Effect of Reaction Temperature on Shape Evolution of Palladium Nanoparticles and Their Cytotoxicity against A-549 Lung Cancer Cells

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ABSTRACT: Palladium nanoparticles (Pd NPs) of different shapes and sizes have been synthesized by reducing potassium tetrachloropalladinate(II) by l-ascorbic acid (AA) in an aqueous solution phase in the presence of an amphiphilic nonionic surfactant poly ethylene glycol (PEG) via a sonochemical method. Materials have been characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy dispersive X-ray soectroscopy (EDX), Fourier transform infrared (FTIR), surface-enhanced Raman spectroscopy (SERS), particle distribution, and zeta potential studies. Truncated octahedron/fivefold twinned pentagonal rods are formed at room temperature (RT) (25 °C) while hexagonal/trigonal plates are formed at 65 °C. XRD results show evolution of anisotropically grown, phase-pure, and well crystalline face-centered cubic Pd NPs at both temperatures. FTIR and SERS studies revealed adsorption of ascorbic acid (AA) and PEG at NP’s surface. Particle’s size distribution graph indicates formation of particles having wide size distribution while the zeta potential particle surface is negatively charged and stable. The truncated octahedron/fivefold twinned pentagonal rod-shaped Pd NPs, formed at RT, while thermally stable and kinetically controlled hexagonal/trigonal plate-like Pd NPs, evolved at higher temperature 65 °C. The obtained Pd NPs have a high surface area and narrow pore size distribution. To predict protein reactivity of the Pd cluster, docking has been done with DNA and lung cancer-effective proteins. The cytotoxicity of the Pd NPs has been screened on human lung cancer cells A-549 at 37 °C. The biological adaptability exhibited by Pd NPs has opened a pathway in biochemical applications.

1. INTRODUCTION

In the last few decades, mesoporous materials have gained enormous attention of various scientists globally in both industry and academia because of their high surface area, tunable pore size, and uniform and narrow pore size distribution.1,2 On account of these properties, mesoporous and nanoporous materials have shown high demand in various fields such as energy storage,3 catalysis,4,5 and biomedical applications.6,7 In the past, nanoparticles of desired shapes, such as spherical, films, rods, tubes, and so forth with mesoporous structures have been prepared by a soft template method like self-assembly of micelles.8 On the other hand, in the hard template method, the targeted materials are deposited in the confined spaces of a template with the desired morphology.9 Because the soft template method is a simple and easy approach, hence it is favorable for the generation of desired shapes of nanoparticles using low molecular weight molecules like Brij 58, poly ethylene glycol (PEG), and so forth and high molecular weight amphiphilic molecules, for example, triblock copolymers as pore-directing agents.

In recent years nanotechnology has shown enormous potential in the biomedical field as therapeutic mediators for many diseases, including cancer.10 In this regard, metal nanostructures have attracted great interest because of their size, structure, versatility, and optoelectronic properties.11 Since the introduction of catalytic converters in the USA in 1975 and in Europe in 1986 (Wiseman and Zereini 2009), platinum group metals have shown increasing demands particularly in the area of electronics and catalysis. The latest research demonstrate that palladium (Pd) nanoparticles have widely been used in catalysis, (e.g., oxidation/reduction of methanol,12 stereochemical oxidation of ethanol,13 redox organic reactions,14,15 sensors for detection of various analytes,16 hydrogen generation/storage, methane combustion, supercapacitors, lithium-ion batteries, and in biomedical applications.17 Shim et al. synthesized dendritic platinum nanoparticles and demonstrated their cytotoxicities against human embryonic kidney cells.18 Unciti-Broceta et al. demonstrated that the prodrugs S-fluoro-1-propargyluracil19 and N4-propargyloxycarbonylgemcitabine20 are independently harmless; however, when separately combined with Pd(0)-glycol-polystyrene resin these prodrugs exhibited antiproliferation properties compared to the unmodified drug in colorectal and pancreatic cancer cells. However, one of the major limitations, in the case of metallic NPs is their nonspecific untargeted toxicity. Huang et al. used ultrathin (1.8 nm)
hexagonal Pd nanosheets with a 41 nm edge for cancer photothermal therapy (PT). The nanosheets were able to kill 100% liver cancer cells after 5 min irradiation of 808 nm laser, showing size-dependent and tunable absorption peaks in the NIR region and exhibited high biocompatibility in the absence of irradiation. More interestingly, these Pd nanosheets exhibited better photostability than Au and Ag nanostructures.21 Balbin et al. reported high cytotoxicity of mesoporous silica-supported Pd NPs against four human cancer cell lines, simultaneously displaying catalytic activity for C−C bond formation via Suzuki−Miyaura cross-coupling between small molecules.22,24 Kumar et al. prepared (poly(lactic–glicolic acid)-loaded nanoparticle betulinic acid for improved treatment of hepatic cancer and showed in vitro and in vivo evaluation.23 Several structural modifications have been proposed to improve biomedical efficiency of Pd nanoparticles.25,26 Porous Pd nanoparticles (22.8 nm) were also recently reported as attractive PT agents with a PT conversion efficiency as high as 93.4%, which is comparable to typical Au nanorods.25

There is high interest to expand the applicability of Pd nanoparticles; therefore, it is highly desirable to synthesize shape- and size-controlled Pd NPs for excellent performance in biomedical applications. Generation of Pd nanoparticles using amphiphilic molecules (nonionic surfactants) via a sonochemical process is a novel and rapid approach to tune the kinetics of the reaction. In this investigation, mesoporous Pd nanoparticles have been prepared via a sonochemical route and their cytotoxicity has been screened by using the culture of human lung cancer cells A-549.

2. MATERIALS AND METHODS

2.1. Materials. Analytical reagent grade potassium tetrachloropalladinate(II) (K2PdCl4), PEG and L-ascorbic acid (AA, C6H8O6) were purchased from Sigma-Aldrich and used without further purification. Deionized water and ethanol were used as solvents in this study.

2.2. Synthesis. In the two different vessels, 10 mL solutions of 0.1 M K2PdCl4 were prepared, and 10 mL aqueous 0.1 M ascorbic acid (AA) solutions were added to each vessel. Further, 1 mL of 50 mg/L aqueous PEG solutions were added to each reaction mixtures. The two solution mixtures were reacted at room temperature (RT) and 65 °C, respectively, for 30 min with thorough ultrasonication (220–240 V, 50–60 Hz). After the reactions, the products were collected by centrifugation and washed several times with deionized water and ethanol to remove the residual surfactant and excess reactants.

2.3. Characterization. The X-ray diffraction (XRD) patterns of the obtained products were recorded on a Panalytical’s X’Pert Pro X-ray diffractometer in the 2θ range 10–80° with a step size of 0.025°. Scanning electron microscopy (SEM) images of the materials were observed on JEOL 6490 LB equipment at an operating electrical energy of 3 kV. Particle shapes and sizes of the materials were further examined on a JEOL-2100 transmission electron microscope. The zeta potential of Pd nanoparticles (formed at RT) was measured using a Zetasizer ZS90 (Nano series Malvern Instrument) at RT. Dispersion of nanoparticles was sonicated for 20 min and diluted to make a solution with concentration 80 µg/mL in phosphate buffered saline (pH = 7.4). The particle size and size distribution were carried out on a Zetasizer ZS90 (Nano series Malvern Instrument). The Surface-enhanced Raman spectroscopy (SERS) spectrum of Pd nanoparticles, formed at RT, was recorded on a NSCOM/ Raman/confocal/atomic force microscope used for UV/lithography (200 nm) and near-field imaging of features as small as 100 nm Raman spectra and imaging for an excitation wavelength of 532 nm with an extinction coefficient of 8000 M−1 cm−1. Fourier transform infrared (FTIR) spectra of the products have been recorded on a PerkinElmer Spectrum Two instrument. UV/vis data were collected on a Shimadzu UV-3600 spectrophotometer. Brunauer−Emmett−Teller (BET) analysis of the materials was recorded on a BELsorp-mini II instrument.

2.4. Cytotoxicity Test. The culture of A-549 human lung cancer cells (~100 000 cell mL−1) was taken in 10% fetal bovine serum-supplemented Dulbecco’s modified Eagle’s medium in a 24-well microtitre plate. Different amounts of Pd NPs (formed at RT) were suspended in deionized water to make solutions with concentration from 10 to 60 µg mL−1. Homogenization of each solution was carried out with an ultrasonic processor (Labsonic M, Sartorius Stedim Biotech GmbH) for 15 min and added separately to cultures, keeping one blank as the reference. The cultures were incubated for 24 h in an incubator with 5% CO2 in a humid atmosphere at 37 °C. After incubation, the cells were removed from the culture by trypsinization and washed a coupled by Dulbecco’s phosphate-buffered saline (PBS; pH: 7.4) to remove the residual presence of serum. The cells were again suspended in PBS, and aliquots of 20 µL were prepared from all the cultures. Equal amounts (v/v) of prefiltered 0.4% trypan blue stain were added to the aliquots and were put aside to settle for 1 min. To determine the cell viability, the samples were observed on an inverted microscope in a Fuchs-Rosenthal haemocytometer. The results of cytotoxicity were expressed by plotting cell viability histogram and curve and analyzed using IC50 values.

3. RESULTS AND DISCUSSION

3.1. Characterization of Pd Nanoparticles. When the solution containing [PdCl4]2− complex ions were treated with AA at RT, the solution turned black within 30 min, indicating a reduction of [PdCl4]2− complex ions is completed in this period. This reaction was monitored by the UV−visible absorption spectroscopy experiment as shown in Figure 1. Before formation of Pd NPs, the absorption band corresponding to the Pd complex was clearly detected at 424 nm, which completely disappeared after the reaction, indicating that the complex ions are changed from Pd4+ to Pd(0) owing to their
Moreover, the spectrum of the sample shows broad continuous absorptions in the UV−visible range which is characteristic of the reduced Pd NPs as reported earlier. On increasing the reaction temperature at 65 °C virtually no alteration in the spectral profile has been observed. The yield of this reaction was approximately 91.84%.

To observe the adsorption of organic molecules on the surface of Pd nanoparticles, FTIR spectra of the formed nanoparticles (at RT) were carried out in a liquid phase as well as in a solid phase (Figure 2). In the liquid phase FTIR spectrum (Figure 2a), the intense peak at 3425 cm⁻¹ is corresponding to O−H stretching of water molecules/−OH groups. The peak at 1634 cm⁻¹ is because of the C= C stretching frequency of AA. Red shifting of C= C stretching...
frequency (compared to 1665 cm\(^{-1}\) in pure AA) is because of adsorption of \(\text{L-ascorbic acid}\) on the nanoparticle’s surface.\(^{27}\) The peak at 1452 cm\(^{-1}\) is due to \(-\text{CH}_2\) scissoring, at 964 cm\(^{-1}\) is due to \(-\text{CH}_2\) wagging, at 1029 cm\(^{-1}\) is due to \(-\text{CH}_2\) rocking and at 1268 cm\(^{-1}\) is due to \(\text{C=O-C}\) antisymmetric stretching vibration of adsorbed PEG at the particle’s surface.\(^{28}\) Other peaks at 651 and 458 cm\(^{-1}\) correspond to the vibration of the adsorbed AA nanoparticle’s surface.

In the solid phase FTIR spectrum (Figure 2b), the intensity of peaks is much decreased compared to those in the solution phase. Many peaks have disappeared while the intensity of a few peaks has increased. The increased intensity peaks at 2927 and 2853 cm\(^{-1}\) is due \(-\text{CH}_2\) stretching vibration while the peak at 1452 cm\(^{-1}\) is due to \(\text{CH}_2\) scissoring of alkyl chains of adsorbed PEG. Position of these peaks is much decreased compared to those of pure PEG\(^{28}\) because of adsorption at nanoparticle’s surface. Although peaks corresponding to \(-\text{CH}_2\) stretching do not appear in Figure 2a, however, a small hump is visible at 2927 cm\(^{-1}\) probably because of preferential adsorption of AA at nanoparticle’s surface in the liquid phase.

Further vibrational analysis of Pd nanoparticles (formed at RT) was carried out by Raman measurement, which shows...
very strong, few broad and weak background peaks. The Intensity versus Raman shift graph was plotted to take 20 mM Pd NPs, grafted with PEG and coated with AA (Figure 3). In the SERS spectrum, the strong peaks at 480 and 633 cm$^{-1}$ are because of ascorbic acid, while the peak at 278 cm$^{-1}$ is probably because of $\nu$ (Pd...O) vibration. The bands at 1076, 1170, and 1516 cm$^{-1}$ are because of (C–O–H bend), CH$_2$ rocking, and CH$_2$ scissoring. The structural and morphological investigation of the abovementioned synthesized materials has been performed using SEM and transmission electron microscopy (TEM) analysis. Different shapes and sizes of Pd nanoparticles have been formed at RT and at 65 °C. When the [PdCl$_4$]$^{2-}$ complex ions were treated with AA in PEG medium at RT, truncated octahedron/fivefold twinned pentagonal rodlike Pd NPs have been formed on 30 minutes of the reaction. In the SEM images (Figure 4a,b) and the TEM image (Figure 4c), 8–10 nm edge length truncated octahedron/fivefold twinned pentagonal rodlike Pd nanoparticles were observed. The size of nanostructures varies in the range of 20–50 nm. In the corresponding energy dispersive X-ray spectroscopy (EDX) pattern (Figure 4d), the only peak due to Pd was observed, indicating the formation of phase-pure Pd NPs. When the reaction temperature was increased at 65 °C, keeping reaction time same, that is, 30 min, 17–20 nm edge length hexagonal/trigonal plates were formed. In the SEM image (Figure 5a), although the structures seem to be plate-like, however in the corresponding TEM image (Figure 5b) hexagonal/trigonal plate-like structures are visible.

The particle size and size distribution analysis of Pd NPs, formed at RT were carried out to by plotting the particle’s size distribution curve (Figure 6). The curve indicates that the size of the particles is distributed in a range of 20–60 nm while the maximum population falls at 40 nm. Zeta potential analysis is an effective technique for determining the surface charge of nanoparticles in colloidal solution and hence predicts their stability. The zeta potential curve of the Pd nanoparticle dispersion (formed at RT) was measured in the range of −100 to +100 mV (Figure 7). The obtained zeta potential value (−13 mV) indicates that the surface of nanoparticles is negatively charged and thus maintains their stability.

Table 1. Binding Energies of Protein–Drug Complexes

| s. no | proteins | binding energies (kcal/mol) |
|-------|----------|----------------------------|
| 1     | 2ITW     | −0.44                      |
| 2     | 2ITX     | −0.46                      |
| 3     | 2ITY     | −0.48                      |
| 4     | 2J6M     | −0.42                      |
| 5     | 4LQM     | −0.44                      |

Figure 11. Minor groove binding of the Pd cluster with 1BNA.

Figure 12. Interaction of the Ag–Au cluster with (a) 2ITW, (b) 2ITX, (c) 2ITY, (d) 2J6M, and (e) 4LQM.

Figure 13. Effect of dose of Pd NPs (synthesized at RT) on cell viability of A-549 human lung cancer cells.
growth is anisotropic in shape at both temperatures. Further preferentially toward the {111} facet and that the particle planes at both temperatures, indicating orientation of Pd NPs (111) and (222) planes are larger than that of the rest of the graph, it has been found that crystallite size corresponding to the above formula has been shown in Figure 8b. From the obtained XRD peaks are intense and broadened, indicating the presence of residual PEG moieties. Furthermore, the phase and crystallinity of Pd NPs were investigated by wide-angle XRD measurement. In the XRD pattern of the Pd NPs (formed at RT and at 65 °C), peaks observed at 2θ positions 40.26, 45.78, 68.67, 79.87, and 88.85° correspond to the reflection of (111), (200), (220), (311), and (222) planes of crystalline Pd NPs (Figure 2a). These XRD patterns indicate the formation of phase pure face-centered cubic (fcc) Pd NPs (JCPDS file no. 461043). The weak intensity peak at 27° in the XRD pattern of Pd NPs formed at 65 °C is because of the presence of residual PEG moieties. Furthermore, the obtained XRD peaks are intense and broadened, indicating the formation of good crystalline and small size Pd nanoparticles. The average crystallite size (D) has been determined from the Debye–Scherrer formula

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]

where D is the crystallites size (in nm), λ the wavelength (in nm), β is the full width at half maxima and θ is the Bragg’s diffraction angle. Crystallite size of Pd NPs synthesized at RT and at 65 °C, corresponding to different planes determined by the above formula has been shown in Figure 8b. From the graph, it has been found that crystallite size corresponding to (111) and (222) planes are larger than that of the rest of the planes at both temperatures, indicating orientation of Pd NPs preferentially toward the {111} facet and that the particle growth is anisotropic in shape at both temperatures. Further the particle size determined is smaller than those of the TEM and particle size distribution analyses probably because of wide size distribution of the particles.

Nitrogen adsorption/desorption isotherm plots have been used to evaluate the pore diameter (Dp) and the surface area (S) of the Pd NPs formed at RT. From the Barrett–Joyner–Halenda (BJH) method, an average pore diameter of DPs has been found to be 24.29 nm (Figure 9a). This result is indicative of its porous structure containing mesopores. The specific surface area obtained by the BET method (Figure 9b) was approximately 19.44 m² g⁻¹. Such high surface area of Pd NPs indicates the presence of more catalytic sites.

It is well understood that the shape, size, surface area, and charge of the nanostructure affect the biological cell membrane interaction and thus decide their biological applications. It is reported that cellular uptake of Pd nanoparticles are shape-dependent apart from the surface charge because of membrane binding energy barriers during endocytosis are predominantly responsible for the shape effect. Hence, a better understanding of shape evolution Pd nanoparticles would aid the development of physicochemical and reaction parameters for generation of Pd nanoparticles for effective biochemical applications.

The inside atoms of face-centered cubic metals (e.g., Pd) have coordination number (CN) 12 while the atoms at the various low index surfaces (e.g., \{111\}, \{100\}, and \{110\}) have the CN of 9, 8, and 7, respectively. The planar density of three surfaces increases in the order \{111\} > \{100\} > \{110\}, and hence, the surface energy increases in the order \(\gamma_{\{111\}} < \gamma_{\{100\}} < \gamma_{\{110\}}\). When aqueous solution of K₂PdCl₄ was treated with ascorbic acid in the presence of surfactant PEG, the Pd²⁺ ion was readily reduced to Pd(0) owing to the reaction.

\[
Pd^{2+} + AA(C₆H₁₂O₆) \rightarrow C₆H₁₂O₆ + Pd(0) + 2H^+\]

Here, \([PdCl]^{2-}\) reduction takes place using AA as a reductant via sonication. It is supposed that Pd nanoparticles evolved following three steps: supersaturation of monomers, burnt nucleation, and controlled growth according to the LaMer method. In the prevailing reaction conditions when monomer concentration increases steadily and reaches the stage of the critical point of supersaturation, small clusters spontaneously separate, decreasing the monomer concentration by nucleation. Now, concentration of the monomer decreases below a critical concentration and the available monomer is henceforth used for particle growth; however, during the nucleation period, particle growth may also take place simultaneously. Thus, to control size broadening of particles, a short nucleation span and controlled growth kinetics should be maintained which can be achieved by the presence of adsorbates, additives, or surfactants in the reaction medium.

![Figure 14](image1.png)

**Figure 14.** Cell viability curve: effect of dose of Pd NPs (synthesized at RT) on A-549 human lung cancer cells.

![Figure 15](image2.png)

**Figure 15.** Cell viability curve: effect of dose of Pd NPs (synthesized at RT) and Adriamycin on A-549 human lung cancer cells.
When K$_2$PdCl$_4$ is reduced by AA in an aqueous medium in the presence of PEG, truncated octahedron/fivefold twinned pentagonal rodlike polyhedral structures enclosed by \{111\} and \{100\} mixed facets are formed because \{111\} is the most stable facet followed by \{100\} and then \{110\}. From a stability point of view only \{111\} facet-terminating shapes like octahedral and tetrahedral seed should be formed during the nucleation stage; however, according to Wulff’s theory because the octahedron and tetrahedron have a larger surface area than the cube per unit volume, the truncated octahedron, known as Wulff’s polyhedron, nucleated at the most stable speed in order to minimize both the surface area and interfacial face energy. On increasing the reaction temperature at 65 °C the concentration of the monomer increases, thus increasing the rate of reaction. Now, among the two facets \{111\} and \{100\} of an octahedron, the \{111\} surface grows more rapidly than \{100\} because of availability of higher monomer concentration at an elevated temperature. Thus, thermodynamically stable and kinetically controlled hexagonal/trigonal plate-like Pd NPs have been evolved at higher temperature 65 °C.

3.2. Molecular Docking Studies of Palladium Clusters with DNA. 3.2.1. Computational Details. 3.2.1.1. Dataset. DNA: the PDB format file of DNA sequences with PDB ID 1BNA was downloaded from RCSB Protein Data Bank.41 Ligands and water molecules were removed from the DNA sequence using CHIMERA.42

Drugs: the structure of the Pd cluster was taken after optimization. Figure 1 shows the chemical structure of the cluster.

3.2.2. Molecular Docking. AutoDock 4.2 was used for molecular docking simulations using Lamarckian Genetic Algorithm (LGA).43 Docking was performed using DNA sequences as a rigid receptor molecule, whereas the Pd cluster was treated as a flexible ligand. The receptor and ligand files were prepared for docking using AutoDockTools (ADT).44 The grid box size was set at 50-50 and 100 Å for \(x, y\) and \(z\) respectively, and the grid center was set to 14.748, 20.984, and 8.809 for \(x, y\), and \(z\) respectively. The Gasteiger charges were added to the complex by AutoDockTools (ADT) before performing docking calculations. Lamarckian genetic algorithms, as implemented in AutoDock, were employed to perform blind docking calculations. All the other parameters were default settings. For metals, modifications were done in the parameter file to include Pd. According to the AutoDock scoring function, the lowest energy docked conformation was selected as the binding mode.

3.3. Molecular Docking Studies of Palladium Clusters with Lung Cancer Proteins. 3.3.1. Computational Details. 3.3.1.1. Dataset. DNA: the PDB format file of proteins with PDB ID 2ITW, 2ITX, 2ITY, 2J6M, and 4LQM were downloaded from RCSB Protein Data Bank.45 These are crystal structures of the EGFR kinase domain. Mutations in the EGFR kinase are a cause of non-small cell lung cancer.44 Ligands and water molecules were removed from each protein using CHIMERA.46

Drugs: the structure of the Pd cluster was taken after optimization. Figure 10 shows the chemical structure of the cluster.

3.3.2. Molecular Docking. AutoDock 4.2 was used for molecular docking simulations using Lamarckian Genetic Algorithm (LGA).43 The docking was performed using protein as a rigid receptor molecule, whereas the Pd cluster was treated as a flexible ligand. The receptor and ligand files were prepared for docking using AutoDockTools (ADT).44 Grid boxes of various dimensions were used to prepare grid maps using Auto-Grid for each protein. The Gasteiger charges were added to the complex by AutoDockTools (ADT) before performing docking calculations. Lamarckian genetic algorithms, as implemented in AutoDock, were employed to perform blind docking calculations. All the other parameters were default settings. For metals, modifications were done in the parameter file to include Pd. According to the AutoDock scoring function, the lowest energy docked conformation was selected as the binding mode.

3.3.3. Result. The computationally calculated binding energies of all protein—drug complexes are given in Table 1. From the tabulated data it is very much clear that binding energies of all EGFR proteins with the Pd cluster are of the same range. The binding modes and geometrical orientations of all the compounds were almost identical; suggesting that all the inhibitors occupied a common cavity in the receptor. The lowest binding energy is with the 2ITY complex. Molecular Docking gives the best and stable conformations of the ligand with proteins in the receptor active pocket. Figure 12 shows interaction of the ligand with proteins.

In silico studies revealed that the entire synthesized molecule showed good binding energy toward the target protein. The Pd cluster binds in the pocket of the proteins (Table 1).

3.4. Cytotoxicity. With a view of the above fact, it is also necessary to observe the use of Pd nanoparticles (formed at RT) in biochemical systems, we performed the cytotoxicity effects using A-549 human lung cancer cells. The cytotoxicity result was analyzed by plotting viability histogram, curve, and IC$_{50}$ values. As per the data obtained from Figure 15, the positive control, that is, Adriamycin kills all the cytotoxic cells at 10 μg/ml concentration indicating that our cell culture experiment moved to a positive direction in all respects.47 It is found that the cell viability is dose-dependent with noticeable changes in shape and size from 10 to 30 μg/mL concentrations (Figures 13 and 14).48 The observed IC$_{50}$ is ≤10 μg/mL, indicating good therapeutic efficacy in the biological system, that is, against lung carcinoma. This action may be because of the cytotoxic effect of the palladium nanoparticle on the DNA (shown in the docking experiment in Figure 11).49 Cell viability decreased with the increased concentration, which implies that our synthesized compound may be active against lung cancer which is beneficial for future drug-design perspectives.50

4. CONCLUSIONS

In summary, we have successfully synthesized Pd nanoparticles of different shapes and sizes, like 8–10 nm edge length truncated octahedron/fivefold twinned pentagonal rods and 17–20 nm edge length hexagonal/trigonal plates in an aqueous solution phase by reducing K$_2$PdCl$_4$ with ascorbic acid in the presence of surfactant PEG via a sonochemical method at RT. XRD study revealed that particle growth took place anisotropi-
cally at both temperatures. FTIR and SERS studies revealed adsorption of AA and PEG at NP’s surface. The particle’s size distribution graph indicates formation of particles having a wide size distribution while the zeta potential value $-13 \text{ mV}$ indicated that the particle’s surface is negatively charged and hence stable. The truncated octahedron/fivefold twinned pentagonal rod-shaped Pd NPs formed at RT, while thermally stable and kinetically controlled hexagonal/trigonal plate-like Pd NPs, evolved at a higher temperature $65 ^\circ \text{C}$. The obtained Pd NPs has a high surface area and narrow pore size distribution. The computationally calculated binding energy indicates that this Pd cluster is an effective drug against cancer cells. The lowest binding energy is with the 2ITY complex.

Pd NPs has a high surface area and narrow pore size potential for use of these NPs in biomedical applications. The results described here indicate much dose of NPs. The results described here indicate much cytotoxicity is dependent on the cancer cells exhibited that cytotoxicity is dependent on the pentagonal rod-shaped Pd NPs formed at RT, while thermally hence stable. The truncated octahedron/fivefold twinned pentagonal rod-shaped Pd NPs formed at RT, while thermally stable and kinetically controlled hexagonal/trigonal plate-like Pd NPs, evolved at a higher temperature $65 ^\circ \text{C}$. The obtained Pd NPs has a high surface area and narrow pore size distribution. The computationally calculated binding energy indicates that this Pd cluster is an effective drug against cancer cells. The lowest binding energy is with the 2ITY complex.

Biochemically, the effect of PD NPs on A-549 human lung cancer cells exhibited that cytotoxicity is dependent on the dose of NPs. The results described here indicate much potential for use of these NPs in biomedical applications.

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**Notes**
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