Papain-capped gold nanoflowers: dual functionality as peroxidase mimic and 4-nitrophenol reduction catalysts

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ABSTRACT

A bifunctional ensemble of papain-capped gold nanoparticles (AuNFs) exhibits dual functionality, manifesting peroxidase-like and 4-nitrophenol reduction activities. The AuNFs, possessing an average size of approximately 82.27 ± 1.95 nm, are synthesized under ambient conditions through the mediation of papain, wherein the reduction of $HAuCl_4$ by ascorbic acid is facilitated. These nanoflowers are capable of catalyzing H_2O_2 to oxidize the target 3,3,5,5-tetramethylbenzidine, resulting in the production of a visual color of blue. Therefore, a simple method providing a sensitivity of 0.44 μM (signal/noise ratio = 2) and a linearity within the range of 0 to 40 μM is available to detect H_2O_2 by colorimetry. Subsequently, the chemical activity associated with the 4-NP (4-nitrophenol) reduction was studied, and it was found to exhibit a catalysis rate of 0.29 min^{-1}, surpassing that of alternative gold catalysts. These findings underscore the potential utility of our AuNFs in catalytic and biosensing applications.

Keywords: Gold nanoflower, peroxidase-like, 4-nitrophenol reduction, biomaterials, sensors

1. INTRODUCTION

4-Nitrophenol (4-NP) is integral to chemical manufacturing, serving as an organic intermediate in compounds like dyes, pharmaceuticals, and surfactants [1-6]. Despite its utility,4-NP poses environmental hazards due to its toxicity to aquatic life and human health risks, primarily from industrial effluents [7-11]. The conversion of 4-nitrophenol to 4-aminophenol, an essential precursor used in manufacturing a wide range of critical organic chemicals, including analgesics and antipyretics, is challenging for reducing agents due to the inherent inertness of nitro groups [3, 5, 12, 13], particularly under ambient conditions. Therefore, there is an urgent need to identify a catalyst that is not only cost-effective, but also has exceptional efficiency and selective properties for facilitating 4-nitrophenol degradation [14-20].

Attributable to a substantial surface-to-volume ratio. Nanomaterials have garnered attention for their utilization as high-efficiency catalysts, with specific variants exhibiting peroxidase-like activities [21-30]. In particular, magnetic Fe_3O_4 nanoparticles were found to have peroxidase-like activities, according to Yan's research [31]. Subsequently, two-dimensional materials like graphene oxide, MoS_2, and their composites similarly exhibit peroxidase-like activity [32-39]. In contrast, gold nanomaterials (AuNMs) are among the most pivotal enzymes, credited to their stability, biocompatibility, and unforeseen activities [40-46]. Among them, gold nanoflowers (AuNFs) have received extensive investigation due to their pronounced surface roughness and high-index facets [47, 48]. The catalytic process of AuNMs is typically assessed using a known response: the transformation with NaBH4 of 4-nitrophenol (4-NP) into a 4-aminophenol (4-AP) [49, 50]. Although different kinds of AuNMs have been widely reported as either enzyme mimics [51-53] or 4-NP reduction catalysts [54-57]. However, to our knowledge, there have been few reports of AuNFs exhibiting both peroxidase-like activity and reducing 4-nitrophenol (4-NP) activity.

In this piece of work, we have developed a green strategy to produce uniform AuNFs with both peroxidase-like and 4-nitrophenol (4-NP) reducing activity by template papain(Figure 1). Specifically, AuNFs provide a blue staining method for H_2O_2 detection by facilitating the H_2O_2-based oxygenation of the enzyme candidate peroxidase inhibitor template

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3,3,5,5-tetramethylbenzidine (TMB). Furthermore, AuNFs activity for catalyzing degradation of 4-NP showed that AuNFs can also act as an efficient reduction catalyst.

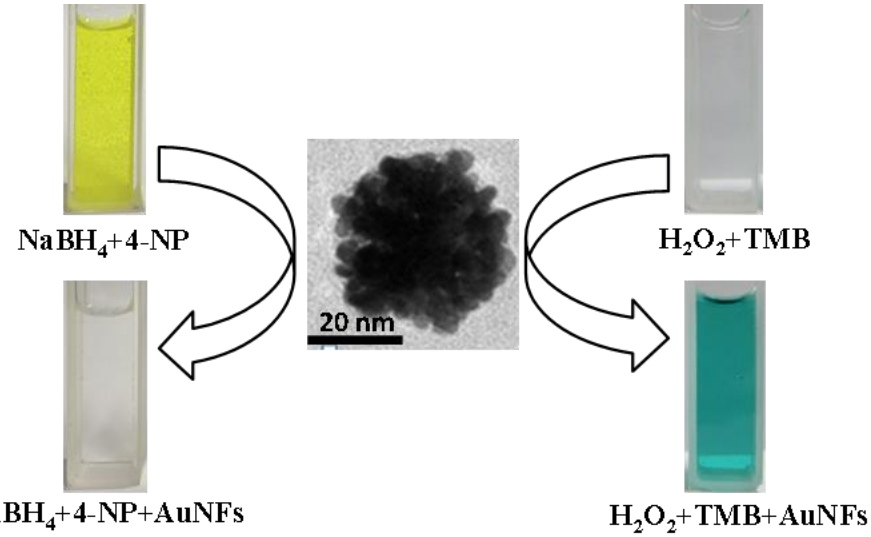

Figure 1. A bi-functional AuNFs catalyst with both peroxidase-like and 4-NP reduction activity has been synthesised by a green strategy with papain as the capping agent.

2. EXPERIMENTAL SECTION

2.1 Synthesis of AuNFs

AuNFs were synthesized following a previously established protocol with minor adaptations, as detailed in reference [58]. In a common method of synthesis, a liquid consisting of HAuCl4 (0.2 mM) and papain (0.2 mg ml^{-1}) was rapidly added to a predetermined amount of ascorbic acid (AA). After a brief period of gentle stirring for 2 minutes, the mixture was continuously agitated for the specified duration at ambient temperature, during which a rapid transition in coloration from a faint yellow hue to a deep blue shade was observed. Subsequently, the resulting gold samples underwent overnight dialysis to eliminate residual AA, $HAuCl_4$, and other incidental byproducts.

2.2 Peroxidase-like activity of AuNFs

Catalytic studies were performed using 50 μg mL-1 AuNFs in an amount of 600 μL of sodium acetate-acetic acid buffer at a 0.02 M concentration (pH 4, 25 °C). The substrate was either 600 μM TMB or 10 mM H_2O_2. Peroxidase-like activity was assessed by detection in situ at 652 nm in a Shimadzu UV2550 UV-vis spectrophotometer.

2.3 Detection of H_2O_2

H2O2 was detected as follows: 300 μL H_2O_2 at various concentrations was added to a mixture containing 180 μL TMB (2 mM) and 120 μL AuNFs stock concentration (50 μg mL^{-1}). The resulting solution was utilized for time-course measurements conducted at a wavelength of 652 nm.

2.4 Catalysed reduction of 4-NPs

NaBH4 solution (0.42 mol/L, 10 mL) was dissolved in 4-NP solution (0.175×10^{-3} mol/L, 70 mL). For recording the UV-vis spectra at identical times, 100 μL of the AuNFs suspension (50 μg mL-1) was dissolved in 3 mL of 4-NP.

3. CONCLUSIONS AND DISCUSSION

3.1 Characterisation of AuNFs

The as-prepared AuNFs displayed a blue suspension that remained stable for approximately one year (Figure 2a), attributed to the capping effect of papain. UV-vis spectra for the product showed a prominent maximum of 568 nm, indicative of the peak of the superficial plasmon resonance, which indicates that Au(0) starts to form. Crystal pattern analysis of the as-prepared Au(0) was carried out by XRD (Figure 2b), exhibiting close conformity with the fcc Au as documented in the PDF card (JCPDS file number 04-0784). SEM and TEM have been applied to characterize the morphological properties of the AuNFs. SEM imagery (Figure 2c-d) revealed the presence of abundant Au nanostructures in a flower-like configuration with a uniform size of 82.27 ± 1.95 nm, further corroborated by TEM imagery (Figure 2e). The electron diffraction pattern corresponded to the fcc structure of gold (Figure 2e inset). The HRTEM image (Figure 2f) delineated that the nanoflowers comprised a significant quantity of AuNPs, exhibiting distinct interplanetary spacing of 0.238 nm (111). Optimization of the effect of AA, a reducing agent, on AuNFs synthesis yielded an optimal concentration of 0.85 mM (Figure S1). The protein and $AuCl_4^-$ complex structures in solution would be influenced significantly by the pH of the system. Thus, the influence of pH on the production of AuNFs needs to be investigated and optimized at pH 6 (Figure S2).

3.2 Intrinsic peroxidase-like activity of AuNFs and H_2O_2 detection

Since colorless TMB is oxidized in the presence of a catalysator to a colored product, the TMB-H_2O_2 reaction is the model reaction used to assess the peroxidase-like action by AuNFs (Figure S3). Figure 3a demonstrates that the absorption of the TMB oxidized product increases with time for the mixed TMB, H_2O_2, and AuNFs. Figure 3b shows that neither H_2O_2 nor as-received AuNFs alone can efficiently oxidize TMB to generate the blue colour. Hence, the oxidization of TMB results is directly proportional to the decomposition of H_2O_2 caused by the as-received AuNFs. Thus, TMB oxidation results from the decomposition of H_2O_2 by the AuNFs as they are obtained. Notably, bare papain exhibits slight peroxidase-like activity, potentially attributable to the presence of multiple His residues, which stabilize radicals capable of effectively oxidizing TMB to produce colored oxTMB [59, 60]. Figure 3c shows an improvement in the velocity at which the reaction takes place as the AuNF concentration is raised up to 60 μg mL^{-1}. The pH value was optimized to be 4 (Figure 3d). H_2O_2 is capable of adsorbing onto the surface of AuNFs, in which the H_2O_2 O-O bond is able to cleave to produce $HO^{\bullet}$ radicals. The resultant $HO^{\bullet}$ radicals could potentially be stabilized by papain (zeta potential: +14.9 mV) *via* partial electron exchange interactions, thereby augmenting the catalytic prowess of positively charged AuNFs [61].

The accelerated oxidation of H_2O_2 by AuNFs shows evidence of concentration-dependent catalysis, making the system potentially applicable for H_2O_2 detection. The relationship between the concentration of H_2O_2 and TMB absorbance is illustrated in Figure 3e. A linear correlation with a correlation coefficient of 0.9989 is found for the 0-40 μM span (Figure 3f). The resulting regression equation is given as Absorbance = 0.009C + 0.004 (where C is the H_2O_2 concentration in μM), giving a limit of quantitation of 0.44 μM (S/N = 2). This detection limit notably surpasses those observed in other gold-based sensors [52, 62].

3.3 Application for 4-NP reduction

The reducibility from 4-NP to 4-AP towards NaBH4 has been used to investigate the reductive catalytic performance of the prepared AgNFs. As observed from the UV-visible spectral data (Figure 4a), the development from 4-AP with the addition of AuNFs was followed by the occurrence at 300 nm of a peak associated with a drop in the intensity of the 400 nm peak. The relationship between ln (Ct/C0) and time (min) showed linearity (ln (Ct/C0) = - 0.2915 t + 0.1896, R2 = 0.984), where C0 and Ct are 4-NP levels at instant 0 and instant t, individually (Figure 4b). The ratio of absorbance, At/A0, could be replaced by the concentration ratio, Ct/C0 (i.e. Ct/C0 = At/A0), since the 4-NP concentration is proportionate to the absorbance. The catalytic efficiency (0.29 min^{-1}) is higher than other gold catalysts [57, 63].

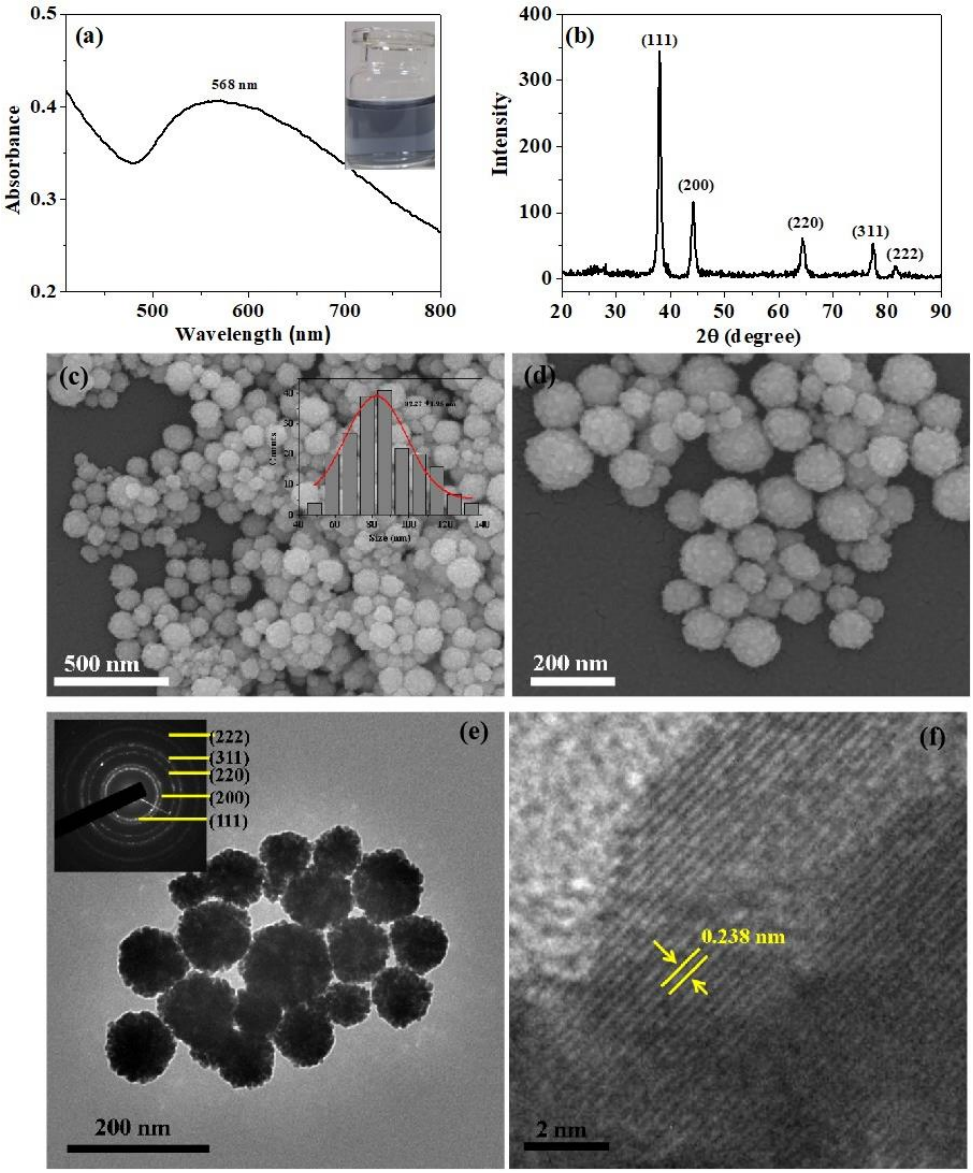

Figure 2. Characterization of AuNFs. (a) UV–vis spectra and optical photo of as-prepared AuNFs (inset). (b) XRD pattern. (c) SEM image and corresponding size distributions of AuNFs (inset). (d) magnified SEM image. (e) TEM image and associated SAED sample (inset). (f) HR-TEM image.

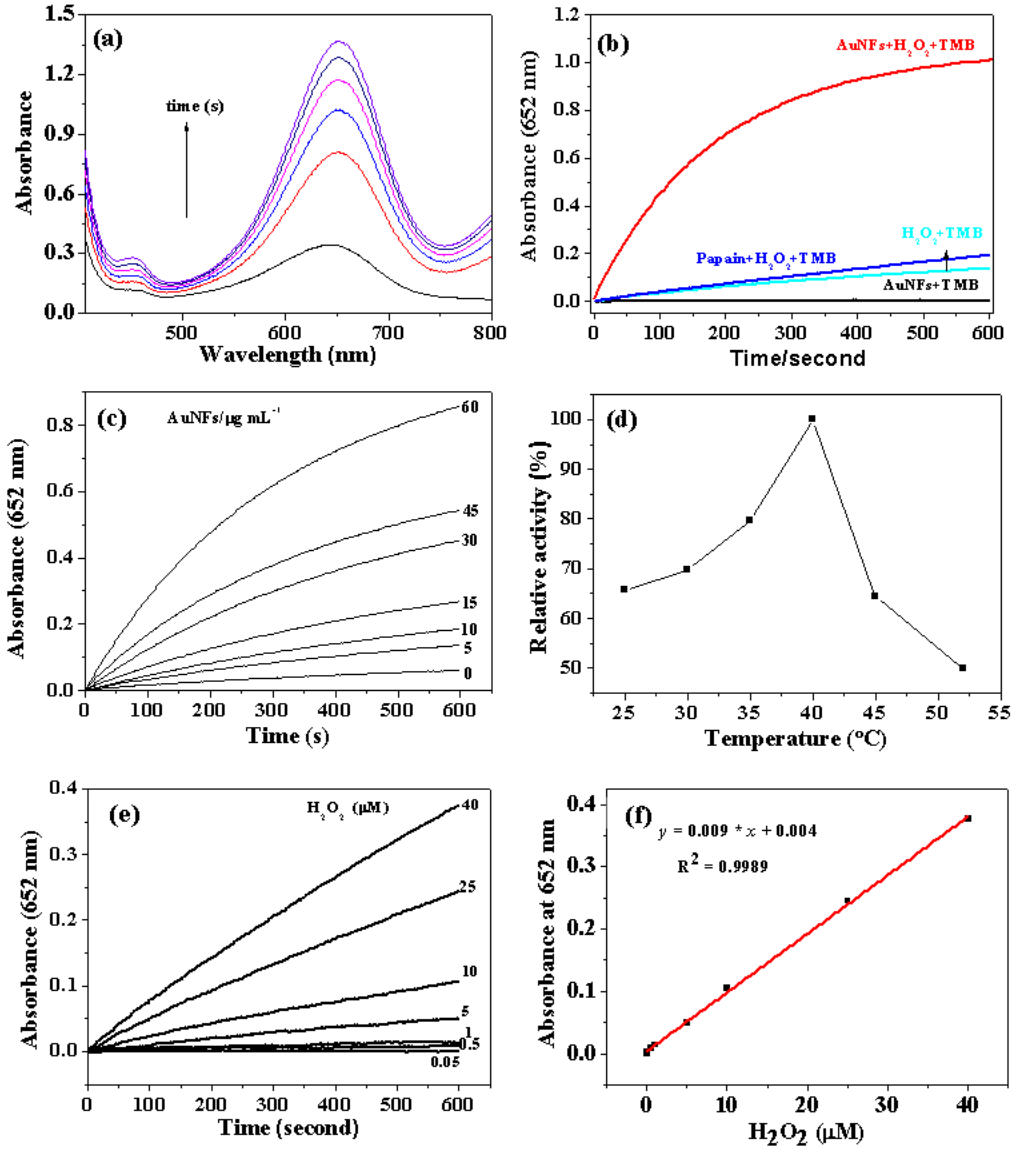

Figure 3. AuNF peroxidase-like activity. (a) UV-vis spectrum of the solution of a mixture of TMB and H2O2, taken at the same intervals after adding 50 μg mL-1 of AuNFs in a pH 4 system. (b) Time dependency of changes in absorbance at 652 nm of TMB solutions in the presence of AuNFs, papain, H2O2, AuNFs, and H2O2, individually. (c) Changes in the absorbance at 652 nm for the TMB and the H2O2 system in the presence of AuNFs at different concentrations. (d) Peroxidase-like activity of AuNFs as a function of pH. (e) Changes in absorbance at 652 nm for various H2O2 concentrations. (f) Calculate from (e) the linearity of the calibration curve for H2O2.

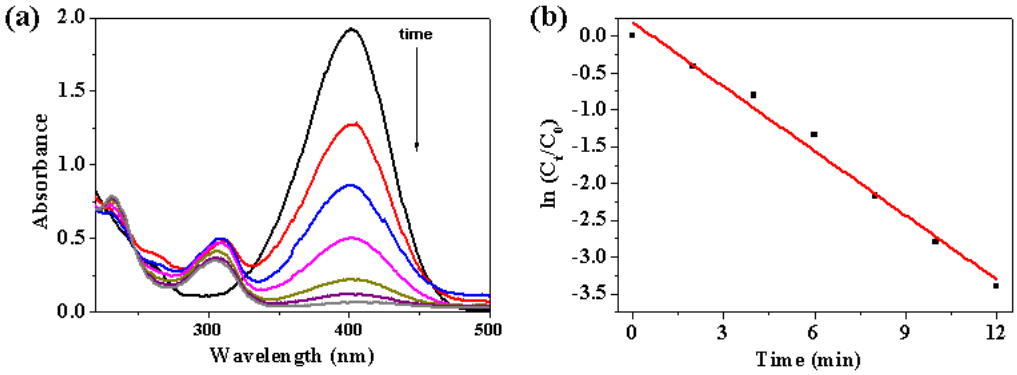

Figure 4. 4-NP reduction. UV-vis spectrums of 4-NP as reduced with NaBH4 in the presence of AuNFs ranging in time from 0 to 300 s. b) Plotting ln(Ct/C0) as a function of time taken from part (a).

4. CONCLUSION

We established that papain-capped AuNFs prepared by a green strategy show both peroxidase-like and 4-NP reduction activity. The colorimetric method has a robust sensitivity to hydroperoxide (H_2O_2), with a detectability level of 0.44 μM and high sensitivity. Moreover, the catalytic capability of AuNFs in the decrease of 4-NP is remarkably efficient, evidenced by catalytic activity of 0.29 min^{-1}. Our work expands the utilization of biomolecule-capped AuNFs in catalysis and biosensing applications.

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