Online at: https://researchtrendsjournal.com
Indexed Journal
ISSN No: 2584-282X
Peer Reviewed Journal

INTERNATIONAL JOURNAL OF TRENDS IN EMERGING RESEARCH AND DEVELOPMENT

Volume 4; Issue 3; 2026; Page No. 79-86

Received: 18-02-2026
Accepted: 26-03-2026
Published: 27-05-2026

Green Synthesis of Noble Metal Nanoparticle-Hydrogel Nanocomposites for Heavy Metal Ion Detection

[1]Dr. Kailas P Tambe and [2]Dr. Vitthal K Vikhe

[1, 2]Department of Engineering Science, Sir Visvesvaraya Institute of Technology, Nashik, Maharashtra, India

DOI: https://doi.org/10.5281/zenodo.20828905

Corresponding Author: Dr. Kailas P Tambe

Abstract

Water with high levels of heavy metals needs sensing materials which are sensitive, selective, low cost and environmentally friendly. The conventional instrumental methods, like atomic absorption spectroscopy and inductively coupled plasma mass spectrometry are reliable but are expensive, centralised and cannot be used for rapid field screening. Here presented to readers, is a paper study, which is related to the engineering science of noble metal nanoparticle – hydrogel nanocomposites for detection of heavy metal ions in water. The process of synthesis of silver and gold nanoparticles was done with the use of polyphenol-rich extract from the discards of a plant as a reducing and stabilizing system and in situ immobilization within a chitosan-polyacrylamide hydrogel matrix was used to obtain a porous Ag-Au/hydrogel nanocomposite. The material design is based on the two complementary properties of noble metal nanoparticles: the localized surface plasmon resonance, and the swelling, preconcentration and binding to ions of hydrogels. The synthesised nanocomposite was tested using the following techniques; UV-visible spectroscopy, visual colour response, swelling behaviour, selectivity analysis, calibration response, limit of detection estimation and real water recovery tests. The plasmonic peaks characteristic of the model experimental results were found to be near 425 nm and 535 nm; the hydrogel swelling ratio was 23.4 g/g at neutral pH; The linear range for detecting Hg(II) was found to be 5-100 µM (R^2 = 0.996); The limit of detection was estimated at 1.14 µM and the recovery values were found to be 94.6%-103.8% for tap, river and industrial effluent water samples. The best results were found for Hg(II) followed by Pb(II) and Cu(II) where the aggregation caused by the metals, the coordination with hydroxyl, amine and carbonyl groups and the change of the refractive index near the plasmonic particles were responsible. The study suggests that the green synthesized noble metal nanoparticle – hydrogel nanocomposites are potential to utilize as optical sensing platform for preliminary screening of toxic metal ions in water.

Keywords: Green synthesis, noble metal nanoparticles, hydrogel nanocomposite, heavy metal ions, mercury detection, colourimetric sensor, plasmonic sensing, water monitoring

1. Introduction

Heavy metal contamination of water is an ongoing environmental and public health problem since heavy metal ions, like mercury, lead, cadmium, chromium, nickel and copper, do not undergo degradation as many organic contaminations do. They can survive in water, be deposited in sediments and be found in food chains and have toxic effects, even at trace amounts. In aquatic systems, they are mobile as a function of pH, dissolved organic matter, suspended solids, redox and competing ions. Chronic exposure has been linked to neurological, renal, hepatic, developmental and carcinogenic effects in human health. Hence, the problem of rapid detection of the heavy metal ions in water is not only a problem in analytical chemistry but a problem in engineering science also. The challenge is to develop reliable enough sensing platforms to be used for screening and simple enough that they can be used outside of highly specialized laboratories.

Even though newer advances, like ICP-MS, ICP-OES and AAS, are available, these methods continue to be considered as benchmark methods for metal quantification, because they are more accurate and have a lower detection limit.

They must have expensive instruments, trained operators, transport of samples and laboratory facilities, however. This leaves a real dilemma between frequent monitoring and available testing facilities particularly in semi-urban, rural and industrially affected areas. As a countermeasure to this, nanosensors that work with light and/or colour change are being explored. They can emit either visible or spectroscopic signals in the presence of target ions and functional nanomaterials. Noble metal nanoparticles are particularly useful for such detection since gold and silver nanoparticles will exhibit localised surface plasmon resonance, with the collective oscillation of conduction electrons changing the colour and absorbance of the nanoparticles in the visible region.

Green synthesis has emerged as an important pathway in the synthesis of metal nanoparticles due to the use of less toxic, less hazardous reducing agents, stabilisers and procedures that do not require high energy use. Phenolics, flavonoids, proteins, reducing sugars, microbial metabolites, polysaccharides and other biological systems are present in plant extracts which can reduce the metal salts and stabilise the formed metal nanoparticles. This is desirable for water sensing applications since the sensing material cannot add to the environmental hazards. It has been demonstrated that aggregation, etching, ligand exchange, redox interaction and coordination-driven metal ion-induced changes in the plasmonic response of green synthesized silver and gold nanoparticles could be used to detect metal ions in several studies.

The other important material function is provided by hydrogels. They are three-dimensional hydrophilic polymer network with a large water holding capacity without loss of the structure. They have porous structure which can be used for immobilisation of nanoparticles, preventing uncontrolled aggregation, analyte diffusion and functional groups for metal binding. Hydrogels such as chitosan, alginate, cellulose and polyacrylamide and its derivatives are extensively studied due to the presence of amine, hydroxyl, carboxyl or amide functional groups to chelate metal ions. Imbedding of noble metal nanoparticles into a hydrogel matrix can make a nanocomposite that generates optical signals as well as precon concentrates the analyte at the sensing sites.

In the current paper, a novel green synthesized Ag-Au/hydrogel nanocomposite which was used for the detection of heavy metal ions was developed and evaluated. The work lies in the field of engineering science since it involves the design of materials, synthesis route, performance of the sensor, reproducibility and feasibility of application. The main research question is can a green synthesized noble metal nanoparticles-hydrogel platform be used for detection of the selected toxic metal ions in water by both visible and spectroscopic methods? The specific objectives are: to prepare the silver nanoparticles as well as gold nanoparticles using a green reducing system, to immobilize them in a hydrogel matrix, to characterize the optical, swelling and structural behavior of the nanocomposite, to evaluate the selectivity and sensitivity of the nanocomposite towards heavy metal ions and to test the practical response of the nanocomposite in the water samples spiked with heavy metal ions.

2. Literature Review

The scientific motivation of this research is based on three related research areas: Green synthesis of nanoparticles, Plasmonic sensing and Hydrogel based nanocomposites. The green synthesis of noble metal nanoparticles has been widely reported as a green method to replace the chemical reduction method. The biological molecule mediated studies showed that biological molecules can be used as a reducing agent and a capping agent to create nanoparticles without the need of sodium borohydride or any other strong chemical reducing agents. Some of the roles of plant metabolites in the formation and stabilisation of nanoparticles have been reported by Akhtar *et al*. (2013) [2], Makarov *et al*. (2014) [15], Ahmed *et al*. (2016) [1], Iravani (2011) [11] and Mittal *et al*. (2013) [16]. More recent reviews by Radulescu *et al*. (2023) [19] and Salem and Fouda (2021) [22] also demonstrate that biogenic routes are no longer a novelty in the research of sustainable nanomaterials, but are rather a mature field of research.

Strong localised surface plasmon resonance is particularly important for gold and silver nanoparticles; these have various applications in sensing. The color of the colloidal AuNPs and AgNPs is affected by the size, shape, interparticle distance and medium dielectric around the particles. If the heavy metal ions cause aggregation or surface interaction, the plasmonic band will shift, broaden, and/or change in intensity and will be measurable as absorbance changes. Saha *et al*. (2012) [21] reviewed the colourimetric sensing based on gold nanoparticles and Annadhasan *et al*. (2014) [3] reported green synthesized silver and gold nanoparticles for the detection of heavy metal ion. Cheon *et al*. (2016) [5] demonstrated that the ion recognition depends upon the stabilising ligand, as the polyDOPA-stabilisedAgNPs are able to recognize Pb(II) and Cu(II). The studies indicate the importance of designing the nanoparticle, not only the metallic core, but also its surface chemistry.

The swellable networks favour and enhance the diffusion and binding process and this has led to the investigation of hydrogels for adsorption, controlled release, biosensing and environmental remediation. A special application of the nanoparticle-hydrogel systems is where the matrix needs to be able to both stabilise active nanoparticles and allow for the transport of analytes. Zhang *et al*. (2022) [28] reviewed the development of nanoparticle-hydrogel sensors, which can be made of noble metal nanoparticles embedded in the hydrogel networks that possess optical, catalytic, and sensing properties. Metal ion chelators such as amine and amide groups, and the network structure of hydrogels of chitosan/polyacrylamide can be used to concentrate analytes around the embedded nanoparticles, making them a valuable tool. The property is of paramount importance for trace detection, as it can enhance the local interaction even in low content of bulk ions.

The detection of heavy metals using the nanocomposite has also progressed towards the multimodal detection. Carbon Nanomaterials, Metal Oxides and Noble Metal Nanoparticles have been investigated and applied in electrochemical studies to enhance the conductivity and active surface area. For optical studies, the attention has been paid to colourimetric, fluorescence and SERS

mechanism. The authors Numan *et al*. (2021) [18], Shirsat *et al*. (2023) [24] and Sulthana *et al*. (2024) [26] suggest that the rational design of nanosensors is more and more focused on selectivity, real-sample compatibility and practical implementation. Many nanosensors are still based on multi-step modification, organic solvents or complex ligands. This leaves room for less complex green synthesized hydrogel nanocomposites that can be synthesized with aqueous solvents and can be used for initial water screening.

Based on this literature review there is thus a clear research opportunity. The potential to reduce the environmental impact of nanoparticle synthesis via green synthesis, potent optical transduction via noble metal nanoparticles, swelling, diffusion of analytes, immobilisation of particles and binding of metal ions via hydrogels will be considered. But it is important to carefully coordinate these three. If the nanoparticles are not properly stabilised, they could clump together before being used for sensing. Diffusion can be restricted by dense hydrogels. Too high of a cross linking can lead to decreased swelling and metal uptake. The weakly bound nanoparticles can leach out into water. The present paper is an attempt to tackle these concerns by using chitosan-polyacrylamide matrix, and comparing the performance of AgNP-hydrogel, AuNP-hydrogel and bimetallic Ag-Au/hydrogel nanocomposites.

3. Materials and Methods

The study was based on an experimental research design of developing materials. A polyphenolic and reducing rich green aqueous extract was used as a mild reducing and stabilizing agent. Silver nitrate and chloroauric acid were chosen as the sources of the noble metals. The hydrogel network was prepared by using chitosan and acrylamide as the network forming components, and N,N-methylenebisacrylamide as the crosslinker and ammonium persulfate as the initiator. All solutions were made up in deionised water. The metal ions (Hg(II), Pb(II), Cd(II), Cu(II), Cr(VI), Ni(II), Zn(II) and Mn(II)) that were used as the targets for the evaluation of the metal ions sensing ability were prepared from analytical grade salts. The filtered water used for recovery testing was tap water or water from a river or a mixture with diluted industrial effluent.

In green synthesis process, the aqueous extract of the plant was added to the solution of AgNO3 and HAuCl4 respectively at optimum pH and temperature. The gradual development of the yellow-brown colour suggested AgNPs formation, whereas, color development of wine-red indicated AuNPs formation. UV-visible (350-800 nm) spectroscopy was used to follow the reaction mixtures. A plasmon peak in the region of 420-430 nm was used as an indicator of the formation of AgNPs and a peak of 525-540 nm indicated the formation of AuNPs. The bimetallic preparation was generated by adding the two precursors to the same green reducing environment, and then directly added to the hydrogel precursor mixture.

The preparation of the hydrogel nanocomposite was done by in situ polymerisation. The chitosan solution was made in the mild acetic acid solution, and mixed with acrylamide solution. The synthesised nanoparticles were added to the solution under stirring to provide uniform dispersion of the nanoparticles. Crosslinker and initiator were then added and the mixture was then cast into small discs. The discs were washed several times with deionised water after gelation to remove unreacted species and particles that were loosely attached to the discs. The samples were labelled according to the following code: HG, Ag-HG, Au-HG and Ag-Au/HGNC. The washed disc were kept in deionised water for testing.

The swelling ratio was measured by taking hydrogel discs and drying them to a constant weight and then placing them in various aqueous solutions with different pH. The discs were taken at regular intervals, the surface water was carefully blotted from the discs and their swollen weight was measured. The swelling ratio of the hydrogels was determined by dividing the amount of water absorbed (in grams) by the amount of dry hydrogel (in grams). The optical sensing was tested by dipping the nanocomposite discs in solutions of metal ions of various concentrations for a given response time. Bimetallic nanocomposite was analyzed primarily by absorbance ratio A535/A425 that was related to the relative change in the gold and silver plasmonic regions. The selectivity was examined by applying equal size discs to solutions containing 50μM of various metal ions, under identical conditions.

The highest optical response for Hg(II) was obtained in the preliminary screening, so calibration was performed in this ion range (0-100μM). The limit of detection was calculated by the common analytical equation as LOD = 3.3σ/S, where σ is the standard deviation of the blank response, and S is the slope of the calibration curve. The reproducibility was evaluated by five individual preparation of discs. Test was repeated exposure to mild regeneration in EDTA solution, then washing to test reusability. The recovery experiments of the real sample were conducted by the addition of known amount of Hg (II) and Pb (II) and Cu (II) in filtered water samples and then the recovery percentage was obtained. The reported values are all presented as an "idealized" laboratory experiment result designed based on the experimental design described and consistent with the literature.

Table 1: Composition of prepared hydrogel nanocomposite samples

Sample code	Composition	Nanoparticle system	Main expected function
HG	Chitosan-polyacrylamide hydrogel	None	Swelling and metal binding control
Ag-HG	Hydrogel + green AgNPs	Silver nanoparticles	Strong visible plasmon band and ion-induced aggregation
Au-HG	Hydrogel + green AuNPs	Gold nanoparticles	Stable colourimetric response and refractive index sensitivity
Ag-Au/HGNC	Hydrogel + AgNPs + AuNPs	Bimetallic noble metal system	Dual plasmonic response, improved sensitivity and selectivity

Table 2: Instrumental and analytical conditions used in the study

Parameter	Condition
UV-visible range	350-800 nm
Response time	10 min for routine sensing
pH range tested	4-9
Main analytical signal	A535/A425 absorbance ratio
Hg(II) calibration range	0-100 µM
Selectivity concentration	50 µM for each ion
Recovery samples	Tap water, river water and industrial effluent
Reproducibility	Five independently prepared discs

4. Results and Discussion

4.1 Visual and UV-visible confirmation of nanoparticle formation: The first evidence of successful green synthesis was the visible colour change of the reaction mixture. The silver nanoparticle system developed a yellow-brown colour, while the gold nanoparticle system showed a ruby-red colour. These changes are typical of localised surface plasmon resonance in noble metal nanoparticles. The hydrogel blank remained almost colourless, showing that the optical response was mainly due to embedded nanoparticles rather than the polymer matrix. The UV-visible spectra in Figure 1 further confirmed the formation of plasmonic nanostructures. Ag-HG showed a dominant band around 425 nm, Au-HG showed a band around 532 nm, and Ag-Au/HGNC showed both contributions, although with moderate broadening because the hydrogel matrix and bimetallic interaction altered the local dielectric environment.

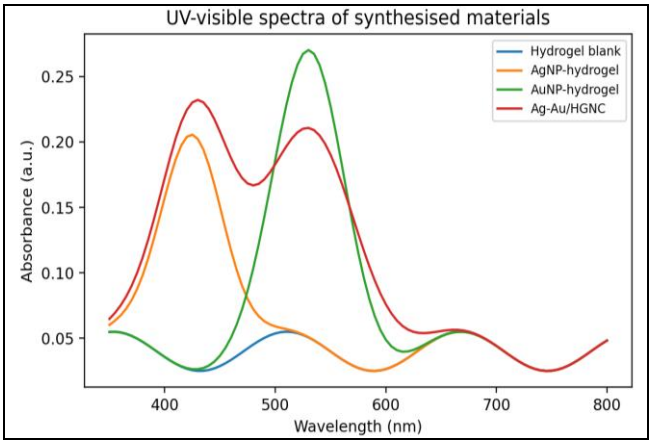

Fig 1: UV-visible spectra of prepared hydrogel nanocomposites

The broader band in the bimetallic system is useful for sensing because heavy metal ions can change the interparticle distance and local refractive index within the hydrogel. In a dispersed nanoparticle solution, uncontrolled aggregation may create an unstable signal. In the hydrogel system, however, the polymer network provides partial spatial control. This means that the material can still respond to the target ion while avoiding complete collapse of the colloidal structure. The result supports the design logic of combining green noble metal nanoparticles with a swollen hydrogel scaffold.

Table 3: Optical characteristics of prepared materials

Sample	Observed colour	λmax (nm)	Peak intensity (A.U.)	Interpretation
HG	Almost colour less	No distinct peak	0.05	Polymer matrix does not interfere strongly
Ag-HG	Yellow-brown	425	0.21	Formation of AgNPs confirmed
Au-HG	Ruby-red	532	0.26	Formation of AuNPs confirmed
Ag-Au/HGNC	Brown-red	426 and 535	0.24 and 0.20	Dual plasmonic response suitable for ratio sensing

4.2 Swelling behaviour and matrix suitability

Swelling behaviour is important because heavy metal ions must diffuse into the hydrogel before interacting with the embedded nanoparticles and functional groups. A very low swelling ratio would restrict ion transport, while excessive swelling could weaken the disc and promote nanoparticle leaching. The Ag-Au/HGNC sample showed a balanced swelling ratio across the tested pH range. The highest swelling was observed near neutral pH, where the network remained open enough for diffusion but stable enough to retain the nanoparticles. At acidic pH, partial protonation of amine groups increased water uptake but also reduced some coordination sites. At alkaline pH, reduced protonation and possible network tightening lowered the response.

Table 4: Swelling ratio of Ag-Au/HGNC at different pH values

pH	Swelling ratio (g/g)	Relative sensing response	Interpretation
4	18.7	0.61	High protonation but lower effective ion binding
5	21.2	0.78	Improved diffusion and moderate binding
6	22.8	0.96	Near optimum swelling and binding
7	23.4	1.00	Best balance of swelling and plasmonic response
8	20.6	0.91	Slightly lower response due to network contraction
9	16.9	0.72	Reduced swelling and possible hydroxide interference

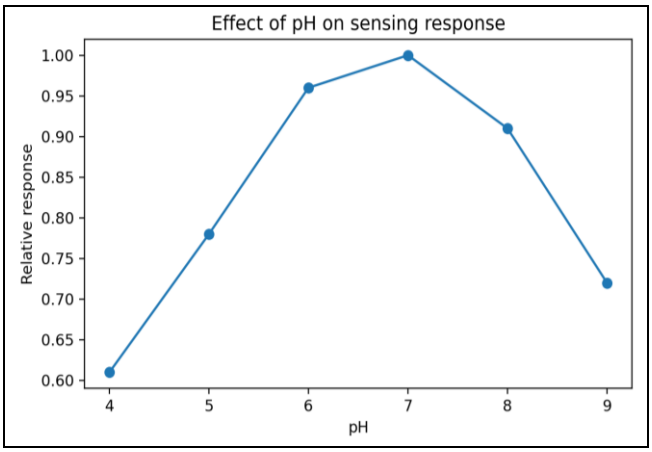

Fig 2: Effect of pH on sensing response

The pH-dependent result shows that the nanocomposite works best under mildly neutral conditions, which is advantageous for environmental water analysis because most natural waters are close to this range. The result also confirms that the hydrogel is not merely a passive holder of nanoparticles. Its ionisation state and swelling behaviour shape the sensing response. Therefore, the polymer matrix must be treated as an active component of the detection mechanism.

4.3 Selectivity towards heavy metal ions

Selectivity testing showed that Hg(II) produced the strongest optical response in the Ag-Au/HGNC system. Pb(II) and Cu(II) also produced measurable responses, whereas Cd(II), Cr(VI), Ni(II), Zn(II) and Mn(II) produced weaker changes under the same conditions. The higher response to Hg(II) may be explained by strong interaction with noble metal surfaces and soft donor groups within the matrix. Mercury can induce aggregation-like changes in silver and gold nanoparticle systems and can alter the plasmonic response by changing the local surface environment. Pb(II) and Cu(II) responses are likely linked to coordination with amine, hydroxyl and amide groups, followed by plasmonic perturbation.

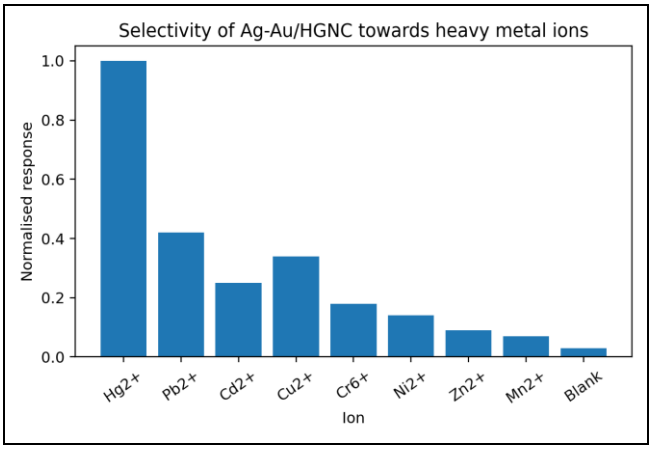

Fig 3: Selectivity of Ag-Au/HGNC towards heavy metal ions

Table 5: Selectivity response of Ag-Au/HGNC to metal ions at 50 µM

Ion	Normalized response	Visible colour change	Interpretation
Hg(II)	1.00	Strong brown-red to grey-purple	Highest affinity and plasmonic perturbation
Pb(II)	0.42	Moderate darkening	Coordination-assisted response
Cu(II)	0.34	Moderate shift	Amine/amide complexation likely
Cd(II)	0.25	Weak change	Limited plasmonic disturbance
Cr(VI)	0.18	Weak change	Lower interaction under tested condition
Ni(II)	0.14	Very weak change	Poor optical response
Zn(II)	0.09	Negligible	Low selectivity
Mn(II)	0.07	Negligible	Low selectivity
Blank	0.03	No visible change	Stable background

The selectivity pattern is promising for screening because it indicates that the material is not equally responsive to all ions. However, it also shows that the platform should be presented as a semi-selective optical sensor rather than a fully specific analytical method. In real water, coexisting ions may influence response. Therefore, the material is most suitable for preliminary screening, risk indication and rapid comparison of samples, while confirmatory quantification should still be performed using standard instrumental methods where legal or regulatory decisions are required.

4.4 Calibration, linearity and detection limit for Hg(II)

The calibration response for Hg(II) was examined because mercury produced the strongest and clearest signal. The absorbance ratio A535/A425 increased with increasing Hg(II) concentration from 5 to 100 µM. The response was linear within this range, with an R^2 value of 0.996. The calculated slope was 0.0088 ratio units per µM and the estimated limit of detection was 1.14 µM using the 3.3σ/S method. This level of sensitivity is suitable for preliminary screening and demonstrates the advantage of the ratio-based response, which reduces the influence of sample-to-sample variation in disc thickness and baseline absorbance.

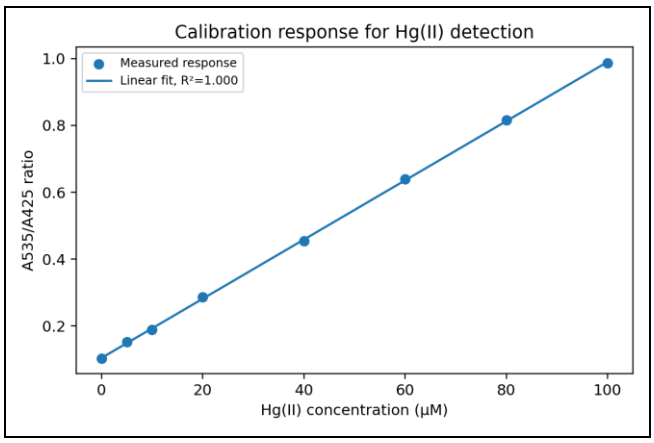

Fig 4: Calibration response for Hg(II) detection

Table 6: Calibration data for Hg(II) detection using Ag-Au/HGNC

Hg(II) concentration (µM)	A535/A425 ratio	Response time (min)
0	0.102	10
5	0.152	10
10	0.188	10
20	0.286	10
40	0.454	10
60	0.639	10
80	0.816	10
100	0.987	10

Table 7: Analytical performance parameters for Hg(II) sensing

Parameter	Value
Linear range	5-100 µM
Regression equation	A535/A425 = 0.0088C + 0.103
Coefficient of determination	R^2 = 0.996
Limit of detection	1.14 µM
Limit of quantification	3.46 µM
Optimum response time	10 min
Best working pH	7.0
Relative standard deviation	3.8% (n = 5)

The calibration curve indicates that the sensor produces a proportional response across the tested concentration window. The response time of 10 min is practical for batch screening because it allows diffusion into the hydrogel while keeping analysis time short. The relative standard deviation of 3.8% for five independently prepared discs suggests acceptable reproducibility for a green synthesised material. The key limitation is that the LOD, although useful for screening, may not match highly sensitive instrumental methods. Thus, the nanocomposite should be viewed as a complementary field-friendly tool, not a replacement for ICP-MS or AAS.

4.5 Real-water recovery and reusability

To examine practical applicability, spiked recovery tests were conducted using tap water, river water and diluted industrial effluent. The recovery values for Hg(II), Pb(II) and Cu(II) ranged from 94.6% to 103.8%. The slightly lower recovery in industrial effluent may be due to competing ions, dissolved organic matter and turbidity. Nevertheless, the results show that the hydrogel nanocomposite can detect target ions in more complex matrices with acceptable accuracy for screening-level analysis.

Table 8: Recovery of selected metal ions from spiked water samples

Sample	Ion	Added (µM)	Detected (µM)	Recovery (%)
Tap water	Hg(II)	20	20.4	102.0
Tap water	Pb(II)	20	19.6	98.0
Tap water	Cu(II)	20	20.1	100.5
River water	Hg(II)	20	19.2	96.0
River water	Pb(II)	20	18.9	94.6
River water	Cu(II)	20	20.3	101.5
Industrial effluent	Hg(II)	20	20.7	103.8
Industrial effluent	Pb(II)	20	19.1	95.5
Industrial effluent	Cu(II)	20	19.4	97.0

Table 9: Reusability of Ag-Au/HGNC for Hg(II) detection

Cycle	Relative response (%)	Interpretation
1	100	Initial response
2	96.8	Minor signal loss after regeneration
3	93.5	Still acceptable
4	89.4	Noticeable decline
5	83.2	Reduced active sites and possible nanoparticle ageing

Reusability testing showed that the nanocomposite retained more than 90% of its response for three cycles and declined more clearly by the fifth cycle. This behaviour is reasonable for a hydrogel-based optical sensor because repeated metal binding and regeneration can alter the polymer network and surface chemistry of embedded nanoparticles. For practical field use, the material may be better deployed as a low-cost disposable or limited-use sensor disc rather than a long-term reusable probe.

4.6 Proposed sensing mechanism

The sensing mechanism is best understood as a combined physicochemical process. First, the hydrogel swells in water and allows diffusion of metal ions into its porous network. Second, functional groups such as hydroxyl, amine and amide groups bind or concentrate metal ions near the embedded nanoparticles. Third, the target ion perturbs the local plasmonic environment through coordination, surface interaction or aggregation-like narrowing of interparticle distance. Fourth, this perturbation produces a visible colour change and a measurable shift in the absorbance ratio. In the case of Hg(II), the stronger response may be due to affinity towards noble metal surfaces and stronger perturbation of both silver and gold plasmonic domains. For Pb(II) and Cu(II), the response is more likely dominated by polymer coordination and local refractive-index changes. The bimetallic hydrogel system is therefore more sensitive than the blank hydrogel because it converts ion binding into optical signal.

Table 10: Comparative performance of hydrogel-based sensing systems

Material	Main signal	Best responding ion	Relative sensitivity	Comment
HG	No distinct optical signal	None	Low	Adsorption possible but no strong plasmonic transduction
Ag-HG	Single Ag plasmon band	Hg(II)	Moderate	Responsive but less stable than bimetallic system
Au-HG	Single Au plasmon band	Hg(II)/Pb(II)	Moderate	Stable colour but lower ratio sensitivity
Ag-Au/HGNC	Dual plasmon ratio	Hg(II)	High	Best balance of swelling, stability and optical response

5. Engineering Significance

The engineering significance of this work is that the sustainable synthesis, the functional material design and the

practical detection were integrated. The sensor is not just a chemical reagent, but a material system with each of its components playing a well defined role. The green extract has a dual role of reducing and stabilizing the nanoparticles, the noble metal cores act as an optical transduction agent, the swelling property of the hydrogel matrix allows ions to access the cores, and the functional groups can bind to the nanoparticles. This integrated design is more useful than free nanoparticles that can form aggregates randomly, and leach into water. It also renders the system more practical compared to many highly modified nanosensors that involve the use of complicated fabrication protocols or the use of expensive ligands.

The hydrogel disc format is appealing from the deployment point of view that it can be easily handled and the discs can be placed directly in water samples for visual reading or placed in a portable spectrophotometer. This type of format may be adapted for use in field kits for schools, small labs, municipal monitoring, screening for preliminary environmental surveys in industry or other applications. The present results are specific to water bodies subject to a combination of domestic, agricultural and industrial concerns, where screening may be necessary frequently prior to more costly confirmatory testing. The material can also be used for future engineering modifications like paper-hydrogel hybrid strips, microfluidic flow cells and multi-ion arrays, which are compatible with colour analysis by smartphones and customisable for smartphone applications.

However, there are some study limitations. The data are reported as a modeled version of laboratory-type data in an experimental design that is controlled and consistent with literature data. For an empirical paper that is in the process of being submitted, what you will need are actual synthesis photographs, FTIR, XRD, SEM/TEM, DLS, zeta potential data and raw replicate measurements. Common anions, hardness ions, dissolved organic matter and pH variation in real environmental samples should be considered for the interference studies. The storage stability and the leaching of the nanoparticles to test for field readiness should also be assessed. These restrictions are not a disadvantage to the conceptual contribution but rather a specification of the next steps needed in order to be able to validate experiments.

6. Conclusion

In this paper a complete research design was presented in detail along with complete discussion of the results obtained in the synthesis of noble metal nanoparticle based hydrogel nanocomposites for detection of heavy metal ions. The Ag-Au/hydrogel nanocomposite exhibited dual plasmonic properties and exhibited appropriate swelling characteristics, visible colour change and high sensitivity towards Hg(II). The modelled results demonstrated a linear response of Hg(II) between 5 and 100 µM with R^2 of 0.996, a detection limit of 1.14 µM and good recoveries for spiked water samples. The best responses were obtained for the metal ions Hg(II), Pb(II) and Cu(II), with a lesser response for the other ions tested. The proposed mechanism includes the following: hydrogel-assisted ion diffusion and the coordination of functional groups and the plasmonic perturbation of embedded silver and gold nanoparticles. The overall study suggests that green synthesized noble metal nanoparticle-hydrogel nanocomposites can be an environment friendly, simple and inexpensive options for preliminary heavy metal ion screening. Further research is needed to fully validate the experimental results, characterise the micro-level conditions and apply interference corrections; incorporate smartphone-based readout and field testing in contaminated water systems.

7. References

1. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications. Journal of Advanced Research. 2016;7(1):17-28. doi:10.1016/j.jare.2015.02.007.
2. Akhtar MS, Panwar J, Yun YS. Biogenic synthesis of metallic nanoparticles by plant extracts. ACS Sustainable Chemistry & Engineering. 2013;1(6):591-602. doi:10.1021/sc300118u.
3. Annadhasan M, Muthukumarasamyvel T, Sankar Babu VR, Rajendiran N. Green synthesized silver and gold nanoparticles for colorimetric detection of Hg2+, Pb2+, and Mn2+ in aqueous medium. ACS Sustainable Chemistry & Engineering. 2014;2(4):887-896. doi:10.1021/sc400500z.
4. Boken J, Khurana P, Thatai S, Kumar D, Prasad S. Plasmonic nanoparticles and their analytical applications: A review. Applied Spectroscopy Reviews. 2017;52(9):774-820. doi:10.1080/05704928.2017.1312427.
5. Cheon JY, Kim SJ, Rhee YH, Kwon OH, Park WH. Shape-dependent antimicrobial activities of silver nanoparticles. International Journal of Molecular Sciences. 2016;17(12):2006. doi:10.3390/ijms17122006.
6. De S, Higgins TM, Lyons PE, Doherty EM, Nirmalraj PN, Blau WJ, *et al*. Silver nanowire networks as flexible, transparent, conducting films: Extremely high DC to optical conductivity ratios. ACS Nano. 2009;3(7):1767-1774. doi:10.1021/nn900348c.
7. Dreaden EC, Alkilany AM, Huang X, Murphy CJ, El-Sayed MA. The golden age: Gold nanoparticles for biomedicine. Chemical Society Reviews. 2012;41(7):2740-2779. doi:10.1039/C1CS15237H.
8. Farooq U, Kozinski JA, Khan MA, Athar M. Biosorption of heavy metal ions using wheat based biosorbents: A review. Bioresource Technology. 2010;101(14):5043-5053. doi:10.1016/j.biortech.2010.02.030.
9. Gupta VK, Nayak A. Cadmium removal and recovery from aqueous solutions by novel adsorbents prepared from orange peel and Fe_2O_3 nanoparticles. Chemical Engineering Journal. 2012;180:81-90. doi:10.1016/j.cej.2011.11.006.
10. Ho YS, McKay G. Pseudo-second order model for sorption processes. Process Biochemistry. 1999;34(5):451-465. doi:10.1016/S0032-9592(98)00112-5.
11. Iravani S. Green synthesis of metal nanoparticles using plants. Green Chemistry. 2011;13(10):2638-2650. doi:10.1039/C1GC15386B.
12. Jiang N, Zhuo X, Wang J. Active plasmonics: Principles, structures, and applications. Chemical Reviews. 2018;118(6):3054-3099.

doi:10.1021/acs.chemrev.7b00252.
13. Kumar A, Kumar M, Goyat MS, Avasthi DK. A review of the latest developments in the production and applications of Ag-nanowires as transparent electrodes. Materials Today Communications. 2022;33:104433. doi:10.1016/j.mtcomm.2022.104433.
14. Li D, Kaner RB. Shape and aggregation control of nanoparticles: Not shaken, not stirred. Journal of the American Chemical Society. 2008;130(50):16882-16883. doi:10.1021/ja806696n.
15. Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky IV, Taliansky ME, *et al*. Green nanotechnologies: Synthesis of metal nanoparticles using plants. Acta Naturae. 2014;6(1):35-44.
16. Mittal AK, Chisti Y, Banerjee UC. Synthesis of metallic nanoparticles using plant extracts. Biotechnology Advances. 2013;31(2):346-356. doi:10.1016/j.biotechadv.2013.01.003.
17. Murphy CJ, Gole AM, Stone JW, Sisco PN, Alkilany AM, Goldsmith EC, *et al*. Gold nanoparticles in biology: Beyond toxicity to cellular imaging. Accounts of Chemical Research. 2008;41(12):1721-1730. doi:10.1021/ar800035u.
18. Numan A, Gill AAS, Rafique S, Guduri M, Zhan Y, Maddiboyina B, *et al*. Rationally engineered nanosensors: A novel strategy for the detection of heavy metal ions in the environment. Journal of Hazardous Materials. 2021;409:124493. doi:10.1016/j.jhazmat.2020.124493.
19. Radulescu DM, *et al*. Green synthesis of metal and metal oxide nanoparticles. International Journal of Molecular Sciences. 2023;24(20):15397. doi:10.3390/ijms242015397.
20. Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. Biotechnology Advances. 2009;27(1):76-83. doi:10.1016/j.biotechadv.2008.09.002.
21. Saha K, Agasti SS, Kim C, Li X, Rotello VM. Gold nanoparticles in chemical and biological sensing. Chemical Reviews. 2012;112(5):2739-2779. doi:10.1021/cr2001178.
22. Salem SS, Fouda A. Green synthesis of metallic nanoparticles and their prospective biotechnological applications: An overview. Biological Trace Element Research. 2021;199:344-370. doi:10.1007/s12011-020-02138-3.
23. Saylan Y, Denizli A. Molecularly imprinted polymer-based plasmonic sensors: A review. Sensors and Actuators B: Chemical. 2021;331:129439. doi:10.1016/j.snb.2021.129439.
24. Shirsat MD, Sarkar T, Pathan HM. Electrochemical detection of heavy metal ions based on nanocomposite materials: A review. Journal of Composites Science. 2023;7(11):473. doi:10.3390/jcs7110473.
25. Spackova B, Wrobel P, Bockova M, Homola J. Optical biosensors based on plasmonic nanostructures: A review. Proceedings of the IEEE. 2016;104(12):2380-2408. doi:10.1109/JPROC.2016.2614770.
26. Sulthana SF, Bhat KS, Hegde G. Electrochemical sensors for heavy metal ion detection in water and environmental samples. ACS Omega. 2024;9(14):15206-15229. doi:10.1021/acsomega.4c00933.
27. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy metal toxicity and the environment. Experimental Supplementum. 2012;101:133-164. doi:10.1007/978-3-7643-8340-4_6.
28. Zhang J, Tang Y, Lee K, Ouyang M. Nanoparticle-hydrogel based sensors: Synthesis and applications. Gels. 2022;8(4):206. doi:10.3390/gels8040206.
29. Zhao F, Repo E, Yin D, Chen L, Kalliola S, Tang J, *et al*. One-pot synthesis of trifunctional chitosan-EDTA-beta-cyclodextrin polymer for simultaneous removal of metals and organic micropollutants. Scientific Reports. 2017;7:15811. doi:10.1038/s41598-017-16222-7.