*E. coli*), and *Enterobacter* [29]. The sample included a control disc containing tetracycline (30 mcg), discs made from extracted chicken feather keratin, discs combining keratin with 5% PVA, and discs incorporating keratin with 5% PVA and ZnO NPs. Nutrient agar plates were inoculated with bacterial suspensions, and each sample disc was carefully placed on the agar surface to ensure even distribution. After overnight incubation at optimal temperatures, the antimicrobial action was assessed via calculating the dimensions of the clear inhibitory zones surrounding each disc with a calibrated ruler. Larger inhibition zones indicated greater antimicrobial effectiveness. To ensure reliability, the experimental was performed in triplicate, enhancing the robustness and credibility of the results.

2.2.6 Arsenic Uptake Study

In this study, a qualitative analysis of arsenic adsorption was performed using a Merquant test kit, which visually indicates arsenic presence in a solution. The process began by partially inserting a test strip into the cap slot on the reaction vessel. A syringe carefully transferred 5 mL of the liquid for testing into the vessel. A tablespoon of Reagent 1 was introduced into the vessel, and the contents were thoroughly shaken to ensure proper mixing. Next, ten drops of Reagent 2 (HCl 32%) were introduced, and the vessel was sealed immediately. The mixture was permitted to respond for 30 minutes, with gentle swirling at regular intervals. After the reaction, the test strip was extracted, concisely rinsed with H₂O, and gently shaken to remove surplus liquid. The color change in the reaction zone on the strip was then compared against the provided color scale. This qualitative assessment determined the presence of arsenic in the solution, with the intensity of the color change correlating to the concentration of arsenic. This method provides a simple yet reliable approach, enhancing the credibility of the findings.

3. Result and Discussion

3.1. Morphological Analysis

Fig. 2(a), captured at 5000x magnification, shows the surface morphology of the extracted keratin. The image reveals a rough, fibrous texture, indicating the successful degradation of feathers and the release of keratin. This roughness is characteristic of the disordered arrangement of protein fibres, a common feature of keratin obtained through chemical degradation [30]. Figure 2(b), taken at a higher magnification of 50,000x, provides a closer look at the intricate details of the keratin structure. The image highlights delicate, needle-like crystalline fragments embedded within the protein matrix. These fragments likely result from structural changes during the chemical degradation [31]. These microstructures are significant for understanding the surface properties of keratin, which influence its potential applications in fields such as biocomposites and nanomaterials. Figure 2(c), captured at 10,000x magnification, illustrates the network structure of the Keratin-PVA/ZnO nanogel. The fibrous keratin strands are uniformly distributed within the matrix, creating a smooth yet interconnected structure. This uniform blending of keratin with polyvinyl alcohol (PVA) and zinc oxide (ZnO) nanoparticles suggests successful integration. Such homogeneity is essential for ensuring the nanogel's mechanical stability and suitability for potential biomedical and industrial applications. Figure 2(d), taken at 98,970x magnification, provides a highly detailed view of the individual fibres within the nanogel. The smooth surface at this scale confirms that the PVA and ZnO nanoparticles are well integrated into the keratin matrix without disrupting its structural integrity. This nanoscale interaction is critical for understanding the antimicrobial properties of the nanogel and its ability to interact with external factors like pollutants or biological agents. Together, these images offer compelling evidence of the successful synthesis of the Keratin-PVA/ZnO nanogel. The structural features highlighted here demonstrate the nanogel's potential for diverse applications, including antimicrobial coatings and environmental remediation.

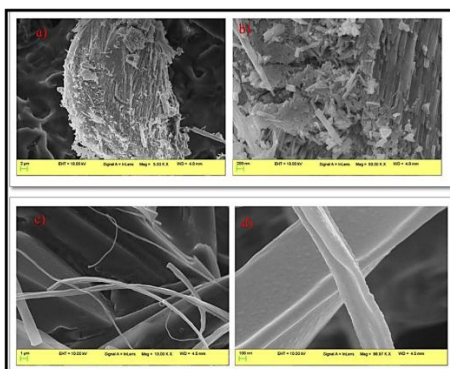


Fig 2 FESEM morphology of Keratin (a, and b), and Keratin-PVA/ZnO Nanogel (c, and d)

3.2 XRD Analysis

The XRD outcomes revealed that the extracted keratin primarily exists in crystalline form, which allows its aqueous condition to maintain the crystalline structure. As shown in Fig. 3(a), the XRD pattern of keratin molecules displayed prominent peaks at 2θ values of 22° , 25° , 30° , 32° , 36° , 38° , 42° and beyond, confirming the proximity of keratin nanoparticles [32]. Notably, the peaks at $2\theta = 22^\circ$ and 32° correspond to the α -helix and β -sheet structures of keratin, respectively [33]. The diffraction properties of keratin nanoparticles further emphasize this observation, with the α -helix appearing at $2\theta = 22^\circ$ and the β -sheet at $2\theta = 25^\circ$ [34]. These findings suggest that keratin molecules possess two primary crystalline structure: α -helix and β -sheet. However, the β -sheet configuration appears more

dominant, highlighting the structural complexity of keratin's crystalline nature. Fig. 3 (b) provides additional insights into the composite nanogel structure. The characteristic semicrystalline peak of PVA was observed around $2\theta = 22^\circ$ and 25° . Moreover, the sharp peaks at 2θ values of 30° , 35° , 38° , 42° , 50° , 58° , and 70° indicate the formation of crystalline ZnO with a hexagonal wurtzite structure [35]. These diffraction patterns confirm the successful incorporation of ZnO particles into the prepared composite nanogel. In summary, the XRD analysis verifies the crystalline nature of keratin and its dominant β -sheet configuration. Furthermore, the presence of ZnO nanoparticles, characterized by their wurtzite structure, confirms the effective formation of the Keratin-PVA/ZnO nanogel.

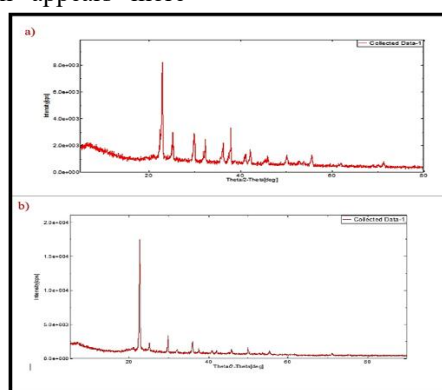


Fig 3 XRD of Keratin (a), and Keratin-PVA/ZnO Nanogel (b)

3.3 FTIR Analysis

The FTIR measurement was used to determine the chemical structure of keratin, as shown in Fig. 4(a). In the FTIR spectra, the absorption band was analyzed in the range of 3600 - 600 cm^{-1} . The results revealed a band

at 3332.2 cm^{-1} , which corresponds to the peptide bonds ($-\text{CO}-\text{NH}-$). Additionally, wavenumbers at 1664 , 1591 , and 1457 cm^{-1} are associated with the peptide bonds and are designated as amide I, II, and III. These bands offer valuable insights into the structure of keratin protein, as



well as alterations in the alignment of its backbone. Amide I comprises an amalgamation of α -helix and β -sheet structures, whereas amide III is associated with the β -sheet structure and can be deconvoluted for enhanced structural insight [36]. For example, at 1149 cm^{-1} , the -OH group of carboxylic acid is observed, and the N-H band is detected in the $702\text{--}600\text{ cm}^{-1}$ range. Therefore, FTIR reveals the presence of amino acids such as glutamine, cysteine, and threonine in the keratin sample [37]. Consequently, it is inferred that the extracted keratin is predominantly made up of β -sheet structures, with fewer α -helices. Next, the chemical reaction between keratin-PVA and ZnO nanoparticles was examined

through FTIR spectroscopy (Fig. 4b). The FTIR spectrum of PVA exhibited bands at $3328, 2920, 2849, 1673, 1457, 1217, 1043,$ and 786 cm^{-1} , which correspond to the vibrations of -OH, -CH₂ asymmetric and symmetric stretching, C=O stretching in the acetate group, CH₂ wagging, -CH₂ stretching, C-H wagging, C-O stretching of the acetyl group, and C-C stretching [38,39]. The FTIR spectrum of Keratin-PVA/ZnO nanogel exhibits a novel peak at 535 cm^{-1} , alongside other peaks associated with PVA attributed to the Zn-O stretching vibration, thereby verifying the existence of zinc oxide nanoparticles [40].

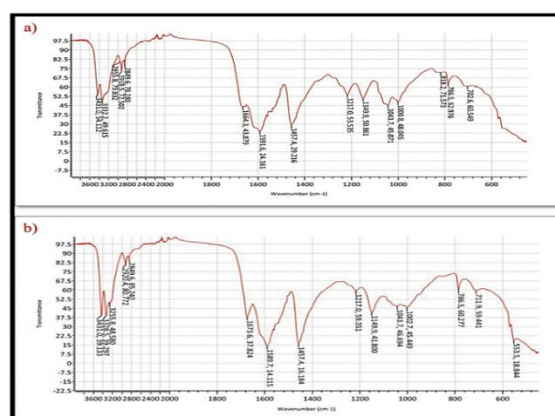


Fig 4 XRD of Keratin (a), and Keratin-PVA/ZnO Nanogel (b)

3.4. Antimicrobial Analysis of Keratin-PVA/ZnO nanogel

To evaluate the antimicrobial effectiveness of the prepared nanogel, we performed a zone of inhibition assay against several bacterial strains. The results clearly showed significant antibacterial activity, with inhibition zones measured in millimeters. Notably, the nanogel demonstrated either comparable or superior effectiveness to Tetracycline (30 mg), especially against *Pseudomonas aeruginosa* and *Staphylococcus aureus*—two bacteria known for their multidrug resistance. Fig. 5(a) shows the bacterial growth before the nanogel treatment, where dense bacterial colonies are visible on the agar plate. On the other hand, Fig. 5(b) presents the post-treatment plate, where clear inhibition zones appear around the nanogel, confirming its antibacterial potential. This

observed antimicrobial activity is consistent with recent advancements in nanogel composites for antibiofilm applications. Studies have shown that nanogels made from natural polymers can effectively serve as carriers for antibacterial agents, inhibiting bacterial growth and biofilm formation [41]. Our findings also support previous research on gelatinase-responsive nanogels, designed for antibacterial phototherapy and wound healing, which further reinforces their potential for clinical use [42]. The improved antibacterial action of nanogel can likely be accredited to the incorporation of ZnO nanoparticles, which are widely recognized for their strong antimicrobial properties. These results highlight the possibility of ZnO-integrated nanogels as encouraging candidates for biomedical applications, particularly in fighting bacterial infections and biofilms.

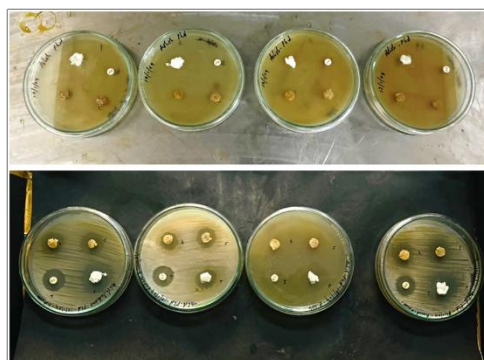


Fig. 5 (a): Bacterial growth before and Fig. 5(b) After nanogel treatment

This study examines the antimicrobial effects of nanogels on four bacterial isolates: *Pseudomonas*, *Staphylococcus aureus*, *Enterobacter*, and *Escherichia coli*. To assess their effectiveness, we measured the zone of inhibition (in millimeters) for each bacterial strain when exposed to different treatments: Tetracycline (30 mg), Keratin, Keratin + PVA, and Keratin + PVA + NP. The results are summarized in Figure 6 below.

The combination of Keratin, PVA, and NP showed the strongest antimicrobial effect against *Pseudomonas*, *S. aureus*, and *Enterobacter*, but it had no impact on *E. coli*. This finding suggests that adding nanogels can significantly boost the antimicrobial properties of treatments, potentially leading to more effective solutions for bacterial infections.

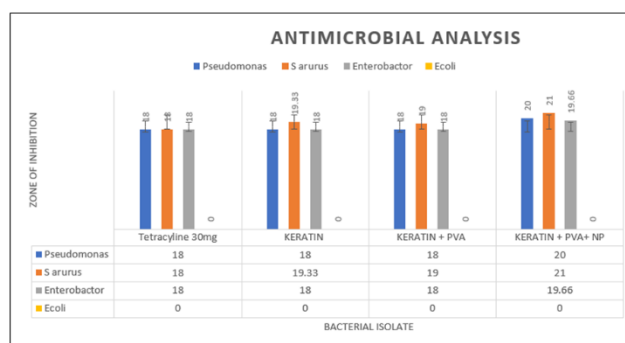


Figure 6 (a): Antimicrobial analysis of nanogel

3.5. Arsenic Adsorption Study

The Merquant test kit's qualitative analysis showed that the keratin-based nano gel effectively removed arsenic from the solution significantly when enhanced with ZnO nanoparticles. In the untreated control sample, the test strip turned brown, confirming the presence of arsenic. When treated with the keratin + PVA nanogel, the strip's colour intensity was reduced, indicating partial arsenic removal. However, no colour change was observed when ZnO nanoparticles were added to the keratin + PVA nanogel, suggesting complete arsenic removal. These results situate with previous examine demonstrating the effectiveness of ZnO nanoparticles in removing arsenic from water. For example, Durthi et al. [43] found that

ZnO nanoparticle-infused membranes exhibited high arsenic removal efficiency. Similarly, Habuda-Stanić and Nujčić [44] reviewed using nanoparticles for arsenic removal and highlighted their advantages over conventional adsorbents. The synergistic effect observed in this study also supports the findings of Singh et al. [45], who used hybrid iron oxide biochar nanocomposites for sustainable arsenite removal at low concentrations. Overall, these results highlight the potential of keratin-based nanogels—particularly when combined with ZnO nanoparticles—as an effective and sustainable solution for arsenic removal in water treatment. This aligns with the ongoing efforts to develop



efficient methods for removing contaminants from water sources.

4. Conclusion

This study fabricated a novel keratin-PVA/ZnO nanogel with promising biomedical and environmental applications. The morphological, structural, and functional examines established the integration of keratin, PVA, and ZnO nanoparticles. The antimicrobial assay demonstrated vigorous antibacterial activity, particularly against drug-resistant strains. Additionally, the nanogel exhibited significant arsenic removal efficiency, highlighting its potential for water purification. These findings underscore the utility of keratin-based composites in developing sustainable biomaterials for healthcare and environmental remediation. Further studies can explore scalability and optimization for industrial applications.

5. Future Directions

Future keratin-PVA/ZnO nanogels research should optimise synthesis parameters to enhance material properties and functional performance. Studies should investigate the long-term stability of the nanogel, particularly under varied environmental conditions, to determine its durability for industrial-scale applications. Additionally, advanced in-vitro and in-vivo biocompatibility assessments will be crucial to evaluate its safety for medical and pharmaceutical applications. Expanding the scope of antimicrobial studies by testing against multi-drug-resistant bacterial strains will provide deeper insights into its potential as an alternative to conventional antibiotics. Further research should also explore the nanogel's effectiveness against fungal and viral pathogens, broadening its biomedical applicability.

The arsenic removal potential demonstrated in this study indicates the need for extensive field trials to validate its performance in real-world water purification scenarios. Future studies should examine the adsorption kinetics and regeneration capabilities of the nanogel to improve its cost-effectiveness and reusability. Integrating other functional nanoparticles or bioactive agents could enhance the nanogel's therapeutic and environmental applications. Exploring its use in wound healing, controlled drug delivery, and heavy metal remediation will help establish its versatility. Finally, scaling up

production while ensuring economic feasibility and sustainability will be key for its commercial adoption.

Acknowledgements

The authors are grateful to director, CSIR-NEERI, for providing the necessary facilities for this work. The manuscript is checked for plagiarism using licensed version of iThenticate software and recorded in the Knowledge Resource Centre, CSIR-NEERI, Nagpur for anti-plagiarism (KRC No.: CSIR-NEERI/KRC/20 NEERI/KRC/2025/MARCH/AR/1)

Reference

- [1] Narkhede S, Phillips E, Singhai A, Dadsena A, Sahu R, Arfin T, Shakya A, Parkhey P. Removal of Inorganic and Organic Pollutants from Soil by Biochar Application: A Sustainable Approach to Improve Soil Health. In *Catalytic Applications of Biochar for Environmental Remediation: Sustainable Strategies Towards a Circular Economy (Vol 2) 2024* (pp. 95-140). American Chemical Society. <https://pubs.acs.org/doi/abs/10.1021/bk-2024-1479.ch005>
- [2] Arfin T. Active Ingredients Enabled Edible Coatings and Films Improve Shelf Life of Food: An Overview. *Biomaterials in Food Packaging*. 2022 Sep 22:49-81.
- [3] Arfin T. Current innovative chitosan-based water treatment of heavy metals: A sustainable approach. In *Handbook of Biopolymers 2018* Oct 31 (pp. 167-182). Jenny Stanford Publishing.
- [4] Shaji E, Santosh M, Sarath KV, Prakash P, Deepchand V, Divya BV. Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. *Geoscience frontiers*. 2021 May 1;12(3):101079. <https://doi.org/10.1016/j.gsf.2020.08.015>
- [5] Shukla DP, Dubey CS, Singh NP, Tajbakhsh M, Chaudhry M. Sources and controls of Arsenic contamination in groundwater of Rajnandgaon and Kanker District, Chattisgarh Central India. *Journal of Hydrology*. 2010 Dec 6;395(1-2):49-66. <https://doi.org/10.1016/j.jhydrol.2010.10.011>
- [6] Shankar S, Shanker U, Shikha. Arsenic contamination of groundwater: a review of sources, prevalence, health risks, and strategies for mitigation. *The scientific world journal*. 2014;2014(1):304524. <https://doi.org/10.1155/2014/304524>
- [7] Fatoki JO, Badmus JA. Arsenic as an environmental and human health antagonist: A review of its toxicity and disease initiation. *Journal of Hazardous Materials Advances*. 2022 Feb



- 1;5:100052.<https://doi.org/10.1016/j.hazadv.2022.100052>
- [8] Nicomel NR, Leus K, Folens K, Van Der Voort P, Du Laing G. Technologies for arsenic removal from water: current status and future perspectives. *International journal of environmental research and public health*. 2016 Jan;13(1):62. <https://doi.org/10.3390/ijerph13010062>
- [9] Rahidul Hassan H. A review on different arsenic removal techniques used for decontamination of drinking water. *Environmental Pollutants and Bioavailability*. 2023 Dec 31;35(1):2165964. <https://doi.org/10.1080/26395940.2023.2165964>
- [10] Marghade D, Mehta G, Shelare S, Jadhav G, Nikam KC. Arsenic contamination in Indian groundwater: From origin to mitigation approaches for a sustainable future. *Water*. 2023 Nov 28;15(23):4125. <https://doi.org/10.3390/w15234125>
- [11] Waghmare S, Arfin T, Lataye D, Rayalu S, Manwar N, Labhsetware N. Adsorption behavior of eggshell modified polyalthia longifolia leaf based alumina as a novel adsorbents for fluoride removal from drinking water. *International Journal of Advance Research and Innovative Ideas in Education*. 2015;1(5):904-25.
- [12] Mengistu A, Andualem G, Abewaa M, Berhane D, Angassa K, Mamuye W, Dinku A, Bekele N. Integrated circular economic approach of solid waste management and resource recovery: Poultry feather-based keratin extraction and its application in leather processing. *Results in Engineering*. 2024 Sep 1;23:102578. <https://doi.org/10.1016/j.rineng.2024.102578>
- [13] Perța-Crișan S, Ursachi CȘ, Gavrița S, Oancea F, Munteanu FD. Closing the loop with keratin-rich fibrous materials. *Polymers*. 2021 Jun 7;13(11):1896. <https://doi.org/10.3390/polym13111896>
- [14] Maurya SD, Singh A. Extraction and Characterization of Keratin from Waste Broiler Chicken Feathers. *Environmental Protection Research*. 2023 Nov 24:372-81. <https://doi.org/10.37256/epr.3220233579>
- [15] Arfin T, Tarannum A. Polymer materials: from the past to the future. *Green polymeric materials: advances and sustainable development*. 2017:35-52.
- [16] Arfin T, Mohammad F. Electrochemical, dielectric behaviour and in vitro antimicrobial activity of polystyrene-calcium phosphate. *Adv Ind Eng Manag*. 2014;3(3):25-38.
- [17] Somanathan A, Mathew N, Arfin T. Environmental impacts and developments in waste-derived nanoparticles for air pollution control. *Waste-Derived Nanoparticles*. 2024 Jan 1:281-318.
- [18] Obulapuram PK, Arfin T, Mohammad F, Khiste SK, Chavali M, Albalawi AN, Al-Lohedan HA. Adsorption, equilibrium isotherm, and thermodynamic studies towards the removal of reactive orange 16 dye using Cu (I)-polyaniline composite. *Polymers*. 2021 Oct 11;13(20):3490. <https://doi.org/10.3390/polym13203490>
- [19] Mohammad F, Arfin T, Al-lohedan HA. Enhanced biosorption and electrochemical performance of sugarcane bagasse derived a polylactic acid-graphene oxide-CeO₂ composite. *Materials Chemistry and Physics*. 2019 May 1;229:117-23. <https://doi.org/10.1016/j.matchemphys.2019.02.085>
- [20] Arfin T, Rangari SN. Graphene oxide-ZnO nanocomposite modified electrode for the detection of phenol. *Analytical Methods*. 2018;10(3):347-58.
- [21] Onwudiwe DC, Arfin T, Strydom CA. Surfactant mediated synthesis of ZnO nanospheres at elevated temperature, and their dielectric properties. *Superlattices and Microstructures*. 2015 May 1;81:215-25.
- [22] Onwudiwe DC, Arfin T, Strydom CA, Kriek RJ. A study of the thermal and AC impedance properties of N-phenyldithiocarbamate complexes of Zn (II). *Electrochimica Acta*. 2013 Oct 30;109:809-17. <https://doi.org/10.1016/j.electacta.2013.07.176>
- [23] Nadda, Ashok & Sharma, Swati. (2019). Keratin as a Protein Biopolymer: Extraction from Waste Biomass and Applications. 10.1007/978-3-030-02901-2. DOI:10.1007/978-3-030-02901-2
- [24] Ghosh NC, Singh RD. Groundwater arsenic contamination in India: vulnerability and scope for remedy. In *Tecnical Paper included in the special session on Ground water in the 5th Asian Regional Conference of INCID 2009 Dec 9 (pp. 9-11)*.
- [25] Dadsena A, Narkhede S, Singhai A, Kolla V, Sahu R, Arfin T, Parkhey P. Green synthesis of zinc oxide nanoparticles from Clitoria ternatea extract: Dual functionality in arsenic adsorption and antibacterial applications," *Research Journal of Pharmacy and Technology*, vol. 18, no. 11, 2025.
- [26] Bushra R, Arfin T, Oves M, Raza W, Mohammad F, Khan MA, Ahmad A, Azam A, Muneer M. Development of PANI/MWCNTs decorated with cobalt oxide nanoparticles towards multiple electrochemical, photocatalytic and biomedical application sites. *New Journal of Chemistry*. 2016;40(11):9448-59.
- [27] Mohammad F, Plessis L, Arfin T. X-ray analysis of metal oxide-metal core-shell nanoparticles. *X-ray*



- diffraction: structure, principles and applications. 2013:161-81.
- [28] Waghmare S, Arfin T, Rayalu S, Lataye D, Dubey S, Tiwari S. Adsorption behavior of modified zeolite as novel adsorbents for fluoride removal from drinking water: surface phenomena, kinetics and thermodynamics studies. *International Journal of Science, Engineering and Technology Research*. 2015 Dec;4(12):4114-24.
- [29] Arfin T, Mohammad F. Dendrimer and its role for the advancement of nanotechnology and bioengineering. *Advances in materials science research*. 2015;21:157-74.
- [30] Amin S, Abbas M, Javed H, Asghar Z, Ghani N, Shaheen S, Hassan F, Akram R, Yousaf HS. Extraction of keratin from chicken feathers and its application in the treatment of contaminated water: an eco-friendly approach. *Brazilian Archives of Biology and Technology*. 2024 Mar 22;67:e24220892. <https://doi.org/10.1590/1678-4324-2024220892>
- [31] Misra M, Kar P, Priyadarshan G, Licata C. Keratin protein nano-fiber for removal of heavy metals and contaminants. *MRS Online Proceedings Library*. 2001 Jan;702:1-7. <https://doi.org/10.1557/PROC-702-U2.1.1>
- [32] Isarankura Na Ayutthaya S, Tanpichai S, Wootthikanokkhan J. Keratin extracted from chicken feather waste: extraction, preparation, and structural characterization of the keratin and keratin/biopolymer films and electrospuns. *Journal of Polymers and the Environment*. 2015 Dec;23:506-16.
- [33] Song K, Xu H, Xie K, Yang Y. Keratin-based biocomposites reinforced and cross-linked with dual-functional cellulose nanocrystals. *ACS Sustainable Chemistry & Engineering*. 2017 Jul 3;5(7):5669-78. <https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.7b00085>
- [34] Esparza Y, Ullah A, Wu J. Preparation and characterization of graphite oxide nano-reinforced biocomposites from chicken feather keratin. *Journal of Chemical Technology & Biotechnology*. 2017 Aug;92(8):2023-31. <https://doi.org/10.1002/jctb.5196>
- [35] Narayanan PM, Wilson WS, Abraham AT, Sevanan M. Synthesis, characterization, and antimicrobial activity of zinc oxide nanoparticles against human pathogens. *BioNanoScience*. 2012 Dec;2(4):329-35.
- [36] Wang YX, Cao XJ. Extracting keratin from chicken feathers by using a hydrophobic ionic liquid. *Process biochemistry*. 2012 May 1;47(5):896-9. <https://doi.org/10.1016/j.procbio.2012.02.013>
- [37] Kamarudin NB, Sharma S, Gupta A, Kee CG, Chik SM, Gupta R. Statistical investigation of extraction parameters of keratin from chicken feather using Design-Expert. 3 *Biotech*. 2017 Jun;7:1-9. <https://doi.org/10.1007/s13205-017-0767-9>
- [38] Arfin T, Falch A, Kriek RJ. Evaluation of charge density and the theory for calculating membrane potential for a nano-composite nylon-6, 6 nickel phosphate membrane. *Physical Chemistry Chemical Physics*. 2012;14(48):16760-9. <https://doi.org/10.1039/C2CP42683H>
- [39] Arfin T, Mohammad F. Synthesis, characterization and influence of electrolyte solutions towards the electrical properties of nylon-6, 6 nickel carbonate membrane: test for the theory of uni-ionic potential based on thermodynamics of irreversible processes. *Halides: chemistry, physical properties and structural effects*. 2013:39-66.
- [40] PT SK, Lakshmanan VK, Raj M, Biswas R, Hiroshi T, Nair SV, Jayakumar R. Evaluation of wound healing potential of β -chitin hydrogel/nano zinc oxide composite bandage. *Pharmaceutical research*. 2013 Feb;30:523-37.
- [41] Ali AA, Al Bostami RD, Al-Othman A. Nanogel-based composites for bacterial antibiofilm activity: advances, challenges, and prospects. *RSC advances*. 2024;14(15):10546-59. <https://doi.org/10.1039/D4RA00410H1>
- [42] Han Q, Wang X, Qiu L, Zhou X, Hui Z, Ni X, Xuan Y, Lei X, Wang J. Gelatinase responsive nanogel for antibacterial phototherapy and wound healing. *Gels*. 2022 Jun 23;8(7):397. <https://doi.org/10.3390/gels8070397>
- [43] Potla Durthi C, Rajulapati SB, Palliparambi AA, Kola AK, Sonawane SH. Studies on removal of arsenic using cellulose acetate-zinc oxide nanoparticle mixed matrix membrane. *International Nano Letters*. 2018 Sep;8:201-11. <https://doi.org/10.1007/s40089-018-0245-3>
- [44] Habuda-Stanić M, Nujić M. Arsenic removal by nanoparticles: a review. *Environmental Science and Pollution Research*. 2015 Jun;22:8094-123. <https://doi.org/10.1007/s11356-015-4307-z>
- [45] Singh P, Sarswat A, Pittman Jr CU, Mlsna T, Mohan D. Sustainable low-concentration arsenite [As (III)] removal in single and multicomponent systems using hybrid iron oxide-biochar nanocomposite adsorbents—A mechanistic study. *Acs Omega*. 2020 Feb 6;5(6):2575-93.