



A Review on Introduction of The Palladium Nanoparticles

Shagufta Bi*, Rashi Srivastava and Tanzeel Ahmed

School of Biotechnology, IFTM University, Lodhipur Rajput, Moradabad, UP, India

Received: 30.06.2025 Accepted: 19.09.2025 Published: 30.09.2025

*shaguftabt@gmail.com



ABSTRACT

Palladium nanoparticles (PdNPs) have risen to prominence as remarkably adaptable nanomaterials owing to their distinctive physicochemical attributes. This review underscores the significance of PdNPs and provides a critical analysis of the primary synthesis methods, specifically physical, chemical, and biological techniques. Biological synthesis utilizing plant extracts presents a sustainable and economically viable alternative, yielding stable and functionalized PdNPs. The outcomes of these approaches demonstrate distinct impacts on particle morphology, stability, and catalytic efficacy, highlighting the correlation between synthesis route and functional characteristics. The review further explores the intrinsic properties of PdNPs, such as optical, plasmonic, magnetic, and catalytic which expand their applicability in sustainable technologies and therapeutic interventions such as catalyst, antioxidant, antimicrobial, and hydrogen sensor and glucose sensor. Future directions emphasize the development of eco-friendly, energy-efficient, and scalable synthesis techniques, alongside a deeper understanding of structure-property relationships to optimize performance.

Keywords: Palladium nanoparticles; Properties; Applications; Catalyst; Antioxidant.

1. INTRODUCTION

The number of possible uses of nanomaterials has been the focus of research in recent days. Their result of nanomaterials ability to modify the materials characteristics by altering their size in nanometer ranges (Jadoun *et al.* 2021; Kanchi and Ahmed, 2018). The different scientific fields that build nanotechnology include interface technology, biological sciences, molecular science, semiconductor physics, and microfabrication (Mousavi *et al.* 2018; Vajtai, 2013). Nanotechnology may produce a variety of innovative materials and has a wide range of users in a variety of fields, including energy production, electronics, biomaterials, and nanotechnology (Dizaj *et al.* 2014; Mittal *et al.* 2014). Although nanoscience has the potential to change many academic and industrial disciplines, extremely useful, even though it can unexpectedly change several disciplines of study and applications (Siddiqi and Husen, 2016). Nanotechnology has recently shown success in several sectors, notably healthcare, nutrition, agriculture, and medicine (Agostini *et al.* 2014). The study of nanoparticles, more especially nanomaterial clusters, about the physical and chemical properties of these particles, where size and structure play a significant role in determining these properties (Zhao *et al.* 2011). Palladium nanoparticles derived from plants, fungi, and bacteria possess various energetic applications, including catalytic degradation, cancer therapy, drug delivery, chemical and biological sensors, bioimaging, methane combustion, hydrogen generation

and storage, and lithium-ion batteries, and are extensively recognized for their catalytic properties. Furthermore, developed seed-mediated synthesis of palladium nanocrystals with regulated dimensions and examined the relationships between surface architectures and catalytic efficacy (Yong *et al.* 2002). Top-down and bottom-up methods for nanoparticle production has used as seen in Fig.1 (Adams and Chen, 2011). Nanoparticles produced by size differentiation in the top-down approach, achievable via several physical and chemical techniques. The fundamental step in Bottom Up manufacturing is reduction, which generates nanoparticles from minuscule particles, including subatomic particles (Anderson *et al.* 2019; Jin *et al.* 2012). Phenolic acids, flavonoids, alkaloids, and terpenoids are phytochemicals present in plant extracts that largely facilitate the conversion of metal ions into solid nanostructured materials (Arole and Munde, 2014; Hussain *et al.* 2016). The synthesis of nanoparticles with diverse chemical compositions, sizes, forms, and controlled disparities is a key focus of research in this discipline (Das *et al.* 2017; Kuppusamy *et al.* 2016). The nucleus of the chemical element palladium, denoted by the symbol Pd, is 46. William Hyde Wollaston, an English scientist, discovered this uncommon silvery-white metal in 1803 (Ovais *et al.* 2018). Palladium was given the same designation as the previously found asteroid Pallas in 1802. The majority of these elements' chemical properties are comparable; palladium, however, has the lowest melting point and lowest density of the group. The majority of palladium comes from mineral

sources in a small number of countries. Palladium recycling provides a backup supply. 96,000 kg of palladium were recycled in 2020, mostly from jewellery and vehicle catalytic converters (Wang *et al.* 2013). Production of palladium was constrained and cannot keep up with the rise in demand. As a result, the cost of palladium has climbed significantly during the past several years (Long *et al.* 2012). Catalytic degradation, cancer treatment, medication administration, chemical and biological sensors, and hydrogen storage and sensors are a few of these applications (Joudeh *et al.* 2022; Michałek *et al.* 2024). As an alternative to the conventional Pt-Rh catalyst, palladium-based catalytic converters were first produced by the combustion industry in 1993 (Bankar *et al.* 2010, Vinodhini *et al.* 2022). The virtue-filled palladium nanoparticles have exceptional physiochemical properties in addition to the typical distinctive characteristics of metals, including high thermal stability, processability, notable photostability, surface charge, optical absorption, and low cost (Bi and Srivastava, 2024; Phan *et al.*, 2020). There are several ways to make palladium nanoparticles in various structures. The required properties of biocompatible particles may be achieved by coating them with extra biopolymers or chemicals. (Haleemkhan *et al.* 2015). Pharmaceutical companies, in particular, often employ palladium nanoparticles as catalysts for carbon-carbon bonding interactions and oxidation activities (Makarov *et al.* 2014). Researchers are investigating palladium-based nanostructures for their catalytic capabilities and distinctive capacity to create hydrides, which are advantageous for hydrogen storage and detection (Kumar *et al.* 2019). Due to the phenolics that reduce palladium to zero valence, *Catharanthus roseus* leaf extract can also produce palladium nanoparticles. They are efficient for degrading dyes. In the creation of palladium nanoparticles, extracts from commercial goods like coffee and tea were used. Palladium chloride was used as a precursor salt at room temperature for the creation of cubic-symmetric palladium nanoparticles that range in size from 20 to 60 nm (Cristoforetti *et al.* 2010; Mattox, 2010). Palladium nanoparticles, a type of nanoparticle used in medical technology, have received the least amount of research. Spherical palladium nanoparticles were synthesized from the white tea extract, with sizes ranging from 6 to 18 nm. *Staphylococcus epidermidis* and *Escherichia coli* are both strongly inhibited by white tea-mediated palladium nanoparticles, which also have high non-scavenging and 1-diphenyl-2-picrylhydrazyl (DPPH) properties (Sarto *et al.* 2014). The biological process based on the protein-rich soybean leaf extract *Glycine max* was used to create palladium nanoparticles. Using UV-visible spectroscopy, the production of palladium nanoparticles from soybean leaf extract was examined. The peak shows the presence of palladium ions in the reaction mixture at 420 nm, which was observed after one minute. The diameter of the synthesized palladium nanoparticles was determined to be in the range of 15 nm (Kim *et al.* 2014).

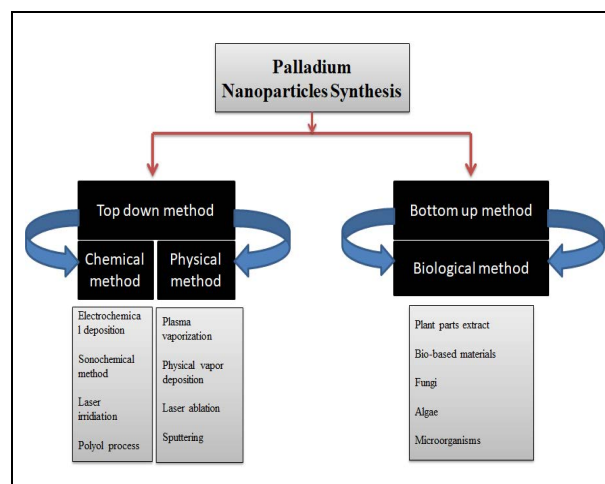


Fig. 1: Schematic representation of different procedures for the synthesis of PdNPs (Khan *et al.* 2019)

2. METHODS FOR SYNTHESIS OF PDNPS

2.1. Physical Synthesis of PdNPs

The physical synthesis processes include the employment of metal resources that are not chemically changed, no new products are formed, no chemical bonds are cleaved, and no artificial form was created, but they slightly undergo molecular rearrangements. Palladium and palladium-based nanomaterials formed by physical methods contain nanoscale films, nanoparticles, nanowires, and nanorods. Physical vapor deposition, laser ablation, plasma vaporization, and magnetic sputtering, and plasma vaporization are all methods for producing palladium nanoparticles (Torrissi *et al.* 2010). Physical vapor deposition is the atomistic deposition of vaporized atoms from solid and liquid sources on a selected substrate (Sikeyi *et al.* 2020). Physical synthesis of films with a depth of thousands of nanometers by the physical method has been broadly used. Arc deposition and Vacuum deposition are types of physical vapor deposition.

Sarto *et al.* demonstrate that they synthesized several palladium catalysts through direct current magnetron sputtering deposition (Rojas and Castano, 2012). In the process of laser ablation, several advantages occur, such as simple preparation and weak agglomeration and the capability of producing multi-component nanoparticles (Corte *et al.* 2013).

Simple approaches for the formation of nanoparticles by various solvents include laser ablation formation in solution. Irradiation of various metals submerged in solution with a laser beam condenses plasma, resulting in nanoparticles. Laser ablation techniques are used to create stable nanoparticles that do not even need any chemical or stabilizing agents. In the laser ablation procedure, on the chosen metal, laser light was used to guide the deposition of vaporized plasma.

Torrise *et al.* have been investigating different palladium plasmas produced at various laser ablation wavelengths (Khandel *et al.* 2018).

2.2 Chemical Method

Last two decades, for the broad formation of metal nanoparticles, the chemical process has become considerably more rapid, becoming fascinating. Chemical synthesis of metal nanoparticles usually includes the use of a photo-reductant or chemical reducing agent, or the use of a stabilizer to generate chemical reducing agents, as well as, but not exclusively, sodium borohydride, ascorbic acid, ethylene glycol, and revision of the item corresponds to a breakthrough in citric acid. In the chemical reduction process, widely use of sodium borohydride (NaBH_4) and potassium borohydride (KBH_4) for the metal ions to zero valent and the use of proper capping agents to nucleate zerovalent, such as a particular dimension and shape of nanoparticles (Singh *et al.* 2011).

These methods have also been analyzed for the formation of different functional materials and structural properties as bimetallic and supporting materials. The blooming extension of platinum branches was supposed to be recognized by the yield of platinum reduction, such as mediated by an autocatalytic method in the presence of L-ascorbic acid, which was improved through the various nucleation sites provided by condensed octahedral palladium seeds. (Sonbol *et al.* 2021). In the above-mentioned sources determine the reaction the synthesis, extension; joint, and lastly structure of the palladium nanoparticles through polyol formation are determined. Additionally, the formation of palladium nanoparticles in liquid media through the resources of energy such as ultrasonic sound, microwave, and gamma radiation has been broadly employed (Bathula *et al.* 2020).

2.3 Biological Method

The biological fabrication of palladium nanoparticles during the aforementioned process required complex experimental techniques in the physical method, a large amount of reducing agents, and a medium in the chemical method. As a result, a simple approach for selecting artificial processing that uses environmentally beneficial resources must be developed (Bi and Srivastava, 2023). Furthermore, biological approaches offer a wider range of resources, such as reducing agents and better control over the size and form of the nanoparticles (Hosseingholian *et al.* 2023). Introduce biological materials to the palladium ions medium to modify the size and structural character of nanoparticles, either intracellularly or extracellularly, and control the reduction of zerovalent palladium and the stability of nanoparticles (Sharma, and Tripathi, 2022). In most cases, bacterial activity takes place inside the cell.

Reduction serves a dual function in the green synthesis of palladium nanoparticles (Azizi *et al.* 2022). An example of plant extract employed in biogenic formation is the reduction of Pd ions to Pd nanoparticles by altering the phytochemical components of the plant parts extract, including reducing sugars, flavonoids, terpenoids, polyols, geniposides, and amino acids (Narasaiah and Mandal, 2020; Bi and Srivastava, 2025). Other plant-based sources, such as fungal and algae biomass, as well as a variety of other bio-based materials, such as honey, gum, and compounds like tannin, have all proven successful in the creation of palladium nanoparticles. The remarkable synthesis of bimetallic palladium nanoparticles with diverse metals such as silver, gold, iron, copper, and platinum, which, when combined, produced unique qualities such as physical, chemical, and catalytic activity of nanoparticles by living organisms. In terms of catalytic activity, the number of research objects concerned with the synthesis of palladium nanoparticles via biological processes is rapidly rising (Pechyen *et al.* 2024).

After all, a detailed study of the creation of palladium nanoparticles via a biological process involving plant-based components such as gum, honey, and other materials has been conducted. As a result, the biological synthesis of palladium nanoparticles using green constituents and plant extracts. Plant extracts employ different biosynthetic pathways of nanoparticles because of their non-toxic nature, eco-friendliness, and the huge amount present in nature (Manjare and Rajendra, 2020). Green synthesis of metal nanoparticles can be divided into main divisions, such as the use of the plant for stabilization of palladium nanoparticles or reduction of metal ions through plant extract (Sridhar and Rani, 2025; Singh *et al.* 2023). In biological methods, synthesis of metallic nanoparticles in various shapes and sizes from diverse plant parts such as flowers, leaves, roots, fruit as shown in the Table.1 (Dubey *et al.* 2010, Sarmah *et al.* 2019).

3. PROPERTIES OF PALLADIUM NANOPARTICLES

Nanomaterials have structural characteristics that fall between those of atoms and those of bulk materials. A nanoscale substance differs in many ways from an atom or a bulk material, even though most micro-structured materials are similar to their conventional counterparts (Fakeh *et al.* 2021; Khan *et al.* 2019). Nanomaterials have a very large volume as a result of their tiny size, which causes a substantial proportion of their atoms to be base, leading to more "surface-dependent" nanomaterial features (Arsiya *et al.* 2017; Mittal *et al.* 2013). Particularly when the dimensions of the nanoparticles are similar to their diameter, the surface characteristics of the nanoparticles will have an impact on the overall material. The qualities of the composite counterparts may then be improved or altered as a result.

For example, metallic nanoparticles are capable of being active as powerful catalysts. The quantum effects of palladium nanoparticles are too influenced by the spatial

internment result of their nanoscale feature sizes (Shah *et al.* 2015; Bi and Srivastava, 2024).

Table 1. Various plants for the synthesis of PdNPs

Plant and their parts	Ion source	Size in nm	Shape of PdNPs	Applications	References
<i>Barleria priontis</i> (leaves)	PdCl ₂	80 ± 5 nm	Spherical and irregular	Anticancer	(Rokade <i>et al.</i> 2017)
<i>Cocos nucifera</i> (coir)	Pd (OA) ₂	62 ± 2nm	Spherical	Agricultural pest	(Elango <i>et al.</i> 2017)
<i>Chrysophyllum cainito</i> (leaves)	PdCl ₂	169.24 nm	Flowerlike structure	Catalyst	(Majumdar <i>et al.</i> 2017)
<i>Dioscorea bulbifera</i> (tubers)	PdCl ₂	10-25 nm	Spherical	Anticancer	(Ghosh <i>et al.</i> 2015)
Fenugreek tea(seeds)	PdCl ₂	20-25 nm	Spherical	Food industry	(Mallikarjuna <i>et al.</i> 2017)
<i>Gloriosa superba</i> (tubers)	PdCl ₂	5-8 nm	Spherical	Breast cancer	(Rokade <i>et al.</i> 2018)
<i>Lagerstroemia speciosa</i> (leaves)	PdCl ₂	136.5 nm	Face-centred cubic	Wastewater treatment	(Garole <i>et al.</i> 2019)
<i>Origanum vulgare</i> Linn (leaves)	PdCl ₂	2.2 nm	Spherical	Catalyst	(Shaik <i>et al.</i> 2017)
<i>Pimpinella Tirupatiensis</i> (leaves)	PdCl ₂	12-25 nm	Spherical	Photo catalyst	(Narasaiah <i>et al.</i> 2017)
<i>Phoenix dactylifera</i> (leaves)	PdCl ₂	13-21 nm	Spherical	Catalyst	(Tahir <i>et al.</i> 2016)
<i>Syzygium aromaticum</i> (clove buds)	PdCl ₂	20 - 25 nm	Spherical	Cytotoxicity	(Shanthi <i>et al.</i> 2017)
<i>Terminalia arjuna</i> (barks)	PdCl ₂	8.9 nm	Spherical	Removal of Industrial Pollutants	(Garai <i>et al.</i> 2018)

The palladium nanomaterial's Coulomb strength and energy band construction may differ significantly from their bulk properties. This was change the nanomaterial's electrical and optical characteristics (Mie *et al.* 2014; Patil and Burungale, 2020). As an example, the future of optoelectronics holds great promise for beams and luminescent devices derived from both quantum wires and quantum dots. Reduced defects have a significant role in determining the characteristics of palladium nanoparticles. Because contaminants and inherent material flaws flow toward the surface during thermal annealing, palladium nanoparticles prefer a self-cleansing process (Feng *et al.* 2020). The characteristics of nanoparticles are impacted by this improved material perfection (Majeed *et al.* 2015).

3.1 Optical Properties of Palladium Nanoparticles

The optical properties of palladium nanoparticles are among the most intriguing and useful ones. Some factors that impact a nanomaterial's optical properties include component width, design, texture, doping, interactions with other materials, and interactions

with nanostructures (Shahmirzadi and Pakizeh, 2018). The contrast between the optical properties of palladium nanoparticles is illustrated by the fact that the optical characteristics of metal nanostructures can be greatly influenced by their form. When an asymmetry is introduced, the nanoparticle's optical properties alter considerably (Kracker *et al.* 2013). A substance changes optically when it is reduced to the nanoscale in two different ways: first, through quantum confinement, and second, through surface plasmon resonance. Charges are quantum-restricted, and energy levels vary when the size of materials is reduced below the de Broglie wavelength. The energy levels are more evident when bulk material is reduced to two dimensions, then to one dimension, and finally to zero dimensions (Ismail *et al.* 2017).

Metallic nanoparticles with various optical properties have found uses in chemo-optics and other sectors, such as bio-nano-photonics. When exposed to environmental factors, palladium nanoparticles reversibly change from the solid solution phase to the hybrid phase by absorbing hydrogen. The structure of palladium nanoparticles changes as a result of a phase transition. Palladium nanostructure LSPR characteristics

can be a useful tool for studying metal-hybrid formation during the hydrogen storage process (Kulikova *et al.* 2020).

3.1.1 Optical Measurement

3.1.1.1 Absorbance

This optical absorption spectrum of palladium nanoparticles was recorded using a UV-visible spectrometer. As concentration increases, the absorption rate also increases as more atoms participate in the absorption process.

3.1.1.2 Optical Band Gap and Absorption Coefficient

Optical characteristics, including the optical energy gap, refractive index, and absorption coefficient, describe and categorize materials. Transmittance and absorbance are two metrics that may be used to analyze these properties: the relationship yields and the absorption coefficient (Ahsan *et al.* 2020).

3.1.2 Theories of Optical Properties

3.1.2.1 Mie Theory

Here, the Mie theory is used to compute the optical characteristics of palladium nanoparticles. This theory consists only of periodic presentations of magnetic waves inside a spherical coordinate system by applying spherical harmonics. Both the Mie theory and electromagnetic simulation take size effects and contributions from higher-order modes into account. However, the dipole approximation approach takes such effects into account. The dipole approximation approach, however, may be employed and even changed for simplicity's sake to corroborate the findings of observations and electrodynamics calculations (Umegaki *et al.* 2017). This leads to unique optical features, such as distinct absorption bands, which depend on the size and form of the particles, their proximity to one another, the surrounding medium's dielectric properties, and the metal's kind and crystal lattice. Few studies have been done on the optical characteristics of palladium nanoparticles, particularly when they come into contact with hydrogen. However, these characteristics are crucial for the creation of photoelectric sensors based on palladium nanoparticles. Recently, an effort to achieve palladium discs with dimensions of a few hundred nm has taken centre stage. (Ament *et al.* 2021).

3.1.2.1 Quasistatic Theory

The quasistatic approximation requirement for low and slowly varying electrons far from the interband absorption region establishes the LSPR. The logic is invalid for palladium metals when an electron is large enough. Thus, it must be taken into account while performing computations. Additionally, by integrating

size adjustment into the theory, also known as the modified long wavelength approximation (Gavia and Young, 2015), the optical responses of big nanoparticles that were produced using the dipole theory may be altered. As a result, the modified polarized.

3.2 Catalytic Properties of Palladium Nanoparticles

The current work examines the effects of silica encapsulation on palladium nanoparticles to preserve the strength of the nanoparticles. It also discusses the catalytic characteristics of palladium nanoparticles under hydrogenation conditions. Solutions of palladium nitrate in methyl alcohol were used to produce the nanoparticles, and different reaction conditions were tested to see how efficient the hydrogenation reaction was. In hydrogenation conditions, reaction pressure had an impact on the nanoparticle turnover number, and at high reaction pressure, we looked at the effect of the silica coating on the palladium nanoparticles in order to prevent them from dissolving (Nasrollahzadeh, 2014).

The process of catalysis involves employing a spatial substance called a catalyst to speed up the reaction. For catalysis to occur, the chemical compound must be absorbed on the surface of the material extremely quickly and desorb slowly (Santoshi *et al.* 2015). Nanoscale materials have higher catalytic activity. As the size of the nanoparticles decreases, the catalytic activity rises. At their bulk scale, noble metals are inert and regarded as subpar catalysts. However, noble metals at the nanoscale are very effective catalysts (Marchi *et al.* 2020; Huang *et al.* 2011; Vadai *et al.* 2018).

3.3 Plasmon Properties of Palladium Nanoparticles

Metal nanostructures have essential characteristics called plasmon resonance. Metal nanoparticle SPR characteristics are very sensitive to composition, size, and shape. Palladium nanostructures with well-defined SPR absorption characteristics that can be systematically modified from the shown to the near-IR spectra scale have been created by the synthesis of nanostructures with regulated size and shape. Only the ultraviolet and visible parts of the spectrum, where palladium nanostructures exhibit wide SPR peaks, are shown by the palladium nanoparticles chemically produced up to this point. Unfortunately, palladium nanoparticles cannot be used in photothermal treatment using NIR lasers because they lack high NIR SPR absorption (Baran and Nasrollahzadeh, 2019). Nanoparticles support optical modes called localized surface plasmon resonance, which emit light at the nanoscale. The shape and size of the nanoparticles, as well as the relationship between the optical characteristics of the metal and the surrounding dielectric

medium, determined their resonance conditions and mode quality factors as optical modes.

As a result, to find the optimal plasmonic nanoparticles for certain applications, it was necessary to investigate the permittivity of the metals for a given nanoparticle shape in a dielectric environment (Baghayeri *et al.* 2019). Here, we examine the intercalation process driven by in situ plasmons that are spatially resolved to less than 2 nm. Investigate the photo-reactivity of nanoparticles and establish a link between chemical activity and nanoparticle structure by combining aberration-corrected imaging, diffraction, and atomic power loss spectroscopy. The study has reported the dehydrogenation of certain palladium nanoparticles near gold nanodiscs in an antenna-reactor system. According to recent research, this structure has been effectively employed to generate plasmon areas in reactive but non-plasmon metals (Darmadi *et al.* 2020).

3.4 Magnetic Properties of Palladium Nanoparticles

In addition to being distinct from bulk atoms, surface atoms can be modified by connecting with other substances or by capping the nanoparticles. This method offers the option to change the nanoparticles' physical characteristics by coating them with suitable materials (Wang *et al.* 2021). In reality, it is reasonable to anticipate the activity of non-ferromagnetic core materials created at the nanoscale. Non-magnetic bulk materials can be converted into diamagnetic or ferromagnetic palladium ferromagnetism. The behavior is similar to ferromagnetic behavior because of the confined charge at the nanoparticle's surface. Nanoparticles with a diameter of 2 nm have ordering temperatures due to the significance of spin-orbit interaction, which might result in considerable anisotropy. The 5D band contains localized carriers for nanoparticles smaller than 2 nm. As with nanoparticles, it has a low density of states and becomes diamagnetic. This finding revealed that metallic clusters can acquire ferromagnetic properties by chemically altering the D-band structure (Ndaya *et al.* 2019).

4. APPLICATION OF PALLADIUM NANOPARTICLES

There are different applications of palladium nanoparticles, as shown below.

4.1 Sensor

4.1.1 Hydrogen Sensor

The gas-sensing ability of the palladium nanoparticles was investigated by monitoring the change in film resistance upon switching the cyclical atmospheric gases from nitrogen to hydrogen. On hydrogen, every film showed an increase in resistance.

Palladium nanoparticles can be found in the film region. The hydrogen sensor reaction time has been established. Atoms of hydrogen disperse into the palladium hybrid that was created using a palladium lattice (Lerch and Reinhard, 2018). At ambient temperature, hydrogen may be detected using palladium nanoparticles that have been electrochemically produced and a palladium thin film that has been sputtered. Compared to sputtered palladium thin films, electrochemically produced palladium nanoparticles have superior hydrogen sensing properties, according to the study. In both types of devices, it has been found that the gas-sensing response improves with decreasing grain size. The enhanced gas sensing performance with smaller particle sizes was shown to be caused by chemical and electrical sensitization processes.

The palladium-based conductivity sensors were found to be extremely robust and repeatable when tested for various concentrations of hydrogen (Singh *et al.* 2014). Recently, metal oxide has been challenged by palladium or its alloy, which exhibits both of these properties. Hydrogen detection at room temperature has a strong response and selectivity (Konda and Chen, 2016). Palladium hydride created as a result of the hydrogen atoms being absorbed, which modifies the way that physical energy was expressed. Due to its improved gas responsiveness, actual sensing, and power efficiency, improved electrochemical methods that use the change in palladium even after exposure to hydrogen have been widely studied. The efficacy of the sensing depends heavily on the mass of palladium nanoparticles, which may be modified through the palladium deposit layer (Nair *et al.* 2015).

4.1.2 Glucose Sensor

The prospect of good assistance for immobilizing enzymes is provided by nanotechnology. Nanomaterials were used to enhance the stability and catalytic activity of enzymes because they have an advanced, exact surface area for covering a greater number of catalysts, a low concentration transfer resistance, and less fouling. Additionally, the orientation of the enzyme molecules could be selectively changed to enable direct charge transfer between glucose oxidase and the electrode. On a glassy carbon electrode, palladium nanoparticles were electrodeposited, and this catalyst effectively oxidized a solution of glucose and H₂O₂. Numerous enzyme-free biosensors for glucose based on palladium nanoparticles have also been developed; these devices showed much increased precision in the conversion of glucose. Palladium nanoparticles may be created in situ within a Nafion graphene film that is constructed on a GC electrode. Create a non-enzymatic glucose sensor made of a monolayer and a thin sheet of carbon atoms. The polymeric film confines the palladium nanoparticles. Because of its high electro-catalytic capacity for glucose

oxidized in an alkaline medium, as well as its good linear dependency and specificity to glucose concentration change, the Nafion graphene palladium glucose sensor is more useful for real-time glucose detection (Ament *et al.* 2022).

4.2 Hydrogen Storage

At ambient temperatures and pressures, palladium has a well-known capacity to absorb significant volumes of hydrogen. Palladium reacts with hydrogen to generate palladium-hydrogen, which fills the interstitial octahedral spaces of the face-centred cubic crystal. Many studies have looked at the storage capacity of H₂ gas in palladium nanowires because of their propensity to hold a huge amount of hydrogen and their enormous interfacial area. Using bridge and dehydration, the study has reported on the production of palladium-based nanowire foams and investigated their hydrogen gas storage capacity (Valencia *et al.* 2016). After being created by electro-deposition onto porous templates, palladium nanoparticles were sonicated to develop a homogeneous dispersion before being dissolved in water.

Recently, a lot of research has been done on hydrogen storage using palladium and palladium-based nanoparticles. Palladium nanoparticles, in particular, have been investigated as an example framework for the clarification of metal nanomaterial hydrogen storage characteristics shown in Fig.2. Palladium and hydrogen intake result in the formation of various stages (Zalineeve *et al.* 2017). The alpha state first arises in a solid solution with low hydrogen levels, although the beta state first forms in a metal hydride with high hydrogen levels. The generation of palladium hydride was found to require lower equilibrium forces and hydrogen levels at smaller nanoparticle sizes. Due to the close correlation between their intrinsic characteristics and their shapes, nanoparticle sizes and surface morphology have been important factors in material science. Their geometries and inherent characteristics exhibit a significant correlation (Zhang *et al.* 2020). New studies reported that temperature is crucial for hydrogen uptake, absorption, and diffusion and that the shape of palladium may have a significant impact on how much hydrogen can be stored. The phase changes of individual palladium nanomaterials during hydrogen cooling were studied using in situ electron energy loss spectroscopy and an ambient transmission electron microscope. Strong changes between the phases occur in palladium nanocrystals, and surface effects control how the hydrogen absorption pressures depend on diameter. Palladium was alloyed to decrease hydrogen oxidation. Palladium found in combination with other metals to minimize hydrogen internal stress, which expands the palladium crystal and makes it less susceptible to hydrogen effects. Palladium-based metals have been used in many experiments to limit hydrogen's internal stress (Edayadulla *et al.* 2015).

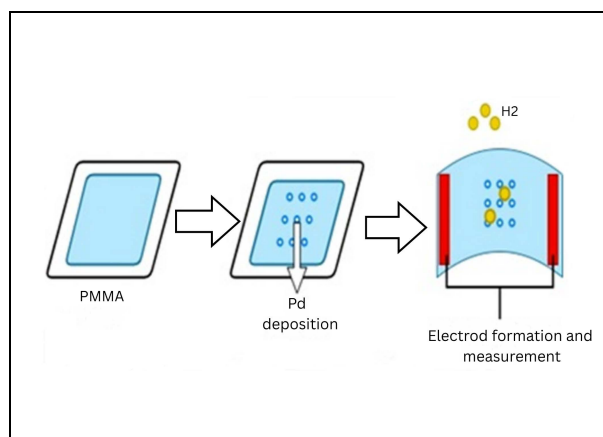


Fig. 2: Schematic representation of hydrogen storage (Chen *et al.* 2017)

4.3 Catalyst

Palladium nanoparticle synthesis from *Artemisia annua* was used as a catalyst in the synthesis of several di-indolyl-indolin-2-ones in media, using a noticeable amount. The palladium nanoparticles produced by the biological method have been generated in five cycles without losing any of their catalytic effectiveness. The innovative g-Al₂O₃-based nanocatalysts were used to hydrogenate olefins. They could be recycled five times, and they were immobilized on bayberry tannin-stabilized palladium nanoparticles (Emam *et al.* 2020). By observing the reduction of synthetic dyes, including Coomassie brilliant blue, rhodamine B, methylene blue, and 4-nitrophenol with sodium borohydride, researchers were able to determine the homogeneous catalytic activity of palladium nanoparticles. The results show the potential use of biogenic palladium nanoparticles as nanocatalysts in environmentally friendly remediation of wastewater contamination (Kora and Rastogi, 2018). Delonix regia leaf extract was used in the synthesis of palladium nanoparticles, which were used as catalysts in the nitro-aromatic hydrogenation process. The Suzuki-Heck coupling reaction was successfully catalyzed in excellent yields and phosphine-free conditions by the comparatively tiny saturated solution of palladium nanoparticles, shown in Fig.3. This work has applications in synthetic organic chemistry. The elimination of harmful toxic compounds can benefit from the excellent catalytic activity of palladium nanoparticles towards the reduction of dyes like methylene blue and rhodamine-B in the presence of sodium borohydride. The electron relay effect linked to palladium nanoparticles has been responsible for driving the hydrogenation process. Additionally, it has been found that lowering the overall reactivity and raising the nanoparticle level both speed up reactions. A quick and effective method for creating N-alkyl amines has been developed that uses a reducing active catalyst with a heterogeneous catalyst made of palladium nanoparticles stabilized by Acacia gum and

sustained by metal oxides and carbon at room temperature and hydrogen stress (Anjum *et al.* 2020).

Palladium nanoparticles were used in many investigations as Suzuki-Miyaura coupling reaction catalysts to create pharmacological intermediates and other essential compounds. A significant quantity of aryl iodide and aromatic ring bromides that were stronger than the palladium nanoparticles used in the associated procedures was produced. One of the most efficient hydro-dechlorination catalysts in the ambient environment was found to be palladium. The use of bimetal palladium-iron thin film for chlorination reduction was investigated. Palladium and iron working together resulted in increased sensitivity in the electro-oxidation of contaminated biomolecules (Dewan *et al.* 2018; Saikia *et al.* 2016).

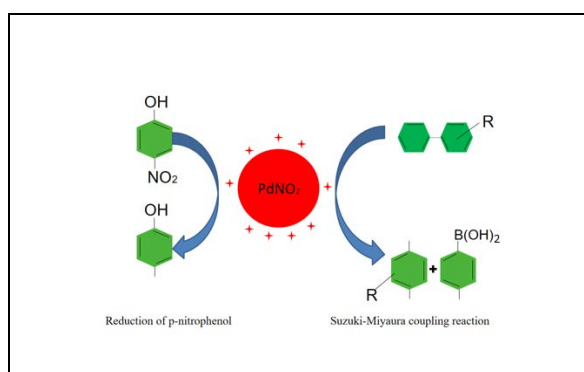


Fig. 3: Schematic diagram of the Suzuki-Miyaura coupling reaction (Baran and Nasrollahzadeh, 2019)

4.4 Antioxidant

Enzymatic and non-enzymatic chemicals that can control the generation of free radicals are the major compounds of antioxidant agents. It has been discovered that such free radicals are exactly what cause cell injury, such as atherosclerosis, cancer, and brain damage (Anju and Gupta, 2020). Reactive oxygen species, including hydrogen peroxide, peroxides, and hydrogen ions, produce free radicals. Biomolecules was tightly regulate the development of free radicals. 1,1-diphenyl-2-picrylhydrazyl (DPPH) was assessed in human T lymphoblasts to evaluate the antioxidant potential of white tea extract-mediated palladium nanoparticles. White tea extract has significant levels of radical scavenging activity for DPPH at low doses, and the amount of the drug was not an issue. In contrast, the DPPH scavenging capacity of palladium nanoparticles was weak at low concentrations and did not match the anti-oxidation potency of white tea extract until dosages were increased. By measuring the DPPH free radical scavenging activity, the whole antioxidant activity of the greenly produced palladium nanoparticles was determined. The shade of the DPPH solution progressively turned from purple to light yellow

throughout the addition of nanoparticles. For example, the antioxidant activity of Lantian-mediated palladium 150 nanoparticles and palladium 250 nanoparticles was evaluated in addition to the catalytic activity of these nanoparticles. Stabilized free radical molecules were used to assess the antioxidant activity of DPPH. Antioxidant activity is crucial for protecting healthy bodies from the injury that free radicals may cause. The antioxidant activity grew from 20% to 60% when the quantity of palladium 150 nanoparticles was raised from 0.27 to 1.33 milligrams/mL, demonstrating efficient free radical control by palladium 150 nanoparticles (Han *et al.* 2019).

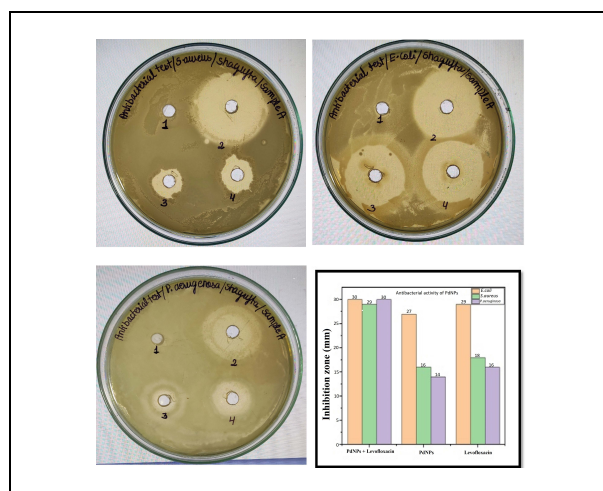


Fig. 4: Antibacterial activity (Bi and Nabeel, 2022)

4.5 Antimicrobial

Significant action against antifungal and antibacterial organisms was shown by these greenly produced palladium nanoparticles from *Rosa damascena* leaf extract. Examine the toxic activity of palladium nanoparticles on *E. coli* (gram-negative) and *Staphylococcus aureus* during the 24-hour test period. *Candida albicans*, *Aspergillus niger*, and *Aspergillus flavus* were all successfully eradicated by the palladium nanoparticles, showing antifungal activity, as shown in Fig.4 (Bi and Nabeel, 2022; Chlumsky *et al.*, 2021). It has been demonstrated that the antibacterial effects of palladium nanoparticles reflect their dimension. It was discovered that palladium nanoparticles are still more harmful to gram-positive *Staphylococcus aureus* bacteria than palladium ions. Palladium nanoparticles with a diameter of 2 nm or less were more hazardous than those with a diameter of 2.5 or 3.1 nm. The highest antifungal activity, even against fungi, was seen for the diameters of 200, 220, and 250 nm in the green production and characterization of palladium nanoparticles using flavonoids derived from quercetin. Palladium nanoparticles created from the fruit extract of *Couroupita guianensis* were tested at a dose of 25 mg/ml, and they demonstrated remarkable antimicrobial application even

against gram-positive and gram-negative microorganisms (Gnanasekar *et al.* 2018). Additionally, the substance successfully combated a brand new drug-resistant diagnostic microbial culture of *Cronobacter sakazakii* variety AMD04 while exhibiting outstanding antibacterial and anti-biofilm applications. Palladium nanoparticles were shown to have minimal bactericidal and prohibitive concentration MIC and MBC of 0.06 and 0.12 mm, respectively (Chang *et al.* 2021). The antibacterial and antifungal application of the phyto-synthesized palladium nanoparticles against *Candida albicans* and *Bacillus subtilis* has been shown. Palladium ions were mixed with the leaf extract of *Santalum album* in a 9:1 ratio and left to set at ambient temperature for four days to produce the palladium nanoparticles. The generated round-shaped palladium nanoparticles ranged in size from 10 to 40 nm on average. In comparison to gram-positive bacteria, nanoparticles demonstrated more powerful antibacterial action against gram-negative bacteria (Sharmila *et al.* 2017).

5. CONCLUSION

The above review study concludes that the synthesis of palladium nanoparticles can be achieved through different methods like physical, chemical and biological. Biologically synthesized PdNPs exhibit excellent properties and applications in different fields. Palladium nanoparticles have extensive properties such as optical, plasmonic, catalytic, and magnetic. the characteristics of the PdNPs in different fields, palladium used in excellent catalysts, sensors, as well as storage and many other fields. The synthesis of palladium nanoparticles via plant extract are widely used as a catalyst, such as the Suzuki-Miyaura coupling reaction, Heck reaction, dye degradation, etc and also exhibit antibacterial activity. The palladium nanostructures show significant applications in various fields, such as sensors, like hydrogen and glucose sensors and antioxidant.

ACKNOWLEDGMENTS

I am (Shagufta Bi) very thankful to NFPWDs UGC New Delhi for financial assistance. ID:- 201819-NFPWDs-2018-20-UTT-8128 and serial no. is 305.

FUNDING SOURCE

201819-NFPWDs-2018-20-UTT-8128

DATA AVAILABILITY

The manuscript incorporates all datasets examined throughout this review paper.

AUTHORS' CONTRIBUTION

ShaguftaBi: Writing—draft manuscript, Writing—original draft, Writing—review and editing.

Rashi Srivastava: Supervision. Tanzeel Ahmed: Supervision

ETHICS STATEMENT

This review paper did not involve human participants, animal subjects, or any material that requires ethical approval.

CONFLICTS OF INTEREST

Authors declare that no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Adams, B. D. and Chen, A., The role of palladium in a hydrogen economy, *Mater. Today*, 14(6), 282-289 (2011).
[https://doi.org/10.1016/S1369-7021\(11\)70143-2](https://doi.org/10.1016/S1369-7021(11)70143-2)
- Agostini, G., Piovano, A., Bertinetti, L., Pellegrini, R., Leofanti, G., Groppo, E. and Lamberti, C., Effect of different face centered cubic nanoparticle distributions on particle size and surface area determination: a theoretical study, *J. Phys. Chem. C.*, 118(8), 4085-4094 (2014).
<https://doi.org/10.1021/jp4091014>
- Ahsan, M. A., Hosur, M., Tareq, S. H. and Hasan, S. M. K., Quasi-static compression characterization of binary nanoclay/graphene reinforced carbon/epoxy composites subjected to seawater conditioning, *Mater. Res. Express*, 7(1), 015033 (2020).
<https://doi.org/10.1088/2053-1591/ab62fb>
- Ament, K., Kobayashi, H., Kusada, K., Breu, J. and Kitagawa, H., Enhancing Hydrogen Storage Capacity of Pd Nanoparticles by Sandwiching between Inorganic Nanosheets, *Z. Anorg. Allg. Chem.*, 648(10), e202100370 (2022).
<https://doi.org/10.1002/zaac.202100370>
- Ament, K., Wagner, D. R., Götsch, T., Kikuchi, T., Kröhnert, J., Trunschke, A., Lunkenbein, T., Sasaki, T. and Breu, J., Enhancing the catalytic activity of palladium nanoparticles via sandwich-like confinement by thin titanate nanosheets, *ACS Catal.*, 11(5), 2754-2762 (2021).
<https://doi.org/10.1021/acscatal.1c00031>

- Anderson, S. D., Gwenin, V. V. and Gwenin, C. D., Magnetic Functionalized Nanoparticles for Biomedical, Drug Delivery and Imaging Applications, *Nanoscale Res. Lett.*, 14, 188 (2019). <https://doi.org/10.1186/s11671-019-3019-6>
- Anju, A. R. Y. A. and Gupta, K., Chundawat, T.S. In vitro antimicrobial and antioxidant activity of biogenically synthesized palladium and platinum nanoparticles using *Botryococcus braunii*, *Turk. J. Pharm. Sci.*, 17(3), 299-306 (2020). <https://doi.org/10.4274/tjps.galenos.2019.94103>
- Anjum, F., Gul, S., Khan, I. M. and Khan, A. M., Efficient synthesis of palladium nanoparticles using guar gum as stabilizer and their applications as catalyst in reduction reactions and degradation of azo dyes, *Green Process. Synth.*, 9(1), 63-76 (2020). <https://doi.org/10.1515/gps-2020-0008>
- Arole, V. and Munde, S., Fabrication of Nanomaterials by Top-down and Bottom-up Approaches- An overview, *J. Adv. Appl. Sci. Technol.*, 1(2), 89-93 (2014).
- Arsiya, F., Sayadi, M. H. and Sobhani, S., Green synthesis of palladium nanoparticles using *Chlorella vulgaris*, *Mater. Lett.*, 186, 113-115 (2017). <https://doi.org/10.1016/j.matlet.2016.09.101>
- Azizi, S., Shahri, M. M., Rahman, H. S., Rahim, R. A., Rasedee, A. and Mohamad, R., Green Synthesis Palladium Nanoparticles Mediated by White Tea (*Camellia sinensis*) Extract with Antioxidant, Antibacterial, and Antiproliferative Activities Toward the Human Leukemia (MOLT-4) Cell Line, *Int. J. Nanomed.*, 17, 1227-1228 (2022). <https://doi.org/10.2147/IJN.S366532>
- Baghayeri, M., Alinezhad, H., Tarahomi, M., Fayazi, M., Motlagh, G. M. and Maleki, B., A non-enzymatic hydrogen peroxide sensor based on dendrimer functionalized magnetic graphene oxide decorated with palladium nanoparticles, *Appl. Surf. Sci.*, 478, 87-93 (2019). <https://doi.org/10.1016/j.apsusc.2019.01.201>
- Bankar, A., Joshi, B., Kumar, R. A. and Zinjarde, S., Banana peel extract mediated novel route for the synthesis of palladium nanoparticles, *Mater. Lett.*, 64(18), 1951-1953 (2010). <https://doi.org/10.1016/j.matlet.2010.06.021>
- Baran, T. and Nasrollahzadeh, M., Facile synthesis of palladium nanoparticles immobilized on magnetic biodegradable microcapsules used as effective and recyclable catalyst in Suzuki-Miyaura reaction and p-nitrophenol reduction, *Carbohydr. Polym.*, 222, 115029 (2019). <https://doi.org/10.1016/j.carbpol.2019.115029>
- Bathula, C., Subalakshmi, K., Kumar, A., Yadav, H., Ramesh, S., Shinde, S., ... & Kim, H., "Ultrasonically driven green synthesis of palladium nanoparticles by *Coleus amboinicus* for catalytic reduction and Suzuki-Miyaura reaction." *Colloids and Surfaces B: Biointerfaces* 192 (2020): 111026. <https://doi.org/10.1016/j.colsurfb.2020.111026>
- Bi, S. and Nabeel, A., Green synthesis of palladium nanoparticles and their biomedical applications, *Mater. Today: Proc.*, 62, 3172-3177 (2022). <https://doi.org/10.1016/j.matpr.2022.03.441>
- Bi, S. and Srivastava, R., Bottom-up synthesis of palladium nanoparticles: Kinetics effect and catalytic activity, *Polyhedron*, 269, 117426 (2025). <https://doi.org/10.1016/j.poly.2025.117426>
- Bi, S. and Srivastava, R., Rosa damascena flower mediated phytofabrication of palladium nanoparticles, in-vitro and in-vivo applications, *Mater. Today: Proc.*, (2023). <https://doi.org/10.1016/j.matpr.2023.07.305>
- Bi, S. and Srivastava, R., Rosa damascena leaf extract mediated palladium nanoparticles and their anti-inflammatory and analgesic applications, *Inorg. Chem. Commun.*, 162, 112122 (2024). <https://doi.org/10.1016/j.inoche.2024.112122>
- Bi, S., Srivastava, R. and Ahmad, T., The Potential Antifungal Activity of the Developed Palladium Nanoparticles, *Biomed. Pharmacol. J.*, 17(4), 2617-2628(2024). <https://dx.doi.org/10.13005/bpj/3053>
- Chang, Y., Xing, M., Hu, X., Feng, H., Wang, Y., Guo, B., Sun, M., Ma, L. and Fei, P., Antibacterial activity of Chrysanthemum buds crude extract against *Cronobacter sakazakii* and its application as a natural disinfectant, *Front. Microbiol.*, 11, 632-177 (2021). <https://doi.org/10.3389/fmicb.2020.632177>
- Chen, M., Mao, P., Qin, Y., Wang, J., Xie, B., Wang, X., and Wang, G., Response characteristics of hydrogen sensors based on PMMA-membrane-coated palladium nanoparticle films, *ACS Applied Materials & Interfaces* 9.32 (2017): 27193-27201. <https://pubs.acs.org/doi/10.1021/acsami.7b07641>
- Chlumsky, O., Purkrtova, S., Michova, H., Sykorova, H., Slepicka, P., Fajstavr, D., Ulbrich, P., Viktorova, J. and Demnerova, K., Antimicrobial properties of palladium and platinum nanoparticles: A new tool for combating food-borne pathogens, *Int. J. Mol. Sci.*, 22(15), 7892. <https://doi.org/10.3390/ijms22157892>
- Corte, D. S., Hennebel, T., Segers, J., Nevel, V. S., Verschuere, S., Verstraete, W. and Boon, N., Influence of physicochemical parameters on stability and performance of biosupported Pd nanocatalysts, *Nanomater. Environ.*, 1, 31-39 (2013). <https://doi.org/10.2478/nanome-2013-0002>
- Cristoforetti, G., Pitzalis, E., Spiniello, R., Ishak, R. and Miranda, M. M., Production of palladium nanoparticles by pulsed laser ablation in water and their characterization, *J. Phys. Chem. C*, 115(12), 5073-5083 (2010). <https://doi.org/10.1021/jp109281q>
- Darmadi, I., Nugroho, F. A. A. and Langhammer, C., High-performance nanostructured palladium-based hydrogen sensors—current limitations and strategies for their mitigation, *ACS Sens.*, 5(11), 3306-3327 (2020). <https://doi.org/10.1021/acssensors.0c02019>

- Das, R. K., Pachapur, L. V., Lonappan, L., Naghdi, M., Pulicharla, R., Maiti, S., Cledon, M., Dalila, A. M. L., Sarma, J. S. and Brar, K. S., Biological synthesis of metallic nanoparticles: plants, animals and microbial aspects, *Nanotechnol. Environ. Eng.*, 2(1), 18 (2017). <https://doi.org/10.1007/s41204-017-0029-4>
- Dewan, A., Sarmmah, M., Thakur, J. A., Bharali, P. and Bora, U., Greener biogenic approach for the synthesis of palladium nanoparticles using papaya peel: An eco-friendly catalyst for C–C coupling reaction, *ACS Omega*, 3(5), 5327-5335 (2018). <https://doi.org/10.1021/acsomega.8b00039>
- Dizaj, S. M., Lotfipour, F., Jalali, B. M., Zarrintan, M. H. and Adibkia, K., Antimicrobial activity of the metals and metal oxide nanoparticles, *Mater. Sci. Eng.: C.*, 44, 278-284 (2014). <https://doi.org/10.1016/j.msec.2014.08.031>
- Dubey, S. P., Lahtinen, M., Särkkä, H. and Sillanpää, M., Bioprospective of *Sorbus aucuparia* leaf extract in development of silver and gold nanocolloids, *Colloids Surf. B: Biointerfaces*, 80(1), 26-33 (2010). <https://doi.org/10.1016/j.colsurfb.2010.05.024>
- Edayadulla, N., Nagaraj, B. and Yong, R. L., Green synthesis and characterization of palladium nanoparticles and their catalytic performance for the efficient synthesis of biologically interesting di (indolyl) indolin-2-ones, *J. Ind. Eng. Chem.*, 21, 1365-1372 (2015). <https://doi.org/10.1016/j.jiec.2014.06.007>
- Elango, G., Roopan, M. S., Dhobi, A. A. N., Arasu, V. M., Damodharan, I. K. and Elumalai, K., Cocos nucifera coir-mediated green synthesis of Pd NPs and its investigation against larvae and agricultural pest, *Artif. Cells, Nanomed., Biotechnol.*, 45(8), 1581-1587 (2017). <https://doi.org/10.1080/21691401.2016.1262382>
- Emam, H. E., Saad, N. M., Abdallah, A. E. M. and Ahmed, H. B., Acacia gum versus pectin in fabrication of catalytically active palladium nanoparticles for dye discoloration, *Int. J. Biol. Macromol.*, 156, 829-840 (2020). <https://doi.org/10.1016/j.ijbiomac.2020.04.018>
- Fakeh, -A. M. S., Osman, S. O. M., Gassoumi, M., Rabhi, M. and Omer, M., Characterization, antimicrobial and anticancer properties of palladium nanoparticles biosynthesized optimally using Saudi propolis, *Nanomater.*, 11(10), 2666 (2021). <https://doi.org/10.3390/nano11102666>
- Feng, E. Y., Zelaya, R., Holm, A., Yang, A. C. and Cargnello, M., Investigation of the optical properties of uniform platinum, palladium, and nickel nanocrystals enables direct measurements of their concentrations in solution, *Colloids Surf. A: Physicochem. Eng. Aspects*, 601, 125007 (2020). <https://doi.org/10.1016/j.colsurfa.2020.125007>
- Garai, C., Hasan, N. S., Barai, C. A., Ghorai, S., Panja, K. S. and Bag, G. B., Green synthesis of Terminalia arjuna-conjugated palladium nanoparticles (TA-PdNPs) and its catalytic applications, *J. Nanostruct. Chem.*, 8(4), 465-472 (2018). <https://doi.org/10.1007/s40097-018-0288-z>
- Garole, V. J., Choudhary, B. C., Tetgure, R. S., Garole, D. J. and Borse, A. U., Palladium nanocatalyst: green synthesis, characterization, and catalytic application, *Int. J. Environ. Sci. Technol.*, 16(12), 7885-7892 (2019). <https://doi.org/10.1007/s13762-018-2173-1>
- Gavia, D. J. and Young, S. S., Catalytic properties of unsupported palladium nanoparticle surfaces capped with small organic ligands, *ChemCatChem*, 7(6), 892-900 (2015). <https://doi.org/10.1002/cctc.201402865>
- Ghosh, S., Nitnavare, R., Dewle, A., Tomar, G. B., Chippalkatti, R., More, P., Kitture, R., Kale, S., Bellare, J. and Chopade, A. B., Novel platinum–palladium bimetallic nanoparticles synthesized by *Dioscorea bulbifera*: anticancer and antioxidant activities, *Int. J. Nanomed.*, 17(10), 7477-7490 (2015). <https://doi.org/10.2147/IJN.S91579>
- Gnanasekar, S., Murugaraj, J., Dhivyabharathi, B., Krishnamoorthy, V., Jha, P. K., Seetharaman, P., Vilwanathan, R. and Sivaperumal, S., Antibacterial and cytotoxicity effects of biogenic palladium nanoparticles synthesized using fruit extract of *Couroupita guianensis* Aubl, *J. Appl. Biomed.*, 16(1), 59-65 (2018). <https://doi.org/10.1016/j.jab.2017.10.001>
- Haleemkhan, A.A.; Naseem, B.; Vardhini, B.V. Synthesis of nanoparticles from plant extracts, *Int J Mod Chem Appl Sci.*, 2(3), 195-203 (2015).
- Han, Z., Dong, L., Zhang, J., Cui, T., Chen, S., Ma, G., Guo, X. and Wang, L., Green synthesis of palladium nanoparticles using lentinan for catalytic activity and biological applications, *RSC Adv.*, 9(65), 38265-38270 (2019). <https://doi.org/10.1039/C9RA08051A>
- Hosseingholian, A., et al. "Recent advances in green synthesized nanoparticles: from production to application, *Materials Today Sustainability*, 24 (2023). <https://doi.org/10.1016/j.mtsust.2023.100500>
- Huang, X., Tang, S., Mu, X., Dai, Y., Chen, G., Zhou, Z., Ruan, F., Yang, Z. and Zheng, N., Freestanding palladium nanosheets with plasmonic and catalytic properties, *Nat. Nanotechnol.*, 6(1), 28-32 (2011). <https://doi.org/10.1038/nnano.2010.235>
- Hussain, I., Singh, B. N., Singh, A., Singh, H. and Singh, C. S., Green synthesis of nanoparticles and its potential application, *Biotechnol. Lett.*, 38(4), 545-560 (2016). <https://doi.org/10.1007/s10529-015-2026-7>
- Ismail, E., Khenfouch, M., Dhlamini, M., Dube, S. and Maaaza, M., Green palladium and palladium oxide nanoparticles synthesized via *Aspalathus linearis* natural extract, *J. Alloys Compd.*, 695, 3632-3638 (2017). <https://doi.org/10.1016/j.jallcom.2016.11.390>

- Jadoun, S., Arif, R., Jangid, N. K. and Meena, R. K., Green synthesis of nanoparticles using plant extracts: A review, *Environ. Chem. Lett.*, 19(1), 355-374 (2021).
<https://doi.org/10.1007/s10311-020-01074-x>
- Jin, M., Zhang, H., Xie, Z. and Xia, Y., Palladium nanocrystals enclosed by {100} and {111} facets in controlled proportions and their catalytic activities for formic acid oxidation, *Energy Environ. Sci.*, 5(4), 6352-6357 (2012).
<https://doi.org/10.1039/C2EE02866B>
- Joudeh, N., Saragliadis, A., Koster, G., Mikheenko, P. and Linke, D., Synthesis methods and applications of palladium nanoparticles: A review, *Front. Nanotechnol.*, 4, 106-608 (2022).
<https://doi.org/10.3389/fnano.2022.1062608>
- Kanchi, S. and Ahmed, S., Green metal nanoparticles: synthesis, characterization and their applications, *John Wiley Sons.*, 1-21 (2018).
<https://doi.org/10.1002/9781119418900.ch1>
- Khan, I., Saeed, K. and Khan, I., Nanoparticles: Properties, applications and toxicities, *Arabian J. Chem.*, 12(7), 908-931 (2019).
<https://doi.org/10.1016/j.arabjc.2017.05.011>
- Khandel, P., Yadaw, K. R., Soni, K. D., Kanwar, L. and Shahi, K. S., Biogenesis of metal nanoparticles and their pharmacological applications: present status and application prospects, *J. Nanostruct. Chem.*, 8(3), 217-254 (2018).
<https://doi.org/10.1007/s40097-018-0267-4>
- Kim, J., Reddy, A. D., Ma, R. and Kim, K., T., The influence of laser wavelength and fluence on palladium nanoparticles produced by pulsed laser ablation in deionized water, *Solid state sci.*, 37, 96-102, (2014).
<https://doi.org/10.1016/j.solidstatesciences.2014.09.005>
- Konda, S. K. and Chen, A., Palladium based nanomaterials for enhanced hydrogen spillover and storage, *Mater. Today*, 19(2), 100-108 (2016).
<https://doi.org/10.1016/j.mattod.2015.08.002>
- Kora, A. J. and Rastogi, L., Green synthesis of palladium nanoparticles using gum ghatti (*Anogeissus latifolia*) and its application as an antioxidant and catalyst, *Arabian J. Chem.*, 11(7), 1097-1106 (2018).
<https://doi.org/10.1016/j.arabjc.2015.06.024>
- Kracker, M., Worsch, C. and Rüssel, C., Optical properties of palladium nanoparticles under exposure of hydrogen and inert gas prepared by dewetting synthesis of thin-sputtered layers, *J. Nanopart. Res.*, 15, 1594 (2013).
<https://doi.org/10.1007/s11051-013-1594-5>
- Kulikova, D. P., Dobronosova, A. A., Kornienko, V. V., Nechepurenko, I. A., Baburin, A. S., Sergeev, E. V., Lotkov, E. S., Rodionov, I. A., Baryshev, A. V. and Dorofeenko, A. V., Optical properties of tungsten trioxide, palladium, and platinum thin films for functional nanostructures engineering, *Opt. Express.*, 28(21), 32049-32060 (2020).
<https://doi.org/10.1364/OE.405403>
- Kumar, A., Mohammadi, M. M. and Swihart, M. T., Synthesis, growth mechanisms, and applications of palladium-based nanowires and other one-dimensional nanostructures, *Nanoscale*, 11(41), 19058-19085 (2019).
<https://doi.org/10.1039/C9NR05835D>
- Kuppusamy, P., Yusoff, M. M., Maniam, P. G. and Govindan, N., Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications—An updated report, *Saudi Pharm. J.*, 24(4), 473-484 (2016).
<https://doi.org/10.1016/j.jsps.2014.11.013>
- Lerch, S. and Reinhard, B. M., Effect of interstitial palladium on plasmon-driven charge transfer in nanoparticle dimers, *Nat. Commun.*, 9(1), 1608 (2018).
<https://doi.org/10.1038/s41467-018-04066-2>
- Long, N. V., Hayakawa, T., Matsubara, T., Chien, N. D., Ohtaki, M. and Nogami, M., Controlled synthesis and properties of palladium nanoparticles, *J. Exp. Nanosci.*, 7(4), 426-439 (2012).
<https://doi.org/10.1080/17458080.2010.543988>
- Majeed, M. S., Dhahir, M. K. and Mahdy, Z. F., Studying the Structure and the Optical Properties of Pd Nanoparticles Affected by Precursor Concentration, *Int. J. Eng. Res. Appl.*, 6(1), 12-17 (2015).
<https://api.semanticscholar.org/CorpusID:53588443>
- Majumdar, R., Tantayanon, S. and Bag, G. B., Synthesis of palladium nanoparticles with leaf extract of *Chrysophyllum cainito* (Star apple) and their applications as efficient catalyst for C–C coupling and reduction reactions, *Int. Nano Lett.*, 7, 267-274 (2017).
<https://doi.org/10.1007/s40089-017-0220-4>
- Makarov, V. V., Love, J. A., Sinitsyna, V. O., Makarova, S. S., Yaminsky, V. I., Taliansky, E. M. and Kalinina, O. N., Green nanotechnologies: synthesis of metal nanoparticles using plants, *Acta Nat.*, 6(1), 35-44 (2014).
- Mallikarjuna, K., Bathula, C., Buruga, K., Shrestha, K. N., Noh, Y. Y. and Kim, H., Green synthesis of palladium nanoparticles using fenugreek tea and their catalytic applications in organic reactions, *Mater. Lett.*, 205, 138-141 (2017).
<https://doi.org/10.1016/j.matlet.2017.06.081>
- Manjare, S. B. and Rajendra, A. C., Palladium nanoparticle-bentonite hybrid using leaves of *Syzygium aqueum* plant from India: Design and assessment in the catalysis of C–C coupling reaction, *Chem. Afr.*, 3(2), 329-341 (2020).
<https://doi.org/10.1007/s42250-020-00139-2>
- Marchi, D. S., Sánchez, N. S., Bodelón, G., Juste, P. J. and Santos, P. I., Pd nanoparticles as a plasmonic material: synthesis, optical properties and applications, *Nanoscale*, 12(46), 23424-23443 (2020).
<https://doi.org/10.1039/D0NR06270G>

- Mattox, D. M., Handbook of physical vapor deposition (PVD) processing, WilliamAndrew, 98(1), 410-423 (2010).
[https://doi.org/10.1016/S0026-0576\(00\)80350-5](https://doi.org/10.1016/S0026-0576(00)80350-5)
- Michalek, T., Hessel, V. and Wojnicki, M., Production, recycling and economy of palladium: A critical review, *Mater.*, 17(1), 45 (2024).
<https://doi.org/10.3390/ma17010045>
- Mie, R., Samsudin, M. W., Din, L. B., Ahmad, A., Ibrahim, N. and Adnan, S. N. A., Synthesis of silver nanoparticles with antibacterial activity using the lichen *Parmotrema praesorediosum*, *Int. J. Nanomed.*, 9, 121-127 (2014).
<https://doi.org/10.2147/IJN.S52306>
- Mittal, A. K., Chisti, Y. and Banerjee, U. C., Synthesis of metallic nanoparticles using plant extracts, *Biotechnol. Adv.*, 31(2), 346-356 (2013).
<https://doi.org/10.1016/j.biotechadv.2013.01.003>
- Mittal, J., Batra, A., Singh, A. and Sharma, M. M., Phytofabrication of nanoparticles through plant as nanofactories, *Adv. Nat. Sci.: Nanosci. Nanotechnol.*, 5(4), 043002 (2014).
<https://doi.org/10.1088/2043-6262/5/4/043002>
- Mousavi, S. M., Hashemi, S. A., Ghasemi, Y., Atapour, A., Amani, A. M., Dashtaki, S. A., Babapoor, A. and Arjmand, O., Green synthesis of silver nanoparticles toward bio and medical applications: review study, *Artif. cells, nanomed., biotechnol.*, 46(sup3), 855-872 (2018).
<https://doi.org/10.1080/21691401.2018.1517769>
- Nair, A. A. S., Ramaprabhu, S. and Anitha, N., Hydrogen storage performance of palladium nanoparticles decorated graphitic carbon nitride, *Int. J. Hydrogen Energy*, 40(8), 3259-3267 (2015).
<https://doi.org/10.1016/j.ijhydene.2014.12.065>
- Narasaiah, B. P. and Mandal, B. K., Remediation of azo-dyes based toxicity by agro- waste cotton boll peels mediated palladium nanoparticles, *J. Saudi Chem. Soc.*, 24(2), 267-281 (2020).
<https://doi.org/10.1016/j.jscs.2019.11.003>
- Narasaiah, P., Mandal, B. K. and Sarada, N. C., Green synthesis of Pd NPs from *Pimpinella tirupatiensis* plant extract and their application in photocatalytic activity dye degradation, *IOP Conf. Ser.: Mater. Sci. Eng.*, 263(2), 022013 (2017).
<https://doi.org/10.1088/1757-899X/263/2/022013>
- Nasrollahzadeh, M., Green synthesis and catalytic properties of palladium nanoparticles for the direct reductive amination of aldehydes and hydrogenation of unsaturated ketones, *New J. Chem.*, 38(11), 5544-5550 (2014).
<https://doi.org/10.1039/C4NJ01440E>
- Ndaya, C. C., Javahiraly, N. and Brioude, A., Recent advances in palladium nanoparticles-based hydrogen sensors for leak detection, *Sens.*, 19(20), 4478 (2019).
<https://doi.org/10.3390/s19204478>
- Ovais, M., Khalil, T. A., Islam, U. N., Ahmad, I., Ayaz, M., Saravanan, M., Shinwari, K., Z. and Mukherjee, S., Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles, *Appl. Microbiol. Biotechnol.*, 102(16) 6799-6814 (2018).
<https://doi.org/10.1007/s00253-018-9146-7>
- Patil, S. P. and Burungale, V. V., Physical and chemical properties of nanomaterials, *Nanomedicines for Breast Cancer Theranostics - Micro and Nano Technologies*, Elsevier, 17-31 (2020).
<https://doi.org/10.1016/B978-0-12-820016-2.00002-1>
- Pechyen, C., Tangnorawich, B., Toommee, S., Marks, R., & Parcharoen, Y "Green synthesis of metal nanoparticles, characterization, and biosensing applications. *Sensors International*, 5, 100287 (2024).
<https://doi.org/10.1016/j.sintl.2024.100287>
- Phan, T. T. V., Huynh, T. C., Manivasagan, P., Mondal, S. and Oh, J., An up-to-date review on biomedical applications of palladium nanoparticles, *Nanomater.*, 10(1), 66 (2020).
<https://doi.org/10.3390/nano10010066>
- Rojas, J. V. and Castano, H. C., Production of palladium nanoparticles supported on multiwalled carbon nanotubes by gamma irradiation, *Radiat. Phys. Chem.*, 81(1), 16-21 (2012).
<https://doi.org/10.1016/j.radphyschem.2011.08.010>
- Rokade, S. S., Joshi, A. K., Mahajan, K., Patil, S., Tomar, G., Dubal, S. D., Parihar, S. V., Kitture, R., Bellare, R. J. and Ghosh, S., Gloriosa superba mediated synthesis of platinum and palladium nanoparticles for induction of apoptosis in breast cancer, *Bioinorg. Chem. Appl.*, 2018, 4924186 (2018).
<https://doi.org/10.1155/2018/4924186>
- Rokade, S. S., Joshi, K., Mahajan, K., Tomar, G., Dubal, S. D., Parihar, S. V., Kitture, R., Bellare, J. and Ghosh, S., Novel anticancer platinum and palladium nanoparticles from *Barleria prionitis*, *Global J. Nanomed.*, 2(5), 555600 (2017).
<https://doi.org/10.19080/GJN.2017.02.555600>
- Saikia, P. K., Bhattacharjee, P. R., Sarmah, P. P., Saikia, L. and Dutta, K. D., A green synthesis of Pd nanoparticles supported on modified montmorillonite using aqueous *Ocimum sanctum* leaf extract: a sustainable catalyst for hydrodechlorination of 4-chlorophenol, *RSC Adv.*, 6(11), 110011-110018 (2016).
<https://doi.org/10.1039/C6RA22788K>
- Santoshi, K. A., Venkatesham, M., Ayodhya, D. and Veerabhadram, G., Green synthesis, characterization and catalytic activity of palladium nanoparticles by xanthan gum, *Appl. Nanosci.*, 5, 315-320 (2015).
<https://doi.org/10.1007/s13204-014-0320-7>

- Sarmah, M., Neog, A. B., Boruah, P. K., Das, M. R., Bharali, P. and Bora, U., Effect of Substrates on Catalytic Activity of Biogenic Palladium Nanoparticles in C-C Cross-Coupling Reactions, *ACS Omega*, 4(2), 3329–3340 (2019).
<https://doi.org/10.1021/acsomega.8b02697>
- Sarto, F., Castagna, E., Francesco, D. M., Dikonimos, M. T., Giorgi, L., Lecci, S., Sansovini, M. and Violante, V., Morphology and electrochemical properties of Pd-based catalysts deposited by different thin-film techniques, *Int. J. Hydrogen Energy*, 39(27), 14701–14711 (2014).
<https://doi.org/10.1016/j.ijhydene.2014.07.038>
- Shah, M., Fawcett, D., Sharma, S., Tripathy, S. K. and Poinern, G. E. J., Green synthesis of metallic nanoparticles via biological entities, *Mater.*, 8(11), 7278–7308 (2015).
<https://doi.org/10.3390/ma8115377>
- Shahmirzadi, V. N. and Pakizeh, T., Optical characterization of broad plasmon resonances of Pd/Pt nanoparticles, *Mater. Res. Express*, 5(4), 045038 (2018).
<https://doi.org/10.1088/2053-1591/aabc36>
- Shaik, M. R., Ali, Q. J. Z., Khan, M., Kuniyil, M., Assal, E. M., Alkathlan, Z. H., Warthan, A. A., Siddiqui, H. R. M., Khan, M. and Adil, F. S., Green synthesis and characterization of palladium nanoparticles using *Origanum vulgare* L. extract and their catalytic activity, *Mol.*, 22(1), 165 (2017).
<https://doi.org/10.3390/molecules22010165>
- Shanthi, K., Sreevani, V., Vimala, K. and Kannan, S., Cytotoxic effect of Palladium nanoparticles synthesized from *Syzygium aromaticum* aqueous extracts and induction of apoptosis in cervical carcinoma, *Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci.*, 87(4), 1101–1112 (2017).
<https://doi.org/10.1007/s40011-015-0678-7>
- Sharma, R., & Tripathi, A., "Green synthesis of nanoparticles and its key applications in various sectors." *Materials Today: Proceedings* 48 (2022): 1626–1632.
<https://doi.org/10.1016/j.matpr.2021.09.512>
- Sharmila, G., Haries, S., Fathima, M. F., Geetha, S., Kumar, N. M. and Muthukumaran, C., Enhanced catalytic and antibacterial activities of phytosynthesized palladium nanoparticles using *Santalum album* leaf extract, *Powder Technol.*, 320, 22–26 (2017).
<https://doi.org/10.1016/j.powtec.2017.07.026>
- Siddiqi, K. S. and Husen, A., Green synthesis, characterization and uses of palladium/platinum nanoparticles, *Nanoscale res. lett.*, 11, 482 (2016).
<https://doi.org/10.1186/s11671-016-1695-z>
- Sikeyi, L., Matthews, T., Adekunle, A. S. and Maxakato, N. W., Electro-oxidation of Ethanol and Methanol on Pd/C, Pd/CNFs and Pd–Ru/CNFs Nanocatalysts in Alkaline Direct Alcohol Fuel Cell, *Electroanal.*, 32(12), 2681–2692 (2020).
<https://doi.org/10.1002/elan.202060260>
- Singh, B., Bhardwaj, N., Jain, V. K. and Bhatia, V., Palladium nanoparticles decorated electrostatically functionalized MWCNTs as a non enzymatic glucose sensor, *Sens. Actuators, A: Phys.*, 220, 126–133 (2014).
<https://doi.org/10.1016/j.sna.2014.09.030>
- Singh, C., Sharma, V., Naik, K. P., Khandelwal, V. and Singh, H., A green biogenic approach for synthesis of gold and silver nanoparticles using *Zingiber officinale*, *Dig. J. Nanomater; Biostruct.*, 6(2), 535–542 (2011).
<http://ir.juit.ac.in:8080/jspui/jspui/handle/123456789/8550>
- Singh, H., Desimone, M. F., Pandya, S., Jasani, S., George, N., Adnan, M., ... & Alderhami, S. A. "Revisiting the green synthesis of nanoparticles: uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications." *International journal of nanomedicine* (2023): 4727–4750.
<https://doi.org/10.2147/IJN.S419369>
- Sridhar, V, and Rani, S, S. "A review on green synthesis, characterization and applications of plant mediated metal nanoparticles." *Next Research* 2.2 ,100356. (2025).
<https://doi.org/10.1016/j.nexres.2025.100356>
- Sonbol, H., Ameen, F., AlYahya, S., Almansob, A. and Alwakeel, S., Padina boryana mediated green synthesis of crystalline palladium nanoparticles as potential nanodrug against multidrug resistant bacteria and cancer cells, *Sci. Rep.*, 11(1), 5444 (2021).
<https://doi.org/10.1038/s41598-021-84794-6>
- Tahir, K., Nazir, S., Ahmad, A., Li, B., Shah, A. A. S., Khan, U. A., Khan, M. G., Khan, U. Q., Khan, H. U. Z. and Khan, U. F., Biodirected synthesis of palladium nanoparticles using *Phoenix dactylifera* leaves extract and their size dependent biomedical and catalytic applications, *RSC Adv.*, 6(89), 85903–85916 (2016).
<https://doi.org/10.1039/C6RA11409A>
- Torrisi, L., Caridi, F. and Giuffrida, L., Comparison of Pd plasmas produced at 532 nm and 1064 nm by a Nd:YAG laser ablation, *Nucl. Instrum. Methods Phys. Res. Sect. B*, 268(13), 2285–2291 (2010).
<https://doi.org/10.1016/j.nimb.2010.03.029>
- Umegaki, T., Satomi, Y. and Kojima, Y., Catalytic properties of palladium nanoparticles for hydrogenation of carbon dioxide into formic acid, *J. Jpn. Inst. Energy*, 96(11), 487–492 (2017).
- Vadai, M., Angell, D. K., Hayee, F., Sytwu, K. and Dionne, J. A., In-situ observation of plasmon-controlled photocatalytic dehydrogenation of individual palladium nanoparticles, *Nat. Commun.*, 9(1), 4658 (2018).
<https://doi.org/10.1038/s41467-018-07108-x>
- Vajtai, R. Science and engineering of nanomaterials, *Handbook of Nanomaterials*, Springer, 1–36 (2013).
https://doi.org/10.1007/978-3-642-20595-8_1

- Valencia, J. F., González. I. R., Tramontina, D., Rogan, J., Valdivia, A. J., Kiwi, M. and Bringa, M. E., Hydrogen storage in palladium hollow nanoparticles, *J. Phys. Chem., C*, 120(41), 23836-23841 (2016).
<https://doi.org/10.1021/acs.jpcc.6b07895>
- Vinodhini, S., Vithiya, B. S. M. and Prasad, T. A. A., Green synthesis of palladium nanoparticles using aqueous plant extracts and its biomedical applications, *J. King Saud Univ.-Sci.*, 34(4), 102017 (2022).
<https://doi.org/10.1016/j.jksus.2022.102017>
- Wang, B., Sun, L., Ramelow, M. S., Lang, K. D. and Ngo, H. D., Recent advances and challenges of nanomaterials-based hydrogen sensors, *Micromach.*, 12(11), 14-29 (2021).
<https://doi.org/10.3390/mi12111429>
- Wang, Y., Xie, S., Liu, J., Park, J., Huang, C. Z. and Xia, Y., Shape-controlled synthesis of palladium nanocrystals: a mechanistic understanding of the evolution from octahedrons to tetrahedrons, *Nano Lett.*, 13(5), 2276-2281 (2013).
<https://doi.org/10.1021/nl400893p>
- Yong, P., Rowson, N. A., Farr, J. P. G., Harris, I. R. and Macaskie, L. E., Bioreduction and biocrystallization of palladium by *Desulfovibrio desulfuricans* NCIMB 8307, *Biotechnol. Bioeng.*, 80(4), 369-379 (2002).
<https://doi.org/10.1002/bit.10369>
- Zalineeva, A., Baranton, S., Coutanceau, C. and Jerkiewicz, G., Octahedral palladium nanoparticles as excellent hosts for electrochemically adsorbed and absorbed hydrogen, *Sci. Adv.*, 3(2), 1600542 (2017).
<https://doi.org/10.1126/sciadv.1600542>
- Zhang, J. H., Wei, M. J., Lu, Y. L., Wei, Z. W., Wang, H. P. and Pan, M., Ultrafine palladium nanoparticles stabilized in the porous liquid of covalent organic cages for photocatalytic hydrogen evolution, *ACS Appl. Energy Mater.*, 3(12), 12108-12114 (2020).
<https://doi.org/10.1021/acsaem.0c02222>
- Zhao, H., Yang, J., Wang, L., Tian, C., Jiang, B. and Fu, H., Fabrication of a palladium nanoparticles/graphene nanosheets hybrid via sacrifice of a copper template and its application in catalytic oxidation of formic acid, *Chem. Commun.*, 47(7), 2014-2016 (2011).
<https://doi.org/10.1039/C0CC04432F>