AN OVERVIEW: NOVEL BIMETALLIC NANOPARTICLES AND ITS APPLICATIONS

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ABSTRACT

BMNPs, or bimetallic nanoparticles, are a family of nanomaterials that are more effective and adaptable than their monometallic counterparts. As a result of the nanoscale combination of two distinct metals, BMNPs have special physicochemical properties like better thermal and chemical stability, increased catalytic activity, and adjustable optical, electronic, and magnetic characteristics. A vast array of applications in various disciplines are made possible by these synergistic effects, which result from the interaction of the constituent metals' electrical and geometric structures.
The synthesis techniques for BMNPs, such as co-reduction, sequential reduction, galvanic replacement, sol-gel, microemulsion, and green synthesis approaches, are well covered in this study. The functional performance of the various structural configurations—including core-shell, alloyed, and heterostructured BMNPs—is examined. Their uses in biology, environmental cleanup, sensing and diagnostics, and catalysis are highlighted in particular. Along with their roles in pollutant degradation, chemical sensing, and as electro catalysts and photo catalysts, the biomedical significance of BMNPs in medication delivery, imaging, and antimicrobial therapy is examined.
The review also focuses on contemporary issues such environmental effects, large-scale synthesis, toxicity, and biocompatibility. The advancement of BMNPs in sustainable and application-driven research is examined, along with potential future paths. BMNPs are an all-around promising class of materials that could help solve urgent issues in the energy, healthcare, and environmental sectors.

***Keywords:** Bimetallic nanoparticles, Catalysis, Antimicrobial activity, monometallic nanoparticles.*

INTRODUCTION

Researchers focus on particles in the nano size range since current technology is applied in a new age. Nanoparticles fall into the nano size range. Carbon-based materials, polymers, lipids, metals, and metal oxides can all be used to make them. The metal pure metal nanoparticles, metal oxide nanoparticles, polymeric nanoparticles, composed of natural or manufactured polymers, carbon-based nanoparticles, which are allotropes of carbon, and lipid-based nanoparticles are utilized in drug delivery. Shown in figure no. 1. Metal atoms make up the type of nanomaterial known as metallic nanoparticles (MNPs), which are usually between one and one hundred nanometers in size. Their small size and huge surface area give them unique physical, chemical, catalytic and optical capabilities compared to their bulk counterparts.
Different type of metallic nanoparticles are monometallic, bimetallic and multimetallic nanoparticles.

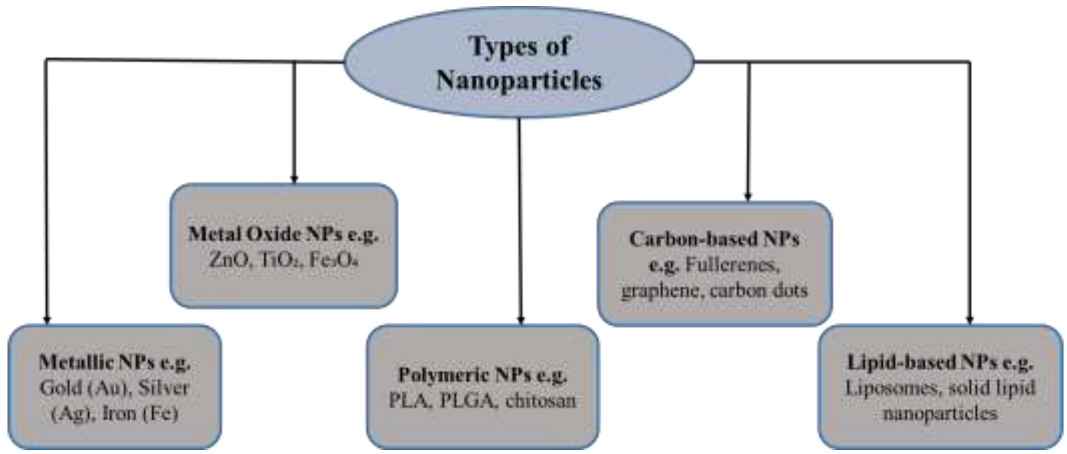

Fig. 1: Types of nanoparticles

We elaborate on the use of geometrical descriptors to read a monometallic nanoparticle's genome because its shape and size may affect their chemical-physical properties. The resulting geometrical genome uses the generalized co-ordination number as a description to identify, catalog, and count the range of adsorption sites that are accessible on each isomer with a up to10 nm diameter; consequently, it depends on the shape and size of the nanoparticle. (Rossi, K. et al., 2019) Two distinct metal elements combine to form bimetallic nanoparticles, which are materials at the nanoscale. These particles are useful in sensing, energy storage, medicinal applications, and catalysis because of their synergistic qualities, which are frequently better than those of their monometallic counterparts. (Nasrabadi, H. T. et al., 2016)

Bimetallic Nanoparticle Structural Types

The distinctive optical, electrical, magnetic, and catalytic properties of bimetallic nanoparticles have drawn special attention in the last 10 years in both research and technology fields. Frequently, these characteristics differ significantly compared to those of their monometallic counterparts.(Arora, N. et al., 2020) Two different kinds of metal nanoparticles are mixed together to generate bimetallic nanoparticles, which can have a variety of shapes and configurations.(Ziaei-azad, H., et al., 2013) (Beveridge, T. J. et al., 1999) Bimetallic nanoparticles can be aligned in randomly metal alloys, alloys with intermetallic compounds, cluster-in-cluster, or core-shell structures, depending on a variety of factors, including relative atomic sizes, bulk element surface energies, relative metal-metal bond strengths, and preparation conditions.(Zaleska-Medynska, A. et al., 2016)

In alloy at the atomic level, both metals are uniformly mixed. (Yao, Y. et al., 2021) Nanoparticles of bimetallic core-shell While one metal makes up the core, another makes up the shell.(Eom, N. et al., 2021) Within one particle, there are two separate areas of several metals present in janus type of bimetallic nanoparticles. . (Ye, S., & Carroll, R. L., 2010) Smaller groups of one metal encased in another group of metals in Cluster-in-cluster type of bimetallic nanoparticles. (Kotzé, G. 2018) All structures shown in fig. 2.

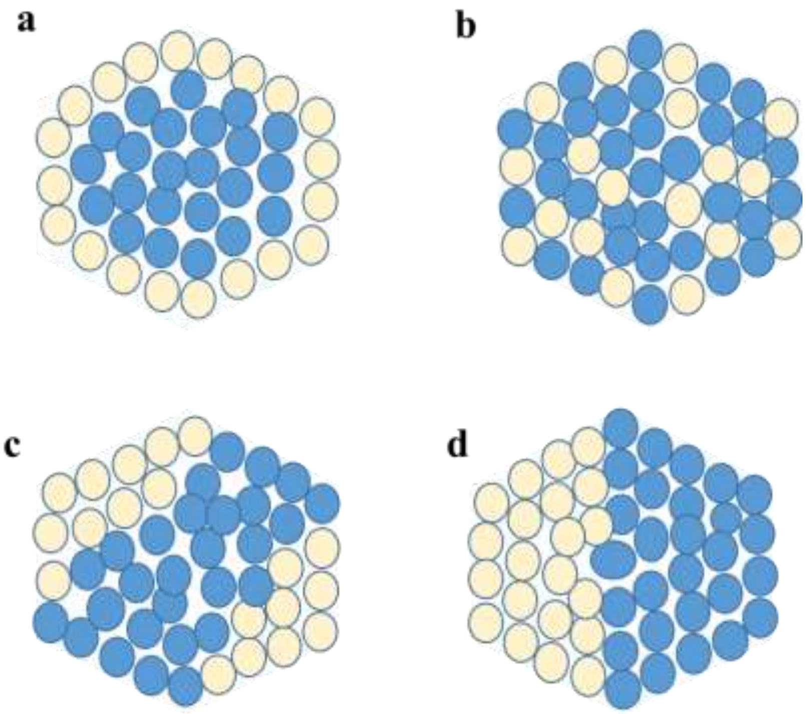

Fig. 2: Structural Types of Bimetallic Nanoparticles. [Ref 3- 10]

SYNTHESIS METHODS

Bimetallic nanoparticle synthesis typically entails either assembling the nanoparticles from their individual atoms or dissolving bulk materials into nano sized particles. These two approaches are known as top-down and bottom-up. When using the bottom-up method, two distinct metal precursors are typically mixed in a reaction vessel under ideal conditions before a stabilizing and reducing agent is added. Nonetheless, there are three primary categories into which the basic process of creating bimetallic nanoparticles can be divided: physical, chemical, and biological techniques. (Idris, D. S., & Roy, A. 2023). Different bottom-up approaches of bimetallic nanoparticles are:

Co-reduction

When both metals can be reduced under comparable circumstances, the co-reduction process is one of the most popular ways to create bimetallic nanoparticles (BMNPs). The co-reduction method creates bimetallic nanoparticles by simultaneously reducing two metal precursors in a solution. This method often produces BMNPs of the core-shell or alloy types, depending on the metals' miscibility and rate of reduction. During the process of bimetallic nanoparticles two metal salts (e.g., chlorides, nitrates) are dissolved in a common solvent. A chemical reducer (e.g., $NaBH_4$, hydrazine, ascorbic acid) is added to simultaneously reduce both metal ions. Surfactants like PVP, CTAB, or citrate are used to prevent agglomeration. Controlled parameters like temperature, pH, concentration, and stirring rate influence the final NP structure. In a single reaction mixture, two metal precursors are chemically reduced simultaneously using the co-reduction process. It is frequently employed to prepare BMNPs of the alloy or core-shell types, depending on the metal ions standard reduction potentials and reaction kinetics.(Zhan, F. et al., 2020)

Sequential reduction

By reducing two distinct metal precursors in a stepwise manner, the sequential reduction process creates a core by first reducing one metal ion and then reducing the second metal to create a shell or decorative layer on top of the preformed core. (Nagaonkar, D., & Rai, M. 2015)

Galvanic replacement

Using a spontaneous redox reaction, the replacement galvanic method is a redox-driven synthetic procedure that replaces a lower reduction potential entirely or partially with a higher reduction potential from a more noble metal. This leads to BMNPs that are porous, hollow, or core-shell. In this process in solution, a preformed nanoparticle template of a less noble metal (such as Ag^0) is suspended. A salt of a more noble metal is added, such as H_2PtCl_6 or $HAuCl_4$. The high-grade metal ions oxidize the template metal's surface atoms, allowing them to dissolve into solution. The noble metal ions deposit onto the template surface as a result of sequential reduction. (El Mel, A. A. et al., 2016)

$$3Ag^0_{(s)} + AuCl_4^{-} \longrightarrow Au^0_{(s)} + 3Ag^+ + 4Cl^-$$

Sol-gel and microemulsion methods

Metal alkoxides or metal salts are hydrolyzed and polycondensed to create a colloidal sol, which progressively transforms into a gel-like network that may be dried and heated to produce metallic or metal oxide nanoparticles. Utilizing a thermodynamically stable blend of water, oil, surfactant, and co-surfactant, the microemulsion technique creates nanoscale droplets, or reverse micelles, that serve as nanoreactors for the regulated nucleation and development of bimetallic nanoparticles. (Li, T. et al., 2014)

Phytochemical Synthesis

Green synthesis is a sustainable, non-toxic, and environmentally friendly method of creating bimetallic nanoparticles (BMNPs) from biological resources such as bacteria, fungi, algae, plant extracts, or biomolecules (e.g., proteins, polysaccharides). By doing this, the environmental impact is reduced and harsh chemicals are avoided. (Al-Haddad, J. et al., 2020) Table 1. shows the various method of synthesis of bimetallic nanoparticles with examples and table 2. shows overview of some synthesized bimetallic nanoparticles and its applications.

Table 1. Various method of synthesized bimetallic nanoparticles with description and examples.

Synthetic Method	Description	Examples of used bimetals	References
Co-reduction	Two metal precursors being reduced simultaneously	Pd-Cu bimetals are used	Zhan, F. et al., 2020
Sequential reduction	Core-shell formation	Ag-Au bimetals are used	Nagaonkar, D. et al., 2015
Galvanic replacement	More noble metal takes the place of sacrificial metal.	Ag-Pd bimetals are used	Jing, H. et al., 2015

Sol-gel and microemulsion methods	The sol-gel process can be improved or managed with the use of microemulsion techniques.	Pd-Au bimetals are used	Li, T. et al., 2014
Green synthesis	Extracts from plants as stabilizing and capping agents	Cu-Ag bimetals are used	Al-Haddad, J. et al., 2020

Table 2. Overview of Synthesis Techniques and Combinations of BMNPs.

Bimetallic Nanoparticles	Types of Metal	Structural type	Synthesis Methods	Applications	References
Fe–Co	Magnetic – Magnetic	Alloy	Thermal decomposition, Co-precipitation	Magnetic fluids and the treatment of hyperthermia	Nochehdehi, A. R. et al. 2022
Ni–Co	Base – Base	Alloy, Janus	Thermal and Solvothermal	Battery and Supercapacitor devices	Ding, R. et al., 2017
Zn–Ag	Base – Unique	Core-shell, Janus	Hydrothermal, Green synthesis	Antimicrobial and photocatalytic	Mazhar, T. 2022
Cu–Au	Base – Unique	Alloy, Core-shell	Green synthesis and wet chemical reduction	Surface-enhanced Raman spectroscopy (SERS), Electronics	Kumar-Krishnan, S. et al., 2020
Cu–Ag	Base – Unique	Alloy	Chemical reduction, Green synthesis	Conductive, antimicrobial	Al-Haddad, J. et al., 2020
Co–Pt	Magnetic – Unique	Intermetallic, Core-shell	Sol-gel, Thermal decomposition	Cancer therapy and Magnetic materials	Islam, M. 2018
Fe–Pt	Magnetic – Unique	Intermetallic, Core-shell	Thermal decomposition, Chemical vapor deposition	Data storage, MRI contrast agents	Chang, Z. X. et al., 2022

Ni–Pt	Base – Unique	Core-shell, Alloy	Thermal decomposition, Solvothermal	Oxygen Reduction Reaction catalysis (ORRC), Hydrogen evolution reaction	Ma, Y. et al., 2018
Pt–Pd	Unique - Unique	Alloy	Sol-gel, Co-precipitation	Fuel cells, Catalysis	Li, M. et al., 2022
Ag–Pt	Unique - Unique	Alloy, Core-shell	Co-reduction, Thermal decomposition	Electrochemistry , Antibacterial	Liu, H. et al., 2014
Au–Pd	Unique - Unique	Core-shell, Janus, Alloy	Co-reduction and seed-mediated growth	Using hydrogen and electro catalysis	Ma, T. et al., 2017
Au–Pt	Unique - Unique	Alloy, Core-shell	Wet chemical reduction, Co-reduction	Fuel cells, Catalysis	Gowthaman, N. S. K. et al., 2018
Au–Ag	Unique - Unique	Core-shell, alloy	Co-reduction, Seed-mediated, Galvanic replacement	Drug delivery, SERS, biosensors, and catalysis	Berahim, N. 2020

Monometallic NPs have a limited capacity to improve performance, but they are simpler and easier to manufacture. But the interaction and combination of two metals, bimetallic nanoparticles (NPs) have higher functional characteristics that improve performance in biological, sensing, and catalytic applications. Table 3. shows the comparative study of bimetallic and bimetallic nanoparticles.

Table 3. Comparative Study of Bimetallic and Monometallic Nanoparticles

Characteristic Properties	**Nanoparticles**	
	Monometallic (MMNPs)	**Bimetallic (BMNPs)**

Composition	Composed of a single metal, such as Pt, Au, or Ag.	Made up of two distinct metals, such as Au-Pd and Fe-Ni.
Variability of Structure	Easier structures are found with uniform metal lattice.	Variability in structure is found such as alloy, core-shell, and Janus difficult structures are founds.
Configurable Features	Constrained; size and form affect tuning	Using metal ratio, structure, and arrangement, broad tunability
Activity of Catalysis	High catalytic activity (but unique to a single metal)	Frequently better because of the complementary effects of two metals
Stability	May oxidize or disintegrate more quickly.	usually more resilient to oxidation and more stable
Magnetic Properties	Metal-based(e.g. Co, Fe) fixed	Magnetic behavior that can be adjusted (for example, Fe-Ni has superior soft magnetism)
Optical Properties	Explained by Surface Plasmon Resonance of one metal (e.g., Ag or Au)	Surface Plasmon's Definition A single metal's resonance (for example, Cu-Ag).
Antimicrobial properties	Good antimicrobial activity	Excellent as compare to monometallic NPs
Synthesis Complexity	Easier to synthesize and scale	More difficult due to control needed for structure and composition
Expense	Reduced if base metal (such as Zn or Cu) is utilized	Noble metal composition can be decreased, but it can be increased if noble metals are used.
Phytochemical Synthesis Feasibility	Typical of green techniques	Metal-based (e.g., Fe, Co, Ni) fixed

APPLICATIONS OF BIMETALLIC NANOPARTICLES

Biomedical Applications

When compared to their monometallic counterparts, bimetallic nanoparticles (BMNPs), which are made up of two distinct metallic elements, have improved physicochemical and biological characteristics. These improvements result from the two metals working in concert to improve stability, catalytic activity, and surface plasmon resonance. Because of their versatility, BMNPs have become potential agents in the biomedical domains. Therapeutic drugs can be delivered precisely and under control using BMNPs as effective nanocarriers. Anticancer medications such as doxorubicin have been administered via Au-Ag or Au-Pt nanoparticles. The significant optical absorption of BMNPs makes them useful in photodynamic therapy (PDT) and photo thermal therapy (PTT). Au-Pd and Au-Fe BMNPs for combined photo thermal and chemotherapeutic effects. BMNPs are more effective against bacteria than individual metals due to their broad-spectrum antibacterial activity. The antibacterial properties of Copper-Silver and Gold-Silver

BMNPs are improved against S. aureus, E. coli, and other microorganisms. Because of BMNPs' high surface-to-volume ratio, conductivity, and catalytic activity, they are incorporated into biosensors. Electrochemical sensors using Au-Pt BMNPs for early illness detection.(Iravani, S., & Varma, R. S. 2020) (Barui, S., & Cauda, V. 2020) (Medina-Cruz, D. et al., 2020).

Sensors and Diagnostics

The improved catalytic activity, high surface area, tunable optical/electronic properties, and synergistic impacts between the two metals that make up bimetallic nanoparticles (BMNPs) make them essential for the advancement of sensor and diagnostic technologies. BMNPs are very useful in chemical and biological sensing applications because of these characteristics.

In electrochemical sensors, BMNPs function as signal amplifiers and catalysts, allowing for the sensitive and targeted detection of analytes. Strong surface plasmon resonance (SPR) BMNPs are frequently employed in optical sensing systems, especially those containing gold or silver components. (Li, G. et al., 2021)

Environmental Remediation

The enhanced redox properties, synergistic effects between the two metals, and enhanced catalytic activity of bimetallic nanoparticles (BMNPs) have made them highly useful materials for environmental remediation. BMNPs exhibit quicker kinetics and greater reactivity against a range of contaminants, such as pesticides, organic dyes, heavy metals, and chlorinated chemicals, in contrast to monometallic nanoparticles. (Das, S. et al. 2018)

Catalysis

Bimetallic nanoparticles (BMNPs), with their customizable composition, synergistic interactions, and changed electronic and geometric structures, are highly versatile and efficient catalysts for a range of industrial and chemical applications. The bimetallic synergism that BMNPs exhibit improves selectivity, activity, and stability, causing their catalytic activity to frequently surpass that of monometallic nanoparticles. (Wang, A. et al., 2018)

CONCLUSION

The synergistic interactions, increased surface activity, and customizable physicochemical features of bimetallic nanoparticles (BMNPs) make them superior to monometallic nanoparticles and constitute a major breakthrough in nanotechnology. Fine control over reactivity, selectivity, and stability in a variety of applications is made possible by their many structural configurations, which include core–shell, alloy, and heterostructures.

BMNPs have demonstrated significant potential in biomedicine for antimicrobial therapies, drug delivery, cancer therapy, and bio imaging. Through catalytic and plasmonic effects, they improve sensitivity and specificity in sensors and diagnostics. BMNPs effectively break down heavy metals and hazardous contaminants for environmental cleanup, and they facilitate a variety of industrial, organic, and electrocatalytic reactions with enhanced selectivity and efficiency in catalysis. Despite their potential, real-world applications require addressing issues like toxicity, environmental effect, and synthesis scalability. Their use across scientific and economic areas will be further expanded by ongoing research into green synthesis techniques, biocompatibility, and mechanistic understanding.

In conclusion, BMNPs are multipurpose nanomaterials that have the ability to revolutionize a variety of biological, environmental, and catalytic domains. As such, they are a fundamental component of next-generation nanotechnology solutions.

REFERENCES

1. Rossi, K., Asara, G. G., & Baletto, F. (2019). A genomic characterisation of monometallic nanoparticles. Physical Chemistry Chemical Physics, 21(9), 4888-4898.
2. Nasrabadi, H. T., Abbasi, E., Davaran, S., Kouhi, M., & Akbarzadeh, A. (2016). Bimetallic nanoparticles: Preparation, properties, and biomedical applications. Artificial cells, nanomedicine, and biotechnology, 44(1), 376-380.
3. Arora, N., Thangavelu, K., & Karanikolos, G. N. (2020). Bimetallic nanoparticles for antimicrobial applications. Frontiers in Chemistry, 8, 412.
4. Ziaei-azad, H., Yin, C. X., Shen, J., Hu, Y., Karpuzov, D., & Semagina, N. (2013). Size-and structure-controlled mono-and bimetallic Ir–Pd nanoparticles in selective ring opening of indan. Journal of Catalysis, 300, 113-124.
5. Beveridge, T. J. (1999). Structures of gram-negative cell walls and their derived membrane vesicles. J. Bacteriol. 181, 4725–4733. doi: 10.1128/JB.181.16.4725-4733.1999
6. Zaleska-Medynska, A., Marchelek, M., Diak, M., & Grabowska, E. (2016). Noble metal-based bimetallic nanoparticles: the effect of the structure on the optical, catalytic and photocatalytic properties. Advances in colloid and interface science, 229, 80-107.
7. Yao, Y., Huang, Z., Hughes, L. A., Gao, J., Li, T., Morris, D., ... & Hu, L. (2021). Extreme mixing in nanoscale transition metal alloys. Matter, 4(7), 2340-2353.
8. Eom, N., Messing, M. E., Johansson, J., & Deppert, K. (2021). General trends in core–shell preferences for bimetallic nanoparticles. ACS nano, 15(5), 8883-8895.
9. Ye, S., & Carroll, R. L. (2010). Design and fabrication of bimetallic colloidal "Janus" particles. ACS applied materials & interfaces, 2(3), 616-620.
10. Kotzé, G. (2018). Mono-and Bimetallic Au-Cu dendrimer micelle encapsulated nanoparticles as catalysts in the oxidation of styrene (Doctoral dissertation, Stellenbosch: Stellenbosch University).
11. Idris, D. S., & Roy, A. (2023). Synthesis of bimetallic nanoparticles and applications—an updated review. Crystals, 13(4), 637.
12. Zhan, F., Yin, J., Zhang, A., Zhou, J., Wang, M., & Jiao, T. (2020). Controllable morphology and highly efficient catalytic performances of Pd–Cu bimetallic nanomaterials prepared via seed-mediated co-reduction synthesis. Applied Surface Science, 527, 146719.
13. Nagaonkar, D., & Rai, M. (2015). Sequentially reduced biogenic silver-gold nanoparticles with enhanced antimicrobial potential over silver and gold monometallic nanoparticles. Adv. Mater. Lett, 6(4), 334-341.
14. El Mel, A. A., Chettab, M., Gautron, E., Chauvin, A., Humbert, B., Mevellec, J. Y., ... & Tessier, P. Y. (2016). Galvanic replacement reaction: a route to highly ordered bimetallic nanotubes. The Journal of Physical Chemistry C, 120(31), 17652-17659.
15. Li, T., Zhou, H., Huang, J., Yin, J., Chen, Z., Liu, D., ... & Kuang, Y. (2014). Facile preparation of Pd–Au bimetallic nanoparticles via in-situ self-assembly in reverse microemulsion and their electrocatalytic properties. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 463, 55-62.

16. Al-Haddad, J., Alzaabi, F., Pal, P., Rambabu, K., & Banat, F. (2020). Green synthesis of bimetallic copper–silver nanoparticles and their application in catalytic and antibacterial activities. Clean Technologies and Environmental Policy, 22, 269-277.
17. Zhan, F., Yin, J., Zhang, A., Zhou, J., Wang, M., & Jiao, T. (2020). Controllable morphology and highly efficient catalytic performances of Pd–Cu bimetallic nanomaterials prepared via seed-mediated co-reduction synthesis. Applied Surface Science, 527, 146719.
18. Nagaonkar, D., & Rai, M. (2015). Sequentially reduced biogenic silver-gold nanoparticles with enhanced antimicrobial potential over silver and gold monometallic nanoparticles. Adv. Mater. Lett, 6(4), 334-341.
19. Jing, H., & Wang, H. (2015). Structural evolution of Ag–Pd bimetallic nanoparticles through controlled galvanic replacement: effects of mild reducing agents. Chemistry of Materials, 27(6), 2172-2180.
20. Li, T., Zhou, H., Huang, J., Yin, J., Chen, Z., Liu, D., ... & Kuang, Y. (2014). Facile preparation of Pd–Au bimetallic nanoparticles via in-situ self-assembly in reverse microemulsion and their electrocatalytic properties. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 463, 55-62.
21. Al-Haddad, J., Alzaabi, F., Pal, P., Rambabu, K., & Banat, F. (2020). Green synthesis of bimetallic copper–silver nanoparticles and their application in catalytic and antibacterial activities. Clean Technologies and Environmental Policy, 22, 269-277.
22. Nochehdehi, A. R., Thomas, S., Sadri, M., Hadavi, S. M., Grohens, Y., Kalarikkal, N., & Revaprasdu, N. (2022). Fe, Co Based Bio-Magnetic Nanoparticles (BMNPs): Synthesis, Characterization, and Biomedical Application. In Recent trends in nanomedicine and tissue engineering (pp. 157-196). River Publishers.
23. Ding, R., Li, X., Shi, W., Xu, Q., & Liu, E. (2017). One-pot solvothermal synthesis of ternary Ni-Co-P micro/nano-structured materials for high performance aqueous asymmetric supercapacitors. Chemical Engineering Journal, 320, 376-388.
24. Mazhar, T. (2022). Bio-assisted synthesis of bi-metallic (Ag-Zn) nanoparticles by leaf extract of Azadirachta indica and its antimicrobial properties. International Journal of Nano Dimension, 13(2).
25. Kumar-Krishnan, S., Esparza, R., & Pal, U. (2020). Controlled fabrication of flower-shaped Au–Cu nanostructures using a deep eutectic solvent and their performance in surface-enhanced Raman scattering-based molecular sensing. ACS omega, 5(7), 3699-3708.
26. Al-Haddad, J., Alzaabi, F., Pal, P., Rambabu, K., & Banat, F. (2020). Green synthesis of bimetallic copper–silver nanoparticles and their application in catalytic and antibacterial activities. Clean Technologies and Environmental Policy, 22, 269-277.
27. Islam, M. (2018). Synthesis and Characterization of CoPt Magnetic Nanoparticles by Sol-gel Method and First Principles Study (Doctoral dissertation, University of Rajshahi).
28. Chang, Z. X., Li, C. H., Chang, Y. C., Huang, C. Y. F., Chan, M. H., & Hsiao, M. (2022). Novel monodisperse FePt nanocomposites for T2-weighted magnetic resonance imaging: biomedical theranostics applications. Nanoscale Advances, 4(2), 377-386.
29. Ma, Y., Miao, L., Guo, W., Yao, X., Qin, F., Wang, Z., ... & Gan, L. (2018). Modulating surface composition and oxygen reduction reaction activities of Pt–Ni octahedral nanoparticles by microwave-enhanced surface diffusion during solvothermal synthesis. Chemistry of Materials, 30(13), 4355-4360.
30. Li, M., Fu, S., Saedy, S., Rajendrakumar, A., Tichelaar, F. D., Kortlever, R., & van Ommen, J. R. (2022). Nanostructuring Pt-Pd Bimetallic Electrocatalysts for CO2 Reduction Using Atmospheric Pressure Atomic Layer Deposition. ChemCatChem, 14(24), e202200949.

31. Liu, R., Liang, H., Liu, J., Zhong, H., Cui, R., Li, X., ... & Zhou, H. (2025). Catalytic and biological properties of Ag–Pt bimetallic nanoparticles: composition-dependent activity and cytotoxicity. Nanoscale, 17(17), 10865-10875.
32. Ma, T., Liang, F., Chen, R., Liu, S., & Zhang, H. (2017). Synthesis of Au-Pd bimetallic nanoflowers for catalytic reduction of 4-nitrophenol. Nanomaterials, 7(9), 239.
33. Gowthaman, N. S. K., Sinduja, B., Shankar, S., & John, S. A. (2018). Displacement reduction routed Au–Pt bimetallic nanoparticles: a highly durable electrocatalyst for methanol oxidation and oxygen reduction. Sustainable Energy & Fuels, 2(7), 1588-1599.
34. Berahim, N. (2020). Synthesis and Characterization of Bimetallic Gold-Silver (Au-Ag) Nanocatalyst Via Seed Colloid Technique (Master's thesis, University of Malaya (Malaysia)).
35. Iravani, S., & Varma, R. S. (2020). Green synthesis, biomedical and biotechnological applications of carbon and graphene quantum dots. A review. Environmental chemistry letters, 18, 703-727.
36. Barui, S., & Cauda, V. (2020). Multimodal decorations of mesoporous silica nanoparticles for improved cancer therapy. Pharmaceutics, 12(6), 527.
37. Medina-Cruz, D., Saleh, B., Vernet-Crua, A., Nieto-Argüello, A., Lomelí-Marroquín, D., Vélez-Escamilla, L. Y., ... & Webster, T. (2020). Bimetallic nanoparticles for biomedical applications: A review. Racing for the Surface: Antimicrobial and Interface Tissue Engineering, 397-434.
38. Li, G., Zhang, W., Luo, N., Xue, Z., Hu, Q., Zeng, W., & Xu, J. (2021). Bimetallic nanocrystals: Structure, controllable synthesis and applications in catalysis, energy and sensing. Nanomaterials, 11(8), 1926.
39. Das, S., Chakraborty, J., Chatterjee, S., & Kumar, H. (2018). Prospects of biosynthesized nanomaterials for the remediation of organic and inorganic environmental contaminants. Environmental Science: Nano, 5(12), 2784-2808.
40. Wang, A., Li, J., & Zhang, T. (2018). Heterogeneous single-atom catalysis. Nature Reviews Chemistry, 2(6), 65-81.