ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun878

Chemical Characteristics of Gold and its Modern Applications

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Publication Date: 2026/06/27

Abstract: Among the various precious metals, gold is the most popular. Gold has diverse uses in many industries due to its unique properties, such as flexibility, high electrical conductivity, and resistance to corrosion. The research covers its: characteristics, chemistry, coordination compounds, synthesis and significance of its nanoparticles, and finally modern studies and applications have been published.

Keyword: *Gold, Compounds, Nanoparticles; Characterization Techniques, Applications.*

How to Cite: Ayman H. Ahmed; Moaleef E. Al Sharary; Noof F. Al Enazy; Hadeel B. Al Enazy; Anhar N. Al Sharary (2026) Chemical Characteristics of Gold and its Modern Applications. *International Journal of Innovative Science and Research Technology*, 11(6), 1557-1562. https://doi.org/10.38124/ijisrt/26jun878

I. INTRODUCTION

Gold is a chemical element with the atomic number 79 and the chemical symbol Au, which comes from the Latin aurum. It is a bright, slightly orange-yellow, dense, soft, malleable, and ductile metal when it is pure [1]. In terms of chemistry, gold is a noble metal, a group 11 element, and a transition metal. It ranks second in the reactivity series, making it one among the least reactive chemical elements; only platinum is listed lower. It is solid under standard conditions. Throughout recorded history, gold has been utilized for coinage, jewelry, and other artistic creations. It is most frequently found on Earth as a pure (native) metal in alloys like gold/silver alloys. Typically, these alloys include 8–10% silver. Electrum, also referred to as white gold, is elemental gold that contains more than 20% silver. In its natural state, the metal can also be found as loose flakes, bigger nuggets, or grains. In addition to the rare bismuthide maldonite (Au_2Bi) and antimonide aurostibite ($AuSb_2$), gold can occasionally be found in combination with tellurium as the minerals calaverite, krennerite, nagyagite, petzite, and sylvanite. Microbes may occasionally be a significant factor in the formation of gold deposits. Gold can be found in the world's waters. The Atlantic and Northeast Pacific have gold concentrations between 50 and 150 femtomol/L. Traces of gold are found in the waste produced by human societies, whether from the jewelry industry or from gold dental crowns, such as in crematoriums, or to a greater extent from electronic waste. About 20% of the 2700 tons of gold supplied to the market in 1997 came from recycled gold. Approximately 50% of the gold produced worldwide is used for jewelry, 40% for investments, and 10% for industrial. In fact, gold production is accompanied by the use of polluting chemicals that have a serious negative impact on the environment, especially sodium cyanide, which is used to dissolve gold in its ores. This is a highly toxic substance and can kill living organisms even at small concentrations. Therefore, when disasters occur in gold mining areas, there is a high possibility of environmental disasters that threaten the atmosphere and biosphere, especially the Earth's hydrosphere. On the other hand, large quantities of ore are processed to ultimately yield a few ounces of gold. This means disposing of many toxic heavy metals including lead, zinc, arsenic, mercury, cadmium, and selenium. When sulfide minerals are exposed to air and moisture, sulfuric acid is formed which dissolves these metals, allowing them to pass into surface and groundwater, in a process called acid mine drainage. Gold mine waste is similar in hazard to nuclear waste. Pure gold is occasionally used as a food ingredient in the form of flakes for dish decoration or in certain drinks because it is neither toxic nor irritating when consumed. In contrast, dissolved gold salts are toxic, particularly damaging to the liver and kidneys. On the other hand, gold cyanide salts used in gold production and electroplating are more dangerous, as the toxicity comes from both sides. Examples include potassium dicyanogold ($K[Au(CN)_2]$). Gold or its alloys can cause allergies in some people, especially women. However, this topic has not yet been fully researched, and the allergy may be caused by other elements in the alloy, such as zinc in gold dental crowns. Actually, gold is the most malleable of all metals. It can be drawn into wire. A gold nugget of 5 mm (0.20 in) in size can be hammered into a gold foil of about 0.5 m2 in area. Gold leaf can be beaten thin enough to become semi-transparent. Due to gold's intense

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun878

reflection of red and yellow, the transmitted light appears greenish-blue. Whereas most metals are gray or silvery white, gold is slightly reddish-yellow. Common colored gold alloys include the distinctive eighteen-karat rose gold created by the addition of copper. Alloys containing palladium or nickel are also essential in commercial jewelry as these produce white gold alloys. Blue gold can be made by alloying with iron, and purple gold can be made by alloying with aluminum. The karat is a unit of measurement used to determine the purity of gold based on its division into 24 perfect parts. When jewelry is made entirely of a single element with a purity of 100%, it is classified as 24 karat. Karat expresses the percentage of gold present in an alloy or gold jewelry, and determines the quality and purity of gold according to standard classifications. Gold is a monoisotopic element because it only has one stable isotope, ^{197}Au, which is also the only isotope that occurs naturally. Thirty-six radioisotopes with atomic masses between 169 and 205 have been created. With a half-life of 186.1 days, ^{195}Au is the most stable of these. The majority of gold's radioisotopes with atomic weights less than 197 decay through a mixture of β+ decay, α decay, and proton emission. Depending on the type of ore present, a variety of techniques are employed in practice to extract gold [2]. Gold can be extracted as the primary ore in a mine, or as a byproduct in other metal mines. The oldest methods for extracting gold were based on sifting silt and sand in riverbeds, separating fine gold particles based on their high density. However, the yield of this method is extremely low, and its use is limited to amateurs.

Gold can be separated according to the chemical equations 1 and 2 using cyanide treatment method. This method is employed when its concentration in the ore is high. The ore is first mechanically processed, crushed, and then treated in open air with a sufficient amount of oxygen and a sodium cyanide solution, which causes the fine gold powder to dissolve. Reduction by zinc metal leads to produce gold in its final form.

$$2Au + H_2O + 1/2\ O_2 + 4NaCN \rightarrow 2Na[Au(CN)_2] + 2\ NaOH \quad \text{……Eq. 1}$$

$$2Na[Au(CN)_2] + Zn \rightarrow Na2[Zn(CN)_4] + 2\ Au \quad \text{……Eq. 2}$$

II. CHEMISTRY

Although gold may create a wide variety of compounds with oxidation states ranging from −1 to +5, its chemistry is dominated by Au(I) and Au(III) [1-4]. Gold is frequently in the +1 and +3 oxidation states. The oxidation states of gold that are less prevalent are −1, +2, and +5. The most prevalent oxidation state with soft ligands such thioethers, thiolates, and organophosphines is Au(I), also known as the aurous ion. Usually, Au(I) complexes are linear. The soluble form of gold found in mining, $Au(CN)^{-2}$, is a good example. Zigzag polymeric chains with linear coordination at Au are formed by binary gold halides like AuCl. Au(I) derivatives make up the majority of gold-based medications. Gold(III) chloride, Au_2Cl_6, serves as an example of Au(III), also known as auric, a common oxidation state. Like other d8 compounds, Au(III) complexes usually have square planar gold atom centers with both covalent and ionic chemical connections. Another recognized example of a mixed-valence combination is gold(I,III) chloride. Gold is resistant to ozone damage up to 100 °C and does not react with oxygen at any temperature. The equivalent gold halides, such as AuF_3, $AuBr_3$, AuBr, and AuI, are created when certain free halogens react. Although it doesn't immediately react with sulfur, hydrogen sulfide can be converted to gold(III) sulfide by passing it through a diluted solution of chlorauric acid or gold(III) chloride. In contrast to sulfur, phosphorus directly combines with gold at high temperatures to form gold phosphide (Au_2P_3). At normal temperature, gold easily dissolves in mercury to produce an amalgam; at higher temperatures, it forms alloys with numerous other metals. These alloys can be made to control melting point, alter hardness and other metallurgical characteristics, or produce unusual colors. It is unaffected by most acids. It does not react with hydrofluoric, hydrochloric, hydrobromic, hydriodic, sulfuric, or nitric acid. It does react with selenic acid, and is dissolved by aqua regia, a 1:3 mixture of nitric acid and hydrochloric acid. Nitric acid oxidizes the metal to +3 ions, but only in minute amounts, typically undetectable in the pure acid because of the chemical equilibrium of the reaction. However, the ions are removed from the equilibrium by hydrochloric acid, forming $AuCl^{-4}$ ions, or chloroauric acid, thereby enabling further oxidation. Likewise, most bases have little effect on it. Aqueous, solid, or molten sodium or potassium hydroxide do not react with it. However, in alkaline conditions with oxygen present, it reacts with potassium or sodium cyanide to produce soluble complexes. By using any other metal as the reducing agent, gold ions in solution can be easily reduced and precipitated as metal. The gold is removed from solution and recovered as a solid precipitate when the additional metal oxidizes and dissolves. Aurides, or compounds containing the Au− anion, are in the −1 oxidation state. Additionally known are tetramethylammoniumaurides, potassium, rubidium, and caesium auride (CsAu). With Au–Au bonds, gold (II) compounds like $[Au(CH_2)_2P(C_6H_5)_2]_2Cl_2$ are often diamagnetic. Red crystals of gold(II) sulfate, $Au_2(SO_4)_2$, are produced when a solution of $Au(OH)_3$ in concentrated H_2SO_4 evaporates. Gold pentafluoride, along with its derivative anion, AuF_6^-, and its difluorine complex, AuF_7^{2-}, is the sole example of gold(V), the highest verified oxidation state. There are many well-defined cluster compounds. Gold can have a fractional oxidation state. The octahedral species $[Au(P(C_6H_5)_3)]_6^{2+}$ is a good illustration.

III. COORDINATION COMPOUNDS

The complexes are chemical substances made up of a central metal atom or ion connected to nearby molecules or ions called ligands [5-11]. Gold forms interesting coordination complexes [12], mainly when it has a charge of +1 (Au(I)) and +3 (Au(III)). These complexes are very important in areas like making chemical reactions happen faster, medicine (like cancer treatment), and materials science because of their special electronic features and stability. Gold(I) complexes usually have a straight-line shape, while Gold(III) complexes tend to have a flat square shape. The

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun878

conversation talks about new developments in gold chemistry, focusing on important structures and what they mean [13]. For gold, the usual coordination numbers are 2 for Au(I) and 4 for Au(III). Ligands can be monodentate (with one attachment point) or polydentate (with multiple attachment points). Complexes can be homoleptic (made of the same ligands) or heteroleptic (made of different ligands) [14]. Gold(I) has a special electron arrangement that mostly allows it to form two-coordinate linear complexes. This creates strong bonds between atoms that are 180° apart. Three-coordinate complexes are unusual and have a flat triangular shape, while complexes with more than three connections are not common unless specific ligands are present. Linear complexes can stick together through gold-gold bonds, creating pairs, groups of three, or chains. These interactions are weak but important, usually shown with connected lines that represent side-by-side relationships. Organic compounds such as phosphines (like Pph_3), carbenes, and alkynes help keep these structures stable. For example, complex compounds with two alkyl groups, like [AuMe(Pph)], have a straight shape and can withstand heat [15]. A common example is $[Au(CN)_2]^-$, which is used in gold mining, has a straight shape with gold connected to two CN parts. Diagram description: Picture a straight line with Au in the middle, connected by single lines to CN on both sides, with angles of 180°. Another one is $[AuCl(Pph_3)]$, which is linear. Dimers such as $[Au_2X_2L_2]$ have two straight parts linked together by an Au-Au bond. Diagram: Two straight lines (Au-L and Au-X) connected by a dashed line to show how they interact with each other. Research shows that compounds like [Au(R-bimy)L] (where bimy stands for benzimidazol-2-ylidene) have a straight shape and have connections between gold atoms. Organometallic complexes such as ferrocenyl dinuclear Gold(I) complexes have been synthesized and made of two gold atoms connected by ligands with straight gold parts. Gold(III) has a configuration that prefers a square shape with four connections, which is similar to platinum(II) and palladium(II). The following figure shows some examples for square planar gold(III) phosphine complexes. This comes from dsp^2 hybridization, where the ligands are positioned at 90-degree angles. Complexes often include halides, nitrogen, oxygen or sulphur as contributors. Nanoparticles are extremely small particles, typically 1 to 100 nanometers in size, which exhibit unique physical and chemical properties due to their large surface area to volume ratio compared to larger materials. This property makes them valuable in various fields, including medicine for targeted drug delivery, electronics for enhanced conductivity, and cosmetics for improved texture. Gold nanoparticles (AuNPs) are noble metal nanoparticles characterized by distinctive electronic and optical properties and their applications in imaging, drug delivery, and cancer therapeutics [16,17]. Their color varies depending on their shape, size, and aggregation, and they can generate a temperature increase when exposed to near-infrared light.

Gold NPs' can have various shapes, including spherical, rod, triangular, star, cubic, or branched, depending on the synthesis method. Several methods are used to produce . The Chemical synthesis involves chemical reduction of gold salts using reducing agents like sodium citrate or ascorbic acid. Environmentally benign methods using biological sources like plants or bacteria, which is an area of growing interest for large-scale production. Physical methods includes techniques like laser ablation to create nanoparticles with specific shapes and properties.

IV. RECENT STUDIES AND APPLICATIONS

The prominent areas of recent research include: (1) Biofabrication ("green"), studies focus on producing gold nanoparticles in environmentally friendly ways, using living organisms such as bacteria, fungi, and plants to reduce the use of harmful chemicals. (2) Cancer treatment, gold nanoparticles are being explored as platforms for the targeted delivery of cancer-fighting drugs to affected tissues, reducing side effects. (3) Dual diagnostics and therapy, gold can be used as imaging agents to locate tumors and, at the same time, can destroy cancer cells via photothermal therapy. (3) Treatment of nervous system disorders, Gold show promising potential in treating nervous system disorders, such as Alzheimer's disease. (4) Biotoxicity Evaluation, Studies are being conducted to evaluate the effects of gold particles on biological tissues. These studies demonstrate that the size and shape of the particles can influence their penetration into tissues and their potential for causing inflammation or cell death, requiring in-depth studies to translate the results from animal models to humans.

In fact, many studies have been published on gold. The production of cyclometalated gold(III) complexes with (P^N^C) ligands was described using a novel technique [18]. By forming two Au–C bonds in a single pot from a structurally varied spectrum of $C(sp^2)$- and C(sp)-iodide substrates, this procedure uses a tandem oxidative addition/cycloauration mechanism to enable the creation of (P^N^C)gold(III)-aryl, -alkenyl, and -alkynyl derivatives. To obtain (P^N^C)gold(III)-alkynyl complexes, which show emission in the blue and green light areas, a complementary two-step approach was also established.

The abundance of N sites in covalent organic frameworks (COFs) connected by imine linkages makes them perfect adsorbents for iodine and gold [19]. Since the N site has been extensively studied as an electron-deficient group, It was investigated in this work how its conjugation degree affected the adsorption of gold and iodine by varying the electron-rich unit. Gold adsorption increases (492.0, 711.3, and 1080.7 mg/g) with increasing donor conjugation (COF-Be, COF-Na, and COF-An), but iodine adsorption decreases (3.8, 2.9, and 2.02 g/g). According to theoretical calculations and characterization, the reduction of gold by COFs is improved by an increase in the conjugation degree. On the other hand, the adsorption capacity for iodine decreased as the density of N sites decreased and the pore volume decreased. The article explains how these three COFs adsorb gold and iodine differently and offers a novel strategy to maximize gold's adsorption capacity by varying the degree of donor conjugation of COFs.

Dimeric gold(I) complexes were reduced to create a series of gold nanoparticles (AuNPs) stabilized by bidentate acyclic diamino carbenes (ADCs). NMR spectroscopy, UV–vis spectroscopy, X-ray photoelectron spectroscopy (XPS),

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun878

transmission electron microscopy (TEM), and thermogravimetric analysis (TGA) were used to characterize the resultant ADC-AuNPs [20].

These methods revealed nanoparticles with a limited size range with diameters ranging from 1.7 to 3.3 nm. An asymmetric dinuclear ADC-gold(I) combination was created using this synthetic method, which produced somewhat bigger AuNPs (about 4 nm) upon reduction. The reduction of 4-nitrophenol was significantly catalyzed by the ADC-AuNPs with shorter linkers, showing a flexible and effective pathway to catalytically active gold nanoparticles stabilized by both symmetric and asymmetric ADC ligands.

A series of structurally diverse gold(I) complexes bearing the 9-(4-ethynylphenyl)-9*H*-carbazole chromophore were synthesized, featuring mononuclear, dinuclear, tricoordinated, and supramolecular architectures [21]. Alkynylation processes or the reaction of polymeric alkynyl species $[Au(C{\equiv}CR)]_n$ with auxiliary ligands were involved in their production. The dynamic nature of these systems was highlighted by the observation of an equilibrium between bimetallic and tricoordinated species when diphosphine ligands were used. The pure tricoordinated complex was shown to be isolable in a nonpolar solvent, indicating that this equilibrium was solvent-dependent. The carbazole-functionalized alkyne was reacted with azide-phosphine gold(I) precursors to create the triazole complexes. Hydrogen-bonding frameworks and the lack of π–π stacking were verified by structural analysis. Photophysical studies demonstrated intense solid-state phosphorescence, with blue-green luminescence markedly enhanced at 77 K. In comparison to the free ligand, emission redshifted and widened (450–600 nm) at room temperature, suggesting a synergistic contribution of intramolecular charge transfer (ICT) and carbazole-centered (3IL) transitions. The promise of these gold complexes in luminous materials is highlighted by their metal-tuned photophysical activity. The phenyl ring mediates this charge transfer from the carbazole to the ligand system, and metal coordination modifies it. The chemical orbitals involved in the complex's emission and absorption transitions were examined using theoretical calculations (TD-DFT).

Three structural families of gold ADC (acyclic diaminocarbene) complexes were generated by nucleophilically adding amines to [AuCl(CNCy)]: thiolate-gold-ADC complexes, bis(carbene), and gold-chloride-ADC (chiral and achiral) [22].. Their molecular architecture is greatly shaped by noncovalent interactions like hydrogen bonding and aurophilic contacts, which were discovered by extensive analysis, including X-ray diffraction. When applied to drug-resistant cancer cell lines (A549, HCT116 WT, Jurkat, MiaPaca2), these complexes demonstrate strong cytotoxicity (IC_{50} in submicromolar), and several of them have a high selectivity index (up to 74) for cancer cells over healthy lymphocytes. According to mechanistic studies, they increase reactive oxygen species (ROS), interfere with mitochondrial activity, and bind DNA in the case of bis(carbene) species. At low quantities, apoptosis is induced; at larger amounts, other death processes are triggered. Interestingly, they have an efficacy similar to auranofin in substantially inhibiting thioredoxin reductase (TrxR). The multitargeted anticancer potential of gold-ADC complexes is highlighted by the combination of ROS generation, DNA interaction, mitochondrial disruption, and TrxR inhibition, which also promotes their continued development as effective and selective chemotherapeutic treatments.

The nitrosonium ion was used as a nitrating reagent to develop a selective nitration at the β-positions of gold(III) corrole, which is the first known case of gold(III) corrole nitration. This nitration process's underlying mechanism has also been clarified. A one-electron oxidized $[(\text{corrolato}^{\bullet 2-})Au^{III}]^{\bullet +}$ species is created as the reaction progresses [23]. It has been described by DFT, EPR, and UV-vis computations. The addition of two nitro groups to the corrole's bipyrrole unit significantly increases the corrole ligand's electron-withdrawing properties, which causes a noticeable upshift in the corresponding metal complex's oxidation and reduction potentials when compared to its non-nitrated counterparts. The best way to characterize the 3,17-dinitro-corrolato-gold(III) complex is as having partial inverse hypercorrole character, with partial corrole-to-nitro charge transfer occurring at the lowest energy transition. With air and light acting as cofactors, the produced molecules catalyze the selective oxidation of sulfides to sulfoxides in ambient circumstances. It achieves over 99% selectivity and demonstrates a wide substrate scope.

A new synthesis technique using aryldiazonium gold(III) salts was presented to manufacture a magnetic-plasmonic Fe_3O_4@CS-AuNPs nanocomposite [24]. Because chitosan (CS) promotes electron transport, the low reduction potential of aryldiazonium goldsalts allows for their spontaneous reduction on the surface of Fe_3O_4 NPs stabilized with CS. For Fe_3O_4@CS-AuNPs, XPS demonstrated the full reduction of gold(III) supported by the Au 4f peak. A green reduction, in which chitosan reduced Au(III) to Au(0), is suggested by the elevated Fe(II) ratio in XPS. Fe_3O_4@CS-AuNPs had an average nanoparticle size of 17.0 ± 3.8 nm, according to HR-TEM images. Fe_3O_4@CS-AuNPs' increased adsorption and elimination of E. coli bacteria is supported by their large surface area of 55.15 m^2/g. Fe_3O_4@CS-AuNPs outperformed Fe_3O_4@CS bacteria removal of 3%, 21%, and 40% with removal efficiencies of 100%, 99%, and 97%. Fe_3O_4@CS-AuNPs demonstrated remarkable capture efficiency and bactericidal activity, eradicating live bacteria at a minimum inhibitory concentration (MIC) of 50% thanks to surface modification with arylated AuNPs, which improved adsorption and bacterial binding. These results demonstrate Fe_3O_4@CS-AuNPs' potential for improved microbial elimination.

AuSNCs, or gold subnanoclusters, have exceptional catalytic activity [25]. Different functional groups' capacity to stabilize the AuSNCs system has been assessed. Matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) experiments, density functional theory (DFT) calculations, and topological tools (QTAIM and NCI) provide decisive insights into the mechanism of stabilization of the short-lived AuSNCs species. Additionally, stabilization analysis to an application in catalysis was extended. Thorough NCI analysis of an optimized energy

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun878

pathway, it was demonstrated how a number of weak secondary interactions, such as hydrogen bonds to gold (Au···H–C) and Au···π interactions in intermediates and transition states, can stabilize an Au^{III} subnanocluster.

The gold antimony tellurides AuSbTe and $Au_{1.9}Sb_{0.46}Te_{2.64}$ (montbrayite) were studied for stability, electronic characteristics, and synthesis [26]. AuSbTe is melting incongruently, whereas $Au_{1.9}Sb_{0.46}Te_{2.64}$ is melting congruently, according to differential thermal analysis and in situ powder X-ray diffraction. Four-point resistivity tests and band structure calculations demonstrated that AuSbTe is a semiconductor.

Two families of mononuclear gold (I) complexes containing Au-chromophore units were produced; the chromophores were either dibenzofuran (c), carbazole (a), or phenanthrene (b). The Au(I) atoms are coordinated to two phosphanes, either PMe_2ArXyl_2($ArXyl_2$ = 2,6-C_6H_3-(2,6-C_6H_3–Me_2)$_2$) (**P1**) or the bulkier $PCyp_2ArXyl_2$ (Cyp = cyclopentyl) (**P2**). Many studies were conducted on the photophysical characteristics of these compounds [27]. The absorption and emission assignments were confirmed by time-dependent density functional theory (TD-DFT) calculations, which also shed light on the relative populations of the electronic state gaps involved in photophysical processes. Under mild circumstances and with little Au loading (0.1–0.2 mol%), the parent complex AuClP2 in combination with $NaBAr_4F$, a chloride scavenger, functioned as an effective catalyst for the hydroamination of a range of alkynes and amines.

It was reported that homochiral AuNP synthesis was un expectedly discovered under cryogenic settings (0 ° C) without chiral ligand induction [28]. The unexpected discovery of homochiral AuNP formation under cryogenic conditions (0 °C) without chiral ligand induction was reported. The 0 °C-synthesized chiral AuNPs demonstrated exceptional enantioselective recognition capabilities, particularly as colorimetric probes for glutamine (Gln) enantiomer discrimination. In this work, a chiral ligand-free synthesis technique for chiral AuNPs was developed. The results show that temperature engineering is an essential factor in regulating nanoscale chirality materials.

V. CONCLUSION

Gold remains the most widely valued and utilized precious metal because of its exceptional physical and chemical properties such as its malleability, excellent electrical conductivity, and outstanding resistance to corrosion. These characteristics have enabled its extensive use across a broad range of fields, from traditional uses in jewelry and finance to advanced medical and technological industries. The study of gold's chemistry, coordination compounds, and nanoparticle synthesis has expanded our understanding of its behavior and potential. NMR spectroscopy, UV–vis spectroscopy, X-ray photoelectron spectroscopy (XPS), transmission electron microscopy (TEM), and thermogravimetric analysis (TGA) are powerful techniques to characterize gold nanoparticles (AuNPs). In particular, gold nanoparticles have attracted significant attention due to their unique catalytic, optical and biomedical properties. Modern research continues to reveal new applications for gold in catalysis, nanotechnology, medicine, environmental science, and materials engineering, highlighting its enduring scientific and industrial importance. It is worth to point out that pure gold is not harmful when swallowed, in contrast dissolved gold salts are toxic particularly destructive to the liver and kidneys.

ACKNOWLEDGEMENT

The authors wishes to express their sincere thanks to Dr. Ahmed H. Alenezy, head of chemistry department, faculty of science, Jouf University's (KSA) for all the facilities provided for the preparation of this project work.

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