

## Review

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# Green synthesis: Proposed mechanism and factors influencing the synthesis of platinum nanoparticles

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**Abstract:** Platinum nanoparticles (Pt NPs) have attracted interest in catalysis and biomedical applications due to their unique structural, optical, and catalytic properties. However, the conventional synthesis of Pt NPs using the chemical and physical methods is constrained by the use of harmful and costly chemicals, intricate preparation requirement, and high energy utilization. Hence, this review emphasizes on the green synthesis of Pt NPs using plant extracts as an alternative approach due to its simplicity, convenience, inexpensiveness, easy scalability, low energy requirement, environmental friendliness, and minimum usage of hazardous materials and maximized efficiency of the synthesis process. The underlying complex processes that cover the green synthesis (bio-synthesis) of Pt NPs were reviewed. This review affirms the effects of different critical parameters (pH, reaction temperature, reaction time, and biomass dosage) on the size and shape of the synthesized Pt NPs. For instance, the

average particle size of Pt NPs was reported to decrease with increasing pH, reaction temperature, and concentration of plant extract.

**Keywords:** Pt NPs, green synthesis, plant extract, reaction mechanism

## 1 Introduction

In current times, inorganic nanoparticles (NPs) have garnered immense research interest in the field of science and technology [1,2]. Platinum nanoparticles (Pt NPs) are particularly exploited for catalysis and biomedical applications because of their unique crystalline, optical, and catalytic properties, which allow them to play the integrated role of nanoenzymes, nanocarriers, and nano-diagnostic tool [3,4]. Physical and chemical methods were prevalent during the early phases of synthesizing Pt NPs [5–8]. The physicochemical methods guarantee flexibility in modifying the crystal structure of the NPs to achieve the required morphology and size [9,10]. Nonetheless, the utilization of toxic substances and harsh synthesis conditions ultimately lead to health and environmental issues. Therefore, there is a need for “green chemistry” to synthesize eco-friendly materials [11]. Hence, plant-mediated synthesis has been incorporated into the preparation of Pt NPs. Living plants, plant extracts, and plant biomass are basic but efficacious precursor materials for the extracellular biosynthesis of metal NPs [12]. Moreover, the bioactive molecules (such as amino acids, phenols, aldehydes, ketones, carboxylic acid, and nitrogenous compounds) activate the bioreduction of metal nanoparticles, thus reducing, capping, or stabilizing the synthesis process [13]. However, studies on the biosynthesis of Pt NPs are somewhat limited. Till date, no study has investigated the bioreductive mechanism involved in the plant-mediated synthesis of Pt NPs as well as factors that affect the synthesis. Hence, this paper provides a detailed review on the methods of synthesizing Pt NPs,

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proposed reaction mechanism of reduction, and stabilizes Pt NPs, in addition to the parameters (e.g., pH, reaction temperature, reaction time, and biomass dosage) that influence the biosynthesis of Pt NPs.

## 2 Synthesis of Pt NPs

The size, morphology, composition, and structure of Pt NPs as well as the presence of a capping agent control their application for industrial and biomedical purposes [3,9,14–17]. This has required the development of novel synthesis methods for the optimization of these intrinsic properties. The modification and functionalization of Pt NPs for biomedical uses are directed by recently obtained data, which revealed that the physicochemical properties, dispersivity, and stability of the NPs in a biological environment play key roles in determining their safety or toxic levels. The critical challenges encumbering the potential use of Pt NPs as drug carriers and antioxidant materials include biocompatibility, specifically defined properties, and contamination-free production (e.g., endotoxin, Pt precursors, toxic unreacted reagents, organic solvents, etc.) [18]. The several synthesis techniques are discussed in the underlying subsections.

### 2.1 Chemical methods

The chemical synthesis methods, including wet chemical reduction (WCR) [19], electrochemical reduction [20,21], galvanic displacement [22,23], and chemical vapor deposition [24,25], are all employed to precisely define the physicochemical properties of NPs. Mainly, WCR is frequently utilized because of its ability to successfully control the features of NPs. WCR synthesizes Pt NPs from Pt precursor solutions with the aid of a reducing agent [19], which enables the stringent control of features of NPs such as size and morphology by altering the precursor concentration [19], reaction temperature [9], and incorporation of organic or inorganic ligands [26–29]. The use of WCR methods to synthesize Pt NPs with enhanced catalytic performances has been extensively explored. A number of shapes modifying agents (polymers, surfactants, and capping agents) have also been used to facilitate the asymmetric synthesis of NPs. Multiphase synthesis setups have also been developed [30–32], which include utilizing gaseous reducing agents to attain enhanced control of reaction parameters [33].

However, this approach is constrained by the need for vast quantities of organic solvents, surfactants, and capping agents that could increase the toxicity levels of NPs. Besides, a huge volume of production (large-scale) can create an environmental threat. Hence, the use of microwave heating and glycerol, as a reducing agent and solvent, has been developed to allow for industrial upscaling and reduced environmental impact [34,35]. Thiol chemistry is also frequently used to synthesize NPs that are stable in an aqueous environment or inorganic media. Thiol ligands, such as alkane thiols [36–38] or thiols bearing polar groups [29,39,40], have been used to synthesize stable Pt clusters with controlled size and precise morphology. These techniques enable the further decrease in the size of NPs, thereby elevating the surface/volume ratio. Despite the issue of decreased catalytic performance with the addition of thiols, their presence on the surface can transform the properties of the NPs such as the combination of hydrophobic and hydrophilic ligands on the same NP to support selective contact with substrates and the environment [41].

Conversely, these chemicals (aromatic, aliphatic, and amino-terminated thiols) exhibit potential hazardous effects and can be lethal both *in vitro* and *in vivo* [42]. To synthesize Pt NPs that are biocompatible, the approach of using “green reagents” like sodium citrate and ascorbic acid is most promising, due to the fact they allow robust control on solvent and guarantee the purity of reagents [42–45]. This synthesis approach can also assure precise control on size, morphology, and catalytic properties, in addition to reasonably high yield [42]. For example, citrate-capped Pt NPs are reported to display excellent cytocompatibility and high antioxidant capability [43]. Furthermore, the use of green reagents enables simple surface functionalization of NPs, which is essential to the synthesis of Pt NPs for biomedical purposes, since the biological characteristics of nanomaterials are highly dependent on their bare surface area. Therefore, since the surface coating of NPs affects their toxic levels and specific targeting, biogenic synthesis techniques using biomolecules as templates have been initiated [46]. For instance, apoferritin protein encapsulated Pt NPs were proven to enhance the cellular uptake and considerably decrease membrane damage [47–49]. Similarly, Wang et al. [50] developed dendrimers encapsulated Pt NPs to replicate the catalytic centers within natural enzymes. Yamamoto et al. [51] posited that the catalytic activity of Pt clusters was significantly improved when encapsulated with dendrimers, enabling the controlled growth of the nanomaterial. The utilization of dendrimers as encapsulating

agents for the synthesis of Pt NPs and clusters has also been explored in other studies [51,52].

## 2.2 Physical methods

Other synthesis methods that have recently gained attention include laser ablation [53,54], aerosol-assisted deposition [55], electron-beam-induced reduction [56], and flame synthesis [57,58]. These physical methods were developed as efforts to deal with certain constraints of the chemical methods (such as toxic reagents, organic solvents). The laser ablation technique utilizes the continuous or pulsed application of a high-power laser beam for the evaporation of NPs from a solid source. This versatile technique is anchored in the control of pulses, reaction temperature, and atmospheric gas pressure to attain a particular set of NP properties. The key benefit of using this approach is the absence of redundant coatings, solvent contaminations, and stabilizers, which are problems usually associated with synthesis in nanomedicine [59]. However, the mechanism of NP production has not been entirely elucidated. Moreover, the high required dilution in addition to complexities of modifying the size, morphology, and production yield of NPs has constrained their use [42,60,61]. Furthermore, the stability of these NPs in aqueous solutions is a complex procedure. Nonetheless, laser ablation is capable of synthesizing stable NPs in the absence of stabilizers, which is attributable to inherent electrical repulsion effects derived from the presence of surface charges on the NPs [62,63]. Nevertheless, this could pose a problem in biological systems, since clustering/agglomeration and precipitation might simultaneously arise during the incubation of NPs under intricate conditions, such as cell culture media and solutions with high ionic strength. Cathodic corrosion is one more basic physical technique of synthesizing Pt NPs, which entails the conversion of a bulk alloy electrode in a suspension of NPs with similar constituents [64]. However, this approach is similarly constrained by relatively low production yield and size modification.

## 2.3 Green synthesis

Bio-assisted synthesis techniques were developed as viable substitutes of chemical and physical techniques. Their advantages include the absence of unwanted

reaction solvents. The application of biological syntheses has focused on the production of noble metal nanomaterials, because of their ease of reduction using weak reducing agents [65–73]. Few studies have explained the production of Pt NPs by means of the green synthesis approach [74–77]. Nonetheless, procedures have been successfully developed to synthesize monodisperse and stable Pt NPs via the biosynthesis approach, using bacteria [78–81], cyanobacteria [82,83], seaweeds [84,85], fungi [86–88], plants [89–91], in addition to bio-derived products which include honey [92,93]. Some studies exploited the activity of specific hydrogenase enzymes in sulfate-reducing bacteria to reduce Pt(IV) into Pt NPs [94,95]. Like the WCR, the concentrations of Pt salt and protein serve key roles in tuning the morphology and dimension of the NPs during biogenic synthesis [96]. The synthesis of Pt NPs using fungi, such as *Neurospora crassa* [88] and *Fusarium oxysporum* [86,87,97], is a valuable “scale-up” approach. The phytochemical constituents of plant extracts [12] and wood [98,99] have also been exploited as capping agents in the biogenic synthesis of metal NPs. The biosynthesis of Pt NPs via phyto-reduction was first reported in 2009, where 2–12 nm-sized Pt NPs were synthesized using leaf extracts with 90% yield and extremely low leaf biomass [100]. Presently, studies have reported the use of a wide and diverse range of vegetable-derived products such as *Diospyros kaki* [101], *Ocimum sanctum* [102], *Medicago sativa*, and *Brassica juncea* [103] to synthesize Pt NPs. Using the root extract of *Asparagus racemosus* Linn, Raut *et al.* [104] developed a quick procedure of synthesizing monodisperse, spherical Pt NPs with a size range of 1–6 nm in aqueous solution under ambient conditions.

The key benefits of synthesizing Pt NPs from plant extracts are simplicity, convenience, inexpensiveness, easy scalability, low energy requirement, environmental friendliness, and minimum use of hazardous substances and maximized effectiveness of the synthesis process. It is particularly pertinent that the synthesis process of NPs is devoid of toxic materials. The plant extract-based synthesis increases the stability of NPs in terms of size and shape, and produces higher yield compared to other physical and chemical methods.

## 3 Proposed reaction mechanism

Ever since ancient times, plants are principally investigated for their curative value against different diseases and infections [105–107]. As well, plants display huge

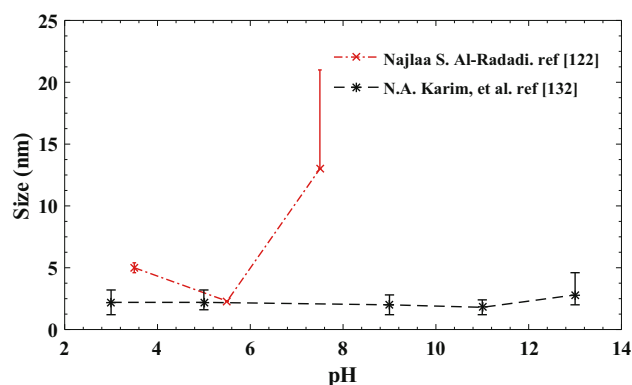
**Table 1:** Studies of the influence of various plant on size, shape, and stabilization of Pt NPs

No.	Plant	The possible biomolecules responsible for		(TEM) Size nm	Shape	Zeta mV	Ref.
		Reduction	Stabilization				
1	<i>Ocimum sanctum</i>	Terpenoids/reducing sugars	Terpenoids	23	Irregular shape	—	102
2	<i>Azadirachta indica</i>	Terpenoids/sugars	Terpenoids	5–50	Sphere	—	119
3	<i>Cacumen platycladi</i>	Sugars/flavonoids	—	$2.4 \pm 0.8$	Sphere	—	12
4	<i>Coffea arabica</i> seed	Protocatechuic acid	Hydroxyl groups of polyphenolic compounds	180–500	Square and rectangular-shaped	—	125
5	<i>Gum olibanum</i>	Chloroplatinic acid	Gum proteins	4.4	Spherical	–12.7	126
6	<i>Maytenus royleanus</i>	Phenol compounds	Phytochemicals	5	Spherical	–41	120
7	<i>Garcinia mangostana</i> L.	Amines/polyols	Amines/polyols	20–25	Spherical	–13	124
8	<i>Sechium edule</i>	Ascorbic acid	Ascorbic acid	10–70	Spherical	–20	127
9	Black cumin seed	Hydroxyl and methyl groups	Hydroxyl and methyl groups	3.47	Spherical	—	128
10	Water hyacinth plant	Hydroxyl, nitrogen and carbohydrate groups	Hydroxyl, nitrogen and carbohydrate groups	3.74	Spherical	–0.0536	92
11	<i>Xanthium strumarium</i> leaf	Limonene/borneol	Limonene/borneol	20	Rectangular	—	129

potential in detoxifying heavy metals in the course of treatment [108]. Also, some plants possess firm and highly resistant biological systems as well as physiology that allows them to withstand acute metal concentrations. This intrinsic property made researchers utilize plants in the field of nanotechnology [109,110]. In addition, aside from simplicity and cost-effectiveness, the use of plant entails decent reaction conditions that are nonhostile to the environment. Presently, biosynthesis of inorganic nanoparticles, for instance, Pt NPs using plants and their derivatives is under enormous investigation. The bio-reduction of metal nanoparticles is attributable to the existence of diverse bioactive molecules that include amino acids, aldehydes, phenols, carboxylic acid, ketones, and nitrogen-bearing compounds, which serve to reduce, cap/functionalize, or stabilize the NPs in the course of synthesis [13]. For instance, Shen et al. [111] employed tea polyphenol in the synthesis of Pt NPs. The phenolic compounds present in tea polyphenols serve as both reducing and capping agents by forming complexes with the Pt ions, reducing them to nanoparticles of diverse sizes and morphologies [112–114].

Nonetheless, the studies on the biosynthesis of Pt NPs are quite limited. Hence, researchers are constantly probing novel ways of rapidly synthesizing Pt NPs using the different plant components which include flower, root, leaf, fruit, bark, or by-products like gum [92,115–118]. Similar to other inorganic NPs, the synthesis of Pt NPs is supported by bioactive molecules that are present in the plants. Thus, the reduction and stabilization mechanisms

of biosynthesized Pt NPs need to be fully elucidated. Fourier transform infrared spectroscopy (FTIR) is a valuable tool for analyzing the bimolecular composition prior and post-reaction. FTIR mechanism can determine the bioactive molecules responsible for reducing and stabilizing the Pt NPs. Generally, FTIR peaks denote the different vibrations of functional groups present in a sample. Comparative analysis shows that some characteristic FTIR peaks of the plant extract disappear or become less intense or are shifted when observed in the FTIR spectrum of Pt NPs synthesized by plant extract, which could be indicative of the reduction process, while the FTIR peaks that remain unchanged are suggestive of the functional groups responsible for stabilizing the NPs.

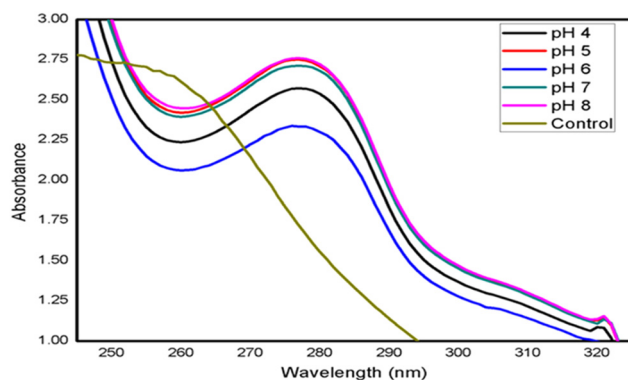
**Figure 1:** The effect of pH on the size variation, adapted from refs. [122 and 132].

For example, Thirumurugan et al. [119] identified distinct FTIR peaks at 1728.22, 1365.60, and 1219.01  $\text{cm}^{-1}$  for Pt NPs biosynthesized from *Azadirachta indica* extract, corresponding to carbonyls, alkanes, and aliphatic amines, respectively. It was inferred that *Azadirachta indica* leaf broth contains terpenoid which is capable of reducing and stabilizing the nanoparticles [101].

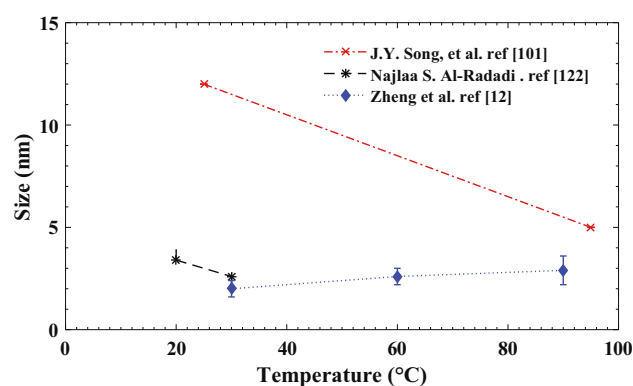
Ullah et al. [120] reported that the phytochemicals existing in the aqueous leaf extract of *Maytenus royleanus* reduce Pt ions into Pt NPs and cap them. The FTIR analysis of *Maytenus royleanus* mediated Pt NPs reveals a decline in the peak intensities, signifying a possible reaction of phytochemicals with inorganic compounds in the synthesis and stabilization of Pt NPs. A significant shift in the stretching O–H vibration of phenol compounds from 3,310 to 3,412  $\text{cm}^{-1}$  was observed, while the stretching vibrations of C=O and N–H in amide II shifted from 1,608 to 1,615  $\text{cm}^{-1}$  and 2,938 to 2,925  $\text{cm}^{-1}$ , respectively, which clearly demonstrates that Pt NPs can be stabilized by diverse phytochemicals existing in the aqueous *Maytenus royleanus* extract.

The phytochemical components of black cumin seeds (*Nigella sativa* L.) include alkaloids (nigellimin, nigellimin-N-oxide, nigellidin, and nigellicin), terpenoids (carvone, limonene, citronellol, carvacrol, 4-terpineol), saponins, tannins, and derivatives. These phytochemicals, comprising functional groups, e.g., hydroxyl and methyl groups, can serve as both reducing and capping agents in the biosynthesis of Pt NPs [121].

FTIR spectra of *Ajwa* (dried) and Pt NPs (capped) confirm the presence of diverse kinds of polyphenols in the biosynthesized Pt NPs. The bioreduction and capping of Pt NPs synthesized from water-soluble polyphenols is indicated by the loss of the distinct peak at 1,760  $\text{cm}^{-1}$  in



**Figure 2:** The optical spectra presents the effect of pH on the green synthesis of Pt NPs (reprinted from ref. [124], copyright 2020, with permission from Elsevier).



**Figure 3:** The effect of reaction temperature on the particle size variation of Pt NPs, adapted from refs. [101, 122, and 12].

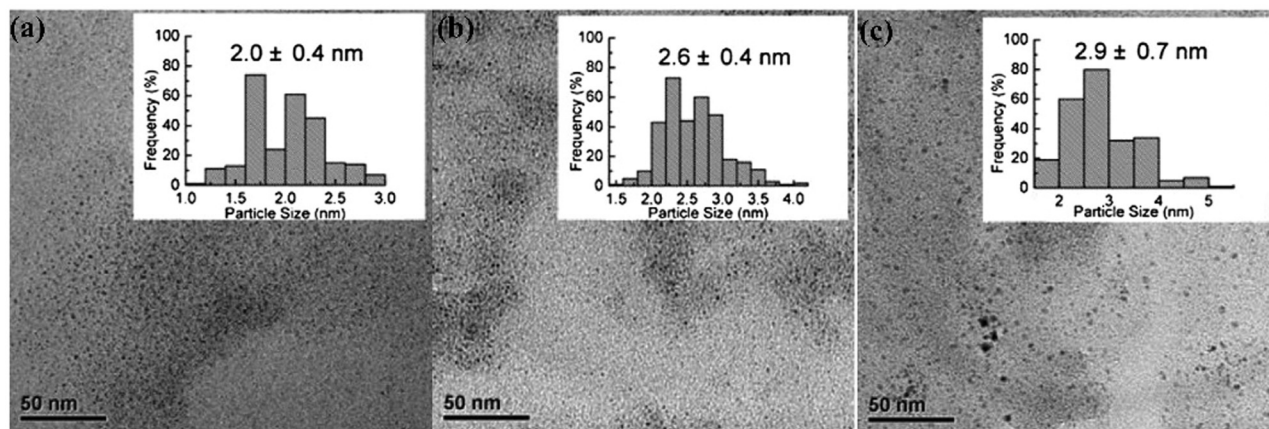
Pt NPs [122]. Ganaie et al. [123] reported that the polysaccharides and proteins in the *Antigonon leptopus* plant extract account for the reduction of Pt ions to Pt NPs as well as the stabilization of Pt NPs, while Nishanthi et al. [124] assigned the bands around 1,430–1,440  $\text{cm}^{-1}$  and 1,275–1,285  $\text{cm}^{-1}$  in the FTIR spectrum of Pt NPs to the secondary aromatic amines and polyols such as hydroxyl flavones and hydroxyl of xanthenes. The amines and polyols contained in *Garcinia mangostana* rind extract were also shown to reduce and stabilize Pt NPs. The biosynthesis of Pt NPs using different plant extract and their respective biomolecules for reduction and stabilization are summarized in Table 1.

## 4 Factors influencing biosynthesis of Pt NPs

There are several variables that control the synthesis, characteristics, and use of nanoparticles in the course of plant-mediated biosynthesis. These factors are discussed in the underlying subsections.

### 4.1 Solution pH

The pH of the solution serves a vital function in plant-mediated biosynthesis of nanoparticles by influencing the size, morphology, and rate of synthesis [130]. This influence is attributed to an increase in the development of nucleation centers as pH increases. The reduction of metal ions to metal nanoparticles increases concomitantly with the expansion of the nucleation center (the effect of protonation–deprotonation of active ingredients could be



**Figure 4:** TEM images of the Pt NPs synthesized at (a) 30°C, (b) 60°C, and (c) 90°C when the *Cacumen platycladi* percentage and initial Pt(II) concentration were 50% and 1 mM, respectively (reprinted from ref. [12], copyright 2020, with permission from Elsevier).

affected and hence the donation of electrons by changing pH). Simultaneously, the solution pH controls the activity of the functional groups in the plant extract/biomass, which in turn determines the reduction rate of the metal salt [131].

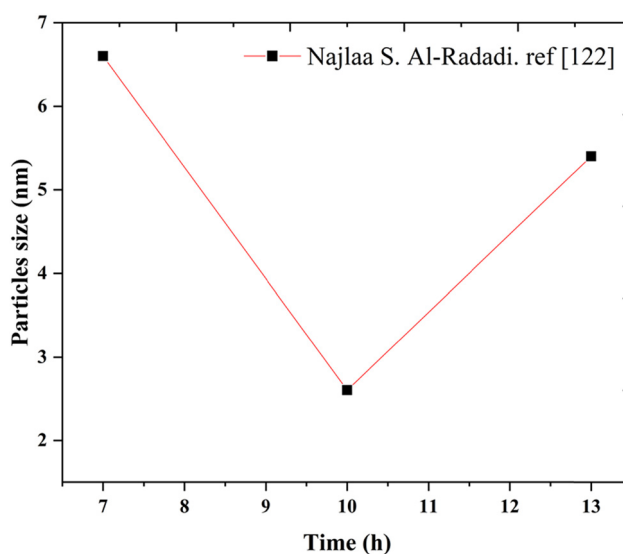
Al-Radadi [122] used solutions of diverse pH (1.5–8.5) to analyze the impact of pH on the rate of reaction and synthesis of Pt NPs. The synthesis of Pt NPs was reported to be faster in the basic medium compared to an acidic solution. Overall, the synthesis of Pt NPs increases as the OH concentration (alkalinity) of the dispersive medium increases. For acidic medium, bundles of Pt NPs are formed with particles of varied shapes and sizes. More specifically, at pH 1.5, 3.5, 5.5, and 7.5, the shapes and sizes of the synthesized Pt NPs are rod-shaped with a size of  $700.5 \times 84.1$  nm, spherical with a size range of 5–5.4 nm, spherical with a size of 2.3 nm, and spherical with a size range of 5–13.8 nm, respectively, as displayed by red data points with size variation bar in Figure 1.

Karim et al. [132] investigated the impact of pH on the synthesis of Pt NPs using orange peel extract. The Pt NPs synthesized at pH 3 showed relatively less agglomeration and asymmetrical distribution of Pt NPs with a mean particle size distribution of 2.2 nm. At pH 5, the Pt NPs remain irregularly distributed with a high concentration of nanoparticles at specific spots, but a portion of spots showing particles with reduced sphericity and average particle size of 2.2 nm. By increasing the pH to 9, the Pt NPs become uniformly distributed, although there are still bare areas at the center. Here, the average particle size slightly decreases to 2 nm. At pH 11, the NPs become more regularly distributed with further reduction in particle size to 1.8 nm. At pH 13, the Pt NPs remain spherically shaped, however, but begin to agglomerate to form larger Pt clusters, as displayed by black dashed line in Figure 1.

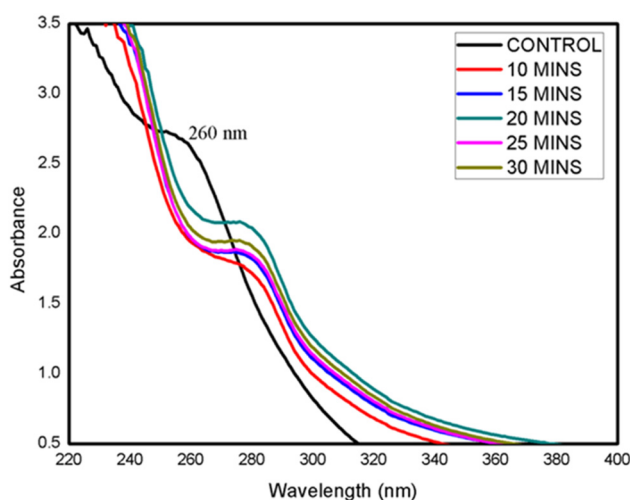
Nishanthi et al. [124] also assessed the pH effect on Pt NPs synthesized using the rind extract of *Garcinia mangostana* L. The optical spectra of Pt NPs synthesized under different pH values (4–8) are shown in Figure 2. A slight redshift (~6 nm) is observed at acidic pH, which is possibly due to the presence of larger nanoparticles, while the blue shift in the SPR (~4 nm) at alkali pH can result from the formation of smaller nanoparticles.

## 4.2 Reaction temperature

Reaction temperature is an additional vital factor that controls the size, morphology, and synthesis rate of



**Figure 5:** The effect of reaction time on the particle size variation of Pt NPs at room temperature, adapted from ref. [122].



**Figure 6:** The optical spectra present the effect of the reaction time of green synthesis on the absorption spectra of Pt NPs (reprinted from ref. [124], copyright 2020, with permission from Elsevier).

Pt NPs. Similarly, the production of nucleation centers increases with increase in reaction temperature which then enhances the biosynthesis rate. Thirumurugan *et al.* [119] investigated the biosynthesis of Pt NPs from *Azadirachta indica* extract. Transmission electron microscopy (TEM) analysis shows the synthesis of polydispersed nanoparticles of small to large spheres (5–50 nm). The rate of Pt NPs synthesis was found to increase with the reaction temperature. In another study, Pt NPs sized 2–12 nm were biosynthesized using the leaf extract of *Diospyros kaki* at 95°C with  $\text{H}_2\text{PtCl}_6 \cdot 6\text{H}_2\text{O}$  as the precursor solution [101]. The reduction process of  $\text{Pt}^{4+}$  to  $\text{Pt}^0$  nanoparticles was optimized at 95°C. As shown in Figure 3 (red dashed line), the average particle size reduced from 12 nm at 25°C to 5 nm at 95°C, which is attributable to the increasing rate of reduction. Al-Radadi [122] investigated the impact of reaction temperature on the biosynthesis of Pt NPs using *Ajwa* dates extract. TEM images reported the average particle sizes of the spherical Pt NPs are 3.4 and 2.6 nm at 20°C and 30°C, respectively, as displayed by black dashed line in Figure 3. On the other hand, Zheng *et al.* [12] explored the effect of reaction temperature on the biosynthesis of Pt NPs using *Cacumen platycladi* extract (CPE). In this work, as shown in Figure 4, the TEM images of the Pt NPs reported particle sizes of  $2.0 \pm 0.4$ ,  $2.6 \pm 0.4$ , and  $2.9 \pm 0.7$  nm at 30°C, 60°C, and 90°C, respectively. This indicates increase in the size of Pt NPs with reaction temperature, as depicted by dotted blue line in Figure 3. Under similar precursor concentration but higher synthesis reaction temperature, smaller particles with narrower size distribution are dominant, due to the fact that

homogeneous nucleation is enhanced at a higher reaction temperature if the precursor undergoes complete reduction [133]. This is plausible as the  $\text{Pt(II)}$  conversion is directly linked to the accessibility of a  $\text{Pt}^0$  source. Thus, the rate of  $\text{Pt(II)}$  conversion was not high at either 30°C or 60°C owing to the deficient  $\text{Pt}^0$  source. In contrast, at higher reaction temperature (90°C), the abundance of  $\text{Pt}^0$  source favors the growth of the Pt NPs. For this reason, the size of the Pt NPs was relatively larger as the reaction temperature increased. The reaction temperature of 90°C was thus implemented in successive tests to guarantee high conversion of  $\text{Pt(II)}$ .

### 4.3 Reaction time

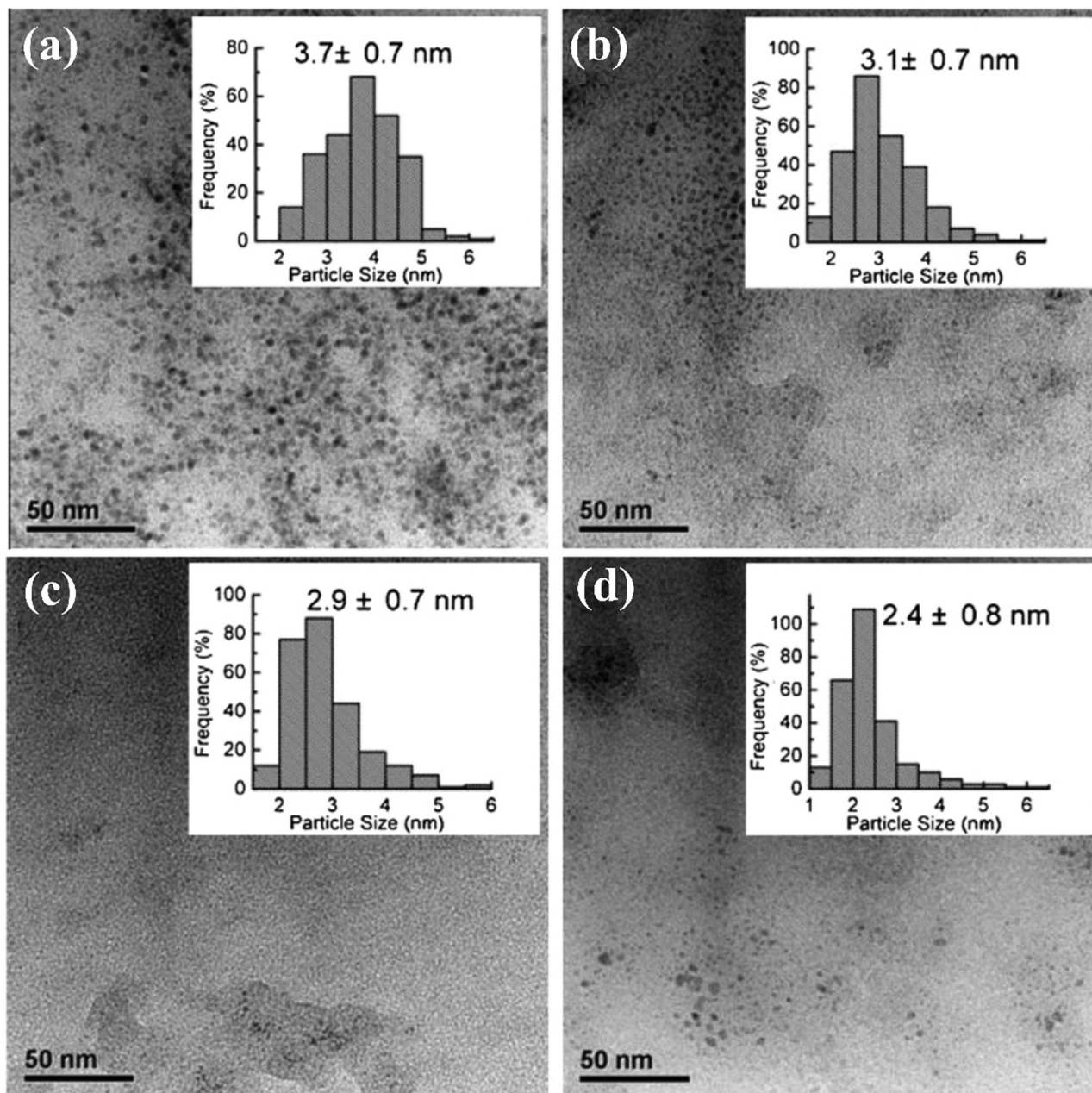
The duration of reaction/incubation of the suspension also significantly affects the size, morphology, and degree of nanoparticle synthesized using plant-based biomaterials. Al-Radadi [122] investigated the impact of reaction time on the properties of Pt NPs synthesized using *Ajwa* dates extract. Figure 5 showed changes in particle size of the synthesized Pt NPs (6.6, 2, and 5.4 nm) with increasing duration of reaction time (7, 10, and 13 h).

Similarly, Nishanthi *et al.* [124] reported that the most favorable reaction time for the biosynthesis of Pt NPs is 10 min after the addition of rind extract of *Garcinia mangostana* at ambient temperature. As observed in the spectra (Figure 6), nucleation growth increased with reaction time, although no significant spectral change is observed after 10 min, which indicated completion of the synthesis within a short duration.

### 4.4 Plant extract/biomass dosage

The concentration of plant extract regularly determines the effectiveness of nanoparticle synthesis. Numerous studies reported that increasing the concentration of plant extract in biomass dosage improves the synthesis of nanoparticles in addition to modifying their morphology [12,134].

Zheng *et al.* [12] evaluated the differences in  $\text{Pt(II)}$  conversion over a period at varied dosages of CPE (10%, 30%, 50%, and 70%).  $\text{Pt(II)}$  conversion was found to proportionally increase with CPE percentage and could surpass 95% following 25 h of bioreduction at CPE percentage of 70%. In addition, TEM images showed the

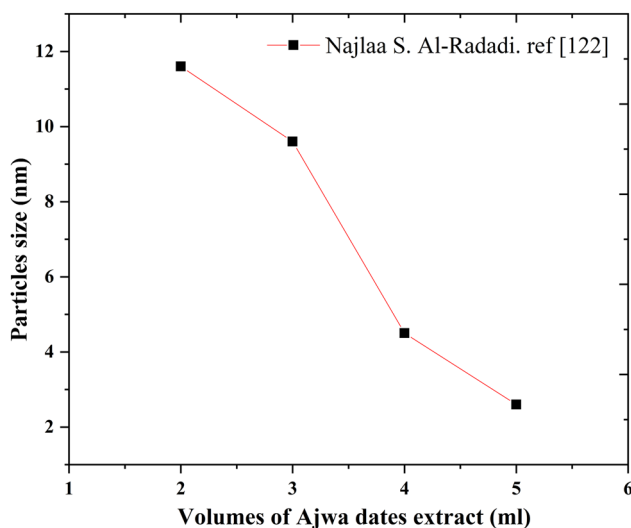


**Figure 7:** TEM images of the Pt NPs synthesized under different percentages of CPE: (a) 10%, (b) 30%, (c) 50%, and (d) 70% for reaction temperature of 90°C and preliminary Pt(II) concentration of 0.5 mM (reprinted from ref. [12], copyright 2020, with permission from Elsevier).

Pt NPs were spherically shaped and the histograms insets indicate (Figure 7) that the particle sizes of Pt NPs synthesized at different percentages of CPE (10%, 30%, 50%, and 70%) were  $3.7 \pm 0.7$ ,  $3.1 \pm 0.7$ ,  $2.9 \pm 0.7$ , and  $2.4 \pm 0.8$  nm, respectively, as shown in Figure 7.

Al-Radadi [122] researched the impact of variable concentration of *Ajwa* dates extract on the properties of synthesized Pt NPs. The NPs were prepared via the addition

of different volumes of *Ajwa* dates extract (2, 3, 4, and 5 mL) to 5 mL of  $\text{H}_2\text{PtCl}_6$  stock solutions under incubation/reaction time of 10 h at ambient temperature. Based on Figure 8, the particle sizes of the synthesized Pt NPs were 11.6, 7.3, 4.5, and 2.6 nm for 2, 3, 4, and 5 mL of *Ajwa* dates extract, respectively. Thus, it can be inferred that the particle size of Pt NPs decreases as the concentration of plant extract increases (*Ajwa* dates).



**Figure 8:** The effect of different concentration of *Ajwa* extract on the particle size variation of Pt NPs with 5 mL of  $\text{H}_2\text{PtCl}_6$  stock solutions after 10 h at the ordinary temperature, adapted from ref. [122].

## 5 Conclusion

The effectiveness of conventional (physical and chemical) methods is constrained by a few critical limitations that include the use of harmful and costly chemicals, intricate preparation requirement, and high energy utilization. Hence, this work emphasizes on the use of green synthesis as an alternative approach for synthesizing Pt NPs from plants due to its simplicity, convenience, inexpensiveness, easy scalability, low energy requirement, environmental friendliness, and minimum use of hazardous substances and maximized the effectiveness of the synthesis process. The biosynthesis of NPs can provide more stability in terms of size and shape, as well as increase in the production yield. The bioreduction of metal nanoparticles is enabled by various bioactive molecules contained in plants. The plant extracts can also serve as capping or stabilizing agents during the synthesis process. Finally, this review affirms the effects of different critical parameters (pH, reaction temperature, reaction time, and biomass dosage) on the size and shape of Pt NPs. For instance, the shape of Pt NPs can be altered with the change of pH value, and the average particle size of Pt NPs was reported to decrease with increasing pH, reaction temperature, and concentration of plant extract.

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