# A Prospective Review On The Development And Application Of Gold Nanoparticles In Detection And Enumeration Of Chemical And Microbial Contaminants In Drinking Water

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***Abstract-*** *Contamination of drinking water with pesticides, heavy metals, and microbial agents poses a growing global health threat. While conventional detection techniques such as LC-MS and GC-MS offer high sensitivity, their cost, complexity, and lack of portability limit widespread use. Gold nanoparticles (AuNPs), particularly those synthesized via green methods using plant extracts, provide a more affordable and eco-conscious solution. Their unique optical properties—driven by localized surface plasmon resonance (LSPR)—make it possible to quickly detect changes in color of waterborne contaminants. This article explores the use of ten Araceae family plants for the green synthesis of AuNPs and explores the development of composite biosensors by integrating these nanoparticles with molecularly imprinted polymers (MIPs). Such sensors promise selective, field-deployable solutions for monitoring water quality, capable of detecting contaminants even at very low concentrations, down to parts per billion. The review further discusses advantages, optimization parameters, and future applications in environmental monitoring and public health.*

***Keywords***- Contamination, pesticides, heavy metals, microbial agents, Green Synthesis, Gold nanoparticles, Araceae, Molecularly imprinted polymers

## I. INTRODUCTION

Environmental contaminants such as pesticides, heavy metals ($Cu^{2+}$, $Zn^{2+}$, $Fe^{3+}$), and microbial pathogens (e.g., Escherichia coli, Salmonella) pose serious risks to both ecosystems and human health. Instrumental methods like liquid chromatography–mass spectrometry (LC-MS) and gas chromatography–mass spectrometry (GC-MS) are highly sensitive and precise (*Gómez-Ramos et al., 2013*), yet their high cost, technical complexity, and infrastructural demands restrict real-time or rural applications.

Colorimetric biosensors based on gold nanoparticles (AuNPs) offer a promising solution due to their simplicity, affordability, and rapid, visual output. Green synthesis methods using plant extracts introduce a sustainable alternative to toxic chemical reducers, employing natural phytochemicals such as flavonoids, phenolic acids, and terpenes (*Akhtar et al., 2013; Bharadwaj et al., 2021*). Embedding green AuNPs within molecularly imprinted polymers (MIPs) enhances detection specificity by integrating molecular recognition with plasmonic sensitivity enabling detection in the ppb range and empowering decentralized water monitoring.

## II. ARACEAE PLANTS FOR GREEN SYNTHESIS OF AuNPs

The Araceae plant family comprises numerous species rich in reducing agents and capping molecules ideal for nanoparticle formation. The following 10 species have promising potential based on their phytochemical profiles and availability:

| **Common Name** | **Scientific Name** | **Function in AuNP Synthesis** |
|---|---|---|
| Golden Pothos / Money Plant | *Epipremnum aureum* | Rich in polyphenols |
| Heartleaf Philodendron | *Philodendron hederaceum* | Known for antioxidant properties |
| ZZ Plant | *Zamioculcas zamiifolia* | High alkaloid and terpene content |
| Taro / Arbi | *Colocasia esculenta* | Contains phenolic acids and vitamin C |
| Swiss Cheese Plant | *Monstera deliciosa* | Rich in lignins and flavonoids |
| Satin Pothos / Silver Vine | *Scindapsus pictus* | High phenolic content for strong reducing |

| Common Name | Scientific Name | Function in AuNP Synthesis |
|---|---|---|
| | | ability |
| Chinese Evergreen | *Aglaonema commutatum* | Contains tannins and reducing sugars |
| Flamingo Flower / Laceleaf | *Anthurium andraeanum* | Rich in anthocyanins and bioflavonoids |
| Dumb Cane | *Dieffenbachia seguine* | Produces phytochemicals suitable for nanoparticle synthesis |
| Angel Wings / Fancy-leaf Caladium | *Caladium bicolor* | High in oxalates and bioactive phytochemicals |

Of the ten plants listed, two—Golden Pothos (*Epipremnum aureum*) and Taro (*Colocasia esculenta*) have documented use in nanoparticle synthesis. The rest have no recorded evidence so far in published reports for producing metal or metal oxide nanoparticles via green plant-extract methods.

*Epipremnum aureum* and *Colocasia esculenta* are particularly promising due to their abundance, strong polyphenol content, and previously reported Silver nanoparticle stability. These plants act as both reducing and capping agents, eliminating the need for hazardous chemicals in nanoparticle synthesis.

**Table 1.1: Nanoparticles Synthesized using *Epipremnum aureum***

| Nanoparticle Type | Plant Extract Used | Size / Morphology | Applications / Notes | Reference(s) |
|---|---|---|---|---|
| Zinc oxide nanoparticles (ZnO NPs) | Leaves (Soxhlet extract) | Spherical / hexagonal, wurtzite structure; ~29 nm | Antioxidant, antimicrobial (E. coli & S. aureus), photocatalytic degradation of methylene blue dye; reusable catalyst | *Kajal et al. (2025)* |
| Silver nanoparticles (AgNPs) | Leaf extract | ~12.9 nm average size; SPR band ~420 nm | Antiproliferative cytotoxicity against MCF-7 breast cancer cells ($IC_{50}$ ≈ 0.11 µg/mL) | *Ale et al. (2024)* |
| Silver nanoparticles (AgNPs) | Leaf extract (green method) | ~13–26 nm; spherical | Colorimetric $Cu^{2+}$ ion sensing; antimicrobial degradation of PAHs | *Royji et al. (2018)* |

**Table 1.2: Nanoparticles Synthesized using *Colocasia esculenta***

| Nanoparticle Type | Synthesized Using | Size / Morphology | Applications / Notes | Reference(s) |
|---|---|---|---|---|
| Silver nanoparticles (AgNPs) | Leaf or root extract | ~20 nm (spherical); nanoplates (anisotropic, 2-D) | Colorimetric detection (e.g. melamine); antibacterial; antioxidant, anti-ulcer | *Jigyasa, & Rajput, J. K. (2018)* |
| Gold nanoparticles (AuNPs) | Root extract | ~85 nm avg (spherical) | Pharmacological potential (nanomedicine, biosensing) | *Reshma Tendulkar.( 2023)* |
| Zinc oxide / Ag-doped ZnO nanoparticles | Leaf extract (microwave-assisted) | ZnO ~ few nm; Ag doped composites | Antibacterial / antifungal activity | *Kumar, K. K. P., Dinesh, N. D., & Murari, S. K. (2019)* |
| Copper–Cerium doped ZnO nanoparticles | Leaf extract (microwave-assisted) | ~16–19 nm crystallite size | Antioxidant and antibacterial functions | *Verma, N., et al. (2024).* |
| Copper oxide nanoparticles (CuO-NPs) | Leaf extract | ~42 nm (hexagonal crystal) | $Pb^{2+}$ detection (LOD ~29 µM), selective adsorption, antimicrobial | *Pal, D. (2025).* |

| Nanoparticle Type | Synthesized Using | Size / Morphology | Applications / Notes | Reference(s) |
|---|---|---|---|---|
| Carbon-based graphene-like nanostructures | Carbonized leaf material | Graphenic domains, small sheet-like | Highly potent antibacterial composites | *Bhatt, S. (2023).* |

## III. APPLICATION IN CONTAMINANT DETECTION

Green-synthesized AuNPs undergo a visible color change—from red to blue—upon aggregation induced by interaction with target contaminants. This is due to LSPR, a phenomenon where surface electron oscillations change in response to nanoparticle clustering (*Lin et al., 2006*). This property can be harnessed for detecting a range of contaminants using Araceae synthesized AuNPs:

- Pesticides: Organochlorines, organothiophosphates, neonicotinoids, and pyrethroids
- Metal Ions: $Cu^{2+}$, $Zn^{2+}$, $Fe^{3+}$, $Co^{2+}$
- Microbes: E. coli, Salmonella spp.
- Disinfection Byproducts: Chloroform, trihalomethanes

## IV. ENHANCEMENT WITH MOLECULARLY IMPRINTED POLYMERS (MIPs)

To enhance selectivity, molecularly imprinted polymers (MIPs) can be integrated with green AuNPs. MIPs are synthetic receptors with specific binding sites for target molecules. Commonly used monomers such as acrylamide and bisacrylamide form cross-linked polymer matrices capable of retaining memory of the imprinted molecule's shape and chemistry (*Matsui et al., 2009; Ellwanger et al., 2001*). The AuNP-MIP composite enables dual functionality: visual detection via color change and high specificity via molecular recognition, achieving detection limits in the ppb range. Recent work by *Agar et al. (2024)* introduced an AptaMIP hybrid that achieved multiplexed bacterial detection in water at concentrations as low as 2 CFU/mL, demonstrating the power of combining molecular imprinting with aptamer binding for ultrasensitive and selective sensing

## V. SYNTHESIS OF AuNPs:

According to *Geethalakshmi & Sarada (2013)*1 mL of plant extract is added to 100 mL of 0.25 mM boiling $HAuCl_4 \bullet 3H_2O$ solution. The mixture is stirred for 20–25 minutes until a red-wine color indicates successful nanoparticle formation. The solution is cooled and stored at 4°C. Besides this commonly used boiling/stirring method, there are several other green synthesis methods for gold nanoparticles (AuNPs) using plant extracts. Each offers variations in temperature, pH, reaction time, and energy input, which can influence nanoparticle size, shape, and stability. One widely used room temperature stirring method involves simply mixing plant extract with aqueous $HAuCl_4$ (~25–30 °C) under continuous stirring, offering energy efficient synthesis with minimal degradation of heat sensitive phytochemicals. For example, *Ghosh et al. (2012)* employed *Gnidia glauca* flower extract at ambient temperature to yield catalytically active AuNPs. Another technique is microwave assisted synthesis, where the plant extract and gold salt mixture is irradiated for 1–5 minutes, producing smaller, uniform nanoparticles with rapid kinetics. *Bar et al. (2009)* demonstrated this with *Jatropha curcas* latex, and *Hibiscus rosa-sinensis* extract under optimized microwave conditions (varying extract concentration, salt concentration, heating time and power) yielded spherical AuNPs of ~16–30 nm in under two minutes . Another method, pH optimized synthesis, adjusts the reaction mixture pH—typically between 5 and 9—prior to addition of the plant extract, enabling tuning of nanoparticle morphology and dispersity. *Shankar et al. (2004)* illustrated pH dependent control over AuNP shape using Pelargonium graveolens extract. Sonochemical (ultrasonicassisted) synthesis uses ultrasonic waves to enhance reaction kinetics through cavitation, often reducing reaction time and improving crystallinity; for instance, synthesis using citrus peel extract under ultrasound produced ~13.6 nm monodispersed spherical AuNPs with significantly enhanced yield and antiinflammatory activity compared to nonsonicated controls. Finally, hydrothermal synthesis entails sealing the plant extract and $HAuCl_4$ in a Teflon lined autoclave at elevated temperatures (≈120–160 °C) for several hours under pressure, yielding highly crystalline, typically spherical nanoparticles; this approach was successfully applied by *GardeaTorresdey et al. (2005)* using *Lemna gibba* extract. Each of these approaches exemplifies how manipulation of reaction conditions—room temperature, microwave energy, pH control, ultrasound cavitation, or hydrothermal pressure—can profoundly impact the size, shape, monodispersity, and biofunctional performance of plant mediated AuNPs.

**Table 1.3: Different Methods of Synthesis of AuNPs:**

| Method | Time | Temp | Special Features | Reference |
|---|---|---|---|---|
| Boiling + Stirring | 20–25 min | 100°C | Standard, well-studied | *Geethalakshmi & Sarada (2013)* |

| Method | Time | Temp | Special Features | Reference |
|---|---|---|---|---|
| Room Temperature | ~1 hr | ~25°C | Eco-friendly, heat-sensitive safe | *Ghosh et al. (2012)* |
| Microwave-Assisted | 1–5 min | Rapid | Uniform, small particles | *Bar et al. (2009)* |
| pH-Optimized | 30–60 min | 30–60°C | Shape-controlled synthesis | *Shankar et al. (2004)* |
| Ultrasound-Assisted | <30 min | Ambient | Fast, high crystallinity | *Caruso et al. (2021)* |
| Hydrothermal | 2–6 hrs | 120–160°C | Crystalline, uniform NPs | *Gardea-Torresdey et al. (2005)* |

While offering increasing convenience, reproducibility, and size/shape precision, the pH optimized synthesis at mild elevated temperatures (40–60 °C) typically offers the best balance. High precision in size and morphology can be seen Adjusting pH (typically 5–9) prior to mixing enables tight control of nucleation, leading to more uniform and often spherical AuNPs with narrow size distributions. Improved reaction kinetics with controlled growth can be achieved by moderate heating (40–60 °C) accelerates nucleation and avoids excessive agglomeration, this temperature range yields sharper SPR peaks and better-defined particle shapes than room temperature alone. Retention of bioactive capping agents in mild conditions is achievable and help preserve phytochemicals that stabilize particles and improve stability unlike high thermal energy or harsh irradiation methods.

**Table 1.4: Comparison between different methods based on convenience, size shape control, speed of production and requirement of equipments:**

| Method | Convenience | Size/ Shape Control | Speed | Equipment Needs |
|---|---|---|---|---|
| Room-Temp Stirring | Very high | Moderate | Slow | None |
| pH-Optimized (40–60 °C) | High | Excellent | Moderate | Basic heating/ stirring |
| Microwave-Assisted | Moderate | Good | Very fast | Microwave reactor |
| Sonochemical | Moderate-low | Good | Fast | Ultrasonic setup |
| Hydrothermal | Low | High crystallinity | Slow | Autoclave, pressure unit |

For a convenient, reproducible, scalable, and size precise green synthesis process, the pH optimized method at moderate temperature (40–60 °C) is superior. It allows reliable tuning of nanoparticle size and shape without complex equipment or extreme conditions, all while preserving the natural stabilizers present in the plant extract.

## VI. CHARACTERIZATION OF AuNPs

In addition to Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and FourierTransform Infrared Spectroscopy (FTIR)—which provide crucial insights into nanoparticle morphology, dispersion, and surface functional groups (*Rajan et al., 2015*)several other analytical techniques are commonly used to characterize gold nanoparticles (AuNPs), especially those synthesized using plant extracts.In addition to Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Fourier-Transform Infrared Spectroscopy (FTIR), these methods help provide information on particle size, surface charge, crystallinity, and optical properties. UV–Visible Spectroscopy (UV–Vis) confirms the formation of AuNPs via the characteristic localized surface plasmon resonance (LSPR) peak, typically observed around 520–540 nm. This enables real-time monitoring of synthesis kinetics and aggregation behavior, with reactions often completing within minutes, as demonstrated with Ziziphus extract yielding stable plasmon peaks after ~3 min. Dynamic Light Scattering (DLS) measures hydrodynamic diameter and size distribution in suspension, while zeta potential analysis quantifies surface charge—absolute values above ±30 mV generally indicate good colloidal stability. For instance, Ziziphus-derived AuNPs exhibited a zeta potential of -40 mV and hydrodynamic diameter ~52 nm, remaining stable over six months . Xray Diffraction (XRD) confirms the crystalline nature and phase purity of AuNPs—typically revealing facecentered cubic (fcc) gold via peaks corresponding to (111), (200), (220), and (311) planes. Energy Dispersive Xray Spectroscopy (EDS/EDX) coupled with SEM or TEM verifies elemental gold content and absence of impurities. Finally,

Atomic Force Microscopy (AFM) offers nanometer-scale 3D topography imaging in both dry and hydrated states, allowing direct visualization of morphological features such as particle height and uniformity. Collectively, this analytical toolkit—UV–Vis, DLS, zeta potential, XRD, EDS, AFM, SEM, TEM, and FTIR—ensures a robust and multidimensional evaluation of AuNP size, shape, crystallinity, surface chemistry, and colloidal stability in green synthesis studies.

**Table 1.5: Different Methods used for characterization of nanoparticles and their application to analyze different properties:**

| Method | Property Analyzed | Application | Reference |
|---|---|---|---|
| **SEM** | Shape, surface morphology | Visualizes nanoparticle surface and structure | *Rajan et al., 2015* |
| **TEM** | Size, internal structure | High-resolution imaging of individual nanoparticles | *Rajan et al., 2015* |
| **FTIR** | Surface functional groups | Identifies capping agents and phytochemical bonds | *Rajan et al., 2015* |
| **UV–Vis Spectroscopy** | Optical properties, LSPR | Confirms nanoparticle formation and aggregation via LSPR shift | *Lin et al., 2006* |
| **DLS (Dynamic Light Scattering)** | Particle size distribution | Measures hydrodynamic diameter and stability in solution | *Nath & Chilkoti, 2004* |
| **Zeta Potential** | Surface charge | Predicts colloidal stability; values ±30 mV suggest good dispersion | *Mody et al., 2010* |
| **XRD (X-ray Diffraction)** | Crystalline structure | Confirms gold phase ($Au^0$) and crystal structure (FCC lattice) | *Akhtar et al., 2013* |
| **EDS / EDX (Energy-Dispersive X-ray Spectroscopy)** | Elemental composition | Confirms gold presence and purity when combined with SEM | *Rajan et al., 2015* |
| **AFM (Atomic Force Microscopy)** | Surface roughness, 3D shape | Nanoscale morphology in both dry and wet states | *Ravindran et al., 2013* |

For the most accurate, compact, and reliable measurement of gold nanoparticle (AuNP) size and size distribution, Transmission Electron Microscopy (TEM) combined with Small-Angle X-ray Scattering (SAXS) or Nanoparticle Tracking Analysis (NTA) offer the best analysis.

**Table 1.6: Comparative Analysis showing core size accuracy, sample state and usage:**

| Technique | Core Size Accuracy | Distribution Quality | Sample State | Best Used For |
|---|---|---|---|---|
| **TEM** | ±3% (core imaging) | High (image-based) | Dried | Morphology,size, shapes |
| **SAXS** | Ensemble accuracy | Excellent (bulk stats) | In suspension | Size distributionand shape analysis |
| **NTA (NanoSight)** | Good (~10 nm +) | Real-time, individual-based | In suspension | Distribution and particle count |
| **DLS** | Lower | Biased, intensity-weighted | In suspension | Quick check of hydrodynamic size |

For highest precision and core-size accuracy TEM can be used with automated image analysis and statistical fitting.Similarly for statistically robust, ensemble-wide characterization in solution, SAXS can be used. For real-time distribution and concentration measurements in liquid, especially with polydisperse or mixed-size samples,using NTA will be beneficial.

## VII. SCREENING FOR CONTAMINANT DETECTION

According to *Zhou et al., 2008* contaminants are added to A-AuNPs (90 µg/µL) in 1:1 ratios. Color change and aggregation are assessed both visually and through UV–Vis spectrophotometry in the 400–900 nm range For environmental relevance, concentrations are screened starting from 1–100 ppb. In addition to visual observation and UV–Vis spectroscopy for monitoring color change and aggregation, there are several other sensitive and reliable methods for assessing gold nanoparticle (AuNP)–contaminant interactions, especially at environmentally relevant concentrations (1–100 ppb). These methods can improve quantification, selectivity, and limit of detection (LOD) in environmental applications. In this study for Araceae synthesized AuNPs, contaminants can be introduced to gold nanoparticles (A-AuNPs) at a concentration of 90 µg/µL using a 1:1 volume ratio. Color change and nanoparticle aggregation can be monitored visually and using UV–Vis spectrophotometry across the 400–900 nm wavelength range, in accordance with established protocols (*Zhou et al., 2008*). To ensure environmental relevance, contaminant concentrations need to be screened from 1 to 100 ppb.

While visual observation and UV–Vis are widely used for rapid and preliminary detection, several additional analytical techniques can enhance the sensitivity, specificity, and quantification of A-AuNP–contaminant interactions at trace levels.

**Table 1.7: Different analytical techniques for detection of contaminants with their sensitivity range:**

| Method | Target | Detection Type | Sensitivity Range | Reference |
|---|---|---|---|---|
| UV–Vis Spectroscopy | General contaminants | Colorimetric | 1–100 ppb | *Zhou et al., 2008* |
| Surface-Enhanced Raman (SERS) | Pesticides, antibiotics | Vibrational signature | sub-ppb | *Liu et al., 2023* |
| DLS | Metals, microbes | Size/aggregation | 1–100 ppb | *Nath & Chilkoti, 2004* |
| Zeta Potential | Metals, ionic species | Surface charge | ~1 ppb and above | *Mody et al., 2010* |
| Electrochemical (DPV, EIS) | Pesticides, metals | Redox/current shift | sub-ppb to 10 ppb | *Prasad et al., 2023* |
| Fluorescence-Based | Microbes, DNA targets | Emission quenching/enhancing | ~10 CFU/mL | *Singh et al., 2022* |

**Table 1.8:Different Analytical Methods stating their purpose and advantages in different documented cases:**

| Method | Purpose | Advantages | Representative Use Case | Reference |
|---|---|---|---|---|
| **1. Surface-Enhanced Raman Spectroscopy (SERS)** | Detects molecular vibrational fingerprints of adsorbed contaminants. | Ultra-sensitive; capable of single-molecule detection at sub-ppb levels. | Pesticide detection (e.g., atrazine) in water using gold nanorods with molecularly imprinted polymers (MIPs). | *Liu, B., Sun, D. D., & Zhu, L. (2023). Sensors and Actuators B: Chemical, 384, 134629.* |
| **2. Dynamic Light Scattering (DLS)** | Measures shifts in hydrodynamic diameter upon contaminant binding. | Provides quantitative aggregation data. | Detection of size increase in nanoparticle suspensions due to target interaction. | *Nath, N., & Chilkoti, A. (2004). Analytical Chemistry, 76(18), 5370–5378.* |
| **3. Zeta Potential Measurements** | Assesses surface charge variations post-contaminant adsorption. | Indicates degree of electrostatic interaction or aggregation. | Particularly effective for monitoring ionic species such as heavy | *Mody, V. V., et al. (2010). Journal of Laboratory Automation, 15(1), 16–23.* |

| Method | Purpose | Advantages | Representative Use Case | Reference |
|---|---|---|---|---|
| | | | metals. | |
| **4. Smartphone-Based Colorimetric Image Analysis** | Quantifies color shifts in solution via RGB analysis from smartphone images. | Portable, low-cost, field-deployable. | On-site detection of metal ions (e.g., lead) in water. | Maity, A., *et al.* (2024). *Environmental Nanotechnology, Monitoring & Management*, 24, 100857. |
| **5. Electrochemical Methods (e.g., DPV, EIS)** | Detects electrical signal changes due to contaminant-AuNP interaction. | High sensitivity; adaptable for integration with recognition elements like MIPs. | On-site detection of organophosphates (e.g., chlorpyrifos). | *Prasad, B. B., et al. (2023). Biosensors and Bioelectronics, 222, 114983.* |
| **6. Fluorescence Quenching/Enhancement** | Monitors quenching or enhancement of fluorescent signals by AuNPs. | Highly sensitive; useful in microbial or DNA-probe-based detection. | Detection of *E. coli* using DNA-AuNP conjugates. | *Singh, R. R., et al. (2022). Talanta, 251, 123755.* |

Combining multiple detection modalities (e.g., UV–Vis + DLS or SERS + electrochemistry) improves reliability and limit of detection.Methods like SERS and electrochemical sensing offer ppb to sub-ppb sensitivity, ideal for regulatory thresholds in environmental monitoring.Smartphone-based platforms are increasingly favored for field analysis due to their accessibility and portability.

## VIII. OPTIMIZATION OF DETECTION PARAMETERS

- AuNP Concentration: Optical densities of 1.0 and 2.0
- Target:Nanoparticle Ratio: 1:1 to 1:5
- Linker Molecules: e.g., $ZnCl_2$, $AgNO_3$
- pH Range: 5–9
- Temperature Range: 5°C to 100°C
- Reaction Time: Monitored at optimal conditions

## IX. LIMIT OF DETECTION (LOD)

LOD is defined as the lowest concentration causing a statistically significant color change (≥3σ above control) within 30 minutes. Detection is evaluated between 1 ppb and 250 ppm.

## X. POST-DETECTION CHARACTERIZATION

Post-contaminant interaction, AuNPs are recharacterized by SEM, TEM, and FTIR to observe aggregation and surface changes.

## XI. MIP AND AuNP-MIP SYNTHESIS

Molecularly Imprinted Polymers (MIPs) are synthetic materials engineered to possess specific binding sites for target molecules, created by polymerizing functional monomers and crosslinkers in the presence of a molecular template. A common method, as demonstrated by *Matsui et al.(2009)*, involves polymerizing acrylamide and bisacrylamide between glass plates, followed by template extraction and exposure to target analytes to assess selectivity. However, numerous alternative MIP synthesis methods exist, each with unique advantages depending on the target analyte, physical format, and intended application. Bulk polymerization is the most traditional technique, in which monomers and crosslinkers are polymerized with the template in a solvent (porogen), producing a bulk material that is ground and sieved into particles. While widely used due to its simplicity, this method yields irregular particles and may result in the loss of binding sites during grinding (*Wulff, 1995; Sellergren, 2000*). Precipitation polymerization offers a more refined approach, where monomers are polymerized in dilute solution, forming uniform spherical particles directly without the need for grinding. This method enhances particle uniformity but typically requires large volumes of solvent (*Ye & Mosbach, 2001*). Emulsion or suspension polymerization involves creating MIPs as spherical beads within a dispersed

phase, such as water-in-oil emulsions. This method enables better control over particle size and is scalable, though issues such as template extraction and surfactant contamination may arise (*Mayes & Mosbach, 1997*). Surface imprinting focuses imprinting at or near the surface of support materials like silica or magnetic nanoparticles, facilitating faster binding kinetics and easier template removal—particularly advantageous for large biomolecules—though it may result in reduced total binding capacity (*Haupt & Mosbach, 2000*). Sol-gel polymerization uses silica precursors (e.g., tetraethyl orthosilicate, TEOS) to form inorganic MIPs through hydrolysis and condensation reactions. This technique is well-suited for sensitive templates such as proteins due to its mild reaction conditions, although the resulting structures can be brittle with weaker template-monomer interactions (*Xu & Yan, 2001*).Electropolymerization allows electroactive monomers to be polymerized directly onto electrode surfaces in the presence of a template under an applied voltage. This method is especially useful for creating thin-film MIPs on sensors, but is limited by the requirement for electroactive monomers (*Piletsky et al., 2001*).Finally, in situ polymerization involves forming MIPs directly within devices such as columns, capillaries, or microfluidic systems. This technique eliminates the need for post-polymerization processing, allowing seamless integration into analytical platforms (*Pichon & Chapuis-Hugon, 2008*).Collectively, these techniques provide a broad toolkit for tailoring MIP synthesis based on desired physical formats, target specificity, and application context—whether for sensors, environmental monitoring, or biomedical diagnostics.

**Table 1.9: Different techniques used for synthesis of Molecularly imprinted Polymers stating theirs advantages and disadvantages:**

| Method | Description | Advantages | Disadvantages | References |
|---|---|---|---|---|
| **Bulk Polymerization** | Monomers, crosslinkers, and template polymerized in solvent; product ground. | Simple, widely used. | Irregular particles, labor-intensive grinding, potential site damage. | *Wulff (1995); Sellergren (2000)* |
| **Precipitation Polymerization** | Dilute solution polymerized to form spherical particles. | Uniform particles, no grinding. | Requires large volumes of solvent. | *Ye & Mosbach (2001)* |
| **Emulsion/Suspension Polymerization** | Polymerization in dispersed phase (e.g., water/oil) forming beads. | Controlled size, scalable. | Template removal can be harder, surfactant contamination possible. | *Mayes & Mosbach (1997)* |
| **Surface Imprinting** | Imprinting occurs on or near support surface (e.g., nanoparticles). | Fast kinetics, good for large templates (e.g., proteins), easier template removal. | Lower capacity than bulk or core-imprinted methods. | *Haupt & Mosbach (2000)* |
| **Sol-Gel Polymerization** | Uses silica precursors (e.g., TEOS) under mild hydrolysis/condensation. | Mild conditions, good for biomolecules. | Brittle matrix, limited interaction control. | *Xu & Yan (2001)* |
| **Electropolymerization** | Electroactive monomers polymerized on electrode under applied voltage. | Excellent for sensor applications, thin films. | Limited to electroactive monomers. | *Piletsky et al. (2001)* |
| **In Situ Polymerization** | Polymer formed directly inside columns or microchannels (monolithic format). | No grinding, directly usable in analytical devices. | Less flexible for certain templates or geometries. | *Pichon & Chapuis-Hugon (2008)* |

Considering convenience, simplicity, environmental compatibility, and minimal equipment needs, the most convenient method is Surface Imprinting on Biogenic Gold Nanoparticles (AuNPs). AuNPs from Araceae are typically synthesized using plant extracts (rich in phenolics, alkaloids, etc.), which serve as reducing and capping agents.These biogenic AuNPs are generally capped with phytochemicals, which may influence surface interactions.Surface imprinting enables functionalization of AuNP surfaces with MIP layers without encapsulating the nanoparticle core, preserving their

optical/electronic properties (important for colorimetric or electrochemical detection).Offers fast binding kinetics, ideal for detecting low concentrations (ppb level) in water.Template removal is easier, reducing the risk of residual interference in detection.It is best for Small organic molecules, heavy metals, pesticides, hormones, antibiotics (*Haupt & Mosbach, 2000*). Electropolymerization can create thin MIP layers directly on AuNP-modified electrodes.This combination gives excellent sensitivity, especially for heavy metals and organophosphates. Biogenic AuNPs can be drop-cast onto electrodes and functionalized in situ, making it compatible with plant-derived AuNPs (*Piletsky et al.,2001*).Precipitation polymerization is a good option for uniform MIP particles incorporating Araceae-synthesized AuNPs.The process is cleaner, doesn't require grinding, and AuNPs can be embedded or surface-coated during synthesis.

The most convenient, low-cost, and scalable method using green-synthesized AuNPs from Araceae for water contaminant detection is surface imprinting. It balances sensitivity, ease of use, and environmental compatibility.

**Table 1.10: Features and Benefits of Surface Imprinting on Biogenic Gold Nanoparticles (AuNPs)**

| **Feature** | **Benefit** |
|---|---|
| **Mild Conditions** | Compatible with **green-synthesized AuNPs** from Araceae (no harsh solvents or temperatures). |
| **Simple Setup** | No need for grinding, sieving, or complex emulsions. Just functionalize AuNPs with monomer/template mix. |
| **Fast Template Removal** | Since imprinting is at the surface, template molecules can be washed off easily using ethanol or buffer. |
| **No Special Equipment** | Can be done on the benchtop using beakers, stirrers, and UV light (if needed for polymerization). |
| **Preserves AuNP Optical Properties** | Ideal for colorimetric detectionusing UV–Vis or even smartphones. |
| **Scalable and Field-Compatible** | Can be dried onto paper strips or incorporated into portable sensors. |

## XII. MIP SPECIFICITY AND DENSITY EVALUATION

Various acrylamide densities (7.5%, 10%, 12%) are tested to determine optimal binding strength and specificity (*Piletsky et al., 2001*).To evaluate the specificity of molecularly imprinted polymers (MIPs) designed for Araceae-synthesized gold nanoparticles (AuNPs) used in the detection of environmental contaminants, several analytical and comparative methods can be employed. These methods assess the ability of the MIPs to selectively recognize and bind target analytes amidst similar or structurally related compounds. Specificity evaluation begins with synthesizing MIPs at various acrylamide densities (e.g., 7.5%, 10%, and 12%), as reported by *Piletsky et al. (2001)*, to identify the optimal polymer network density that supports efficient template recognition. Comparative binding studies are conducted using non-imprinted polymers (NIPs) as controls. Binding capacity and imprinting factor (IF) are calculated by measuring the adsorption of the target and non-target molecules using techniques such as UV-Vis spectroscopy, high-performance liquid chromatography (HPLC), or surface plasmon resonance (SPR). Competitive binding assays are also employed to evaluate the ability of MIPs to discriminate between the target contaminant and analogs. Additionally, Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) can be used to analyze the surface morphology and chemical composition changes due to selective binding. In conjunction with these, selectivity coefficients (k) are calculated to quantify specificity, typically expressed as the ratio of binding of the target to that of interfering species. Moreover, reusability and regeneration studies help understand the specificity retention over multiple use cycles. All these methods together provide a robust framework to determine the specificity of MIPs functionalized on green-synthesized AuNPs for environmental contaminant sensing.

**Table 1.11: Methods for Evaluating Specificity of MIPs for Araceae-Synthesized AuNPs:**

| **Method** | **Purpose** | **Measurement Technique** | **Specificity Indicator** |
|---|---|---|---|
| Acrylamide Density Variation | Optimize polymer network for target binding | Synthesis variation (7.5%, 10%, 12%) | Best-performing density with highest binding |
| Binding Capacity Comparison | Assess target molecule affinity | UV-Vis, HPLC, or SPR | Amount bound by MIP vs NIP |
| Imprinting Factor (IF) | Quantify imprinting efficiency | IF=QMIP /QNIP | Higher IF indicates stronger imprinting |
| Competitive Binding Assays | Test binding preference over analogs | UV-Vis/HPLC before and after exposure | % binding of target vs competitors |
| Selectivity | Compare | k=Qtarget / | Higher k |

| Method | Purpose | Measurement Technique | Specificity Indicator |
|---|---|---|---|
| Coefficient (k) | selectivity between target and interferents | Qinterferent | indicates better selectivity |
| FTIR Analysis | Confirm target-molecule-specific interactions | FTIR spectra comparison | Shifts or new peaks due to target binding |
| SEM Imaging | Observe surface morphology and changes post-binding | Surface imaging | Morphological changes indicating template imprinting |
| Reusability Tests | Confirm stability and specificity over cycles | Binding efficiency over repeated use | % retention of initial binding capacity |
| Control Studies with NIPs | Baseline comparison for non-specific binding | Parallel testing | Lower binding in NIPs confirms specificity in MIPs |

## XIII. REAL SAMPLE TESTING

Field samples (groundwater, river, tap water) are spiked with known contaminants and analyzed under optimized conditions. Results are validated visually and via spectrophotometry. Different pesticides have been detected in water samples using AuNPs. Molecularly imprinted polymer (MIP)-based methods have been validated across a wide range of environmental water samples for detecting various contaminants. For instance, atrazine was detected in groundwater and river water using HPLC-UV, with performance evaluated through recovery studies and comparison against non-imprinted polymers (NIPs) (*Zhang et al., 2012*). In tap water, bisphenol A (BPA) was quantified using UV–Vis spectrophotometry, where spiking experiments and recovery percentages were employed to assess method accuracy (*Li et al., 2014*). Similarly, tetracycline antibiotics were detected in river and lake water using HPLC in combination with a visible color change, providing both qualitative and quantitative assessment (*Gao et al., 2018*).
Detection of heavy metals such as $Pb^{2+}$ and $Cd^{2+}$ in groundwater and wastewater was performed using Flame Atomic Absorption Spectroscopy (FAAS), with validation based on recovery tests using certified reference materials (*Khan et al., 2021*). Ibuprofen in tap water was monitored using UV–Vis spectrophotometry, with visual detection results cross-validated against standard analytical methods (*Saylan et al., 2017*). Lastly, 17β-estradiol in surface water (river) was analyzed through fluorescence spectroscopy, and validation was achieved using the standard addition method and recovery analysis (*Suedee et al., 2011*).

**Table 1.12: Different contaminants detected in water samples:**

| Sample Type | Spiked Contaminant(s) | Detection Method | Validation Approach | Reference |
|---|---|---|---|---|
| Groundwater, River Water | Atrazine | HPLC-UV | Recovery studies, comparison with non-imprinted polymer (NIP) | *Zhang et al. (2012), J. Chromatogr. A, 1227, 56–64.* |
| Tap Water | Bisphenol A (BPA) | UV-Vis Spectrophotometry | Recovery %, spiking experiments | *Li et al. (2014), Anal. Methods, 6, 791–798.* |
| River and Lake Water | Tetracycline Antibiotics | HPLC | Visual color change + quantitative analysis | *Gao et al. (2018), Talanta, 186, 133–141.* |
| Groundwater, Wastewater | Heavy Metals ($Pb^{2+}$, $Cd^{2+}$) | FAAS (Flame Atomic Absorption Spectroscopy) | Recovery test with certified reference materials | *Khan et al. (2021), J. Hazard. Mater., 403, 123608.* |
| Tap Water | Ibuprofen | UV-Vis Spectrophotometry | Visual detection and method comparison | *Saylan et al. (2017), Sens. Actuators B, 241, 926–933.* |

| Sample Type | Spiked Contaminant(s) | Detection Method | Validation Approach | Reference |
|---|---|---|---|---|
| Surface Water (River) | 17β-Estradiol | Fluorescence Spectroscopy | Standard addition method + recoveries | *Suedee et al. (2011), Anal. Chim. Acta, 703, 245–253.* |

## XIV. ADVANTAGES OF THE GREEN AUNP-MIP BIOSENSOR

The biosensor platform offers several key advantages that make it highly suitable for real-world applications. It is eco-friendly, as it avoids the use of hazardous chemicals, and low-cost, significantly reducing the need for complex instrumentation. Visual detection capabilities enable naked-eye observation, eliminating the requirement for advanced analytical tools. Its field-deployable nature makes it ideal for rural and resource-limited settings. The platform is also highly versatile, capable of detecting a wide range of contaminants including pesticides, heavy metals, microbes, and disinfection by-products (DBPs). Moreover, it is scalable, allowing for low-cost mass production, and supports smart integration with mobile devices, offering strong potential for smartphone-based diagnostics and real-time data analysis.

## XV. FUTURE PROSPECTS

Upon successful validation, the biosensor platform can be adapted into various practical formats, including portable kits for water testing in rural and disaster-affected areas, and smartphone-based detection systems equipped with apps capable of real-time absorbance reading and digital reporting. Additionally, the platform can be customized for use in agriculture, food safety, and industrial wastewater monitoring. Its versatility also extends to applications in food packaging, medical diagnostics, and controlled drug delivery. *He et al. (2023)* provided a comprehensive review on the integration of molecularly imprinted polymer (MIP) sensors with smartphones, emphasizing their significant potential for portable, field-based sensing. Demonstrating real-world applicability, developed a smartphone-linked biosensor for on-site detection of organophosphate pesticides in water, highlighting the feasibility of such systems in practical environmental monitoring.

## XVI. CONCLUSION

The green synthesis of gold nanoparticles (AuNPs) using plant extracts from the Araceae family offers a sustainable and eco-friendly alternative to conventional chemical and physical nanoparticle synthesis methods. This approach minimizes the use of hazardous reagents and reduces energy consumption, aligning with the principles of green chemistry and sustainable nanotechnology.Among the Araceae species studied, *Epipremnum aureum* (commonly known as Devil's Ivy or Golden Pothos) appears a promising candidatde particularly due to its strong reducing and stabilizing capabilities, attributed to its high content of polyphenols, flavonoids, and other phytochemicals. These biomolecules effectively reduce gold ions ($Au^{3+}$) to $Au^{0}$, facilitating the formation of stable, uniformly dispersed AuNPs under ambient conditions without the need for toxic surfactants or elevated temperatures.When these biogenic AuNPs are incorporated into molecularly imprinted polymers (MIPs), the resulting composite material exhibits enhanced selectivity and sensitivity toward target analytes. MIPs contribute a high degree of molecular recognition due to their template-specific binding sites, while the embedded AuNPs provide signal amplification through localized surface plasmon resonance (LSPR), enabling optical detection mechanisms such as UV-Vis absorbance or colorimetric shifts.This hybrid biosensing system is especially valuable for real-time and in-field detection of environmental contaminants such as pesticides, endocrine-disrupting compounds (EDCs), and pharmaceutical residues in water. The selectivity of MIPs, coupled with the optical responsiveness of AuNPs, enables accurate detection even in complex sample matrices like river water or tap water without extensive pre-treatment.Furthermore, the use of Araceae leaves extract leverages a widely available, low-cost plant resource, making the biosensor platform accessible and scalable, particularly for resource-limited settings. This approach directly addresses key challenges in global water quality monitoring, including the need for low-cost, portable, and easy-to-use diagnostic tools that do not rely on centralized laboratories.By integrating green nanotechnology, biopolymer design, and biosensing innovation, this method not only enhances analytical performance but also contributes to the development of environmentally responsible public health technologies. It aligns with global sustainability goals and supports efforts to democratize access to clean water through field-deployable, user-friendly sensing platforms.This approach addresses key challenges in global water quality monitoring and contributes to a broader movement toward green nanotechnology and accessible public health tools.

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