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REVIEW ARTICLE

Plant–Based Biosynthesis of Ruthenium Nanoparticles: A Comprehensive Review

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ABSTRACT: The growing field of nanotechnology demands environmentally responsible production methods. Ruthenium nanoparticles (Ru NPs) are particularly valuable for their exceptional catalytic, electronic, and biomedical potential. However, conventional physical and chemical syntheses rely on hazardous reagents and intensive energy, posing ecological and safety risks. In response, plant-based biosynthesis has emerged as a compelling green alternative. This method utilizes extracts from various plants, where natural phytochemicals, such as polyphenols, flavonoids, and terpenes, serve dual roles as reducing agents and stabilizing capping ligands. This facilitates the facile, room-temperature production of biocompatible and stable Ru NPs. This comprehensive review systematically examines this sustainable approach. It details the diverse botanical sources employed, elucidates the proposed reduction and stabilization mechanisms, and analyzes critical synthesis parameters like pH and temperature. Standard characterization techniques for verifying nanoparticle properties are also outlined. Furthermore, the review extensively covers the resultant bioactivities of plant-synthesized Ru NPs, including potent antimicrobial, antioxidant, and anticancer effects, alongside their catalytic prowess in chemical transformations. By evaluating the current advantages, such as cost-effectiveness and reduced toxicity, alongside existing scalability challenges, the review underscores the significant future potential of this green methodology. It ultimately positions plant-mediated synthesis as a vital pathway for advancing sustainable nanotechnology and pioneering new biomedical applications.

Keywords: Green synthesis, Ruthenium nanoparticles, Plant-mediated synthesis, Phytochemicals, Biomedical applications, Catalysis.

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1. INTRODUCTION

Nanoparticles (NPs) are ultrafine particles with dimensions ranging between 1 and 100 nanometers in any dimension. Owing to their extremely small size and high surface area-to-volume ratio, nanoparticles exhibit unique physicochemical properties that differ markedly from their bulk counterparts [1, 2]. These properties include enhanced mechanical strength, chemical reactivity, electrical conductivity, and optical behavior, which enable their application across a wide spectrum of scientific fields [3, 4]. The synthesis of nanoparticles has traditionally relied on chemical and physical methods. However, these techniques often involve toxic reagents, high energy input, and hazardous byproducts, raising environmental and safety concerns [5]. The physical route of synthesis requires costlier instruments further the nanomaterials produced from physical route of synthesis are non-uniform. Therefore, there was extreme need for the development of a suitable method, which could produce nanomaterials of uniform size. Thus, there was development of chemical route of synthesis. Again, there was problem that chemical route of synthesis needs hazardous chemicals. When materials at nanoscale is to be used for biological applications then it should be free from hazardous chemicals [6-8]. Considering this, there was the development of biological route of synthesis for the nanomaterials. In earlier attempts, various microbes were for the synthesis of materials at nanoscale. However, it was difficult to maintain aspect condition for the growth of microorganisms. Thus, the researchers tried to turn towards green route of synthesis using plant extracts, Plants contain various heterocyclic organic compounds, which contain Nitrogen atom. The

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Nitrogen atom present in heterocyclic organic compound acts as electron donor. Thus, various plant extract acts as natural reducing agent [9-11].

The synthesized nanomaterials exhibit different properties than their bulk counterparts and hence finds applications in diverse area such as gas sensing, supercapacitors, chemical sensors, Nano-catalyst and so on [12-14]. It is well known that various molecules cannot cross blood brain barrier. Thus, it becomes difficult to treat brain related disease. Glioma is a deadly tumor observe due to uncontrolled growth of glial cells. The treatment of glioma or any other brain tumor is very difficult owing to inability of the drug molecule to penetrate into brain. However, due to extremely small size and biocompatible nature, the nanomaterials can effectively cross blood brain barrier. Thus, use of nanomaterial is the hope for the treatment of neurological disease. Here it is worth to mention that the effect of nanomaterial on brain issue is equally important [15, 16]. Apart from medicinal field the nanomaterials are effectively used for various purposes such as in environmental science for degradation of heavy molecular weight organic compounds, in energy storage devices, in solar cells and so on [17, 18].

Moreover, nanoparticles synthesized via green methods often exhibit enhanced biocompatibility and stability, making them particularly suitable for biomedical applications such as drug delivery, antimicrobial treatments, and anticancer therapies. This biogenic approach aligns with the principles of green chemistry and supports the development of sustainable nanotechnology that minimizes risks to human health and the environment [8, 19-21]. In the context of metal nanoparticles like ruthenium, which are known for their potent catalytic, antimicrobial, and therapeutic properties, green synthesis provides a viable route to harness these benefits without the associated toxicological implications of chemical synthesis. The utilization of a medicinal plant with well-documented pharmacological activities, not only offers a bio-based route for nanoparticle synthesis but also contributes to the valorization of native and underutilized plant resources [22-24]. Ultimately, eco-friendly synthesis strategies present a critical step toward sustainable nanoscience, ensuring that the advances in nanotechnology do not come at the expense of environmental integrity or public health [25, 26].

Ruthenium nanoparticles (Ru NPs), composed of the rare transition metal ruthenium (Ru), have garnered increasing attention due to their exceptional physicochemical and catalytic properties. As a member of the platinum group metals (PGMs), ruthenium exhibits characteristics such as multiple oxidation states, high thermal and chemical stability, and excellent redox behavior, making it a highly versatile material for various scientific and technological applications [27-29]. One of the most prominent features of Ru NPs is their remarkable catalytic efficiency, which has been widely exploited in organic transformations, hydrogenation reactions, and fuel cell technologies. Their high surface-to-volume ratio and ability to stabilize reaction intermediates render them superior catalysts in comparison to their bulk counterparts [30, 31]. Notably, Ru NPs are integral to electrocatalysis in water splitting, hydrogen evolution, and oxygen reduction reactions, processes that are crucial for sustainable energy solutions [32, 33].

Beyond catalysis, Ru NPs have shown promising biomedical applications. Due to their biocompatibility and tunable surface chemistry, Ru NPs have been studied for drug delivery, photothermal therapy, and as antimicrobial agents. Ruthenium-based compounds have already demonstrated anticancer activity, and nanoscale formulations may enhance their therapeutic index while reducing systemic toxicity [34, 35]. Figure 1 exhibits the graphical representation of plant-mediated synthesis of Ruthenium nanoparticles, characterization and biological activities.

In the field of environmental science, Ru NPs contribute to pollutant and dyes degradation and water treatment by facilitating advanced oxidation processes. Their redox-active nature enables them to degrade organic contaminants in aqueous environments efficiently [36]. Furthermore, their stability under harsh environmental conditions makes them suitable candidates for long-term applications. Recent interest has also emerged in the green synthesis of Ru NPs using biological systems such as plant extracts. This approach not only reduces the use of toxic reagents and harsh conditions but also enhances the biocompatibility of the resulting nanoparticles, opening avenues for safer biomedical and environmental applications [37, 38]. Ru NPs represent a class of multifunctional nanomaterials with broad application potential spanning catalysis, medicine, energy, and environmental remediation. Their synthesis via eco-friendly methods further amplifies their value, particularly in the context of sustainable nanotechnology. The utilization of plant extracts in the synthesis of nanoparticles represents a sustainable and environmentally benign alternative to conventional chemical and physical methods. Plants contain a diverse array of bioactive phytochemicals such as flavonoids, terpenoids, alkaloids, phenolics, and sugars, which act as natural reducing, capping, and stabilizing agents during nanoparticle formation [39, 40]. These biomolecules facilitate the conversion of metal ions into stable nanoparticles under mild reaction conditions, typically without the need for high temperatures, pressures, or toxic solvents.

The mechanism of nanoparticle formation using plant extracts generally involves the donation of electrons from phytochemicals to metal ions, reducing them to their zerovalent state. Concurrently, secondary metabolites bind to the nanoparticle surface, preventing aggregation and ensuring colloidal stability [41-44]. This process is not only simple and scalable but also cost-effective and compatible with green chemistry principles. Plant-mediated synthesis not only aligns with the global pursuit of green and sustainable technologies but also imparts additional bifunctionalities to the nanoparticles. For instance, nanoparticles synthesized using medicinal plant extracts often exhibit intrinsic antimicrobial and antioxidant properties derived from the phytochemicals involved in their formation [45, 46].

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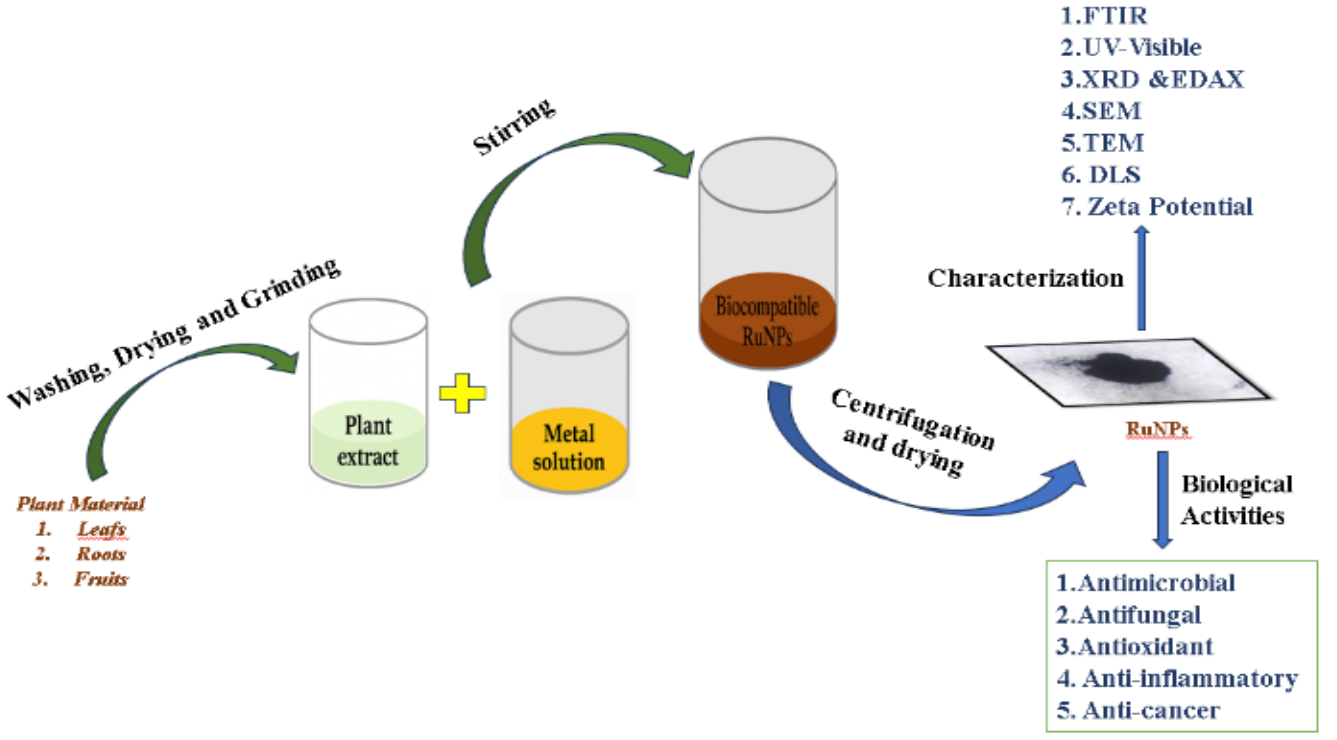

Fig. 1. Graphical representation of Plant-Mediated Synthesis of Ruthenium Nanoparticles, characterization and Biological Activities.

This dual-functionality is especially beneficial in biomedical and environmental applications where efficacy and safety are critical. Moreover, this approach addresses the limitations of microbial synthesis, such as the need for sterile conditions and longer synthesis times. Plants offer a rapid, safe, and reproducible platform for nanoparticle synthesis, making them ideal candidates for industrial-scale production [47, 48].

2. PLANT-MEDIATED SYNTHESIS OF RUTHENIUM NANOPARTICLES

The use of plant extracts for the synthesis of ruthenium nanoparticles (Ru NPs) offers a promising eco-friendly alternative to conventional chemical and physical methods. This approach utilizes various bioactive compounds present in plants, such as polyphenols, flavonoids, alkaloids, terpenoids, and carbohydrates, to reduce metal ions into their nanoparticle forms, while also capping and stabilizing the nanoparticles [5, 38, 42]. The green synthesis of Ru NPs through plant extracts presents several advantages, including simplicity, cost-effectiveness, and environmental sustainability. The process typically involves mixing plant extracts with metal salt solutions (such as $RuCl_3$), where the bioactive compounds in the plant extracts donate electrons to reduce the metal ions, resulting in the formation of nanoparticles. The plant extract also serves to stabilize the nanoparticles, preventing aggregation and ensuring their colloidal stability [9, 49, 50]. Figure 2 exhibits the schematic for the synthesis of biogenic nanoparticles. Table 1 demonstrates the common plant extracts used for Ruthenium nanoparticles (Ru NPs) synthesis. Common plant extracts used for Ru NPs synthesis are as follows:

2.1. *Gloriosa superba*

Gloriosa superba L., commonly known as the flame lily, is a pharmacologically significant climbing plant celebrated both for its striking beauty and its potent bioactive constituents. Beyond its traditional medicinal uses, its chemical profile, rich in flavonoids, alkaloids (notably colchicine), tannins, saponins, and phenolic compounds, renders it a highly effective agent in the domain of green nanotechnology. These metabolites function as dual-purpose bioreducing and stabilizing agents, facilitating the eco-friendly synthesis of metallic nanoparticles without toxic byproducts.

While research has primarily documented *G. superba's* efficacy in producing antimicrobial silver and gold nanoparticles, this established success strongly advocates for its potential in synthesizing more complex nanomaterials, such as ruthenium nanoparticles (Ru NPs). The plant's proven capability to reduce metal ions and cap nascent nanostructures suggests it could provide a sustainable, plant-based route for Ru NP fabrication. Given ruthenium's important applications in catalysis, electronics, and emerging biomedical therapies, utilizing *G. superba* extract aligns with the principles of green chemistry.

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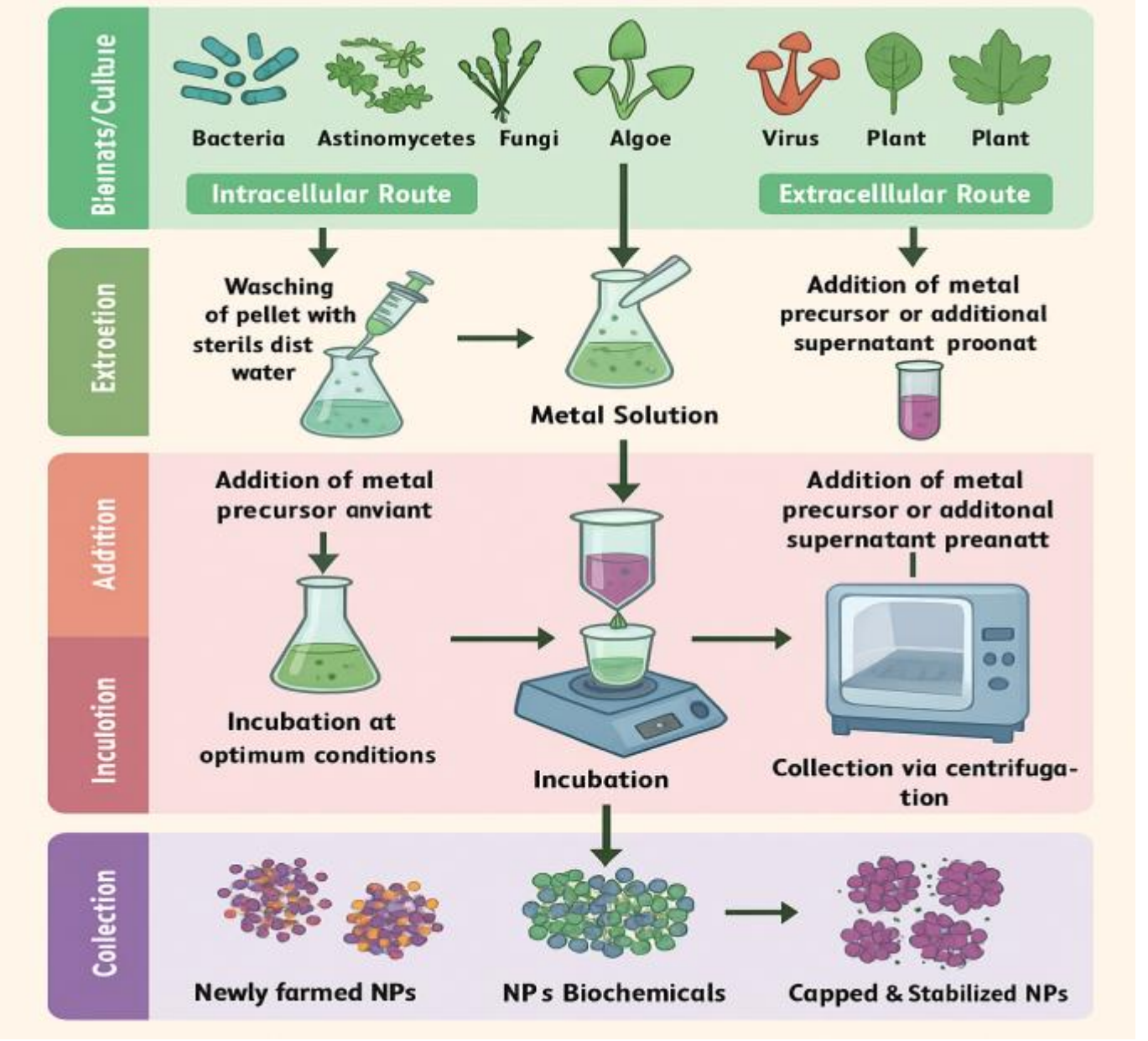

Fig. 2. Biogenetic Synthesis of Nanoparticles.

It offers a promising, biocompatible alternative to conventional physical and chemical methods, warranting further investigative focus to fully harness this botanical resource for advanced nanomaterial synthesis [37].

2.2. *Acalypha indica*

Acalypha indica is a highly valued medicinal herb in traditional Indian systems, renowned for its diverse therapeutic applications. Its pharmacological potential stems from a complex phytochemical composition rich in flavonoids, alkaloids, tannins, phenolic acids, and saponins. Beyond direct medicinal use, these bioactive compounds have positioned the plant as an excellent resource in green nanotechnology. They act as effective, non-toxic reducing and capping agents for the eco-friendly synthesis of metallic nanoparticles, eliminating the need for harsh chemicals. Specifically, extracts from A. indica have been successfully utilized to produce antimicrobial and antioxidant silver, copper, and zinc oxide nanoparticles. While documented use for synthesizing ruthenium nanoparticles (Ru NPs) remains scarce, the plant's proven efficacy with other metals strongly indicates its untapped potential for Ru NP biosynthesis. Given ruthenium's significant catalytic and biomedical interest, employing *A. indica* offers a promising, sustainable route. Its natural abundance, biocompatibility, and potent phyto-constituent profile make it an ideal candidate for developing eco-friendly nanomaterials for advanced applications in catalysis, drug delivery, and targeted therapies, aligning with the principles of green chemistry [51].

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Table 1. Common Plant Extracts Used or Proposed for Ruthenium Nanoparticle (RuNP) Synthesis.

S. No.	Plant Name	Phytochemicals Present	Use in RuNP Synthesis	Other Metal NPs Synthesized	Observed Activities	Ref.
1	*Gloriosa superba*	Flavonoids, alkaloids, tannins, saponins, phenolics	Potential (limited studies)	Ag, Au	Antibacterial	[37]
2	*Acalypha indica*	Flavonoids, alkaloids, tannins, phenolic acids, saponins	Yes (Used in RuNP synthesis)	Ag, Cu, ZnO	Antibacterial	[51]
3	*Cacumen Platycladi (Platycladus orientalis)*	Flavonoids, lignans, phenolics, essential oils	Yes (Used in RuNP synthesis)	Ag, Au	Catalytic	[52]
4	*Caryota urens (Fishtail fern)*	Flavonoids, tannins, phenolics	Yes (Used in RuNP synthesis)	Ag, Cu	Antioxidant and antifungal activities	[53]
5	*Cycas revoluta (Sago palm)*	Saponins, flavonoids, polyphenols	Yes (Used in RuNP synthesis)	Ag, Au	Antioxidant and antifungal activities	[53]
6	*Catharanthus roseus (Rosy periwinkle)*	Alkaloids, flavonoids, terpenoids, phenolics	Yes (Used in RuNP synthesis)	Ag, Au	Antioxidant, antifungal activities and Catalytic	[53]
7	*Ocimum sanctum (Holy basil)*	Flavonoids, phenolics, essential oils, tannins	Yes (Used in RuNP synthesis)	Ag, Au, ZnO	antioxidant and antifungal activities	[53]
8	*Anacyclus pyrethrum*	Alkaloids, flavonoids, phenolics, essential oils	Yes (Used in RuNP synthesis)	Ag, Au	Supercapacitor	[54]
9	*Moringa oleifera*	Flavonoids, tannins, phenolic acids	Yes (Used in RuNP synthesis)	Ag, Au	Catalytic, antimicrobial	[55]
10	*Gunnera perpensa*	Flavonoids, tannins, saponins, alkaloids, phenolics	Yes (Used in RuNP synthesis)	Ag, Au	Anticancer	[56]
11	*Iris kashmiriana*	Flavonoids, alkaloids, tannins, glycosides, essential oils	Yes (Used in RuNP synthesis)	Ag, Au	Antimicrobial, antioxidant	[57]
12	*Aloe vera*	Polysaccharides, vitamins, enzymes	Yes (Used in RuNP synthesis)	Ag, Au	Drug delivery, anticancer	[58]
13	*Causonis trifolia*	Flavonoids, tannins, phenolics, saponins, alkaloids	Yes (Used in RuNP synthesis)	Ag, ZnO	Antioxidant, anti-cancer	[59]

2.3. *Cacumen Platycladi*: The Coniferous Nano-Agent

Cacumen Platycladi, derived from the tender branchlets of *Platycladus orientalis* (Chinese arborvitae), is a cornerstone of traditional Chinese medicine, primarily used for its hemostatic, antitussive, and calming properties. Its

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pharmacological value is rooted in a complex matrix of bioactive compounds, including amentoflavone and other biflavonoids, lignans like hinokiresinol, phenolic acids (e.g., caffeic acid, ferulic acid), and volatile essential oils. phenolic acids act as potent electron donors, reducing metal ions (Ru^{3+}/Ru^{4+}) to their zero-valent metallic state (Ru^0). Concurrently, these large organic molecules adsorb onto the nascent nanoparticle surfaces, providing steric or electrostatic stabilization that prevents aggregation, thus controlling size and morphology. While literature specifically on Ru NPs remains sparse, the extract's documented success in producing well-dispersed, biologically active silver and gold nanoparticles with significant antimicrobial and catalytic efficacy forms a compelling precedent. The inherent antioxidant and anti-inflammatory properties of its constituent phytochemicals could also be imparted to the synthesized Ru NPs, enhancing their biocompatibility for therapeutic applications such as targeted cancer treatment or as nano-catalysts in green chemistry reactions [52].

2.4. Fishtail Fern (*Caryota urens*): A Tropical Phytochemical Reservoir

The Fishtail Fern, native to tropical Asia, is not only an ornamental plant but also a source of traditional remedies. Its leaves are a treasure trove of polyphenols, including condensed tannins (proanthocyanidins) and flavonoid glycosides. These compounds are characterized by multiple phenolic hydroxyl groups, making them excellent natural reductants. In the context of nan synthesis, the polyphenolic skeleton facilitates the rapid reduction of metal precursors. The documented synthesis of silver and copper nanoparticles using *C. urens* extract results in particles with pronounced antioxidant and antifungal activities, a direct transfer of the plant's own bioactivity. This "bio-functionalization" is key for Ru NP applications. Ruthenium-based complexes are already known in chemotherapy, such as KP1019, NAMI-A; synthesizing Ru NPs using *C. urens* could yield a novel nanoplatform where the Ru core provides therapeutic activity, and the phytochemical capping layer offers additional antioxidant protection to healthy cells, mitigating side effects. Its potential in creating stable, bioactive Ru NPs for antifungal coatings or catalytic degradation of environmental pollutants is significant and warrants dedicated investigation [53].

2.5. Sago Palm (*Cycas revoluta*): An Ancient Cycad with Modern Nano-Utility

Cycas revoluta, one of the most ancient plant species, contains unique phytochemicals like cycasin and macrozamin, alongside common but potent agents like saponins and biflavonoids (amentoflavone, hinokiflavone). Saponins, with their amphiphilic glycosidic structure, are particularly intriguing. They can act as both reducing agents (via their aglycone moiety) and exceptional bio-surfactants, directing the formation of nanoparticles with very specific shapes and sizes. The successful green synthesis of silver nanoparticles using *C. revoluta* leaf extract, yielding particles with strong antifungal activity against plant pathogens, demonstrates this capability. For Ru NP synthesis, saponins could facilitate the creation of highly dispersed, small-sized nanoparticles critical for catalytic surface area and tissue penetration in biomedical applications. The biflavonoids further contribute robust antioxidant capping. Exploring this ancient plant for Ru NP synthesis bridges botanical antiquity with cutting-edge nanotechnology, potentially opening avenues for novel anticancer Ru nano-formulations [53].

2.6. Rosy Periwinkle (*Catharanthus roseus*): A Pharmaceutical Powerhouse

Catharanthus roseus is pharmacologically legendary as the source of the vinca alkaloids vinblastine and vincristine, used in cancer chemotherapy. Beyond these potent alkaloids, it contains a vast array of other indole alkaloids, terpenoid indole alkaloids, flavonoids, and phenolic acids. This makes its extract a uniquely powerful and multifaceted cocktail for nanoparticle synthesis. Alkaloids can act as nitrogen-donor ligands, potentially forming interesting coordination complexes with ruthenium during synthesis, influencing the electronic properties of the final NP. The plant's proven track record in producing highly stable and catalytically active silver and gold nanoparticles suggests an extract capable of fine-tuned reduction kinetics. For Ru NPs, this could translate to superior control over oxidation states and surface chemistry, which are crucial for their catalytic performance in reactions like hydrogen evolution or ammonia synthesis. Moreover, the synergistic potential of a Ru NP capped with *C. roseus* alkaloids could be explored for enhanced, multi-targeted anticancer activity [53].

2.7. Holy Basil (*Ocimum sanctum*): The Quintessential Elixir of Life

Revered in Ayurveda as "Tulsi" or "The Incomparable One," *Ocimum sanctum* is adaptogenic, antimicrobial, and anti-inflammatory. Its nano-synthesis capability stems from high concentrations of eugenol (a phenylpropanoid), rosmarinic acid, and various flavonoids like orientin and vicenin. Eugenol, with its allylic and phenolic groups, is a particularly effective reductant. Extensive studies show *O. sanctum* can synthesize a wide range of nanoparticles (Ag, Au, ZnO, CuO) with enhanced biological activities. The biosynthesis of Ru NPs using Tulsi is a logical and promising extension. The adaptogenic and radioprotective properties of the phytocapping could be particularly valuable in creating Ru NPs for radiotherapy sensitization or for mitigating oxidative stress in diseased tissues. Its antimicrobial capping could also lead to Ru NPs useful in antibiotic-resistant

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biofilm disruption [53].

2.8. *Anacyclus pyrethrum*: The Potent Unani Medicament

Anacyclus pyrethrum (Akarkara) root is a stimulant and sialagogue in traditional medicine, rich in N-alkylamides (pellitorine), alkaloids like pyrethrine, and flavonoids. The N-alkylamides are interesting bioactive lipophiles that could facilitate reduction and provide a unique hydrophobic capping layer, potentially improving the biocompatibility and cellular uptake of Ru NPs. Its successful use in synthesizing antimicrobial silver nanoparticles confirms its reducing potency. For Ru NPs, this could mean the creation of particles with a distinct surface chemistry that optimizes them for crossing biological barriers like the blood-brain barrier, expanding their utility in treating neurological cancers or infections [54].

2.9. *Moringa oleifera*: The Prolific and Proven Workhorse

Moringa oleifera stands out as one of the most extensively studied and successful plants for green nanoparticle synthesis, including for Ru NPs [55]. Its leaves are exceptionally rich in antioxidants, quercetin, kaempferol, and chlorogenic acid, making reduction rapid and efficient. The synthesis of Ru NPs using *Moringa* is not just potential but documented, resulting in nanoparticles with excellent catalytic activity in organic transformations and pronounced antimicrobial properties. This establishes *Moringa* as a benchmark against which the Ru NP synthesis potential of other plants can be measured. Its reliability, speed, and the superior functionality of its produced NPs solidify its role as a premier bio-resource in nanobiotechnology.

2.10. *Gunnera perpensa*: The Indigenous African Contributor

Gunnera perpensa (River Pumpkin), used in southern African medicine for various ailments, contains bioactive saponins, flavonoids, and tannins. Its reported use in synthesizing gold nanoparticles with anti-cancer properties is highly significant. This indicates that its phytocapping can confer direct cytotoxic activity to nanoparticles. Applying this to Ru NP synthesis is exceptionally promising, as it could yield a "double-barreled" therapeutic agent: the intrinsic cytotoxicity of Ru NPs combined with the plant's own anti-proliferative phytochemicals. This represents a compelling model for developing novel, plant-enhanced nanomedicines for oncology, rooted in indigenous knowledge [56].

2.11. *Iris kashmiriana*: The Himalayan Perennial

This less-explored but phytochemically rich plant from the Himalayas contains iridal-type triterpenoids, unique to the Iridaceae family, along with flavonoids and glycosides. These triterpenoids could impart novel surface functionalization to nanoparticles. Its demonstrated ability to synthesize bioactive silver nanoparticles suggests strong reducing capacity. For Ru NPs, *I. kashmiriana* offers the opportunity to create particles with a unique botanical fingerprint, potentially possessing novel biological activities worthy of exploration in drug discovery and nanomedicine [57].

2.12. *Aloe vera*: The Ubiquitous Healing Gel

Aloe vera gel is a complex mixture of polysaccharides (acemannan, glucomannan), vitamins, and enzymes. Its mechanism in NP synthesis often involves the hydroxyl groups of polysaccharides and the redox action of enzymes. Its documented use in Ru NP synthesis for drug delivery and wound healing, leveraging the gel's inherent biocompatibility and bioadhesive properties, is a key success story [58]. The polysaccharide coat can facilitate targeted delivery and provide a hydrogel-like matrix, making Ru NPs suitable for topical or injectable therapeutic formulations with anticancer and healing benefits.

2.13. *Causonis trifolia*: The Climbing Phytochemical Source

This fast-growing climber is rich in flavonoids and saponins, with reported anti-cancer properties. Its effectiveness in synthesizing zinc oxide nanoparticles points to an ability to handle metal oxides, which is relevant for synthesizing RuO_2 nanoparticles or controlling the surface oxidation state of Ru NPs. The resulting Ru NPs from *C. trifolia* could be prime candidates for investigating plant-mediated combination therapy in cancer and as catalysts in environmental remediation processes [59].

The collective phytochemical richness of these medicinal plants, from the flavonoids of *Cacumen Platycladi* to the saponins of *Gunnera perpensa* and the polysaccharides of *Aloe vera,* establishes a formidable toolkit for the green synthesis of ruthenium nanoparticles. While only *Moringa oleifera* and *Aloe vera* have documented reports for Ru NP synthesis, the consistent success of all these species in producing other metallic nanoparticles with enhanced biological and catalytic functions provides a robust, rational foundation for their exploration with ruthenium. The future of this field lies in moving beyond proof-of-concept synthesis to meticulous optimization of parameters (pH, temperature, concentration) to control Ru NP size, shape, and crystallinity. Detailed mechanistic studies on the role of specific phytochemicals, comprehensive characterization of the phytocapping layer, and in-depth evaluation of the resulting Ru NPs in targeted catalytic and biomedical applications are essential next steps. By harnessing this botanical diversity, researchers can develop libraries of bio-functionalized Ru NPs, paving the

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way for sustainable, effective, and novel solutions in nanotechnology, medicine, and environmental science.

3. MECHANISMS OF PLANT-MEDIATED SYNTHESIS OF RUTHENIUM NANOPARTICLES

The green synthesis of ruthenium nanoparticles (Ru NPs) using plant extracts involves several key mechanisms, including the reduction, stabilization, and capping of ruthenium ions. These processes are mediated by various bioactive compounds naturally present in plants, such as polyphenols, flavonoids, alkaloids, and proteins. These compounds play critical roles in reducing metal salts into nanoparticles while also stabilizing and capping them to prevent aggregation [47]. Understanding these mechanisms is essential for optimizing the synthesis of Ru NPs and tailoring their properties for specific applications. The general mechanism for synthesis of ruthenium nanoparticles is shown in Figure 3.

3.1. Reduction Mechanism

The reduction of metal ions (such as Ru^{6+} or Ru^{3+}) to their nanoparticle forms (Ru^0) is a critical step in plant-mediated nanoparticle synthesis. In this process, bioactive compounds in the plant extract act as reducing agents by donating electrons to the metal ions, converting them into their elemental form. The main reducing agents typically involved are:

Phenolic compounds: These compounds, including flavonoids and tannins, have hydroxyl groups (-OH) that readily donate electrons to metal ions, reducing them to their nanoparticulate form. The aromatic rings in phenolic compounds also help stabilize the nanoparticles by preventing aggregation [5, 11, 60].

Terpenoids: These natural compounds, often found in essential oils of plants like Cinnamomum camphora and Ocimum sanctum, are also involved in the reduction of metal salts by donating electrons from their hydroxyl groups or conjugated double bonds [9, 61].

Carbohydrates: Simple sugars and polysaccharides in plants can donate electrons during the reduction process. These compounds also play a role in stabilizing the formed nanoparticles [50, 55, 62].

3.2. Stabilization Mechanism

Once the metal ions are reduced to nanoparticles, the next challenge is to stabilize them to prevent aggregation, which can lead to a loss of desired properties (such as catalytic or antibacterial activity). Plant-derived compounds play a crucial role in preventing particle agglomeration and ensuring the colloidal stability of Ru NPs. Bioactive molecules as stabilizing agents: Compounds such as proteins, flavonoids, and polysaccharides act as natural stabilizers by forming a protective layer around the nanoparticles. These molecules create electrostatic or steric repulsion between nanoparticles, preventing their aggregation [63]. Polyphenols and proteins: In plants like Neem and Aloe vera, polyphenols and proteins contribute to the stabilization of nanoparticles by forming complexes with the surface of the particles. These molecules prevent the nanoparticles from sticking together and help maintain their size and shape [64, 65].

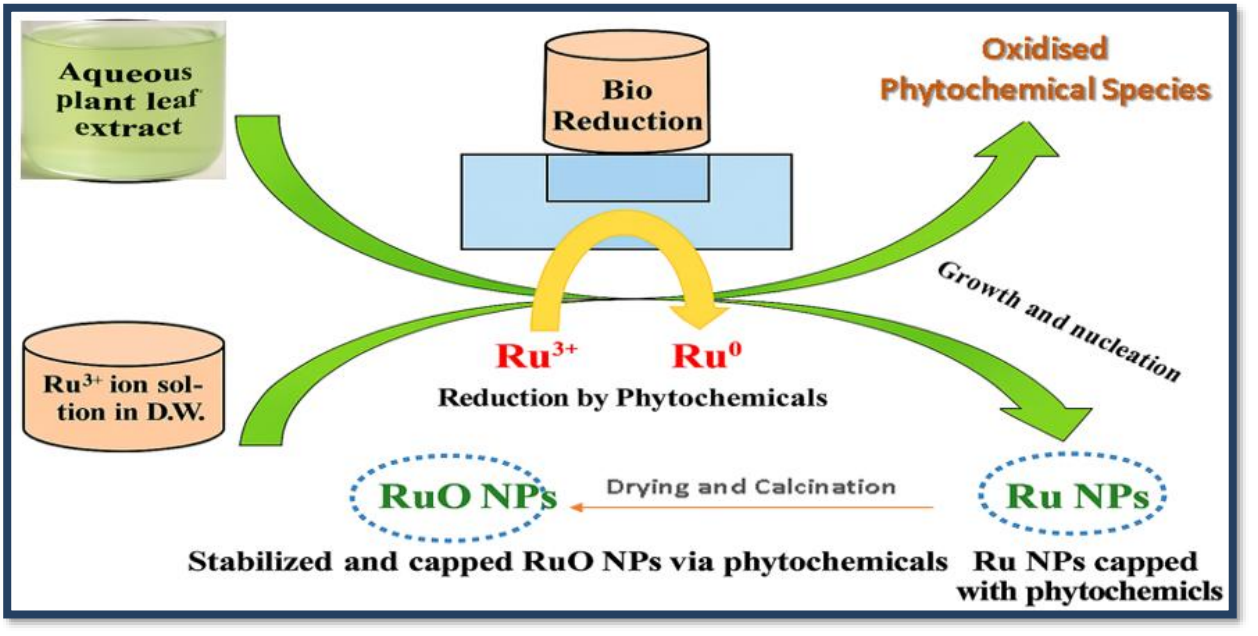

Fig. 3. General mechanism for the formation of Ruthenium nanoparticles.

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3.3. Capping Mechanism

In addition to stabilization, capping agents are crucial in controlling the size, shape, and distribution of nanoparticles. Plant extracts serve as capping agents that bind to the surface of the nanoparticles, forming a protective layer that prevents further growth and agglomeration [45, 66]. The bioactive compounds in plant extracts, such as polyphenols, flavonoids, and proteins, cap the surface of the nanoparticles by binding to the metal atoms, thereby controlling the growth of the particles. This capping layer also prevents the nanoparticles from reacting with other substances, enhancing their stability and prolonging their shelf life [53, 67].

3.4. Role of the Plant Matrix

The plant matrix (the overall extract) plays a supportive role in the synthesis of Ru NPs. In many cases, the synergy between various compounds present in the extract ensures efficient reduction, stabilization, and capping of the nanoparticles. This interaction between different plant molecules allows for the creation of nanoparticles with enhanced functional properties. The combined effect of multiple bioactive compounds in the plant extract ensures that the nanoparticles are not only stable but also possess desirable functional properties, such as antimicrobial or catalytic activity. The plant's matrix, including water-soluble sugars, proteins, and secondary metabolites, contributes to the overall effectiveness of the green synthesis method [68-70].

4. FACTORS INFLUENCING PLANT-MEDIATED SYNTHESIS OF RUTHENIUM NANOPARTICLES

The plant-mediated synthesis of ruthenium nanoparticles (Ru NPs) represents a sophisticated intersection of green chemistry, nanotechnology, and botany. While the principle, using phytochemicals as reducing, capping, and stabilizing agents, is elegantly simple, the process itself is governed by a complex interplay of physicochemical parameters [71-77]. These factors do not act in isolation but form a dynamic network that dictates the critical outcomes of the synthesis: nanoparticle size, morphology (shape), crystallinity, dispersion stability, surface chemistry, and ultimately, their functional efficacy in applications ranging from catalysis to oncology [78-89]. Mastering this parameter space is not merely an optimization exercise but a fundamental requirement for transforming this green approach from a laboratory curiosity into a reliable, scalable nanotechnology platform. The following detailed analysis deconstructs these key influencing factors, elucidating their mechanistic roles and practical implications [90].

To illustrate the versatility and efficacy of the phytogenic approach, Table 2 consolidates representative examples from recent research. It highlights how diverse plant extracts facilitate the synthesis of predominantly spherical Ru NPs, with sizes typically tunable within the 5–60 nm range. The table underscores the broad spectrum of applications enabled by these green-synthesized nanomaterials, spanning from biomedical uses (antimicrobial, anticancer, drug delivery) to catalytic environmental remediation and cutting-edge energy storage and conversion technologies [91-97]. This compilation demonstrates the direct link between the green synthesis method and functional performance in advanced applications. Figure 4 shows the schematic diagram illustrating the key parameters (pH, temperature, precursor concentration, reaction time, plant extract composition) influencing the green synthesis and final properties of ruthenium nanoparticles.

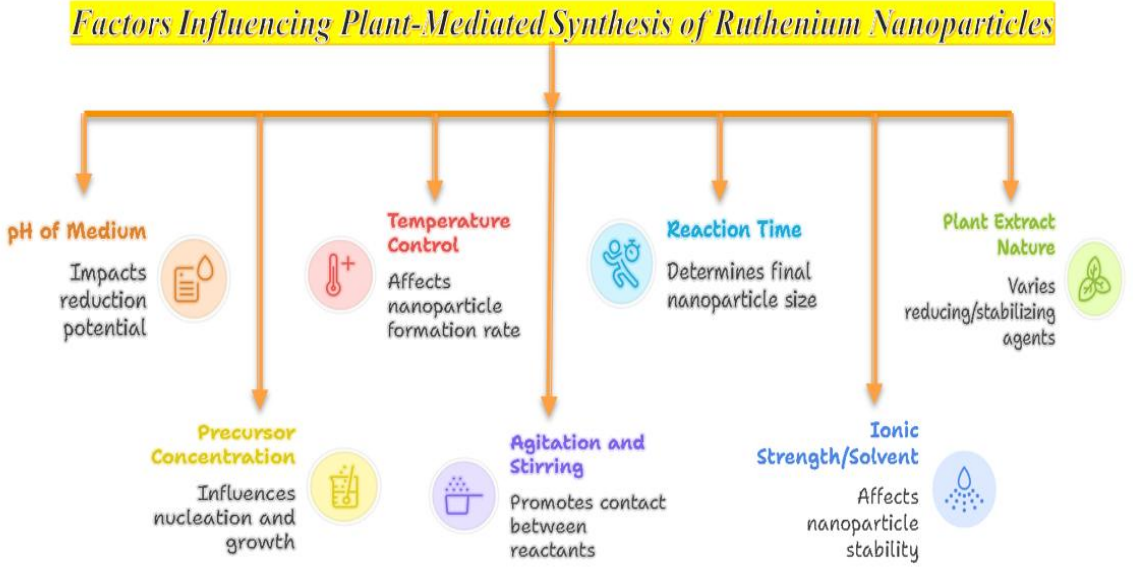

Fig. 4. Key Factors Influencing Green Synthesis of Ruthenium Nanoparticles.

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Table 2. Representative examples of plant-mediated synthesis of Ruthenium Nanoparticles (Ru NPs): Bio-sources, key applications, and resulting nanoparticle characteristics.

S. No	Plant Extract Used	Role of Ru NPs	Average Size (nm)	Shape	Ref.
1.	*Cacumen Platycladi*	Catalytic hydrogenation of maleic anhydride	~10–20	Spherical	[52]
2.	*Moringa oleifera*	Catalytic dye degradation and Antimicrobial	~15–30	Spherical	[55]
3.	*Catharanthus roseus*	Catalytic dye degradation and Antimicrobial	~5–20	Spherical	[55]
4.	*Iris kashmiriana*	Antimicrobial	~20–40	Spherical	[57]
5.	*Gloriosa superba L. leaf*	Antimicrobial	~20–40	Spherical	[37]
6.	*fishtail fern, sago palm, rosy periwinkle and holy basil*	Antifungal, Antioxidant	~10–30	Spherical	[53]
7.	*Andrographis Paniculata*	Antibacterial	20 to 60 nm	Spherical	[92]
8.	*Causonis trifolia*	Antioxidant & anti-skin cancer	~10–25	Spherical	[59]
9.	*Aloe vera*	Drug delivery, anticancer	~20–50	Spherical	[58]
10.	*Gunnera perpensa*	Anticancer (MCF7)	~15–35	Spherical	[56]
11.	*Anacyclus pyrethrum*	Supercapacitor / energy storage	Not specified	Spherical	[93]
12.	Ru NPs based functional nanomaterials	Sensor applications (electrochemical)	Not specified	Spherical	[94]
13.	Generic green Ru NPs	Li–CO_2 battery catalyst	~5–10	Spherical	[95]
14.	Generic organic hybrid Ru NPs	High-performance supercapacitors	~5–20	Spherical	[96]
15.	Ruthenium nanocrystals	Cathode catalyst for Li–O_2 battery	~2–10	Spherical	[97]

4.1. pH of the Reaction Medium: The Master Regulator of Phytochemical Activity and Surface Charge

The pH of the reaction medium is arguably the most critical and nuanced parameter in green synthesis. It acts as a master switch, profoundly influencing the electronic state of both the metal precursor ions and the bioactive phytoconstituents, thereby governing reduction kinetics, nucleation rates, and colloidal stability.

Mechanistic Influence: The pH directly alters the ionization state of the functional groups in plant phytochemicals. Phenolic compounds, such as flavonoids, tannins, phenolic acids, the workhorses of plant-mediated reduction, possess hydroxyl groups whose protonation state is pH-dependent. In highly acidic conditions (low pH), these groups are predominantly protonated (-OH), which can diminish their electron-donating capacity, slowing the reduction rate of Ru^{3+}/Ru^{4+} ions. Furthermore, at low pH, the electrostatic repulsion between nascent nanoparticle nuclei is minimized (point of zero charge is approached), leading to rapid aggregation and the formation of larger, irregular, and often

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polydisperse particles with poor stability. While some studies note that acidic conditions can sometimes promote initial reduction, the overall outcome is typically inferior control over monodispersity [80-84].

Optimal Range and Effects: Transitioning to neutral and, more effectively, slightly alkaline conditions (pH 7–10) unlocks the full potential of the phytochemical cocktail. In alkaline media, phenolic -OH groups undergo deprotonation to form phenolate anions ($-O^-$). These anions are significantly more potent reducing agents due to their enhanced electron density, leading to a faster and more complete reduction of ruthenium ions. This rapid nucleation often results in a larger number of small initial nuclei. Crucially, the anionic capping layer formed by these deprotonated compounds imparts a strong negative surface charge (high zeta potential) to the growing Ru NPs. This creates powerful electrostatic repulsion between particles, preventing aggregation and yielding a colloidal suspension of small, spherical, and highly stable nanoparticles. The alkaline environment can also influence the final oxidation state and crystal phase of the Ru NPs, potentially favoring the formation of metallic Ru(0) over oxide phases. Therefore, meticulous pH optimization, often through the dropwise addition of dilute alkali, such as NaOH, is essential. It is a primary tool for "tuning" particle size and stability, with alkaline conditions generally being the cornerstone for synthesizing high-quality, application-ready Ru NPs.

4.2. Temperature: Controlling Kinetic Energy and Thermodynamic Pathways

Temperature is the lever controlling the kinetic energy within the reaction system, directly impacting reaction rates, nucleation, growth phases, and the thermodynamics of nanoparticle formation.

The Kinetic Drive: Increasing the reaction temperature provides the activation energy required for the redox reaction between phytochemicals and ruthenium ions. Elevated temperatures, such as 60–90°C dramatically accelerate the reduction rate, leading to a rapid burst of nucleation. This can be advantageous for producing a high yield of small nanoparticles, as the high density of nuclei leaves less precursor available for Oswald ripening (where smaller particles dissolve and re-deposit onto larger ones). The increased molecular motion also promotes more uniform mixing of reactants.

The Risk of Thermal Coagulation: However, the relationship is not linear. Excessive heat introduces counterproductive effects. High kinetic energy increases the frequency of particle collisions. If the stabilizing capping layer is not robust enough or if the temperature destabilizes the phytochemicals themselves (denaturing proteins, degrading antioxidants), these collisions will result in irreversible aggregation and fusion, forming large, polydisperse aggregates. This thermal coagulation defeats the purpose of achieving a high surface-area-to-volume ratio, which is vital for catalytic and biological activity.

The Low-Temperature Alternative: Conversely, room-temperature or mildly elevated (30–50°C) syntheses, while slower, offer superior control. The slow reduction kinetics allow for a clear separation between the nucleation and growth phases. This facilitates better size focusing, where minor size variations are smoothed out over time, leading to highly monodisperse populations. It also preserves the integrity of delicate bioactive capping agents. The choice of temperature thus represents a strategic trade-off between synthesis speed and the degree of size/shape control required for the intended application.

4.3. Concentration of Metal Precursor: The Balance between Nucleation and Growth

The concentration of the ruthenium salt, such as $RuCl_3$, K_2RuCl_6, etc, is a fundamental variable that determines the availability of "building blocks" and directly shapes the competition between the nucleation of new particles and the growth of existing ones.

Low Precursor Concentration: When a dilute metal ion solution is used with a fixed amount of potent plant extract, the reduction potential is high relative to the number of metal ions. This leads to rapid, simultaneous nucleation of almost all available ions, resulting in a high number of very small nuclei. With limited remaining precursor in solution, subsequent growth is constrained, yielding a final product of small, relatively uniform nanoparticles. This scenario is ideal for achieving minimal size but may have a lower total yield.

High Precursor Concentration: Using a more concentrated precursor creates a different dynamic. The initial nucleation event still occurs, but the high concentration of surrounding Ru ions leads to rapid growth on these initial nuclei via diffusion and reduction. This often produces larger nanoparticles. More critically, if the concentration of metal ions overwhelms the reducing and capping capacity of the plant extract, it can lead to several problems: incomplete reduction, poor capping coverage, and ultimately, aggregation due to insufficient stabilization. The particles may also exhibit broader size distribution (polydispersity).

Therefore, optimization focuses not on absolute concentration alone, but on the molar ratio of metal precursor to reducing/capping agents in the extract. Finding the "sweet spot" ratio ensures complete reduction and the formation of a dense, passivating phytochemical layer on each nanoparticle, yielding a stable colloid with the desired particle size.

4.4. Reaction Time: Governing the Evolution from Nuclei

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to Mature Nanoparticles

Reaction time dictates the progression of the synthesis from initial reduction through to the maturation of the nanoparticles. It is intrinsically linked to temperature and concentration.

Short Duration Monitoring: In the initial minutes to a few hours, the reaction can be monitored for the development of the characteristic color change (often from the pale yellow of Ru^{3+} to a dark brown or black colloidal suspension of Ru NPs), indicating nucleation. Stopping the reaction at this early stage may harvest small, possibly crystalline nuclei. However, the reduction may be incomplete, and the particles may not have achieved their most stable configuration.

Extended Reaction Periods: Allowing the reaction to proceed for several hours or even days enables the system to approach thermodynamic equilibrium. During this time, several processes occur: Ostwald ripening can increase average size; the capping agents can rearrange into a more stable configuration on the particle surface; and any slow-reducing phytochemicals can complete their action. While this often leads to more stable and fully reduced nanoparticles, it can also result in increased size and, if the capping is ineffective, aggregation. The optimal time is thus the minimum required to achieve complete reduction and sufficient surface passivation without entering a regime of uncontrolled growth or degradation.

4.5. Nature of the Plant Extract

This is the defining variable of green synthesis. The plant extract is not a simple reagent but a complex, variable biochemical mixture that determines the very mechanism of synthesis.

Phytochemical Profile: As detailed in previous sections, the specific blend of reducing agents, for example, flavonoids, terpenoids, alkaloids) and capping/stabilizing agents, for instance proteins, long-chain polysaccharides, saponins, is unique to each plant species, its part (leaf, root, seed), extraction method, and even growth conditions. A flavonoid-rich extract, such as from Moringa, will drive fast reduction, while a polysaccharide-rich extract, such as from Aloe vera, may produce slower reduction but excellent steric stabilization.

Extract Concentration and Preparation: The concentration of the extract (weight of plant material per volume of solvent) determines the dosage of bioactive compounds. A more concentrated extract provides a higher driving force for reduction and more capping material, but excessive concentration can sometimes lead to interference or the formation of a thick, non-functional biomass coating. The extraction solvent (water, ethanol, methanol) and method (maceration, Soxhlet, ultrasound-assisted) also selectively pull different phytochemical classes into the reaction medium, fundamentally altering its nano-synthesis capability.

4.6. Agitation and Stirring: Engineering Mass Transport and Homogeneity

Often overlooked, agitation is an engineering parameter crucial for reproducibility and scalability.

Role of Mixing: Efficient stirring or agitation ensures homogeneous distribution of heat and reactants throughout the reaction vessel. This prevents local "hot spots" of high precursor concentration that can lead to runaway nucleation and broad size distributions. Uniform mixing guarantees that every metal ion has a statistically similar chance of encountering a reducing agent, promoting the formation of a monodisperse population.

Aggregation vs. Dispersion: Appropriate agitation keeps nanoparticles in motion, which can help prevent their sedimentation and aggregation at early stages. However, excessively vigorous stirring (especially with magnetic stir bars) can create high-shear zones that might physically damage weakly capped nanoparticles or induce cavitation if combined with heating. Optimized, consistent, and gentle-to-moderate agitation is a key to reproducible batch-to-batch synthesis.

4.7. Ionic Strength and Solvent Type: The Environmental Modulators

The reaction milieu itself, defined by solvent and dissolved ions, sets the stage for nanoparticle formation.

Ionic Strength: The presence of extraneous ions, such as from buffers or salts, increases the ionic strength of the solution. This compresses the electrical double layer surrounding the charged nanoparticles. High ionic strength effectively screens the electrostatic repulsion provided by anionic capping agents, destabilizing the colloid and promoting aggregation (salting-out effect). Therefore, synthesis is often best performed in low-ionic-strength aqueous media unless specific buffering is required to control pH precisely.

Solvent Choice: While water is the quintessential green solvent, its polarity and ability to dissolve both ionic precursors and polar phytochemicals make it ideal. Occasionally, aqueous-organic mixtures, for instance water-ethanol, are used. Ethanol can improve the solubility of certain non-polar phytochemicals (like some terpenoids) from the extract, potentially introducing different reducing/capping agents into the process. It can also slightly modify the dielectric constant of the medium, affecting nucleation kinetics. However, the core philosophy of green synthesis prioritizes water as the primary solvent.

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In practice, these factors are deeply interconnected. A change in pH can alter the effectiveness of the plant extract. The optimal reaction time is dependent on the chosen temperature. The required extract concentration is a function of the precursor concentration. Therefore, optimizing plant-mediated Ru NP synthesis is a multivariate challenge. Modern approaches employ statistical design-of-experiment (DoE) methodologies, such as Response Surface Methodology (RSM), to systematically explore these interactions and identify the precise combination of parameters that yields nanoparticles with tailored properties for a specific application, be it maximizing catalytic turnover frequency, optimizing plasmonic response, or enhancing cellular uptake for drug delivery. By mastering this intricate parameter space, researchers can fully harness the promise of plants as sustainable, versatile, and powerful nano-factories for the synthesis of advanced ruthenium nanomaterials.

5. APPLICATIONS OF PLANT-MEDIATED SYNTHESIS OF RUTHENIUM NANOPARTICLES

The true measure of any synthetic method lies in the utility and performance of the products it creates. Plant-mediated synthesis of ruthenium nanoparticles (Ru NPs) passes this test with distinction, yielding nanomaterials whose applications span from the heart of industrial chemistry to the frontiers of medicine and environmental science. The unique advantage of this green route is not merely in its process, but in the enhanced functionality it often imparts to the nanoparticles. Capped and stabilized by a corona of phytochemicals, these Ru NPs carry the inherent bioactivity and biocompatibility of their botanical origins into diverse and impactful roles. Table 2 and Figure 5 exhibits various applications of plant mediated ruthenium nanoparticles.

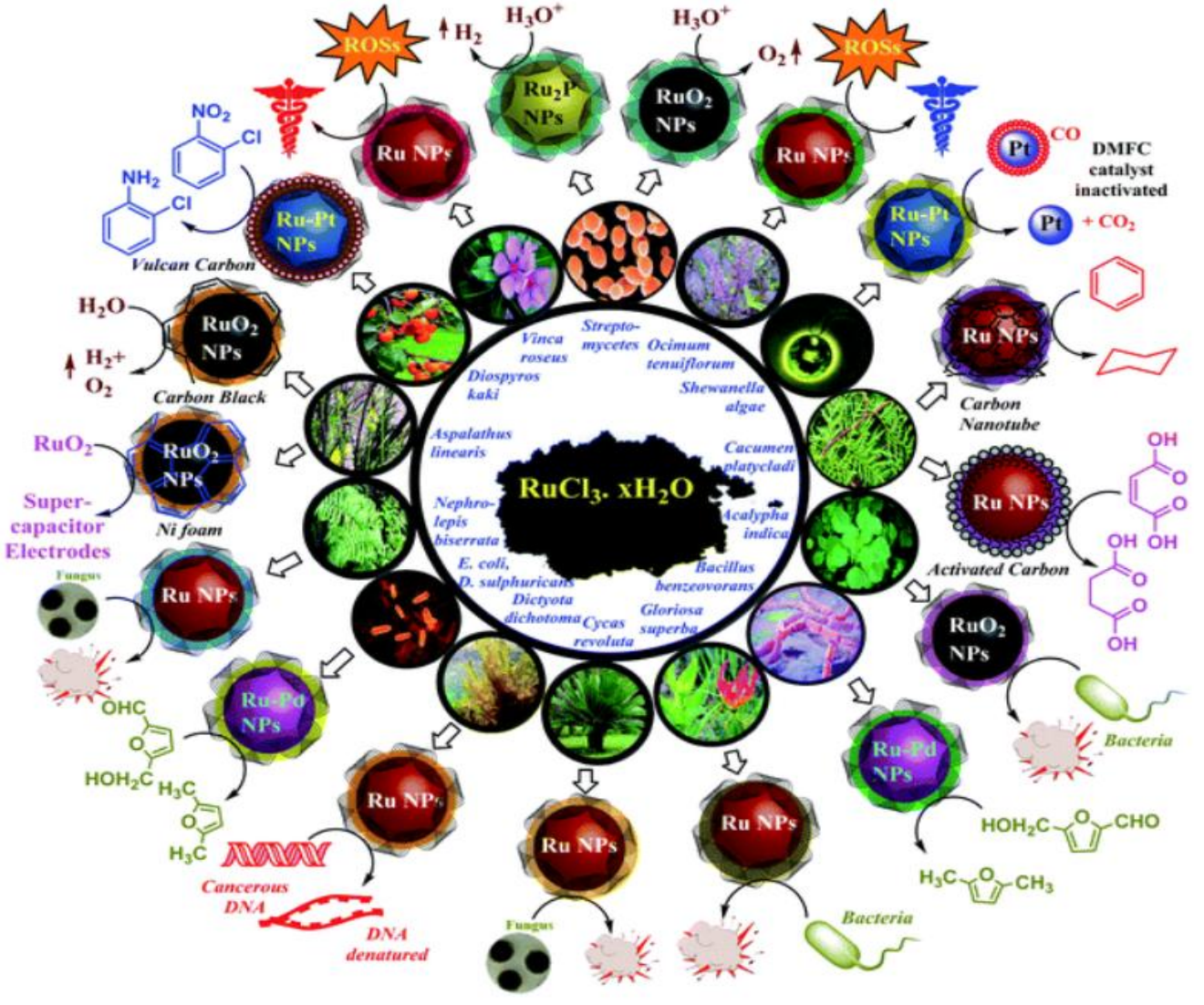

Fig. 5. Overview of Catalysis and Bioactivity of Ru-Based Nanomaterials. [Reprinted with permission from ref. [35], Gupta, P.K., Mishra, L., **2020**. Ecofriendly ruthenium-containing nanomaterials: synthesis, characterization, electrochemistry, bioactivity and catalysis, *Nanoscale Advances*, 2, pp. 1774–1791. Copyright © Royal Society of Chemistry (RSC)].

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In the realm of catalysis, plant-synthesized Ru NPs have proven to be exceptionally competent. Their high surface area and the tunable surface chemistry provided by the plant capping agents make them powerful catalysts for critical reactions. They efficiently drive processes like the hydrogenation of organic compounds, which is fundamental in pharmaceutical and petrochemical manufacturing, and the reduction of toxic pollutants. The plant-derived layer can sometimes even direct catalytic selectivity, making reactions more efficient and reducing unwanted byproducts. This marries the sustainability of their creation with the green chemistry goals of the processes they enable [47, 55, 92].

Perhaps the most immediately beneficial applications are found in antimicrobial and antioxidant therapies. The inherent defensive compounds of plants, flavonoids, tannins, and alkaloids, are transferred to the nanoparticle surface, creating a potent hybrid weapon. These Ru NPs exhibit a broad-spectrum ability to disrupt bacterial and fungal cell membranes, offering a promising avenue to combat the growing crisis of antibiotic resistance [37, 51, 53, 57, 59, 92]. Simultaneously, they act as effective scavengers of harmful free radicals. This dual antimicrobial-antioxidant profile is invaluable for developing advanced wound dressings, antimicrobial coatings for medical devices, and protective formulations that prevent oxidative spoilage in food and cosmetics. This biocompatibility seamlessly extends into biomedical and anticancer applications, where plant-synthesized Ru NPs are emerging as a next-generation therapeutic platform. Their natural coating reduces systemic toxicity, a major hurdle for many metal-based therapies. As drug delivery vehicles, their high surface area allows them to carry large payloads of chemotherapeutic agents. More impressively, they can function as monotherapy agents themselves [93]. Once internalized by cancer cells, these Ru NPs can catalyze the production of reactive oxygen species (ROS), triggering programmed cell death (apoptosis) while leaving healthy cells relatively unharmed. Research on extracts like *Gunnera perpensa* and *Aloe vera* has shown Ru NPs inducing significant cell death in breast and other cancer lines, highlighting their direct therapeutic potential [56, 58, 59, 92].

Beyond the clinic, these nanoparticles are powerful agents for environmental remediation and photocatalysis. Their catalytic prowess is harnessed to break down stubborn organic pollutants, industrial dyes, pesticides, and pharmaceutical waste, in contaminated water. When designed for photocatalysis, they absorb light energy to accelerate these degradation reactions, effectively using sunlight to purify water. Furthermore, they show great promise in advanced processes like carbon dioxide reduction, transforming a greenhouse gas into useful hydrocarbons, and in water-splitting reactions to produce clean hydrogen fuel, positioning them at the forefront of sustainable energy research [55].

The exceptional surface reactivity and electrical conductivity of Ru NPs are also leveraged in sensing and energy technologies. As the core of electrochemical sensors, they can detect minute traces of environmental toxins, biological markers, or glucose with high sensitivity and specificity [93, 94]. In the energy sector, their role is transformative. Incorporated into supercapacitors and advanced batteries, such as lithium-CO_2 or lithium-O_2 batteries, Ru NPs provide unparalleled conductivity and electrochemical stability. They facilitate faster charge-discharge cycles, greater energy density, and longer device lifespans, addressing critical challenges in renewable energy storage and powering next-generation electronics and electric vehicles [54, 93, 95-97].

Hojjati-Najafabadi et al. reported the green synthesis of a novel nanocatalyst using *Bacillus thuringiensis* as a biosupport for ruthenium/nickel co-doped zinc nanoparticles (btRNZn NPs) [98]. They demonstrated its dual functionality, achieving a 68.2% photodegradation efficiency against Methyl Orange dye and exhibiting exceptional catalytic activity for hydrogen production via sodium borohydride methanolysis. The study detailed favorable kinetics, with a high turnover frequency (TOF) of 2497.14 h^{-1} and a low activation energy, positioning the biosynthesized nanocatalyst as a promising and sustainable candidate for both environmental remediation and clean energy generation. Figure 6 exhibits the schematic illustration of the green synthesis of *Bacillus thuringiensis*-supported Ru/Ni/Zn nanoparticles (bRNZn NPs), their proposed photocatalytic degradation mechanism for Methyl Orange (MO) dye, and their catalytic performance in hydrogen production via sodium borohydride ($NaBH_4$) methanolysis. It depicts the biosynthesis process where bacterial metabolites reduce and stabilize metal ions. The figure shows the proposed charge transfer (from Valence Band, VB, to Conduction Band, CB) generating reactive radicals ($^{\bullet}OH$, $^{\bullet}O_2^-$) that degrade MO. The figure also presents the volume of hydrogen generated over time, demonstrating the catalyst's efficiency.

The applications of plant-mediated Ru NPs paint a picture of a truly convergent technology. They are not defined by a single use but by their versatile ability to provide sustainable solutions across critical human domains. From cleaning our water and storing clean energy to fighting infections and targeting tumors, these green-synthesized nanomaterials demonstrate that the most advanced scientific solutions can indeed have their roots in the wisdom of the nature.

6. ADVANTAGES AND CHALLENGES OF PLANT-MEDIATED SYNTHESIS

The journey toward discovering and implementing greener technologies has led scientists to the very roots of our natural world: plants. The synthesis of ruthenium nanoparticles using plant extracts is a shining example of this shift, offering a compelling alternative to traditional laboratory methods. Like any promising technology, however, it comes with its own set of brilliant advantages and very real-world challenges that must be carefully navigated. Understanding both sides of this coin is crucial for appreciating the true potential and the work that still lies ahead for this field.

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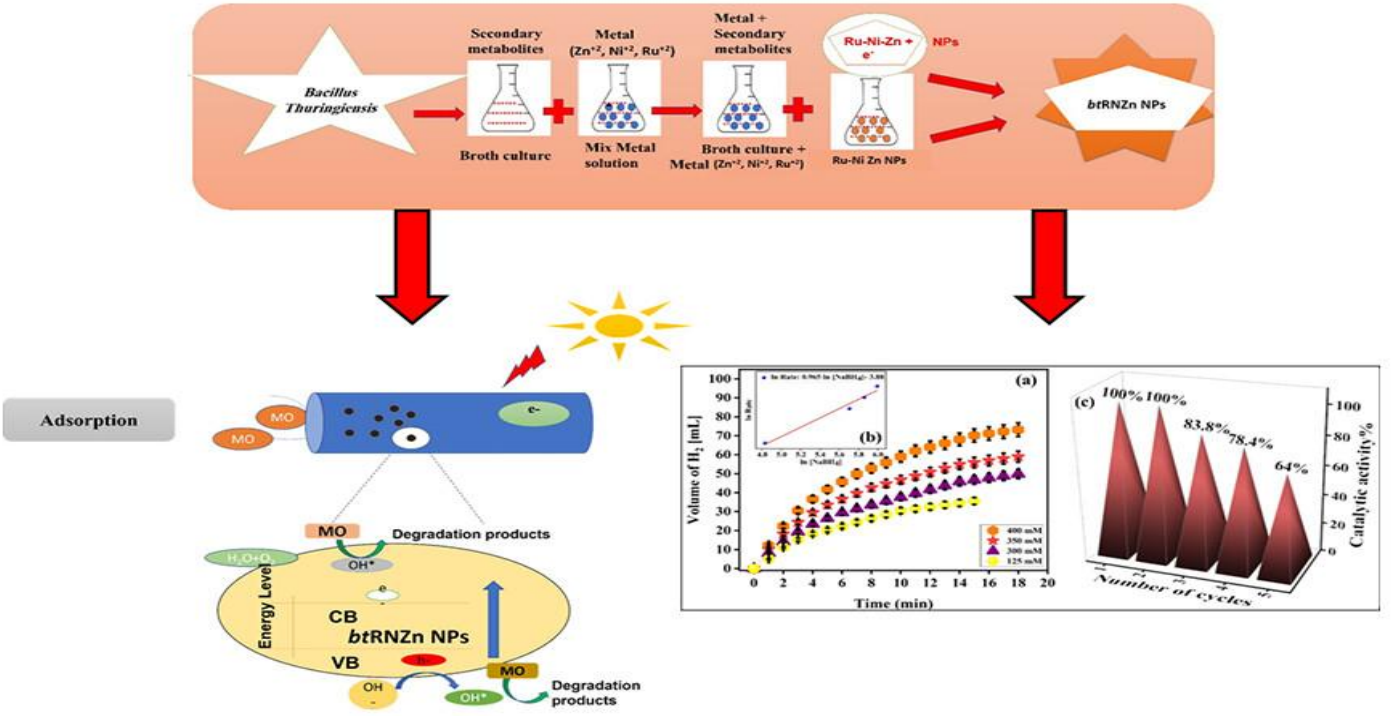

Fig. 6. Schematic illustration of the green synthesis of *Bacillus thuringiensis*-supported Ru/Ni/Zn nanoparticles (bRNZn NPs), their proposed photocatalytic degradation mechanism for Methyl Orange (MO) dye, and their catalytic performance in hydrogen production via sodium borohydride ($NaBH_4$) methanolysis. Upper panel depicts the biosynthesis process where bacterial metabolites reduce and stabilize metal ions. The bottom left panel shows the proposed charge transfer (from Valence Band, VB, to Conduction Band, CB) generating reactive radicals (*OH, $*O_2^-$) that degrade MO. The bottom right panel presents the volume of hydrogen generated over time, demonstrating the efficiency of the catalyst. [Reprinted with permission from ref. [98], Hojjati-Najafabadi, A., Aygun, A., Tiri, R.N.E., Gulbagca, F., Lounissaa, M.I., Feng, P., Karimi, F. and Sen, F., 2023. Bacillus thuringiensis based ruthenium/nickel Co-doped zinc as a green nanocatalyst: enhanced photocatalytic activity, mechanism, and efficient H_2 production from sodium borohydride methanolysis. *Industrial & Engineering Chemistry Research*, *62*(11), pp.4655-4664. Copyright © American Chemical Society].

6.1. Advantages of Plant-Mediated Synthesis

Imagine being able to create one of the most advanced materials of the modern era, a nanoparticle with power in catalysis or medicine, using little more than a leaf extract and some simple salts, all while protecting the environment. This is not a futuristic dream but the present reality of plant-mediated green synthesis. The advantages of this approach are profound and multi-layered, touching on environmental, economic, and practical aspects of science. Figure 7 outlines the key advantages of green nanoparticle synthesis, emphasizing its cost-effectiveness, environmental friendliness, biocompatibility, rapid one-pot process, simplicity, and the high stability of the resulting products.

First and foremost is the undeniable environmental benefit. Traditional ways of making nanoparticles often rely on a cocktail of harsh chemicals, strong reducing agents, toxic solvents, and synthetic stabilizers that pose risks to both human health and the planet. Plant synthesis sweeps this chemical complexity aside. Here, the plant extract itself is the factory, providing all the necessary compounds to transform simple metal salts into sophisticated nanoparticles. The process typically uses water as the main solvent and happens at gentle temperatures, drastically cutting down on energy use and hazardous waste. There are no poisonous fumes or difficult-to-treat byproducts. In a world increasingly conscious of pollution and sustainable practices, this method stands out as a clean and responsible way to produce advanced materials, perfectly aligning with the principles of green chemistry.

Closely tied to the environmental benefit is the tremendous cost-effectiveness of the process. The starting materials are remarkably simple and inexpensive. The plants themselves, like neem, tulsi, aloe vera, or marigold, are often widely cultivated, easily accessible, and affordable. There is no need to purchase expensive, pure chemical reductants. Furthermore, because the reactions usually proceed at room temperature or with mild heating, the energy costs are a fraction of those required by methods that need intense heat, high pressure, or vacuum systems. This combination of cheap raw materials and low energy input makes plant-mediated synthesis particularly attractive for research

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institutions and industries in regions with limited budgets, democratizing access to nanotechnology.



Fig. 7. A conceptual diagram summarizing the key advantages of green synthesis methods for nanoparticles, including cost-effectiveness, environmental compatibility, rapid production, and operational simplicity.

Another critical advantage, especially for any medical application, is the inherent biocompatibility and safety of the resulting nanoparticles. Since the nanoparticles are capped and stabilized by natural plant compounds like flavonoids, polyphenols, and proteins, they tend to be friendlier to biological systems. These natural coatings can make the ruthenium nanoparticles less likely to trigger toxic reactions in cells, a common concern with synthetically capped particles. For applications like targeted drug delivery, cancer therapy, or antibacterial coatings, this built-in biocompatibility is a huge head start. It means scientists spend less time trying to disguise a toxic particle and more time leveraging its therapeutic potential.

The method also offers a surprising degree of versatility and control. While it might seem simplistic, the plant extract is a complex mixture that can be finely tuned. By changing parameters like the type of plant used, the part of the plant (leaf, root, seed), the pH of the solution, or the reaction temperature, researchers can influence the size, shape, and even the crystal structure of the ruthenium nanoparticles. This ability to "dial in" properties is essential because a nanoparticle's behavior in a catalytic reaction or inside the human body depends heavily on its physical form. The diverse chemistry of the plant kingdom provides a rich toolkit for this tailoring.

Perhaps one of the most elegant features is the dual role of the plant compounds. They do not just build the nanoparticle; they also become an integral part of it. The phytochemicals that reduce the metal ions subsequently cling to the nanoparticle's surface, forming a protective shell that prevents them from clumping together. This natural stabilization is often very effective, leading to nanoparticles that remain dispersed and active for long periods. Moreover, these attached molecules are not just inert coatings but they are bioactive. A ruthenium nanoparticle capped with antioxidants from a medicinal plant might carry that antioxidant activity with it, adding an extra layer of therapeutic function. This in situ functionalization is a unique gift of the biological approach.

The process is notably simple and accessible. It doesn't require million-dollar equipment like laser ablation systems or high-pressure reactors. The core synthesis can often be performed with standard glassware on a lab bench, a beaker, a stirrer, and a heater are often enough. This low barrier to entry invites more researchers to explore nanotechnology and fosters innovation. Furthermore, because it relies on renewable plant resources and avoids complex petrochemicals, the entire approach is inherently more sustainable and future-proof, pointing the way toward a circular model for advanced material production.

6.2. Challenges and Hurdles to Overcome

Despite its glowing promise, the path of plant-mediated synthesis is not without its bumps and obstacles. Moving from a promising lab-scale experiment to a reliable, standardized technology requires confronting several significant challenges. The most frequently cited challenge is the issue of reproducibility and standardization. Ask ten different researchers to make ruthenium nanoparticles with "olive leaf extract," and you might get ten subtly different products. Why? Because the chemical composition of that olive leaf is not a constant. It changes with the season, the soil quality, the climate, the time of harvest, and even how the leaves are dried and stored. This natural variability means that one batch of nanoparticles might be 15 nanometers in size and perfectly spherical, while the next, made with a new batch of leaves, might be 25 nanometers and slightly uneven. For scientists and especially for industries that need absolute consistency in their materials, this is a major headache. Developing strict protocols for plant cultivation, harvesting, and extraction is a crucial, yet difficult, step forward. This variability ties directly into the second big challenge: the "black box" nature of the process. We know the plant extract works, but nailing down exactly how it works can be incredibly complex. The extract contains hundreds of different compounds. Which specific molecule is the primary reducing agent? Which ones are responsible for stabilization? How do they interact with each other and with the growing nanoparticle? Without this fundamental mechanistic

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understanding, it becomes more a matter of art and less a matter of predictable science. Controlling the process with precision, to make a nanoparticle of an exact size for a specific purpose, requires moving from "this plant works" to "this compound in this concentration, under these conditions, produces this result."

Next comes the question of scalability and yield. It's one thing to produce a few milligrams of beautiful nanoparticles in a 50-milliliter beaker for lab tests. It's a completely different challenge to scale that up to produce kilograms for commercial use. Scaling up a chemical process is never trivial, and biological processes add extra layers of complexity. Will a large vat of plant extract react the same way as a small beaker? How do you efficiently mix and heat large volumes? Can you source enough plant material of consistent quality? The yields from plant-mediated synthesis, while cost-effective, can sometimes be lower than those from aggressive chemical methods. Overcoming these engineering and logistical hurdles is essential for the method to move beyond the research lab.

From a pure materials science perspective, there can be limitations in control and purity. While plants offer good control, the most advanced chemical synthesis techniques can achieve a level of precision in size, shape, and crystal structure that is hard to match biologically. Plant-synthesized nanoparticles also come wrapped in their organic coating, which is great for biocompatibility but might be a problem for other applications. For instance, in a highly sensitive catalytic reaction, that organic layer could block the active sites on the nanoparticle's surface, reducing its efficiency. Similarly, for ultra-pure electronic applications, any residual biological material might be considered a contaminant. Finding ways to gently remove or modify this capping layer when needed is an active area of research.

There is the challenge of comprehensive characterization and application-specific performance. Rigorously proving that these green nanoparticles are not just "as good as" but truly "better than" or "more suitable than" conventionally made ones is a heavy lift. It requires extensive testing and head-to-head comparisons. A plant-synthesized ruthenium nanoparticle might show excellent antibacterial activity in a petri dish, but will it remain stable and effective in a real-world wound dressing? It might catalyze a reaction well in a lab setup, but will it withstand the harsh conditions of an industrial reactor for thousands of cycles? Answering these questions requires long-term, application-focused studies that go far beyond initial discovery and characterization.

The plant-mediated synthesis of ruthenium nanoparticles presents a breathtakingly elegant proposition: turning the gentle chemistry of leaves and roots into high-tech materials. Its advantages in sustainability, cost, and biocompatibility are transformative. Yet, its future success depends on our ability to tame its inherent variability, unravel its chemical secrets, and engineer robust processes that can deliver consistent quality at scale. It is a field ripe with opportunity, demanding equal parts of a botanist's appreciation for nature's complexity and an engineer's drive for precision and reliability.

7. CONCLUSION

The plant-mediated synthesis of ruthenium nanoparticles stands as a compelling testament to the power of green chemistry, merging the ancient wisdom of botanical medicine with the cutting-edge demands of modern nanotechnology. This innovative approach offers a paradigm shift away from resource-intensive and toxic traditional methods, championing a process that is fundamentally eco-friendly, cost-effective, and biocompatible. By harnessing the diverse phytochemicals within plant extracts as built-in reducing, capping, and stabilizing agents, it bypasses the need for hazardous synthetic chemicals, significantly reducing environmental footprint and aligning with global sustainability goals. The inherent biocompatibility imparted by this natural capping layer further unlocks exceptional potential, making these nanoparticles particularly promising for sensitive applications in biomedicine, including targeted drug delivery and anticancer therapies, as well as in environmental catalysis and sensing. However, the path from a promising laboratory protocol to robust, real-world technology is not without significant hurdles. The very natural variability that provides richness to the process also presents its greatest challenge: ensuring consistency. Fluctuations in plant composition due to season, geography, and extraction methods can lead to batch-to-batch inconsistencies in nanoparticle size, shape, and surface chemistry, raising concerns about reproducibility and scalability for industrial adoption. Furthermore, the complex "soup" of compounds in a plant extract creates a "black box" effect, where the precise mechanistic pathways of reduction and stabilization are often unclear, hindering precise morphological control. Finally, while the green synthesis process itself is benign, the long-term environmental fate and potential biological toxicity of the resulting Ru NPs require thorough, case-by-case investigation to ensure their safe deployment, especially in therapeutic and consumer-facing applications. Plant-mediated synthesis presents a revolutionary and highly advantageous route for producing functional Ru NPs. Its future success and transition from academic innovation to applied technology depend squarely on the scientific community's ability to address its current limitations. Through standardized protocols, deeper mechanistic studies, rigorous toxicological profiling, and innovative engineering for scale-up, this green methodology can be refined to fully deliver on its promise, paving the way for a new generation of sustainable, effective, and safe nanoscale materials.

8. FUTURE DIRECTIONS

Optimization of Synthesis Parameters for Scalability: For large-scale application, there is a pressing need to optimize synthesis parameters, including pH, temperature,

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concentration of plant extract, and reaction time. The synthesis conditions must be standardized to ensure the uniformity and quality of the nanoparticles across different production batches. Moreover, research into continuous synthesis methods for Ru NPs could help overcome some of the challenges related to scalability, enabling efficient and cost-effective large-scale production.

Mechanistic Insights and Plant-Compound Interactions: One of the key areas for future exploration is gaining a deeper understanding of the mechanisms involved in the plant-mediated reduction of metal ions to nanoparticles. Detailed studies on how different plant compounds interact with metal ions, and how these interactions influence the size, shape, and stability of Ru NPs, could help improve control over particle properties. Identifying the specific biomolecules responsible for nanoparticle synthesis would provide valuable insights into enhancing the reproducibility and stability of Ru NPs.

Standardization and Quality Control: The development of standardized protocols for the synthesis and characterization of Ru NPs from plant extracts is crucial for ensuring consistency in nanoparticle properties. Establishing clear guidelines for quality control, including characterization methods like UV-Vis spectroscopy, XRD, FTIR, and TEM, will help in monitoring and controlling nanoparticle synthesis, ensuring that the final product meets the required specifications for specific applications.

Addressing Toxicity and Safety Concerns: Although Ru NPs synthesized through plant extracts are generally considered biocompatible, there is still a need for thorough toxicological evaluations. In vivo studies on the biocompatibility, toxicity, and bioaccumulation of plant-synthesized Ru NPs should be conducted to assess their safety in biomedical applications, particularly for use in drug delivery, wound healing, and anticancer therapies. Ensuring the long-term safety of Ru NPs is critical for their broader acceptance and use in medical fields.

Sustainable Plant Selection and Supply Chain Management: The sustainability of plant resources used for nanoparticle synthesis should be a key consideration moving forward. Research into selecting renewable, abundant, and non-endangered plant species that are readily available throughout the year will help address concerns related to supply chain instability. Additionally, developing cultivation techniques to grow these plants in a controlled and sustainable manner will ensure the long-term availability of plant extracts for nanoparticle production without depleting natural resources.

Expanding Applications and Multifunctional Ru NPs: Future research should also explore the broader range of applications for plant-synthesized Ru NPs. In addition to their use in catalysis, antimicrobial, and antioxidant applications, Ru NPs hold potential for photocatalysis, biosensing, and energy storage. Investigating multifunctional Ru NPs, where nanoparticles are designed for combined environmental remediation and biomedical applications, could open new avenues for their use in sustainable technologies.

Addressing Plant Extract Variability: Plant extracts inherently exhibit variability due to factors such as geography, seasonality, and plant maturity. Future studies should focus on minimizing this variability by exploring uniform plant cultivation and identifying the optimal harvest time for the plant species of interest. This would help improve the consistency of nanoparticle properties and ensure reproducibility across different batches of nanoparticles.

Industrial Integration and Commercialization: To make the plant-mediated synthesis of Ru NPs commercially viable, research should focus on scaling up the process while maintaining its cost-effectiveness. Integrating the green synthesis process into industrial settings will require the development of efficient extraction methods and techniques to optimize energy consumption. Furthermore, regulatory challenges related to the use of plant-derived nanoparticles in consumer products will need to be addressed, ensuring compliance with safety standards and enhancing public confidence in their use.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

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Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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