Review Article

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A Review on Palladium Nanoparticles

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ABSTRACT

Palladium nanoparticles (PdNPs) have risen to prominence as remarkably adaptable nanomaterials owing to their distinctive physicochemical properties. 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. 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 possible uses of nanomaterials have been the focus of research in recent days (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, and biomaterials (Dizaj *et al.* 2014; Mittal *et al.* 2014). Nanoscience has the potential to change many academic and industrial disciplines (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 nanomaterial clusters has also gained a special importance (Zhao *et al.* 2011). Palladium nanoparticles derived from plants, fungi, and bacteria possess various 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. Yong *et al.* (2002) developed seed-mediated synthesis of palladium nanocrystals with regulated dimensions and examined the relationships between surface architectures and catalytic efficacy. Fig.1 shows the top-down and bottom-up methods for nanoparticle synthesis (Adams and Chen, 2011). Nanoparticles produced by size differentiation in the top-down approach are achievable *via* several physical and chemical techniques. The fundamental step in bottom-up synthesis is reduction, which generates nanoparticles from small particles, including subatomic particles (Anderson *et al.* 2019; Jin *et al.* 2012). Phenolic acids, flavonoids, alkaloids, and terpenoids are phytochemicals present in plant extracts 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). William Hyde Wollaston, an English scientist discovered Pd, an uncommon silvery-white metal in 1803 (Ovais *et al.* 2018). The majority of palladium comes from mineral sources in a small number of countries. Palladium recycling provides a backup supply. About 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). 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 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 form 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 aid the formation of palladium nanoparticles. They are efficient for degrading dyes. In the synthesis 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 formation of cubic-symmetric palladium nanoparticles that range in size from 20 to 60 nm (Cristoforetti *et al.* 2010; Mattox, 2010). Spherical palladium nanoparticles were synthesized from white tea extract, with sizes ranging from 6 to 18 nm. *Staphylococcus epidermidis* and *Escherichia coli* are strongly inhibited by white tea-mediated palladium nanoparticles, which also have high radical scavenging properties (Sarto *et al.* 2014). The biological process based on the protein-rich soybean leaf extract was used to synthesize palladium nanoparticles. Using UV-visible spectroscopy, the production of palladium nanoparticles from soybean leaf extract was examined. The peak at 420 nm shows the presence of palladium ions in the reaction mixture, 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).

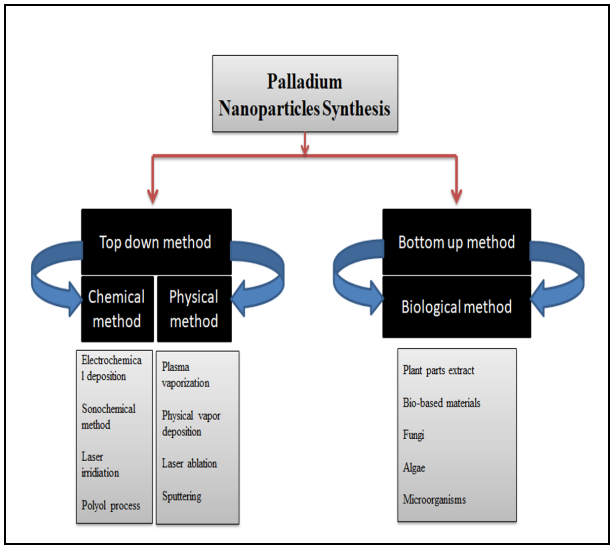


Fig. 1: Schematic representation of different procedures for the synthesis of PdNPs (Khan *et al.* 2019)

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. 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 (Torrisi *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.

Rojas and Castano, (2012) synthesized several palladium catalysts through direct current magnetron sputtering deposition. 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 form stable nanoparticles that do not even need any chemical or stabilizing agents. In the laser ablation procedure, laser light is used to guide the deposition of vaporized plasma. Khandel *et al.* (2018) investigated different palladium plasmas produced at various laser ablation wavelengths.

2.2 Chemical Method

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 citric acid. In the chemical reduction process, sodium borohydride ($NaBH_4$) and potassium borohydride (KBH_4) are widely used for the reduction of metal ions (Singh *et al.* 2011).

These methods have also been analyzed for the formation of different functional materials. L-ascorbic acid has been found to improve the various nucleation sites provided by condensed octahedral palladium seeds. (Sonbol *et al.* 2021). Additionally, ultrasonic sound, microwave, and gamma radiation has been broadly employed in the formation of palladium nanoparticles in liquid media (Bathula *et al.* 2020).

2.3 Biological Method

The fabrication of palladium nanoparticles during the aforementioned process requires 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 has been 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). Introduction of biological materials to palladium ions modifies the size and structural character of nanoparticles and control the reduction of zerovalent palladium and the stability of nanoparticles (Sharma, and Tripathi, 2022). (Azizi *et al.* 2022). An example of plant extract employed in biogenic formation is the reduction of Pd ions to Pd nanoparticles by 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 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 fabrication of palladium nanoparticles. Bimetallic palladium nanoparticles with diverse metals such as silver, gold, iron, copper, and platinum produce unique qualities such as physical, chemical, and catalytic activity of nanoparticles by living organisms. The synthesis of palladium nanoparticles *via* biological processes for catalytic applications is rapidly rising (Pechyen *et al*. 2024).

Plant extracts are preferred for the synthesis of nanoparticles because of their non-toxic nature, eco-friendliness, availability and their ability to employ different biosynthetic pathways (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, metallic nanoparticles in various shapes and sizes are synthesized 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 small size, leading to more "surface-dependent" nanomaterial features (Arsiya *et al.* 2017; Mittal *et al.* 2013). 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 (Shah *et al.* 2015; Bi and Srivastava, 2024).

The energy band construction of palladium nanomaterials may differ significantly from their bulk counterparts. This changes the electrical and optical characteristics of nanomaterials (Mie *et al.* 2014; Patil and Burungale, 2020). 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 intrinsic 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). 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. The localized surface plasmon resonance (LSPR) characteristics of palladium nanostructures can be a useful tool for studying metal-hybrid formation during the hydrogen storage process (Kulikova *et al.* 2020).

Table 1. Various plants for the synthesis of PdNPs

Plant and their Parts	Ion Source	Size in nm	Shape of PdNPs	Applications	References
Barleria priontis (leaves)	$PdCl_2$	80 ± 5 nm	Spherical and irregular	Anticancer	(Rokade *et al.* 2017)
Cocos nucifera (coir)	$Pd(OAc)_2$	62 ± 2nm	Spherical	Agricultural pest	(Elango *et al.* 2017)
Chrysophyllum cainito (leaves)	$PdCl_2$	169.24 nm	Flowerlike structure	Catalyst	(Majumdar *et al.* 2017)
Dioscorea bulbifera (tubers)	$PdCl_2$	10-25 nm	Spherical	Anticancer	(Ghosh *et al.* 2015)
Fenugreek tea(seeds)	$PdCl_2$	20-25 nm	Spherical	Food industry	(Mallikarjuna *et al.* 2017)
Gloriosa superb (tubers)	$PdCl_2$	5-8 nm	Spherical	Breast cancer	(Rokade *et al.* 2018)
Lagerstroemia speciosa (leaves)	$PdCl_2$	136.5 nm	Face-centred cubic	Wastewater treatment	(Garole *et al.* 2019)
Origanum vulgare Linn (leaves)	$PdCl_2$	2.2 nm	Spherical	Catalyst	(Shaik *et al.* 2017)
Pimpinella Tirupatiensis (leaves)	$PdCl_2$	12-25 nm	Spherical	Photo catalyst	(Narasaiah *et al.* 2017)
Phoenix dactylifera (leaves)	$PdCl_2$	13-21 nm	Spherical	Catalyst	(Tahir *et al.* 2016)
Syzgium aromaticum (clove buds)	$PdCl_2$	20 - 25 nm	Spherical	Cytotoxicity	(Shanthi *et al.* 2017)
Terminalia arjuna (barks)	$PdCl_2$	8.9 nm	Spherical	Removal of Industrial Pollutants	(Garai *et al.* 2018)

3.1.1 Optical Measurement

3.1.1.1 Absorbance

As concentration increases, the UV-visible absorption rate of palladium nanoparticles 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 (Ahsan *et al.* 2020).

3.1.2 Theories of Optical Properties

3.1.2.1 Mie Theory

The Mie 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 to corroborate the findings of the study 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 and the dielectric properties of the surrounding medium, and the type of 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 fabrication 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.

3.2 Catalytic Properties of Palladium Nanoparticles

Nasrollahzadeh (2014) examined the effects of silica encapsulation on palladium nanoparticles to preserve the strength of the nanoparticles. The work also discussed 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.

Nanoscale materials have higher catalytic activity (Santoshi *et al.* 2015). As the size of the nanoparticles decreases, the catalytic activity increases. 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. Palladium nanostructures with well-defined SPR absorption characteristics that can be systematically modified from the visible to the near-IR spectra scale have been synthesized. Unfortunately, palladium nanoparticles cannot be used in photothermal treatment using NIR lasers because they lack high NIR SPR absorption (Baran and Nasrollahzadeh, 2019). 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 is necessary to investigate the permittivity of the metals for a given nanoparticle shape in a dielectric environment (Baghayeri *et al.* 2019). According to a recent research, palladium nanoparticles have 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 physical characteristics of the nanoparticles by coating them with suitable materials (Wang *et al.* 2021). In reality, it reasonable to anticipate the activity of non-ferromagnetic core materials formed at the nanoscale. Non-magnetic bulk materials can be converted into diamagnetic or ferromagnetic palladium systems. Nanoparticles with a diameter of 2 nm might result in considerable anisotropy. The 5D band contains localized carriers for nanoparticles smaller than 2 nm. 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. With 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). Hydrogen detection at room temperature has a strong response and selectivity (Konda and Chen, 2016). 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 exact surface area for covering a greater number of catalysts. 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 H_2O_2. 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 formed *in situ* within a Nafion graphene film constructed on a glassy carbon electrode. 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 can absorb hydrogen. Palladium reacts with hydrogen to generate PdH_2, which fills the interstitial octahedral spaces of the face-centred cubic crystal. Many studies have looked at the storage capacity of H_2 gas in palladium nanowires because of their propensity to hold a huge amount of hydrogen and their enormous interfacial area. Valencia *et al.* (2016) reported on the production of palladium-based nanowire foams and investigated their hydrogen gas storage capacity. In the work, 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 (Fig. 2). Palladium and hydrogen intake result in the formation of various stages (Zalineeva *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 intrinsic 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. 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).

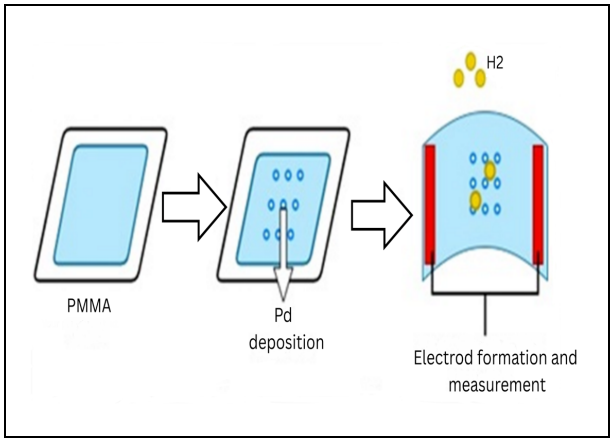


Fig. 2: Schematic representation of hydrogen storage (Chen *et al.* 2017)

4.3 Catalysis

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-Al_2O_3-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 (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 speed up reactions. A quick and effective method for synthesizing 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 form 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).

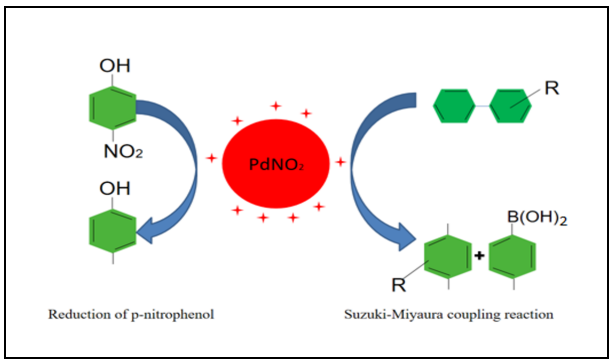


Fig. 3: Schematic diagram of the Suzuki-Miyaura coupling reaction (Baran and Nasrollahzadeh, 2019)

4.4 Antioxidant activity

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. 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 green-synthesized palladium nanoparticles was determined. The colour of the DPPH solution progressively turned from purple to light yellow on the addition of nanoparticles. 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 mg/mL, demonstrating efficient free radical control by palladium nanoparticles (Han *et al.* 2019).

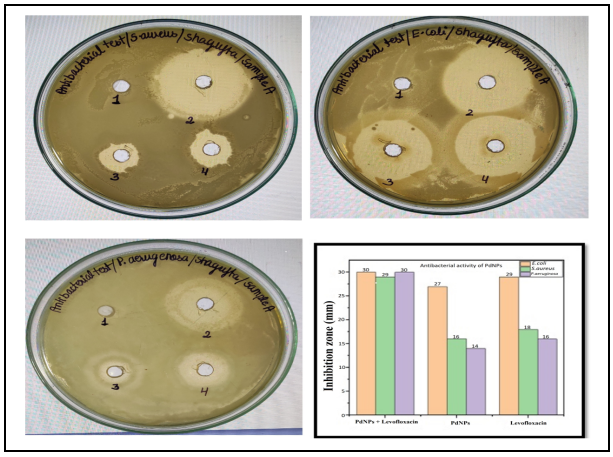


Fig. 4: Antibacterial activity (Bi and Nabeel, 2022)

4.5 Antimicrobial activity

Significant action against antifungal and antibacterial organisms was shown by the green synthesized palladium nanoparticles from *Rosa damascena* leaf extract. The antimicrobial activity of palladium nanoparticles was examined on *E. coli* 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. Palladium nanoparticles synthesized from the fruit extract of *Couroupita guianensis* were tested at a dose of 25 mg/mL, and they demonstrated remarkable antimicrobial application (Gnanasekar *et al.* 2018). Additionally, the substance successfully controlled the growth of drug-resistant culture of *Cronobacter sakazakii* 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 size of the spherical palladium nanoparticles ranged 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 are suitable for their use use as catalysts and sensor. They find use in storage and many other fields. Green-synthesized palladium nanoparticles are widely used as a catalyst, such as the Suzuki-Miyaura coupling reaction, Heck reaction, dye degradation, etc and also exhibit antibacterial activity.

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DATA AVAILABILITY

The manuscript incorporates all datasets examined throughout this review paper.

AUTHORS' CONTRIBUTION

Shagufta Bi: 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.

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