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Fagonia stabilized gold nanoparticles as antimicrobial agents

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Abstract

In this study, gold nanoparticles (GNPs) were synthesized using an aqueous extract of Fagonia, as a stabilizing and reducing agent, applying the green approach. The phytochemicals present in Fagonia extract are responsible for the creation of GNPs. The reaction kinetics of Fagonia stabilized GNPs (FGNPs) was observed through the optical absorption spectra and the absorption maxima occurred at 547 nm. The face-centered cubic (FCC) nature of the GNPs was analyzed by the XRD pattern and average crystallite size ($D$) was measured about 10 nm. TEM images showed roughly spherical shapes of FGNPs. Evidence of successful formation of FGNPs was revealed by FTIR spectra of pure Fagonia and FGNPs. Fluorescence spectroscopic analysis of FGNPs exhibited a sharp red emission at about 700 nm. TGA technique showed a weight loss of about 19.3% in FGNPs confirming the presence of ligand onto the surface of GNPs. As-synthesized GNPs were investigated for their biomedical application i.e. antimicrobial activities against E. coli and Cocci. The eco-friendly prepared GNPs could play an important role in antimicrobial applications and their visible emission property may suggest the use of such FGNPs as potential biomarkers.

1. Introduction

Nanotechnology is a propitious arena marketing with the design, consumption and utilization of nanoparticles (NPs) in creating advanced applications [1–3]. Nanoparticles have tremendous and unique optical, electromagnetic, and biological features to serve in various fields. Nanoparticles also interpret basic phenomena taking place at the nanoscale range [4]. Metal NPs come up with an obviously prevalent field of implementation [5]. Gold nanoparticles (GNPs) are amongst the utmost substantial metal nanoparticles because of their peculiar physicochemical characteristics and therefore can be implemented in chemical and biological diagnosis and treatments [6].

During the last few decades, an increasing number of current occurrences of diseases owing to microbial infections have been cured by the noble metal NPs, with GNPs having a noticeable antimicrobial performance [7]. It is well documented that silver possesses an enhanced toxicity potential than elements Au and Cu [8, 9]. Recently, the cytotoxicity of silver nanoparticles (AgNPs) has been revealed to be associated with their accumulation and penetration in the mitochondrial membrane resulting in the impairment of mitochondrial function [10]. Unfortunately, the strong oxidative activity of AgNPs releases silver ions, which results in several negative effects on biological systems by inducing cytotoxicity, genotoxicity, and even cell death [11, 12].

Although many researchers have reported the formation of NPs using silver metal, it is found that gold is more compatible than silver [13]. Gold NPs have chemical inertness and are optically active in biomedicines [14, 15], such as in cancer treatment, biomedical imaging and sensing, and also have excellent antioxidant, antifungal, antibacterial activities [16, 17]. Gold NPs are highly photostable that is why photoluminescence (PL) in GNPs is not quenched by light like in organic dyes. The PL in gold nanostructures usually results when an excited electron from the 6sp conduction band recombines with a hole in the 5d10 band. In this perspective, Imura group measured a visible PL band around 650 nm in gold nanostructures [18]. The remarkable PL efficiency and their chemical
inertness propose the high potential of GNPs as a material for wide biomedical applications. Apart from the shape and size, the surface capping also influences the PL emission and cytotoxicity of GNPs [19].

There are many methods to synthesize GNPs like chemical reduction method [20], sol-gel method [21–23], chemical method [24], photochemical method [25], chemical vapour deposition [26, 27], citrate reduction method [28] and many more. But most of these methods have exploited lethal and hazardous compounds and with these drawbacks, physicochemical strategies are not considered suitable for some applications [29].

Nowadays, green chemistry has received great attention from researchers to avoid the use of toxic stabilizing agents like sodium borohydride and sodium citrate that are increasing the health hazard and environmental poisonousness [30]. To eliminate this factor, a harmless green approach is being used which is economically safer and it follows an ecofriendly environmental procedure to construct metal NPs [31]. A green method is also an alternative approach to physical and chemical methods [32]. Among various biomaterials, plant extraction is most popular because of the extensive availability of plants [33]. Metal NPs based on plant extract as reducing and stabilizing agents are found more stable and green [34–36]. The role of GNPs as an environmental disinfectant and their safe synthesis are sections that remain to be explored.

In this present article, GNPs were synthesized using green strategy and Fagonia indica aqueous extract was used as a reducing and stabilizing agent together. The as-prepared NPs were characterized by UV–visible spectroscopy, x-ray diffraction (XRD) analysis, Fluorescence spectroscopy, Thermo-gravimetric analysis (TGA), Fourier-transform infrared (FTIR) spectroscopy, and transmission electron microscopy (TEM). The antimicrobial activities of Fagonia stabilized GNPs were also investigated (figure 1).

2. Experimental

2.1. Chemicals and materials
Sigma Aldrich (99.9% pure) acquired hydrogen tetrachloroaurate trihydrate (HAuCl₄·3H₂O) was used as the precursor of gold. Fagonia indica shrub (in powder form) was collected from Cholistan Institute of Desert
Studies (CIDS), The Islamia University of Bahawalpur, Pakistan. The bacterial strains *E. coli* and *Cocci* were collected from Civil Hospital Bahawalpur, Pakistan. Deionized water (DI H$_2$O) was used as a solvent throughout our experimental work.

2.2. Preparation of fagonia extract

*Fagonia indica* (a medicinal plant) powder is used for extract formation. A 2 g of *Fagonia indica* (commonly known as *Dhaman*) powder was added to 100 ml of DI H$_2$O. This solution was heated at about 100 °C using a hotplate magnetic stirrer for 30 min. The extract was well filtered to remove any residues. The filtrate was stored at 4 °C in a glass bottle for further use in the experiments. This freshly prepared *Fagonia* plant extract was used for the biological reduction and stabilization of GNPs.

2.3. Biosynthesis of gold nanoparticles

For the formation of GNPs, 5 ml (0.01 M) aqueous solution of HAuCl$_4$$\cdot$3H$_2$O and 3 ml *Fagonia* extract were mixed in a glass vial and stirred for 30 min at room temperature. The mixture solution turned to purplish-brown color from pale yellow, indicating the formation of colloidal GNPs. For the separation of GNPs from colloidal solution, the prepared GNP solution was washed 3–4 times with DI H$_2$O while centrifuging at a speed of 6000 rpm at room temperature for 15–20 min, to eliminate the water-soluble biological molecules and secondary metabolites. The concentrated solution of GNPs was dried at room temperature for 48 h and finally crushed to get fine powder for further characterization.

2.4. Instrumentation

To confirm the formation and stability of *Fagonia* stabilized gold nanoparticles (FGNPs), the UV-Vis absorption spectroscopic analysis was done by using Aquarius 7400 model Cecil spectrophotometer having a scale from 290 to 1100 nm. The XRD technique was used to investigate the structural analysis of FGNPs and applied using a Bruker D8 advance x-ray diffractometer in the 2θ range of 20°–80° while operating at 40 keV and 35 mA. A JEOL JEM-1010 transmission electron microscopy (TEM) operated at 100 kV was used to analyze the shape and size of FGNPs. For the purpose, a drop of the solution containing the FGNPs sample was put on an amorphous carbon-coated copper grid and kept for 10 min at room temperature in order to stand the film. Any additional solution was removed by means of blotting paper and the grid was dried for the next few minutes. In order to determine the size distributions of FGNPs appearing in TEM images, the ImageJ analyzer was utilized. The Cary Eclipse MY18060003 photoluminescence spectrometer was utilized to measure the fluorescence of pure *Fagonia* extract and FGNPs in the wavelength range 350–800 nm while the sample was excited at 350 nm wavelength. Thermal gravimetric analysis (TGA) being a very useful technique to determine initial and final destroy temperatures of the NPs and amount of weight loss of the NPs, was run using Indium TGA/DTA 6000 under a Nitrogen gas environment at the flow rate of 50 ml/min. To perform the experiment, a 1.32 mg powder sample was put into a combustion cell and the temperature of the sample was gradually raised from 30 °C to 450 °C at a constant heating rate of 10 °C/min. After the completion of experimentation, a solid piece of gold was residue at the bottom of the combustion cell. To confirm the attachment of *Fagonia* coating onto the surface of GNP, a Tensor: 27 (Bruker) FTIR spectrometer was operated, where a few mg of the dried sample was mixed with KBr powder to form a pellet for the analysis. The IR spectra of pure *Fagonia* powder and FGNPs were examined in the wavelength range 400 to 4000 cm$^{-1}$.

2.5. Antibacterial performance of fagonia stabilized GNPs

Nutrient agar medium has been utilized to prepare Petri plates for the growth of microorganisms. To sterilize the nutrient agar medium, 20 g of the medium was added in 50 ml DI H$_2$O in a conical flask and kept it in an autoclave at 121 °C. Subsequently, the medium was poured in sterilized Petri plates placed in the incubator to avoid any contaminations. The bacterial culture obtained from Civil Hospital Bahawalpur was already growing in the incubator at 37 °C for 24 h. After 24 h, this bacterial culture was spread on Petri plates followed by the sample disks and the control disks placed on those Petri plates.

3. Results and discussion

To check the kinetics of FGNPs, the optical spectra of reaction solution were observed at various reaction timings. Reaction kinetics is an important feature in understanding the growth progression of GNP. In the present work, the absorbance of samples was investigated after every 30 min run of the reaction, and an average peak position occurred at $\lambda_{max}$ = 547 nm. Pure *Fagonia* extract showed no absorbance at all as shown by an inset in figure 2. When *Fagonia* extract was added to gold salt and stirred for 30 min a prominent absorption peak was observed, as shown by the pink curve in figure 2. The reaction kinetics of GNPs revealed a very small
hyperchromic shift in absorption peak at first (after stirring for 60 min) and then shifted toward longer wavelength with a further increase in growth progression. Additional reaction timing resulted in no countable increase in peak position but caused a little lowering and broadening of the peak position. No more noticeable bathochromic shift in the peak position was observed after 120 min run of the reaction. The actual solution colors are visible by an inset in figure 2.

For structural analysis of FGNPs by XRD technique, figure 3(A) shows four sharp peaks observed at $2\theta = 38.02^\circ$, $44.24^\circ$, $64.64^\circ$, and $77.6^\circ$, corresponding to (111), (200), (220) and (311) Bragg’s reflections.
respectively, based on FCC nature of Gold structure \( [4, 37] \). There were no more considerable peaks observed in the XRD pattern, giving confirmation of the purity of the sample. The average crystallite size \((D)\) was measured about 10 nm by using Debye–Scherrer formula and the average inter-planer spacing measured between \((111)\) peaks was about 0.17685 nm. Figure 3 showing the SAED pattern, ratifies that the formed nanoparticles are crystalline in nature.

The TEM image in figure 3(C) shows that FGNPs are of roughly spherical shape, including few nanotriangles of a rather large size. It is observed that the prepared FGNPs are well dispersed in the solution. The size of nanoparticles while excluding nanotriangles ranges between 21.8 nm to 60 nm with an average particle size \(\sim\) 41 nm, which appears bigger as compared to the size calculated in XRD analysis by Debye–Scherrer formula. Figure 3(D) shows the histogram representing the size distribution of nanoparticles.

Apart from the mechanism discussed earlier, green ligands are also considered responsible for contributing to PL emission from GNP\(s\) \([38]\) that is associated with metal-ligand radiative transferences, strongly suggesting the influence of nanoparticle surface on its PL emission \([19]\). Fluorescence spectroscopic analysis was performed for pure \textit{Fagonia} extract and FGNPs aqueous solution (figure 4). Pure \textit{Fagonia} extract showed one broadened emission peak appearing at about 465 nm with an emission band ranging in 387–582 nm. For FGNPs, a sharp red emission peak appears at 700 nm with an emission band in the range of 688–710 nm. This sharp and very clear emission peak suggests that as-synthesized NPs are provided with minimum surface defects that lead to

Figure 4. Fluorescence spectra of pure \textit{Fagonia} extract and FGNPs representing different emission peaks.

Figure 5. Thermo-gravimetric analysis of \textit{Fagonia} stabilized GNPs.
non-radiative processes. From figure 4, it is cleared that Fagonia extract excites at a lower wavelength than that of GNPs.

TGA technique is used to know about the amount of the ligand present on GNPs surface. Weight loss of Fagonia stabilized GNPs analyzed by TG analysis found about 19.3%. This weight loss indicates the existence of Fagonia ligand on the green synthesized GNPs surface. A gradual weight loss occurs in nanoparticles under temperatures ranging from 100 °C to 350 °C showing the decomposition of Fagonia ligand (figure 5).

The FTIR-spectra of both samples (pure Fagonia and FGNPs) are shown in figure 6. Pure Fagonia IR spectrum exhibits three peaks in the range 553.5–638.3 cm\(^{-1}\) that are corresponding to C–X (chloride) bond lying within the range of 540–785 cm\(^{-1}\). The presence of alkenes and aromatic compounds in Fagonia indica is traced by the existence of certain peaks in the range 800–900 cm\(^{-1}\) representing the out-of-plane bending mode of vibrations. Another set of peaks, between 1000 cm\(^{-1}\) and 1200 cm\(^{-1}\), may contribute from C–N (amines), C–X (fluoride) and/or C–O (alcohols, esters, ethers, anhydrides, carboxylic acid) bonds.

The characteristic bending absorptions at 1375 cm\(^{-1}\) and 1454.1 cm\(^{-1}\) correspond to the presence of methyl (CH\(_3\)) and methylene (CH\(_2\)) groups in Fagonia. The absence of such groups in FGNPs spectrum indicated the non-covalent binding of the ligand to the nanoparticle’s surface. In Fagonia spectrum, an IR peak at about 1600 cm\(^{-1}\) augments the presence of C=\(\text{C}\) bond. Usually, it lies in the range 1680–1600 cm\(^{-1}\). From the available literature, a comparison of Fagonia stabilized various noble metal NPs with present work, is summarized in table 1.

The two peaks at 2915.842 cm\(^{-1}\) (in Fagonia IR spectrum) and 2929.34 cm\(^{-1}\) (in FGNPs IR spectrum) indicate C–H stretching modes of vibrations in alkanes. No clear peaks are observed in the range 3400–3500 cm\(^{-1}\) that represent O–H bond, indicating that our samples were free of any moisture. Most stretching modes of vibration lie in the region 1000–3600 cm\(^{-1}\) and bending modes of vibration are restricted to the region below 1600 cm\(^{-1}\).

A comparable antimicrobial performance of as-prepared FGNPs with different concentrations and control groups (Tigecycline and Levofloxacin) against E. coli and Cocci bacterial strains has been inspected. These microorganisms cause various infections in people. The present work shows that antimicrobial performance of as-prepared GNPs is very significant. In this work, after 24 h of incubation, inhibition zones (ZOI) of GNPs disks are measured against different strains of bacteria. ZOI is a region where the growth of further bacteria ends and no bacterial effect is observed in this region. Against E. coli strain, sample A (5 \(\mu\)g) almost showed no activity or zero ZOI, Sample B (10 \(\mu\)g) and sample C (15 \(\mu\)g) showed a considerable ZOI. While sample D (20 \(\mu\)g) showed a significant result with remarkable ZOI, as shown in figure 7. The control element (Tigecycline) also showed better ZOI but less than the ZOI shown by as-prepared GNPs. An analogous trend is observed for another strain of bacteria that is Cocci; the as-prepared GNPs are more effective as compared to the control element that is Levofloxacin, as clear by table 2.

It is well known that the attachment to and transportation into the cell membrane is essential for the NPs to inhibit the growth of bacteria. Following this, reactive oxygen species (ROS) is an important tool to understand...
the mechanism of antimicrobial activity. According to the literature, ROS generates superoxide (\(O_2^\cdot\)), hydrogen peroxide (\(H_2O_2\)), and extremely toxic radicals of the hydroxyl group (\(\cdot OH\)) during aerobic metabolism while following the reactions:

\[
\text{Au} + h\nu \rightarrow \text{Au}(h^+ + e^-) \\
e^- + O_2 \rightarrow O_2^- \\
O_2^- + 2H^+ + e^- \rightarrow H_2O_2 \\
H_2O_2 + O_2^- \rightarrow \text{OH} + \text{OH}^- + O_2 \\
H^+ + H_2O \rightarrow \text{OH} + H^+ 
\]

Thus, ROS responsible for the antimicrobial activity of FGNPs is supported by the fact that oxygen significantly affects antimicrobial activity. The oxidation of FGNPs into Au\(^+\) ions assist their diffusion into the

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**Table 1. Fagonia mediated synthesis of various noble metal nanoparticles, a comparison with available literature.**

| NPs type | NPs average size (nm) | NPs shape | SPR peak (nm) | Properties | References |
|----------|-----------------------|-----------|---------------|------------|------------|
| Silver   | 16                    | roughly spherical | 440 | antibacterial activity | [39] |
| Silver   | 20–50                 | spherical and clustered | 435 | antibacterial activity | [40] |
| Silver   | not defined           | not defined | 414 | antibacterial activity | [41] |
| Silver   | 56                    | spherical | 415 | antileishmanial activity | [42] |
| Silver   | 16                    | round-shaped | 390–450 | antioxidant, anti-urease and anti-tyrosinase | [43] |
| Gold     | 15–20                 | hexagonal | 542–565 | photo and chemo-catalytic activities, electro-chemical study | [44] |
| Gold     | 41                    | roughly spherical | 547 | antibacterial activity | Present work |

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**Figure 7.** Antibacterial activity of different samples of FGNPs against *E. coli* and *Cocci* bacterial strains via the disc diffusion method.
bio-organism or set oxidative stress to produce ROS that change the permeability of cell membrane, causing DNA, proteins and lipids damage and finally result in cytotoxicity in the cell body of prokaryotes.

From this study, we conclude that as-prepared GNPs with high concentration are more effective and less toxic as compared to commercially available control medicines, as shown in figures 7 (a) and (b). This experiment was executed to know about the antimicrobial performance of FGNPs in comparison to antibiotics, which was taken as a control group. Thus, FGNPs were found to be effective against different clinical segregates of bacteria (figure 8).

4. Conclusion

In present work, GNPs were synthesized via biosynthesis method using Fagonia extract as a stabilizer and reducing agent both. Fagonia stabilized GNPs (FGNPs) showed an average absorption at 547 nm while Fagonia extract showed no visible absorption at all. Investigation revealed that the absorption peak showed a small hyper-chromic shift in absorbance with the increase in growth progression. The peaks position also shifted toward higher wavelength showing an overall bathochromic shift. The average crystallite size (D) was measured 10.44 nm by using Debye–Scherrer formula in x-ray diffraction. The TEM images showed that the NPs were roughly spherical in shape except a few triangular-shaped and the sizes of NPs were within 22–60 nm with an average size of 35.8 nm. FTIR spectroscopy of FGNPs indicated the presence of C-X bond (chloride) and C=C (alkenes group) bond. Optical property of both Fagonia extract and FGNPs has been analyzed by using photoluminescence (PL) spectroscopy and exhibited a sharp and defect-free emission peak at around 700 nm, suggesting these NPs very significant as biomarkers for in vivo. Also, two strains of bacteria were used for the assessment of the antimicrobial behavior of FGNPs. Through this assessment, we can say that GNPs have very significant antimicrobial properties.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Howes P D, Chandrawati R and Stevens M M 2014 Colloidal nanoparticles as advanced biological sensors Science 346 1247390
[2] Beik J, Abed Z, Ghoreishi F S, Hosseini-Nami S, Mehrzadi S, Shakeri-Zadeh A and Kamrava S K 2016 Nanotechnology in hyperthermia cancer therapy: from fundamental principles to advanced applications J. Controlled Release 235 205–21
[3] La Spada L and Vegni L 2018 Electromagnetic nanoparticles for sensing and medical diagnostic applications Materials 11 603
[4] Abdelghany A M, Oraby A H and Asnag M G M 2019 Structural, thermal and electrical studies of polyethylene oxide/starch blend containing green synthesized gold nanoparticles J. Mol. Struct. 1180 15–25
[5] Mohamed A A et al 2018 Synthesis of gold organometallics at the nanoscale J. Organomet. Chem. 877 1–11
[6] Fiouzi M, Housainodkht M R, Izadi-Najafabadi R and Moosavi F 2019 Effect of low dose gamma ray on the plasmonic behavior of gold nanoparticle Radiat. Phys. Chem. 159 190–4
[7] Sunderam V, Thiagarajan D, Lawrence A V, Mohammed S S and Selvaraj A 2019 In-vitro antimicrobial and anticancer properties of green synthesized gold nanoparticles using anacardium occidentale leaves extract Saudi J. of Biological Sciences 26 655–9
[8] Ratte H T 1999 Bioaccumulation and toxicity of silver compounds: a review Environ. Toxicol. Chem. 18 89–108
[9] Ferdous Z and Nemmar A 2020 Health impact of silver nanoparticles: a review of the biodistribution and toxicity following various routes of exposure Int. J. Mol. Sci. 21 2375
[10] Akter M, Sikder M T, Rahman M M, Ullah A K M A, Hosain K F B, Banik S, Hosokawa T, Saito T and Kurasaki M 2018 A systematic review on silver nanoparticles-induced cytotoxicity: physicochemical properties and perspectives J. Adv. Res. 9 1–16
[11] Li Y, Zhao J, Shang E, Xia X, Niu J and Crittenden J 2018 Effects of chloride ions on dissolution, ROS generation, and toxicity of silver nanoparticles under UV irradiation Environmental Science & Technology 52 4842–9
[12] Hackenberg S, Scherzer A, Kessler M, Hummel S, Technau A, Groebel G, Ginzkey C, Koehler C, Hagen R and Kleinsasser N 2011 Silver nanoparticles: evaluation of DNA damage, toxicity and functional impairment in human mesenchymal stem cells Toxicol. Lett. 201 27–33
[13] Bae D F, Gallardo-Toledo E, Oyarrzun M P, Araya E and Kogan M J 2021 The influence of size and chemical composition of silver and gold nanoparticles on in vivo toxicity with potential applications to central nervous system diseases Int. J. Nanomedicine 16 2187–201
[14] Agüinley E, Gavrilidida L and Mazzei L 2017 A mathematical investigation of the Turkevich-organometallic theory in the citrate method for the synthesis of gold nanoparticles Chem. Eng. Sci. 173 275–86
[15] Elahi N, Kamali M and Baghersad M H 2018 Recent biomedical applications of gold nanoparticles: a review Talanta 184 537–56
[16] Agüinley E, Panariello L, Gavriilidis A and Mazzei L 2018 A model for the formation of gold nanoparticles in the citrate synthesis method Chem. Eng. Sci. 191 318–31
[17] Amani H, Habibey R, Hajimeyersali S J, Latifi S, Pazoki–Toroudi H and Akhavan O 2017 Antioxidant nanomaterials in advanced diagnoses and treatments of ischemia reperfusion injuries J. Mater. Chem. B 5 9452–76
[18] Imura K, Nagahara T and Okamoto H 2006 Photoluminescence from gold nanoparticles induced by near-field two-photon absorption Appl. Phys. Lett. 88 1–3
[19] Fernández-Ponce C, Muñoz-Miranda J P, de los Santos D M, Aguado E, García-Cozar F and Litrán R 2018 Influence of size and surface capping on photoluminescence and cytotoxicity of gold nanoparticles J. Nanopart. Res. 20 305
[20] Daruich De Souza C, Gibeiro Nogueira B and Rostelato M E C M 2019 Review of the methodologies used in the synthesis gold nanoparticles by chemical reduction J. Alloys Compd. 798 714–40
[21] Budnyk A P, Cherkasova S O and Damin L 2017 One-pot sol-gel synthesis of porous silica glass with gold nanoparticles Mendeleev Commun. 27 531–4
[22] Owens G J, Singh R K, Foroutan F, Alqaysi M, Han C-M, Mahapatra C, Kim H-W and Knowles J C 2016 Sol–gel based materials for biomedical applications Prog. Mater. Sci. 77 1–79
[23] Adhikary I, Meyerstein D, Marks V, Meistelman M, Gershinsky G, Burg A, Shamir D, Kornweitz H and Albo Y 2018 Sol–gel entrapped Au0- and Ag0-nanoparticles catalyze reductive de-halogenation of halo-organic compounds by BH4 – Appl. Catalysis B 239 450–62
[24] Fattori N, Maroneze C M, Costa L P D, Strauss M, Mazali O I and Gushiken K Y 2013 Chemical and photochemical formation of gold nanoparticles supported on viologen-functionalized SBA-15 Colloids Surf., A 437 120–6
[25] Abdelraoul G N, Cingolani R, Diaspro A, Athanasiou A and Pignatelli F 2014 Photochemical synthesis: effect of UV irradiation on gold nanorods morphology J. Photochem. Photobiol., A 275 7–11
[26] Amannouch F E, Vallejos S, Stoycheva T, Blackman C and Llobet E 2013 Aerosol assisted chemical vapour deposition of gas-sensitive nanomaterials Thin Solid Films 548 703–9
[27] Chen K W, Rahman S A and Asapun Z 2013 Effect of rapid thermal annealing time on Au/SiOx film prepared by hot wire assisted plasma enhanced chemical vapour deposition technique Mater. Chem. Phys. 140 37–41
[28] Doyen M, Bartik K and Bruylants G 2013 UV–Vis and NMR study of the formation of gold nanoparticles by citrate reduction: observation of gold–citrate aggregates J. Colloid Interface Sci. 399 1–5
[29] Pu S, Li J, Sun L, Zhong L and Ma Q 2019 An in vitro comparison of the antioxidant activities of chitosan and green synthesized gold nanoparticles Carbohydrate Polym. 211 161–72
[30] Usman A I, Aziz A A and Noqita O A 2019 Green sonochrome synthesis of gold nanoparticles using palm oil leaves extracts Mater. Today Proc. 7 809–7
[31] Mata R, Bhaskaran A and Sadras S R 2016 Green–synthesized gold nanoparticles from plumeria alba flower extract to augment catalytic degradation of organic dyes and inhibit bacterial growth Particuology 24 78–86
[32] Chokkalingam M, Jahan Rupa E, Huo Y, Mathiyalagan R, Anandapadmanaban G, Chan Ahn J, Park J K, Lu J and Yang D C 2019 Photocatalytic degradation of industrial dyes using Ag and Au nanoparticles synthesized from angelica gigas ribbed stem extracts Optik 185 1213–9
[33] Choudhary B C, Paul D, Gupta T, Tetyure S R, Garole V I, Borse A U and Garole D J 2017 Photocatalytic reduction of organic pollutant under visible light by green route synthesized gold nanoparticles J. Environ. Sci. 55 236–46
[34] Hamelian M, Hemmati S, Varmira K and Veisi H 2018 Green synthesis, antibacterial, antioxidiant and cytotoxic effect of gold nanoparticles using pistacia atlantica extract J. Taiwan Inst. Chem. Eng. 93 21–30
[35] Mohamed M M, Fouad S A, Elshoky H A, Mohammed G M and Salaheldin T A 2017 Antibacterial effect of gold nanoparticles against corynebacterium pseudotuberculosis International Journal of Veterinary Science and Medicine 5 23–9
[36] Hamelian M, Varmira K and Veisi H 2018 Green synthesis and characterizations of gold nanoparticles using thyme and survey cytotoxic effect, antibacterial and antioxidant potential J. Photochem. Photobiol., B 184 71–9
[37] Nakakala J R, Mata R and Sadras S R 2016 The antioxidiant and catalytic activities of green synthesized gold nanoparticles from piper longum fruit extract Process Safety and Environmental Protection 100 288–94
[38] Khalil M M H, Ismail E H and El-Magdoub F 2012 Biosynthesis of Au nanoparticles using olive leaf extract Arabian J. Chem. 5 431–7
[39] Zulfar H, Zafar A, Rashedi M N, Ali Z, Mehmood K, Mazher A, Hasan M and Mahmood N 2019 Synthesis of silver nanoparticles using fagonia cretica and their antimicrobial activities Nanoscale Advances 1 1707–13
[40] Bibi N, Ali Q, Tanveer Z I, Rahman H and Anees M 2019 Antibacterial efficacy of silver nanoparticles prepared using Fagonia cretica L. leaf extract Inorganic and Nano-Metal Chemistry 49 260–6
[41] Adil M, Khan T, Aasim M, Khan A A and Ashraf M 2019 Evaluation of the antibacterial potential of silver nanoparticles synthesized through the interaction of antibiotic and aqueous callus extract of Fagonia indica AMB Express 9 75
[42] Ullah I, Khan Shinwari Z and Khalil A T 2017 Investigation of the cytotoxic and antileishmanial effects of fagonia indica L. extract and extract mediated silver nanoparticles (AgNPs) Pak. J. Bot. 49 1561–8
[43] Aqsa Yousaf A Z et al. 2019 Entities of fagonia cretica for synthesis of silver nanoparticles involves anti-urease, anti-oxidant and anti-tyrosinase activity Advances in Bioscience and Biotechnology 10 455–68
[44] Ahmad A, Wei Y, Syed F, Imran M, Khan Z U H, Tahir K, Khan A U, Raza M, Khan Q and Yuan Q 2015 Size dependent catalytic activities of green synthesized gold nanoparticles and electro-catalytic oxidation of catechol on gold nanoparticles modified electrode RSC Adv. 5 99364–77