Al-Kimia, 13-2-2025, 23-33
Available online at: http://journal.uin-alauddin.ac.id/index.php/al-kimia

Green Synthesis of Gold Nanoparticles from Electronic Waste for Colorimetric Detection of *Salmonella sp.*

Azmalaeni Rifkah Ansyarif[1]*, Nur Aeni[1], Sri Magfirah HS[2]

[1]Chemistry Study Program, Universitas Syekh Yusuf Al Makassari Gowa
[2]Environmental Science Study Program, Universitas Negeri Makassar

**Corresponding Author: azmalaenira@gmail.com*

Received: September, 22, 2025/Accepted: December, 29, 2025
doi:10.24252/al-kimia.v13i2.61562

Abstract: *The rapid increase in electronic waste (e-waste) presents environmental and health risks, while also serving as a secondary source of valuable metals such as gold. This study recovered gold from e-waste and synthesized gold nanoparticles (AuNPs) via a green synthesis approach using ascorbic acid as a natural reducing agent, followed by evaluation of their potential as a colorimetric sensor for Salmonella sp. detection. Gold was extracted through pyrolysis and leaching to obtain* $HAuCl_4$ *precursor solution, which was subsequently reduced by ascorbic acid to form AuNPs. Characterization by TEM, PSA, and UV–Vis confirmed successful synthesis: TEM showed predominantly spherical particles of 20–50 nm, PSA indicated an average size of 82.6 nm, and UV–Vis revealed a distinct Surface Plasmon Resonance (SPR) peak at 520–560 nm. Colorimetric assays demonstrated a linear absorbance response to Salmonella sp. concentration, achieving a detection limit (LOD) of 13.33 CFU/mL. These results demonstrate that gold recovered from e-waste can be converted into functional AuNPs through environmentally friendly synthesis with ascorbic acid, providing a promising platform for rapid and sensitive biosensing applications in food safety.*

Keywords*: Electronic Waste, Gold Recovery, Ascorbic Acid, Nanoparticle, Colorimetric Sensor*

INTRODUCTION

Global electronic waste (e-waste) generation has shown a significant upward trend in line with the accelerated consumption of electronic devices. In 2019, e-waste exceeded 50 million tons, with a recycling rate of only 17.4%, and it is projected to increase to 70 million tons by 2030. The shortened product life cycle, rapid technological advancement, limited processing infrastructure, low public awareness, and inadequate regulations collectively constrain effective e-waste management and pose serious environmental risks (Ahirwar and Tripathi 2021; Forti et al. 2021; Grandhi, et al., 2024).

Unmanaged e-waste accumulation increases the risks of environmental pollution and health impacts, as heavy metals and toxic compounds contained within can contaminate soil, water, and air. This condition disrupts ecosystem balance and elevates heavy metal levels in the human body, potentially triggering hormonal disorders, oxidative stress, and DNA damage (Parvez et al. 2021; Rautela et al. 2021).

One strategy to reduce e-waste accumulation is the recovery of valuable materials contained in it. E-waste is rich in economically valuable metals such as gold, silver, and copper. The concentration of gold in e-waste is much higher than that in conventionally mined ores; one ton of e-waste may contain ten times more gold than one ton of gold ore, and approximately 7% of the world's gold reserves are currently stored in e-waste (Patel 2025; UN 2019; Weick and Ray 2023). Gold recovery from e-waste not only reduces waste accumulation but also supports the principles of circular economy and environmentally friendly technologies.

Beyond producing pure gold, e-waste recovery opens opportunities for advanced technological applications, including the synthesis of gold nanoparticles (AuNPs) (Su-Gallegos et al. 2022). AuNPs are biocompatible and exhibit significant antimicrobial activity, making them suitable for development as biosensors to detect microbial contaminants (Pineda-Vásquez et al. 2024), such as *Salmonella* sp., a major foodborne pathogen. The use of AuNPs as sensors enables rapid and highly sensitive identification of contaminants, thus improving food quality and safety (Ansyarif et al. 2021). AuNPs can be synthesized from e-waste-derived gold using a green synthesis approach with ascorbic acid as a reducing agent (Malassis et al. 2016). This environmentally friendly method yields functional nanoparticles with optimal characteristics for colorimetric detection applications.

Previous studies have extensively demonstrated the effectiveness of AuNPs synthesized from pure gold precursors as biosensors for detecting pathogens such as Salmonella sp. and E. coli, achieving detection limits of 15–20 CFU/mL through colorimetric methods. However, the application of e-waste–derived AuNPs for biosensing—particularly for *Salmonella* colorimetric detection—remains largely unexplored. While most studies on e-waste-derived AuNPs focus on synthesis optimization, morphological characterization, or catalytic applications, their potential as functional biosensors has been underutilized.

This study addresses this critical gap by investigating whether gold recovered from electronic waste can be effectively converted into functional nanoparticles capable of rapid and sensitive pathogen detection. Therefore, this research aims to: (1) synthesize stable AuNPs from e-waste-derived gold using ascorbic acid as a green reducing agent and evaluate their colorimetric performance for Salmonella sp. detection, and (2) demonstrate that e-waste–derived AuNPs can achieve analytical sensitivity comparable to pure-gold nanoparticles while supporting sustainable circular economy principles in food safety applications.

RESEARCH METHODS

Materials and Tools

The materials used included gold-rich e-waste components (PCBs, connectors, electronic chips), nitric acid (HNO_3) and hydrochloric acid (HCl) for metal dissolution, and ascorbic acid ($C_6H_8O_6$) as the reducing agent in the synthesis of gold nanoparticles (AuNPs). Distilled water was used for solution preparation and dilution, while *Salmonella* sp. cultures and nutrient media were employed for AuNPs detection assays. Characterization of AuNPs was carried out using Transmission Electron Microscopy (TEM) for particle morphology and core structure, Particle Size Analyzer (PSA) for particle size distribution, and UV–Vis spectrophotometry for absorbance measurement and evaluation of interactions with *Salmonella* sp. All experiments were performed using standard laboratory equipment and appropriate safety protocols.

Methods

Gold Extraction from E-Waste

Gold extraction from e-waste began with the separation of gold-rich electronic components such as computer PCBs and connectors, with gold concentrations reaching 200–400 g/ton. The selected components were subjected to pyrolysis to remove organic materials and polymers while preventing harmful emissions (Huang, Chou, and Lo 2022). The resulting char residue was ground and treated with HNO_3 to oxidize base metals; gold remains insoluble in pure HNO_3, allowing for preliminary separation from other metals. The solution was then filtered to obtain concentrated gold powder.

$$\mathrm{M + 4HNO_3 \rightarrow M(NO_3)_x + 2NO_2 + 2H_2O}$$

where M = Cu, Zn, Ni, Sn, etc. The concentrated gold powder was subsequently dissolved in aqua regia ($HCl:HNO_3 = 3:1$) to form a tetrachloroaurate complex solution (Au^{3+}):

$$\mathrm{Au + 3HCl + HNO_3 \rightarrow HAuCl_4 + NOCl + 2H_2O}$$

The Au^{3+} solution was used as a precursor for the synthesis of gold nanoparticles for colorimetric sensor applications, as illustrated in Figure 1 (research scheme).

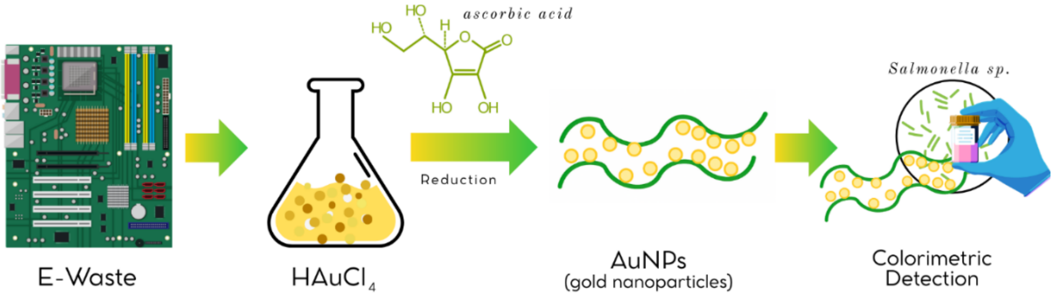

Figure 1. Research Flow: From E-Waste to Gold Nanoparticles and Its Application

Synthesis and Characterization of Gold Nanoparticles (AuNPs)

The gold solution obtained from aqua regia was reduced using ascorbic acid to form gold nanoparticles (AuNPs), as described by the following equation:

$$\mathrm{2HAuCl_4 + 3C_6H_8O_6 \rightarrow 2Au^0 + 3C_6H_6O_6 + 8HCl + 2H_2O}$$

In this reaction, ascorbic acid acts as a reducing agent, converting Au^{3+} ions to metallic gold (Au^0) and resulting in nanoparticle formation. The synthesized nanoparticles were characterized using Transmission Electron Microscopy (TEM) to determine particle morphology and core structure, as well as a Particle Size Analyzer (PSA) to measure particle size distribution in suspension. The characterized AuNPs were subsequently employed for colorimetric applications.

Determination of Limit of Detection (LOD) of AuNPs for Salmonella sp.

The performance of gold nanoparticles (AuNPs) was evaluated to determine their detection capability against Salmonella sp.. Bacterial suspensions with concentrations ranging from 10^{-6} to 10^{-1} CFU/mL were introduced into the AuNPs solution, inducing interactions that affected particle stability.

The Limit of Detection (LOD) was calculated to determine the lowest bacterial concentration that could be significantly detected by the AuNPs sensor, using the following equation:

$$\mathrm{LOD} = \frac{3 \times \mathrm{SD}}{\mathrm{slope}}$$

where SD denotes the standard deviation of the blank measurements, and the slope represents the gradient of the calibration curve (Alankar Shrivastava and Vipin B Gupta 2011; Armbruster and Pry 2008). The LOD values were expressed in CFU/mL, providing an indication of the sensitivity of AuNPs as a biological sensor. This evaluation confirmed the potential of AuNPs for rapid and accurate detection of pathogenic bacteria, particularly *Salmonella sp.*, using a simple and effective colorimetric method.

RESULTS AND DISCUSSION

E-Waste Extraction and Green Synthesis of Gold Nanoparticles (AuNPs)

The extraction of gold from e-waste was carried out in two main stages: pyrolysis and leaching with HNO_3. Pyrolysis served to remove organic materials such as plastics and resins from printed circuit boards, facilitating metal separation while also reducing waste volume and hazardous emissions (Akcil et al. 2015). Subsequent leaching with HNO_3 dissolved base metals such as copper, nickel, and zinc, leaving behind a residue enriched with noble metals including gold.

The gold residue was then dissolved using aqua regia (a mixture of HCl and HNO_3 in a 3:1 ratio) to produce chloroauric acid ($HAuCl_4$). This reagent was selected because it effectively dissolved gold while converting it into stable Au^{3+} ions in solution (Syed 2012). The resulting $HAuCl_4$ solution served as a crucial precursor for the green synthesis of gold nanoparticles, in which ascorbic acid was employed as a reducing agent.

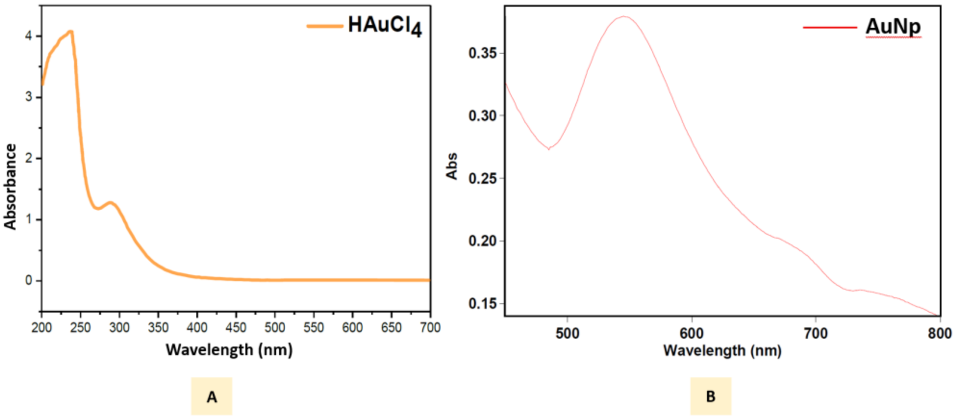

Figure 2. UV–Vis spectra of gold solution extracted from e-waste before (A) and after (B) gold nanoparticle (AuNP) synthesis

The gold precursor solution obtained from e-waste extraction was in the form of chloroauric acid ($HAuCl_4$). UV–Vis spectrophotometric analysis (Figure 2a) revealed a strong absorption peak at ~220–230 nm and a shoulder at ~280–300 nm, corresponding to the ligand-to-metal charge transfer (LMCT) bands of $[AuCl_4]^-$ ions. The absence of a characteristic Surface Plasmon Resonance (SPR) band in the visible region (typically ~520 nm) further confirms that the gold exists purely in its ionic state and has not nucleated into metallic nanoparticles or formed aggregates. Therefore, at this peak, it is not yet possible to evaluate particle size or aggregation.

Following the synthesis using an eco-friendly reducing agent, the UV–Vis spectrum of the gold solution exhibited a distinct change. As shown in Figure 2b, a new absorption peak appeared in the range of 520–560 nm. This peak corresponds to the Surface Plasmon Resonance (SPR), which arises upon the successful formation of gold nanoparticles. The appearance of the SPR band was also consistent with the visual color change of the solution to a reddish-purple hue, a hallmark of gold nanoparticle formation.

A comparison of the two spectra highlights a fundamental difference between the precursor $HAuCl_4$ solution and the AuNPs colloid. While $HAuCl_4$ exhibited absorption only in the ultraviolet region, the AuNPs solution displayed a characteristic SPR band in the visible region. This spectral transition provides direct evidence of the successful green synthesis of gold nanoparticles from e-waste. These findings are in agreement with previous reports that describe the shift from UV absorption of gold ions to visible-region SPR peaks as a key indicator of nanoparticle formation (Bharadwaj et al. 2021; Daniel and Astruc 2004).

Characterization of Gold Nanoparticles from E-Waste (AuNPs)

Characterization of the synthesized gold nanoparticles (AuNPs) derived from e-waste was carried out using Transmission Electron Microscopy (TEM) and Particle Size Analyzer (PSA). TEM provided detailed information on the morphology and core size of individual particles, while PSA was employed to determine the hydrodynamic diameter and particle size distribution in suspension. The combination of both techniques is essential, as TEM reveals the direct structural features of nanoparticles, whereas PSA reflects their behavior in aqueous media, including solvation layers and potential aggregation (Arnida et al. 2011; Jayawardena et al. 2021; Jia et al. 2023).

TEM images (Figure 3) showed that the e-waste-derived AuNPs were predominantly spherical. However, the particle size analysis revealed a broad size distribution spanning 10–200 nm. While the frequency distribution graph confirms a dominant population of primary particles in the 20–50 nm range, the distribution tail extending toward 200 nm directly reflects the presence of larger clusters formed via particle aggregation. This polydispersity suggests that while the synthesis favored small spherical particles, secondary aggregation processes occurred, widening the overall size range. The particle size analysis from TEM indicated a range of 10–200 nm, with a major fraction between 20–50 nm, as confirmed by the frequency distribution graph. This suggests that most particles were relatively small, although some larger particles were also present, likely resulting from aggregation (Domingos et al. 2009; Kato et al. 2012).

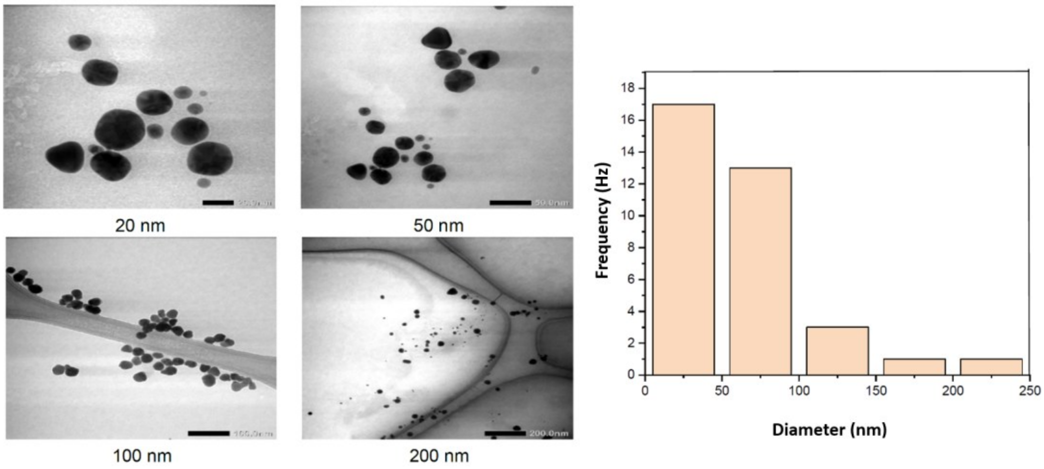

Figure 3. Morphology and Size Distribution of AuNPs from TEM

PSA analysis (Figure 4) revealed a broader particle size distribution, ranging approximately from 20 to 400 nm, with a main peak around 70–120 nm and an average size of 82.6 nm. This broader distribution arises because PSA measures the hydrodynamic diameter, which accounts not only for the nanoparticle core but also for the hydration layer and possible aggregation in aqueous suspension. Consequently, the average size obtained from PSA is typically larger than that measured by TEM. Nevertheless, these findings remain consistent with previous studies, confirming that the nanoparticles are predominantly below 100 nm, while the wider distribution reflects their actual behavior in suspension (Kumar et al. 2017; Singh et al. 2018).

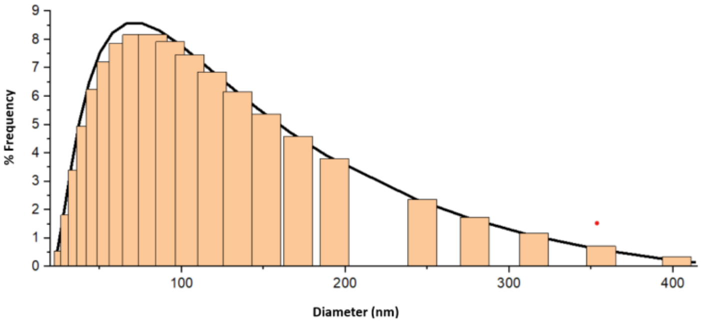

Figure 4. Particle Size Distribution of AuNPs from PSA

The broader and more heterogeneous size distribution of AuNPs synthesized from e-waste is closely related to the impure nature of the precursor solution, as the leachate typically contains other metal ions that can influence nucleation and particle growth. In addition, the use of ascorbic acid as a relatively mild reducing agent causes the reduction process to proceed gradually, leading to nanoparticles of varying sizes. This phenomenon is consistent with previous reports indicating that synthesis systems based on complex precursors or natural reductants tend to produce more variable particle sizes compared to those using pure precursors. Such characteristics reflect the inherent complexity of utilizing electronic waste as a secondary source (Grasseschi et al. 2016; Pineda-Vásquez et al. 2024; Roy et al. 2024). Nevertheless, this environmentally friendly approach successfully yields functional AuNPs, offering broad prospects for future research and applications.

Sensitivity and Limit of Detection of AuNPs toward Salmonella sp.

The performance evaluation of AuNPs derived from e-waste as a colorimetric sensor demonstrated characteristic absorbance changes at the surface plasmon resonance wavelength upon interaction with *Salmonella* sp. (Figure 5a). Increasing bacterial concentrations produced consistent shifts in absorbance intensity, indicating nanoparticle aggregation triggered by interactions with the bacterial cell surface. This optical response generated a linear calibration curve between *Salmonella* sp. concentration and absorbance change, with a high coefficient of determination (R^2) (Figure 5b), confirming a strong correlation between target concentration and optical signal (Quintela et al. 2019; Sun, Zhao, and Dou 2015; Wei, Wang, et al. 2022).

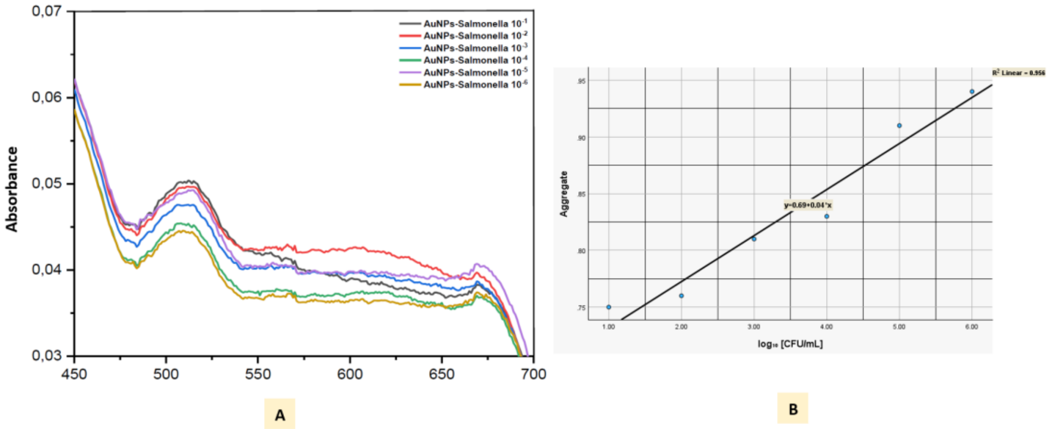

Figure 5. UV–Vis Spectrum (A) and Calibration Curve of AuNPs for *Salmonella sp.* Detection (B)

Based on the calculation results, the limit of detection (LOD) was determined to be 13.33 CFU/mL. This value represents the minimum concentration of *Salmonella* sp. that can still be detected significantly through the absorbance change of AuNPs, while at lower concentrations the optical signal could no longer be distinguished from the blank. These findings indicate that AuNPs synthesized from e-waste are capable of providing a sensitive colorimetric response despite being derived from a complex precursor.

This result is consistent with previous reports on the use of AuNPs synthesized from pure gold for the detection of *Salmonella* sp., where LOD values were reported in the range of 15–20 CFU/mL using either direct aggregation approaches or AuNP–aptamer systems (Duan et al. 2016; Wang et al. 2021; Wei, Su, et al. 2022). In contrast, studies on AuNPs derived from e-waste have generally focused more on synthesis, morphological characterization, or catalytic applications, with little exploration of their potential as biosensors (Kang et al. 2024; Lau et al. 2025). Therefore, this study provides a novel contribution by demonstrating that electronic waste (e-waste) can serve not only as a secondary source of gold but also as a precursor for functional gold nanoparticles applicable in biological detection, particularly for the rapid identification of pathogenic bacteria.

CONCLUSIONS

This study successfully demonstrated that electronic waste (e-waste) can be utilized as a secondary source of gold for the synthesis of gold nanoparticles (AuNPs) through a green synthesis approach using ascorbic acid as a reducing agent. The extraction process involved pyrolysis, leaching with HNO_3, and dissolution of gold with aqua regia to obtain a $HAuCl_4$ precursor solution. Characterization confirmed the formation of spherical AuNPs with a dominant size distribution of 20–50 nm (TEM) and an average of 82.6 nm (PSA). UV–Vis spectra revealed a Surface Plasmon Resonance (SPR) peak at 520–560 nm, confirming the successful synthesis of gold nanoparticles.

The functional evaluation of AuNPs as a colorimetric sensor for *Salmonella* sp. yielded a limit of detection (LOD) of 13.33 CFU/mL, comparable to results obtained from pure-gold-based nanoparticles. This finding demonstrates that AuNPs synthesized from e-waste retain high sensitivity and can be applied as biosensors for the rapid detection of pathogenic bacteria in food. Thus, this study not only supports the reduction of electronic waste accumulation but also contributes to the advancement of environmentally friendly nanotechnology for food safety applications.

ACKNOWLEDGMENTS

This research was funded by the Directorate of Research and Community Service (DPPM), Ministry of Higher Education, Science, and Technology under Contract No. 130/C3/DT.05.00/PL/2025. The authors also gratefully acknowledge the support from LP2M Universitas Syekh Yusuf Al Makassari Gowa, as well as colleagues, laboratory staff, and students who contributed to the data collection and analysis.

REFERENCES

Ahirwar, Rajesh, and Amit K. Tripathi. 2021. ‘E-Waste Management: A Review of Recycling Process, Environmental and Occupational Health Hazards, and Potential Solutions’. *Environmental Nanotechnology, Monitoring & Management* 15:100409. doi:10.1016/j.enmm.2020.100409.

Akcil, Ata, Ceren Erust, Chandra Sekhar Gahan, Mehmet Ozgun, Merve Sahin, and Aysenur Tuncuk. 2015. ‘Precious Metal Recovery from Waste Printed Circuit Boards Using Cyanide and Non-Cyanide Lixiviants – A Review’. *Waste Management* 45:258–71. doi:10.1016/j.wasman.2015.01.017.

Alankar Shrivastava and Vipin B Gupta. 2011. ‘Methods for the Determination of Limit of Detection and Limit of Quantitation of the Analytical Methods’. *Chronicles of Young Scientists* 2(1):21–25. doi:10.4103/2229-5186.79345.

Ansyarif, Azmalaeni Rifkah, Abdul Karim, Paulina Taba, Wahidah Febriya Ramadhani, and Suriadi. 2021. ‘Synthesis of Gold Nanoparticles (AuNPs) with Glutamic Acid Supporting Agent as a Colorimetry Sensor to Salmonella Sp. Bacteria’. *AIP Conference Proceedings* 2360(1):050034. doi:10.1063/5.0059555.

Armbruster, David A., and Terry Pry. 2008. ‘Limit of Blank, Limit of Detection and Limit of Quantitation’. *The Clinical Biochemist Reviews* 29(Suppl 1):S49–52.

Arnida, M. M. Janát-Amsbury, A. Ray, C. M. Peterson, and H. Ghandehari. 2011. ‘Geometry and Surface Characteristics of Gold Nanoparticles Influence Their Biodistribution and Uptake by Macrophages’. *European Journal of Pharmaceutics and Biopharmaceutics* 77(3):417–23. doi:10.1016/j.ejpb.2010.11.010.

Bharadwaj, Kaushik Kumar, Bijuli Rabha, Siddhartha Pati, Tanmay Sarkar, Bhabesh Kumar Choudhury, Arpita Barman, Dorothy Bhattacharjya, Ankit Srivastava, Debabrat Baishya, Hisham Atan Edinur, Zulhisyam Abdul Kari, and Noor Haslina Mohd Noor. 2021. ‘Green Synthesis of Gold Nanoparticles Using Plant Extracts as Beneficial Prospect for Cancer Theranostics’. *Molecules* 26(21):6389. doi:10.3390/molecules26216389.

Daniel, Marie-Christine, and Didier Astruc. 2004. ‘Gold Nanoparticles: Assembly, Supramolecular Chemistry, Quantum-Size-Related Properties, and Applications toward Biology, Catalysis, and Nanotechnology’. *Chemical Reviews* 104(1):293–346. doi:10.1021/cr030698+.

Domingos, Rute F., Mohamed A. Baalousha, Yon Ju-Nam, M. Marcia Reid, Nathalie Tufenkji, Jamie R. Lead, Gary G. Leppard, and Kevin J. Wilkinson. 2009. ‘Characterizing Manufactured Nanoparticles in the Environment: Multimethod Determination of Particle Sizes’. *Environmental Science & Technology* 43(19):7277–84. doi:10.1021/es900249m.

Duan, Nuo, Baocai Xu, Shijia Wu, and Zhouping Wang. 2016. 'Magnetic Nanoparticles-Based Aptasensor Using Gold Nanoparticles as Colorimetric Probes for the Detection of Salmonella Typhimurium'. *Analytical Sciences* 32(4):431–36. doi:10.2116/analsci.32.431.

Forti, Vanessa, Cornelis Peter Baldé, Ruediger Kuehr, and Garam Bel. 2021. *The Global E-Waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential*. Bonn/Geneva/Rotterdam: United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA). https://ewastemonitor.info/gem-2020/.

Grandhi, Sai Preetham, Pranav Prashant Dagwar, and Deblina Dutta. 2024. 'Policy Pathways to Sustainable E-Waste Management: A Global Review'. *Journal of Hazardous Materials Advances* 16:100473. doi:10.1016/j.hazadv.2024.100473.

Grasseschi, Daniel, Filipe S. Lima, Hernan Chaimovich, and Henrique E. Toma. 2016. 'A Critical Evaluation of the Role of the Precursor Complex and Counterions in Synthesis of Gold Nanoparticles in Micellar Media'.

Huang, Yu-Fong, Szu-Ling Chou, and Shang-Lien Lo. 2022. 'Gold Recovery from Waste Printed Circuit Boards of Mobile Phones by Using Microwave Pyrolysis and Hydrometallurgical Methods'. *Sustainable Environment Research* 32(1):6. doi:10.1186/s42834-022-00118-x.

Jayawardena, H. Surangi N., Sajani H. Liyanage, Kavini Rathnayake, Unnati Patel, and Mingdi Yan. 2021. 'Analytical Methods for Characterization of Nanomaterial Surfaces'. *Analytical Chemistry* 93(4):1889–1911. doi:10.1021/acs.analchem.0c05208.

Jia, Zixian, Jiantao Li, Lin Gao, Dezheng Yang, and Andrei Kanaev. 2023. 'Dynamic Light Scattering: A Powerful Tool for In Situ Nanoparticle Sizing'. *Colloids and Interfaces* 7(1):15. doi:10.3390/colloids7010015.

Kang, Seju, Asifur Rahman, Sean McGinnis, and Peter Vikesland. 2024. 'Toward Environmentally Favorable Nano-Sensing by Production of Reusable Gold Nanoparticles from Gold Nano-Waste: Life Cycle and Nanocircular Economy Implications'. *Environmental Science: Nano* 11(4):1499–1507. doi:10.1039/D3EN00505D.

Kato, Haruhisa, Ayako Nakamura, Kayori Takahashi, and Shinichi Kinugasa. 2012. 'Accurate Size and Size-Distribution Determination of Polystyrene Latex Nanoparticles in Aqueous Medium Using Dynamic Light Scattering and Asymmetrical Flow Field Flow Fractionation with Multi-Angle Light Scattering'. *Nanomaterials* 2(1):15–30. doi:10.3390/nano2010015.

Kumar, Brajesh, Kumari Smita, Luis Cumbal, and Alexis Debut. 2017. 'Green Synthesis of Silver Nanoparticles Using Andean Blackberry Fruit Extract'. *Saudi Journal of Biological Sciences* 24(1):45–50. doi:10.1016/j.sjbs.2015.09.006.

Lau, Michelle Y., David C. Young, Jack L. Y. Chen, and Jonathan Sperry. 2025. 'Catalytic Performance of Electronic Waste-Derived Gold Nanoparticles for the Reduction of p-Nitrophenol'. *Environmental Science: Nano* 12(2):1638–56. doi:10.1039/D4EN01077A.

Malassis, Ludivine, Rémi Dreyfus, Ryan J. Murphy, Lawrence A. Hough, Bertrand Donnio, and Christopher B. Murray. 2016. 'One-Step Green Synthesis of Gold and Silver

Nanoparticles with Ascorbic Acid and Their Versatile Surface Post-Functionalization'. *RSC Advances* 6(39):33092–100. doi:10.1039/C6RA00194G.

Parvez, Sarker M., Farjana Jahan, Marie-Noel Brune, Julia F. Gorman, Musarrat J. Rahman, David Carpenter, Zahir Islam, Mahbubur Rahman, Nirupam Aich, Luke D. Knibbs, and Peter D. Sly. 2021. 'Health Consequences of Exposure to E-Waste: An Updated Systematic Review'. *The Lancet Planetary Health* 5(12):e905–20. doi:10.1016/S2542-5196(21)00263-1.

Patel, Prachi. 2025. 'Electronic Waste Is a Gold Mine Waiting to Be Tapped'. https://cen.acs.org/environment/recycling/Electronic-waste-gold-mine-waiting/102/i23.

Pineda-Vásquez, Tatiana, Leidy Rendón-Castrillón, Margarita Ramírez-Carmona, and Carlos Ocampo-López. 2024. 'From E-Waste to High-Value Materials: Sustainable Synthesis of Metal, Metal Oxide, and MOF Nanoparticles from Waste Printed Circuit Boards'. *Nanomaterials* 14(1):69. doi:10.3390/nano14010069.

Quintela, Irwin A., Benildo G. de los Reyes, Chih-Sheng Lin, and Vivian C. H. Wu. 2019. 'Simultaneous Colorimetric Detection of a Variety of Salmonella Spp. in Food and Environmental Samples by Optical Biosensing Using Oligonucleotide-Gold Nanoparticles'. *Frontiers in Microbiology* 10:1138. doi:10.3389/fmicb.2019.01138.

Rautela, Rahul, Shashi Arya, Shilpa Vishwakarma, Jechan Lee, Ki-Hyun Kim, and Sunil Kumar. 2021. 'E-Waste Management and Its Effects on the Environment and Human Health'. *Science of The Total Environment* 773:145623. doi:10.1016/j.scitotenv.2021.145623.

Roy, Angira, Ciaran P. Healey, Nathaniel E. Larm, Piyuni Ishtaweera, Maryuri Roca, and Gary A. Baker. 2024. 'The Huge Role of Tiny Impurities in Nanoscale Synthesis'. *ACS Nanoscience Au* 4(3):176–93. doi:10.1021/acsnanoscienceau.3c00056.

Singh, Jagpreet, Tanushree Dutta, Ki-Hyun Kim, Mohit Rawat, Pallabi Samddar, and Pawan Kumar. 2018. '"Green" Synthesis of Metals and Their Oxide Nanoparticles: Applications for Environmental Remediation'. *Journal of Nanobiotechnology* 16(1):84. doi:10.1186/s12951-018-0408-4.

Su-Gallegos, Javier, Lorena Magallón-Cacho, Jeannete Ramírez-Aparicio, and Edgar Borja-Arco. 2022. 'Synthesis of Gold Nanoparticles from Gold Coatings Recovered from E-Waste Processors'. *Materials* 15(20):7307. doi:10.3390/ma15207307.

Sun, Qian, Guangying Zhao, and Wenchao Dou. 2015. 'Blue Silica Nanoparticle-Based Colorimetric Immunoassay for Detection of Salmonella Pullorum'. *Analytical Methods* 7(20):8647–54. doi:10.1039/C5AY02073E.

Syed, S. 2012. 'Recovery of Gold from Secondary Sources—A Review'. *Hydrometallurgy* 115–116:30–51. doi:10.1016/j.hydromet.2011.12.012.

UN, 2019. 2019. 'UN Report: Time to Seize Opportunity, Tackle Challenge of e-Waste'. https://www.unep.org/news-and-stories/press-release/un-report-time-seize-opportunity-tackle-challenge-e-waste.

Wang, Lijun, Xue Wu, Haixia Hu, Yukun Huang, Xiao Yang, Qin Wang, and Xianggui Chen. 2021. 'Improving the Detection Limit of Salmonella Colorimetry Using Long ssDNA of Asymmetric-PCR and Non-Functionalized AuNPs'. *Analytical Biochemistry* 626:114229. doi:10.1016/j.ab.2021.114229.

Wei, Shengnan, Zhenyue Su, Xiangong Bu, Xuening Shi, Bo Pang, Liang Zhang, Juan Li, and Chao Zhao. 2022. 'On-Site Colorimetric Detection of Salmonella Typhimurium'. *NPJ Science of Food* 6:48. doi:10.1038/s41538-022-00164-0.

Wei, Shengnan, Xuechen Wang, Feng Wang, Xinqing Hao, Hang Li, Zhenyue Su, Yuanyuan Guo, Xuening Shi, Xingxing Liu, Juan Li, and Chao Zhao. 2022. 'Colorimetric Detection of Salmonella Typhimurium Based on Hexadecyl Trimethyl Ammonium Bromide-Induced Supramolecular Assembly of β-Cyclodextrin-Capped Gold Nanoparticles'. *Analytical and Bioanalytical Chemistry* 414(20):6069–76. doi:10.1007/s00216-022-04166-5.

Weick, Mark, and Nicole Ray. 2023. 'How Circular Economy Models Can Address Global E-Waste'. https://www.ey.com/en_us/insights/climate-change-sustainability-services/how-circular-economy-models-can-address-global-e-waste.