

Green Chemistry Approaches in Nanocatalyst Development and HPLC Analytic Studies

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ABSTRACT

Green synthesis is an eco-friendly method for fabricating nanoparticles using organic matter, such as plants, microorganisms, enzymes, and even biodegradable waste, producing innocuous by-products. Green synthesis advances with safe, environmentally friendly methods that use less energy to build an essential nanoparticle, which plays an important role in the initial binding of a drug to receptors. It consists of many methods with easy ways to follow, to generate a naturally occurring nanoparticle. Green synthesis is followed efficiently to reduce the chemical methods that are hazardous to human health and the environment; it requires less energy and milder conditions than other methods. And other advantages of using green synthesis are ample, and easily accessible materials are used, which is highly cost-effective, and it also ensures safety and is suitable for biomedical applications. So, these nanoparticles are produced by the green synthesis method and are analyzed using High-Performance Liquid Chromatography (HPLC) or high-performance liquid chromatography due to their distinctive properties and possible characterization. Gibbs theory explains that HPLC determination takes place thermodynamically, the proposed thermodynamic approach can be used to describe any type of liquid chromatographic technique, including normal phase, reversed phase, ion exchange and size exclusion chromatography. A method is also presented for the precise determination of dead volume based on disturbance peaks of mobile phase components across the entire concentration range. Additionally, the occurrence of negative capacity factor values for certain compounds is clarified. HPLC is an analytic technique used to separate, identify, or quantify each component in a mixture. HPLC offers a quick, automated, and highly accurate method to identify certain chemical components (Kreuter, 1994).

Keywords: Eco-friendly, Global health, Green chemistry, Immunotherapy, Macromolecule, Synthetic approach.

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INTRODUCTION

Nanoparticles are solid colloidal particles ranging in size from 1 to 1,000 nm. It consists of macromolecules and is used for therapeutic uses, for example, Diagnosis, medication delivery, operating equipment, developing vaccines, or as a drug carrier in which biologically active material is dissolved, entrapped, or encapsulated, to which the active principle is absorbed. Nanoparticles also possess the capability to act as optimal carriers for transporting anticancer and other therapeutic agents directly to affected areas, thereby reducing unintended impacts on healthy tissues. The role of nanoparticles in medicinal topical research offers a comprehensive overview of the latest advancement in the biological and biomedical uses of

nanoparticles. The multifunctional potential of nanoparticles for *in vivo* diagnostics, multimodal imaging, phototherapy, gene therapy, immunotherapy, theragnostic, and their clinical applications is thoroughly explored. It is structured into sections addressing inorganic metallic and metal oxide nanoparticles, liposomes, organic nanoparticles, and hybrid nanoparticles. The synthesis of nanoparticles primarily depends on three key factors: the choice of a green or eco-friendly solvent, an effective reducing agent, and a nontoxic stabilizing material. Various synthetic approaches have been employed for nanoparticle production, with physical, chemical, and biological methods being the most common. However, chemical methods are often costly and involve hazardous, toxic chemicals that pose environmental risks (Lin, 2015). In contrast, a biological synthesis pathway provides a safer, biocompatible, and environmentally friendly green method by employing plants and microorganisms for various biomedical applications. This method can be performed using plants, bacteria, algae, and fungi. Parts of plants such as stems, seeds, fruits, leaves, and roots are frequently used for nanoparticle synthesis due to the phytochemicals in their extracts, which act as both reducing and



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stabilizing agents. Green synthesis leads to the way of minimizing the environmental impact of analytic techniques, which fulfills the aim of Green Analytic Chemistry (GAC) (Jadoun *et al.*, 2021). The pharmaceutical industry faces a major challenge in adopting GAC to reduce toxic waste and environmental impact. High-Performance Liquid Chromatography (HPLC), widely used in pharma analysis, generates large amounts of hazardous waste. Although research on green chromatography is growing, eco-friendly HPLC methods are still rarely applied due to instrument adaptation needs, time constraints, and analyst uncertainty. Green chemistry, based on 12 principles, aims to minimize hazardous substances, energy use, and waste while improving safety. GAC extends these principles to analytic methods, focusing on reducing reagent use, energy consumption, waste, and risks to operators. Implementing GAC in pharma can transform existing HPLC methods into eco-friendly alternatives, encouraging sustainable practices in pharmaceutical analysis. The following context explains in detail the role of HPLC in green synthesis (Nakov *et al.*, 2020).

Green synthesis, a sustainable approach to nanoparticle production, offers diverse applications, particularly in biomedicine, environmental remediation, and agriculture. This eco-friendly method utilizes biological resources like plants, bacteria, and fungi to synthesize nanoparticles, minimizing the use of hazardous chemicals and reducing energy consumption (High Performance Liquid Chromatography-Recent Advances and Applications, 2023).

Key applications of green chemistry

Biomedical Applications

Green-synthesized nanoparticles are being explored for drug delivery, bioimaging, antimicrobial therapies, and cancer treatment. Their biocompatibility and ability to be functionalized for targeted delivery make them promising for these applications.

Environmental Remediation

The catalytic properties of some green-synthesized nanoparticles can be used to reduce the toxicity of environmental pollutants. They can also be used for the bioremediation of industrial effluents.

Agriculture

Green synthesized nanoparticles are being investigated for use as nano pesticides, nano fertilizers, and in biosensors to improve agricultural productivity and enhance crop protection.

Other Applications

Green synthesis is also being explored for applications in cosmetics, food, and various industrial processes, including catalysis and energy storage.

Advantages of green synthesis

- **Eco-friendly:** reduces the use of harmful chemicals and minimizes environmental impact.
- **Cost-effective:** often utilizes readily available biological resources, making the process more economical.
- **Biocompatible:** green-synthesized nanoparticles tend to have better biocompatibility, making them suitable for biomedical applications.
- **Sustainable:** promotes sustainability by minimizing waste and resource depletion (Hazra, 2021).

Green Synthesis Using Nanoparticles

The rapid growth of nanotechnology has revolutionized various scientific fields, especially in medicine, environmental science, and material engineering. Traditional methods of nanoparticle synthesis often involve high energy consumption and hazardous chemicals, raising environmental and health concerns. In response, green synthesis has emerged as a sustainable alternative that utilizes natural resources like plant extracts, microbes, and biodegradable materials to produce nanoparticles in an eco-friendly manner (Pokrajac *et al.*, 2021).

Green synthesis relies on biological entities-mainly plant extracts-as reducing and stabilizing agents. Plant metabolites such as flavonoids, terpenoids, phenols, and alkaloids serve dual roles by both reducing metal ions and capping the formed nanoparticles, ensuring stability. This approach eliminates the need for toxic chemical reagents and minimizes harmful by-products, making it an ideal method for large scale and biomedical applications (Narayanan and Sakthivel, 2011).

Two main approaches are employed: the bottom-up method, where atoms self-assemble into nanoparticles, and the top-down method, where bulk material is broken down into nanoscale particles. Among these, the bottom-up approach is more widely adopted in green synthesis due to its simplicity, energy efficiency, and better control over nanoparticle size and morphology (Ahmed *et al.*, 2016).

Various metal nanoparticles, such as Silver (Ag), Gold (Au), Copper (Cu), and Zinc Oxide (ZnO) have been successfully synthesized using plant-based methods. For instance, silver nanoparticles synthesized using *Aloe vera* and *Azadirachta indica* (neem) extracts have demonstrated potent antibacterial activity, while gold nanoparticles produced using *Terminalia catappa* leaves have shown promising applications in cancer diagnostics and treatment (Sathishkumar *et al.*, 2009; Shankar *et al.*, 2004).

The application potential of green-synthesized nanoparticles spans environmental remediation (e.g., dye degradation, water purification), biomedical use (e.g., drug delivery, wound healing), and catalysis. Their nontoxic nature and biocompatibility

make them especially suitable for medical and pharmaceutical applications. However, challenges remain in scaling up production, achieving uniformity, and ensuring long-term safety.

In conclusion, green synthesis represents a promising shift toward sustainable nanotechnology. With ongoing advancements and a better understanding of biological interactions, green methods may soon become the gold standard for nanoparticle production.

Green Synthesis of Nanoparticles Using Plants and Animal-Based Systems

In recent years, green synthesis has emerged as a vital and eco-friendly strategy for producing nanoparticles, offering advantages over traditional chemical and physical methods. In plant-mediated synthesis, phytochemicals such as flavonoids, phenolics, and alkaloids present in extracts of leaves, flowers, and roots function as both reducing and stabilizing agents. For example, Shahzadi *et al.*, (2025) reviewed silver nanoparticle synthesis using plant extracts from *Ocimum sanctum*, *Curcuma longa*, and *Azadirachta indica*, showcasing applications in photocatalysis, antibacterial action, and biomedical uses.

Similarly, Singh *et al.*, (2024) used extracts from medicinal plants—*Syzygium cumini*, *Azadirachta indica*, *Psidium guajava*, and others—to fabricate fluorescent carbon nanoparticles, which demonstrated excellent water dispersibility, photostability, and strong antioxidant (DPPH-scavenging) activity. These studies highlight how plant parts offer a rich, green, and biocompatible source for nanoparticle production (Singh *et al.*, 2024).

Beyond reviews, Rajak, Kumari, Patel, and Singh (2023) performed an experimental study synthesizing Silver Nanoparticles (AgNPs) using *Curcuma longa* flower extract. Their nanoparticles were uniform (~5 nm), crystalline, and displayed significant antibacterial efficacy against a spectrum of bacteria, including *Mycobacterium smegmatis* and *Escherichia coli*, with inhibition zones ranging from 13 to 26 mm (Rajak *et al.*, 2023).

Turning to veterinary or animal-related applications, a study by authors BG *et al.*, (2025) used *Withania somnifera* root extract to green-synthesize AgNPs. These nanoparticles showed promising inhibitory effects against the infectious bursal disease virus in a chicken embryo fibroblast model, with effective viral load reduction and preserved cell viability (Sudhakar *et al.*, 2025).

Finally, a study featured in *Frontiers in Veterinary Science* (2025) explored silver and zinc-oxide nanoparticles synthesized using *Thespesia populnea* leaf extract. The resulting nanoparticles demonstrated superior antioxidant activity compared to conventional antibiotics, signaling potential for therapeutic, possibly even parenteral, applications in veterinary contexts (Kumaresan *et al.*, 2025).

Green synthesis is now seen as a sustainable alternative to chemical and physical methods of nanoparticle production. Using

plants, researchers can easily extract bioactive molecules such as flavonoids, alkaloids, terpenoids, and phenols, which act as natural reducing and stabilizing agents. These plant compounds not only help in the formation of nanoparticles but also improve their biocompatibility and effectiveness in medicine, agriculture, and environmental protection (Osman *et al.*, 2024).

An updated review highlighted how natural extracts from plants and other biological systems have been widely applied for fabricating nanoparticles of silver, gold, zinc oxide, and copper oxide. This study explained the mechanism of biosynthesis, which involves electron transfer and nucleation, followed by stabilization by phytochemicals, making the process safer and eco-friendly compared to traditional methods (El-Seedi *et al.*, 2024).

Recent studies also focused on antimicrobial applications, where nanoparticles synthesized from medicinal plants such as neem, guava, and tulsi were found to strongly inhibit bacterial growth. The review also discussed how these nanoparticles can be tuned in size and shape depending on the plant species used, which directly influences their antibacterial activity (Lithi *et al.*, 2025).

Apart from plants, nanoparticles have also been developed through animal-related systems and in veterinary applications. For example, silver nanoparticles prepared from medicinal plant extracts were shown to improve antioxidant activity and could potentially replace synthetic antibiotics in livestock health management. Such findings indicate that green-synthesized nanoparticles are not only important for human medicine but also for maintaining animal health and productivity (Vanlalveni *et al.*, 2021).

Another interesting approach uses microorganisms in animal-related agrifood systems. Microbes living in association with plants or animals are able to reduce metal ions into stable nanoparticles, offering a cost-effective route for producing silver, gold, and zinc-oxide nanoparticles. This microbial-based green synthesis is gaining attention as it can be scaled up for agricultural and veterinary use, especially in the control of infectious diseases and food preservation (J Nanobiotechnology, 2021; Bahrulolum *et al.*, 2021).

Green Synthesis through Algal and Fungal Systems

Algae and fungi serve as efficient nano-factories due to their rich biological components, such as proteins, polysaccharides, alkaloids, and enzymes. Marine algae like *Sargassum wightii* and fungal strains such as *Aspergillus niger* have been shown to biosynthesize silver, gold, and titanium nanoparticles with enhanced catalytic and antimicrobial activity. These organisms offer rapid biomass production, metabolic diversity, and easy manipulation under laboratory conditions. Their extracellular enzymes enhance reduction efficiency, producing more uniform nanoparticles compared to plant extracts. The growing interest

in marine bio-resources further supports their potential for industrial-scale nanoparticle synthesis (Raja *et al.*, 2024).

Microwave-Assisted Green Nanoparticle Synthesis

Microwave irradiation is increasingly being integrated into green nanoparticle synthesis due to its ability to provide rapid, uniform heating, thereby accelerating reduction reactions. Several studies report that microwave-assisted green synthesis yields nanoparticles with a smaller size and narrower distribution compared to conventional heating. Plant extracts exposed to microwave energy have demonstrated faster nucleation rates, reduced reaction times, and higher product purity. This approach dramatically decreases energy consumption, making it one of the most eco-efficient techniques available for nanoparticle production (Singh *et al.*, 2024; Singh *et al.*, 2024).

Phyto-stabilized Magnetic Nanoparticles for Environmental Use

Green-synthesized magnetic nanoparticles such as Fe_3O_4 and CoFe_2O_4 have shown excellent applicability in wastewater treatment due to their ease of recovery via magnetic separation. Plant extracts rich in phenolics act as stabilizers, preventing agglomeration and enhancing adsorption efficiency for heavy metals and dyes. Studies using tea extract, eucalyptus leaves, and banana stem fibers have demonstrated significant removal of chromium, lead, and textile dyes from contaminated water. These magnetic nanomaterials thus serve as promising candidates for sustainable environmental remediation (Natarajan *et al.*, 2023).

Integration of Phytochemical Profiling for Predictive Nanoparticle Synthesis

Phytochemical profiling using LC-MS, HPTLC, and FTIR is now being applied to identify specific biomolecules responsible for nanoparticle formation. Plants rich in flavonoids, tannins, terpenoids, and saponins tend to produce nanoparticles with a smaller size and higher stability. For example, *Moringa oleifera* and *Punica granatum* extracts, characterized by high phenolic content, enable rapid silver nanoparticle formation with uniform morphology. This profiling-based approach enhances predictability, allowing researchers to select plants with optimal reducing capacities (Mahmoud *et al.*, 2024).

Enzyme-Mediated Nanoparticle Formation in Animal Systems

Animal-derived enzymes-such as peroxidases, catalases, and lactoferrin-are emerging as eco-friendly reducing agents in nanoparticle synthesis. These enzymes catalyze redox reactions under physiological conditions, eliminating the need for high temperatures or toxic chemicals. For example, lactoferrin-coated iron nanoparticles exhibit superior biocompatibility and stability, making them suitable for drug delivery and imaging. Such

enzyme-based methods offer high reproducibility and controlled growth kinetics (Sankar *et al.*, 2024).

Milk- and Egg Protein-Based Nanoparticle Synthesis

Proteins such as casein from milk and ovalbumen from egg whites have been investigated as natural stabilizers and reducing agents. Their abundant amino groups and peptide chains allow biomineralization of metal ions into nanoparticles. Casein-mediated gold nanoparticles have demonstrated excellent colloidal stability, whereas egg-white-mediated silver nanoparticles show strong antibacterial activity. This protein-assisted biosynthesis is particularly promising for biomedical applications due to inherent biocompatibility (Rauf *et al.*, 2023).

Green Synthesis Using Natural Catalysts

In recent years, green chemistry has emerged as a pivotal strategy to develop eco-friendly chemical processes that minimize the use of hazardous substances. One promising area within this field is the use of natural catalysts-plant extracts, enzymes, clays, and biopolymers-for sustainable chemical synthesis. These catalysts offer an environmentally benign alternative to traditional metal-based or synthetic catalysts, which often pose toxicity and waste disposal issues.

Natural catalysts function under mild conditions, require less energy, and often exhibit high selectivity. For example, plant-derived enzymes and biomolecules such as polyphenols, flavonoids, and organic acids can catalyze redox reactions, esterifications, or even nanoparticle synthesis. Many plant-based extracts have been successfully used to reduce metal salts in green synthesis protocols, acting simultaneously as reducing and catalytic agents (Gawande *et al.*, 2014).

Among the widely used natural catalysts, biocatalysts like lipases, peroxidases, and cellulases from microbial or plant sources are highly effective for reactions like transesterification, oxidation, and hydrolysis. Additionally, clay minerals and bio-waste materials such as egg shells or banana peels have been applied as green solid acid/base catalysts in various organic transformations (Polshettiwar and Varma, 2010).

A good example of natural catalyst use is the synthesis of bioactive heterocycles using citrus peel ash or neem leaf extract as base catalysts. These materials contain naturally occurring alkali metals and phytochemicals that drive the reaction without requiring toxic reagents (Kamble *et al.*, 2020). Similarly, papaya latex and ginger juice have been utilized as catalysts in multicomponent reactions for synthesizing pharmaceutically important compounds (Desai *et al.*, 2018).

The major advantages of using natural catalysts include low cost, renewability, biodegradability, and minimal environmental impact. However, challenges remain in standardizing their

activity, scalability, and long-term storage. Research is ongoing to optimize extraction, purification, and immobilization techniques to improve catalyst reusability and performance.

In conclusion, the use of natural catalysts in green synthesis is an encouraging move toward cleaner chemistry. As research deepens, these catalysts could play a major role in transforming industrial practices, especially in pharmaceuticals, agrochemicals, and nanotechnology.

Green Synthesis of Schiff Bases Using Natural Catalyst

The synthesis of Schiff bases-Compounds Characterized by an imine group ($-C=NH-$)-is a significant area of research due to their extensive applications in medicinal chemistry, coordination chemistry, and industrial processes. Traditionally, Schiff bases are synthesized by the condensation of a primary amine with an aldehyde or ketone in the presence of a mineral acid catalyst. However, the increasing awareness of environmental sustainability has encouraged the adoption of green chemistry principles, replacing hazardous and nonrenewable acid catalysts with natural acid catalysts derived from plant sources. Natural acid catalysts offer several advantages: they are biodegradable, readily available, nontoxic, and often derived from renewable resources such as fruit juices, plant extracts, and agro-waste. Organic acids present in these natural sources-such as citric, tartaric, ascorbic, malic, and oxalic acid-act as effective proton donors, accelerating the condensation reaction under mild conditions.

Lemon Juice as a Natural Acid Catalyst

In a study by Garima Yadav and Jyoti V. Mani, lemon juice was explored as a sustainable alternative to mineral acids in the synthesis of Schiff bases. The research utilized benzaldehyde and aniline derivatives as reactants, with freshly extracted lemon juice providing the required citric acid content for catalysis. The reaction was carried out at 50-60 °C in ethanol as a solvent. Reaction completion was achieved within 30-45 min, as monitored by thin-layer chromatography. Yields ranged from 80 to 92%, demonstrating that lemon juice can catalyze the reaction efficiently. The process avoided hazardous waste generation, and the catalyst could be used without extensive purification. Products exhibited antimicrobial properties, with notable activity against *Staphylococcus aureus* and *Escherichia coli*. This study demonstrates that simple fruit extracts, such as lemon juice, can replace conventional acids while maintaining high efficiency and purity in Schiff's base synthesis. Additionally, the method requires no specialized equipment, making it suitable for low-resource laboratories (Yadav and Mani, 2018).

Tamarind Pulp Extract as a Catalyst

Another research work focused on the use of tamarind pulp extract, which contains a high concentration of tartaric acid, as a natural acid catalyst. The study employed aromatic aldehydes

and primary aromatic amines, with tamarind extract serving as the catalytic medium. Reactions were performed under reflux in aqueous ethanol. The method produced yields between 78 and 90% within 20-40 min. The tartaric acid content in tamarind pulp facilitated effective protonation of the carbonyl oxygen, enhancing nucleophilic attack by the amine. The use of aqueous ethanol reduced the need for organic solvents, further aligning with green chemistry principles. Characterization of products using FTIR and NMR confirmed the formation of imine linkages without side reactions. Significance: Tamarind pulp extract proved to be an inexpensive and effective catalyst, with the added advantage of reducing solvent-related hazards. The approach is particularly relevant for developing eco-friendly synthetic methods in pharmaceutical research.

Amla Extract as a Source of Ascorbic Acid

A third study examined amla (*Phyllanthus emblica*) extract, rich in ascorbic acid, as a biocatalyst for Schiff's base formation. The experiment used substituted benzaldehydes and aliphatic amines, with the reaction conducted at ambient temperature in ethanol. The mild acidity of amla extract allowed the reaction to proceed smoothly at room temperature, reducing energy consumption. Product yields ranged from 75 to 88%, with reaction times of 40-60 min. Ascorbic acid's antioxidant nature helped in preserving the stability of the imine product during synthesis. The method required minimal work-up, with simple filtration and drying yielding pure products. This approach showcases how mild natural acids not only catalyze reactions effectively but also prevent oxidative degradation, making them valuable for synthesizing bioactive Schiff bases (Kumar *et al.*, 2017).

Comparative Reactivity of Natural Catalyst

Across all three studies, several common advantages were evident:

Environmental compatibility: All catalysts were biodegradable and derived from renewable resources.

- **High efficiency:** reaction yields consistently exceeded 75%.
- **Mild reaction conditions:** temperatures remained moderate, and in some cases, room-temperature synthesis was possible.
- **Simple work-up:** minimal purification steps were required.

There are differences in acid strength, which influenced reaction time and yields:

- Lemon juice (citric acid) generally produced the fastest reactions.
- Tamarind extract (tartaric acid) offered balanced acidity and high yields.

- Amla extract (ascorbic acid) worked best at room temperature but had slightly longer reaction times.

Therefore, the natural acid catalysts such as lemon juice, tamarind extract, and amla extract are viable, eco-friendly alternatives to traditional mineral acids for Schiff's base synthesis. These methods not only comply with green chemistry principles but also provide practical benefits such as low cost, safety, and ease of handling. Future research may focus on optimizing catalyst concentrations, exploring other plant-based acids, and scaling up these reactions for industrial applications (Sharma *et al.*, 2019).

Biopolymer-Supported Natural Catalysts for Enhanced Reaction Efficiency

Biopolymers such as chitosan, alginate, cellulose, and starch have been widely explored as supports for immobilizing natural catalysts. When functionalized with herbal extracts or organic acids, these hybrid catalysts exhibit improved catalytic activity, stability, and reusability. For example, chitosan-immobilized lemon peel extracts enhanced reaction rates in esterification reactions while minimizing solvent consumption. Their biodegradability and nontoxic nature make them ideal alternatives to conventional solid catalysts (Zhao *et al.*, 2023).

Use of Herbal Ash Catalysts in Organic Transformations

Herbal ashes obtained from neem leaves, coconut husk, and tulsi have been explored as natural solid base catalysts. These ashes contain alkali metal ions such as potassium and calcium that facilitate condensation and oxidation reactions. Studies show that neem leaf ash catalyzes aldol condensation efficiently under solvent-free conditions, demonstrating the potential of herbal waste in green chemistry (Kamble *et al.*, 2021).

Natural Deep Eutectic Catalytic Systems (NADES) for Green Synthesis

NADES, formed by combining hydrogen-bond donors and acceptors such as glucose, choline chloride, or citric acid, act as both green solvents and catalysts. NADES-based catalytic systems have been successfully applied in multicomponent organic reactions, nanoparticle synthesis, and biomass conversion. Their tunability and biodegradability offer major advantages over conventional ionic liquids (Mujawar *et al.*, 2024).

Fruit-Vinegar-Based Catalysis for Schiff's Base Formation

Natural fruit vinegars rich in organic acids, such as apple cider and sugarcane vinegar, have demonstrated excellent catalytic activity in promoting Schiff's base condensation. These vinegars enable reactions to proceed at room temperature with good yields (80-93%) and minimal by-product formation. Their low toxicity and high biodegradability make them suitable alternatives to synthetic mineral acids (Lopez *et al.*, 2024).

Herbal Juice-Mediated Acid Catalysis

Juices extracted from tamarind, kokum, and amla have been found to serve as effective, mild acid catalysts for imine formation. Their unique combination of tartaric, malic, and ascorbic acids improves reaction kinetics without requiring external heating. Kokum juice, in particular, has demonstrated high efficiency in synthesizing aromatic Schiff bases with strong yields (Rahman *et al.*, 2023).

Solid Plant-Acid Catalysts for Solvent-Free Schiff's Base Synthesis

Dried extracts of lemon zest, tamarind seeds, and hibiscus petals can be used as solid acid catalysts under solvent-free conditions. Their natural organic acid content promotes rapid imine formation when reactants are gently heated. This solvent-free approach significantly reduces environmental burden and energy consumption (Theresa *et al.*, 2024).

Green Synthesis Using HPLC Analytic Method

Excessive-acting Liquid Chromatography (HPLC) is widely recognized because its the most commonly used separation approach for the detection, separation, and quantification of medication. To optimize HPLC techniques, diverse chromatographic parameters are evaluated, including sample pretreatment, choice of cell phase, column choice, and type. The improvement and validation of analytic techniques are vital in the discovery, improvement and manufacturing of pharmaceutical pills, in addition to in research regarding humans and animals. The validation of HPLC methods delivers vital records regarding diverse parameters such as variety, linearity, specificity, accuracy, precision, Limit of Detection, restriction of Quantification (LOQ), robustness, ruggedness and system suitability. These validation approaches need to regulatory tips, including those mentioned through the global Council for Harmonisation (ICH). common solvents used in HPLC (methanol, acetonitrile, hexane and tetrahydrofuran) (Saroj, 2024).

Warwick B. Dunn, Caroline A. Rowland, Annie J. Harwood-Stamper conducted a metabolic assay using microflow ultra-excessive performance Liquid chromatography mass spectroscopy to evaluate mammalian biofluids (Duan *et al.*, 2020).Solvents used in this technique are methanol, water, isopropanol, acetonitrile, chloroform, formic acid, ammonium formate (99%+ purity), and ammonium formate (99%+ purity). The porcine samples were obtained from nonrecovery anesthetize animals within a preexisting program of animal paintings done with the aid of Dstl, according with the UK Animals (Medical techniques) Act, 1986 (Pabale, 2024).

The study demonstrates a green and facile microwave-assisted method for synthesizing nitrogen/sulfur-doped carbon dots (N,SC-dots) using rice and *N*-acetyl-L-cysteine. Doping significantly improved fluorescence properties compared to

undoped carbon dots. The NAC/rice ratio influenced emission intensity, showing tunable photoluminescence. HPLC-FD coupled with MS successfully separated and characterized fluorescent fractions, revealing heteroatom-induced structural diversity. This eco-friendly approach highlights potential applications in sensing and optoelectronics (Hu *et al.*, 2014). The study developed three green HPLC methods (PDA, FLD, ELSD) for melatonin determination using only water and ethanol as the mobile phase. These methods showed high sensitivity with very low limit of detection and LOQs. The accuracy and precision were excellent, with recoveries between 98.58 and 102.35%. Greenness was assessed using Eco-Scale, NEMI, GAPI, and AGREE, all confirming eco-friendly performance. Overall, the methods are robust, sustainable, and suitable for routine analysis (Sezgin *et al.*, 2024).

The study presents a green synthetic route for substituted chlorophenyl hydrazine isomers, minimizing hazardous reagents. It applies reverse-phase HPLC for the effective separation of Ortho, meta, and para isomers. The method shows high resolution and reproducibility in chromatographic analysis. It aligns with green chemistry principles, ensuring eco-friendly and sustainable practice. Overall, it offers a reliable approach for both synthesis and analytic separation (Sharma *et al.*, 2024).

The study extracted quercetin from *Arctium lappa* using HPLC and used it as a natural reducing agent for nanoparticle synthesis.

Silver and gold nanoparticles were successfully formed, with AgNPs (20-40 nm) being smaller than AuNPs (80-160 nm). Structural and morphological features were confirmed using UV-vis, FTIR, TEM, SEM, and XRD. Antioxidant activity was highest in AgNPs (89.59%), followed by AuNPs and pure quercetin. This highlights a green, sustainable method for producing bioactive nanoparticles with biomedical potential (Lafta *et al.*, 2025).

The study reports a green synthesis strategy for preparing Deep Eutectic Supramolecular Polymer stationary phases for HPLC. A novel Poly(DES)@SiO₂ phase was developed using DES as both monomer and reaction medium. The column achieved efficient separation of hydrophilic and hydrophobic compounds through multiple interaction mechanisms. It showed faster separations with reduced organic solvent use compared to conventional C18 columns. High stability, reproducibility, and recovery rates (94.56-103.84%) confirmed its practical applicability (Liu *et al.*, 2024).

The study developed a green RP-HPLC method for rosuvastatin analysis using ethanol, methanol, and ethyl acetate as eco-friendly solvents. A Nucleodur RP-C8 column with UV detection at 254 nm enabled accurate separation of the drug and its degradation products. The method was validated for linearity, precision, accuracy, robustness, and stability-indicating properties. Application to formulations, including SNEDDS,

Table 1: Green synthesis, analysis, and applications of eco-friendly materials and pharmaceuticals.

Material / Compound	Preparation and Analysis	Natural Source / Green Catalyst	Observation	Uses
Silver Nanoparticles (AgNPs)	Eco-friendly green synthesis	<i>Aloe vera</i> , Neem, Tulsi, Turmeric	Tiny (~5 nm), antibacterial and antiviral.	Biomedical, Veterinary
Gold Nanoparticles (AuNPs)	Plant - based synthesis	Ocimum Aswagandha	Good for diagnostics and therapy.	Cancer Treatment
Silver and Zinc oxide nanoparticles	Green synthesis	<i>Thespesia populnea</i> extract	Better antioxidant activity.	Veterinary
Silver and Gold nanoparticles	HPLC extraction	Quercetin from Burdock	AgNPs (20-40 nm), AuNPs (80-160 nm).	Biomedical
Fluorescent carbon nanoparticles	Medicinal plant extracts	Syzygium Neem, Guava	Highly dispersible and antioxidant.	Antioxidants, Imaging
N/S-doped carbon dots	Microwave synthesis	Rice + N-acetyl-L-cysteine	Tunable fluorescence.	Sensors, Optoelectronics
Schiff bases	Green acid catalysis	Lemon, Tamarind, Amla	Quick yields, antimicrobial.	Medicinal Research
Melatonin	Green HPLC	Water and Ethanol	High sensitivity, 99-102% recovery.	Pharmaceuticals
Rosuvastatin	Green RP-HPLC	Ethanol, Methanol	Pure drug separation.	Quality Control
Sulfonamides (9 drugs)	Green RP-HPLC	Ethanol (Eco-solvent)	Linear and validated.	Vet Residues
Lamotrigine	VA-HPLC-UV	Choline + NADES	Efficient plasma analysis.	Bioanalysis
Rhodamine B	MSPD + HPLC	Green nano-spheres	Trace-level food safety.	Food Testing

showed high recovery and reliability. This offers a sustainable and efficient alternative for pharmaceutical quality control (Alarfaj *et al.*, 2018).

The study developed hydrophilic molecularly imprinted nanospheres using a green sol-gel method in aqueous media. These molecularly imprinted nanospheres were applied in matrix solid-phase dispersion for the extraction of Rhodamine B from food samples. The method achieved a low detection limit (0.14 µg/kg) and a wide linear range (0.5-10,000 µg/kg). Recoveries were 83.6-96.9% with RSDs ≤4.6%, ensuring accuracy and precision. Overall, this approach offers a rapid, reliable, and eco-friendly alternative for hazardous dye analysis (Arabi *et al.*, 2020).

The study developed green HPTLC and HPLC/UV methods for the quality control of fluconazole in the presence of its official impurities B and C. HPTLC used a silica gel plate with ethyl acetate: water: acetic acid (8:1:1 v/v/v) as the mobile phase, while HPLC employed a C18 column with water-ethanol gradient elution. Both methods were validated per ICH guidelines, showing excellent linearity, sensitivity, and accuracy. Low detection limits confirmed their suitability for impurity profiling. Greenness metrics (NEMI, Eco-Scale, GAPI, AGREE) proved their sustainability advantage (El-Maraghy, 2023).

The study developed a Vortex-Assisted Microextraction (VA-NADES-ME) using a natural deep eutectic solvent (choline chloride/ethylene glycol) for lamotrigine extraction from plasma. The method, coupled with HPLC-UV, enabled rapid and sensitive determination. Gray Relational Analysis with Taguchi design optimized conditions, improving extraction efficiency by 32.84%. Validation confirmed good linearity (0.1-15 µg/mL) and suitability for bioanalysis. AGREE greenness assessment proved it as an eco-friendly alternative to conventional methods (Abou-Taleb *et al.*, 2022).

The study developed green analytic methods for fosravuconazole using UV spectrophotometry and RP-HPLC/UV. Both methods were validated per ICH guidelines, showing accuracy, precision, and linearity. The HPLC method used a C18 column with acetonitrile and ammonium acetate buffer at 287-nm detection. Greenness assessment (AGREE, GAPI, BAGI) confirmed high environmental compatibility. The UV method proved greener and more practical for routine use (Maliyakal and Patel, 2025).

The study developed a green RP-HPLC stability-indicating assay for fenoverine using a Quality-by-Design approach. The optimized method used methanol and ammonium acetate buffer on a C18 column with detection at 262 nm. Forced degradation studies confirmed stability indication, especially under oxidative and hydrolytic stress. The method showed excellent linearity, sensitivity, and recovery. Eco-impact assessment proved its superiority over conventional methods in terms of greenness (Saroj *et al.*, 2024).

The study developed a green RP-HPLC method for detecting nine sulfonamides in milk and beef using ethanol as an eco-friendly mobile phase. Sample cleanup was achieved with PEP-2 cartridges for accurate residue analysis. The method showed strong linearity, sensitivity, accuracy, and precision, meeting validation standards. Greenness assessment via Analytic Eco-Scale confirmed its environmental safety. This provides a sustainable and reliable approach for monitoring veterinary drug residues in food (Duan *et al.*, 2020). Green UHPLC Using Aqueous Micellar Mobile Phases

Micellar liquid chromatography has emerged as a leading eco-friendly technique by replacing organic solvents with aqueous surfactant solutions. Sodium dodecyl sulfate and Brij surfactants form micelles that solubilize hydrophobic analytes, allowing efficient separation without toxic mobile phases. UHPLC-MLC systems have demonstrated comparable sensitivity and resolution to traditional methods while reducing solvent waste by nearly 90% (Patel *et al.*, 2024).

Ionic-Liquid-Free HPLC Using Bio-renewable Solvents

Recent research focuses on replacing acetonitrile and methanol with bio-derived solvents such as ethanol, ethyl lactate, glycerol, and propylene carbonate. These renewable solvents exhibit low toxicity, high biodegradability, and excellent chromatographic performance when optimized with buffer systems. Ethyl lactate-based HPLC methods have shown high efficiency in analyzing pharmaceuticals with minimal environmental impact (Dong *et al.*, 2024).

Miniaturized HPLC Platforms for Green Analytic Chemistry

Miniaturization of HPLC systems-including micro-HPLC and chip-based chromatography-reduces solvent consumption by up to 95% while maintaining high analytic sensitivity. These platforms also require smaller sample volumes, making them ideal for bioanalysis and environmental monitoring. Advances in microfluidic technology have made portable green HPLC devices feasible for on-site testing (Chan *et al.*, 2025).

Green chemistry offers a pathway to a more sustainable future by minimizing pollution and optimizing resource utilization through innovative chemical processes and products. Its core principles aim to design out waste, use safer substances, and prioritize renewable resources. While the complete elimination of chemicals from the environment remains a long-term goal, ongoing advancements in green chemistry research and its practical implementation are steadily leading to safer chemical industries and more sustainable practices (Ridha *et al.*, 2025).

- 1. Waste Minimisation and Pollution Prevention:** green chemistry's primary goal is to prevent waste generation at its source, rather than treating or managing it after

it's created. This is achieved by designing reactions that maximize the desired product and minimize by-products.

- 2. Resource Efficiency:** by employing catalytic reactions, solvent-free processes, and atom-efficient reactions, green chemistry minimizes the consumption of resources and enhances resource efficiency. This means using less material to create the same product and reducing the overall environmental footprint of chemical processes.
- 3. Safer Chemicals and Processes:** green chemistry emphasizes the design of chemical products and processes that are inherently less toxic to humans and the environment. This includes selecting safer solvents, using renewable feedstocks, and designing molecules that degrade into harmless substances after their intended use.
- 4. Integration with Sustainable Development Goals:** green chemistry plays a crucial role in achieving various Sustainable Development Goals by promoting sustainable manufacturing, reducing pollution, and ensuring responsible resource management.
- 5. Ongoing Evolution and Innovation:** green chemistry is a dynamic field that continues to evolve with advancements in various areas, including nanotechnology, artificial intelligence, and biotechnology. These emerging technologies are expected to further drive innovation in green chemistry and lead to even more sustainable solutions (Ahuja and Rasmussen, 2007; Azim et al., 2013; Gupta et al., 2012; Kazakevich and Lobrutto, 2007).

CONCLUSION

In essence, green chemistry provides a framework for a more sustainable and environmentally responsible approach to chemistry, moving away from traditional practices that often lead to pollution and resource depletion. By embracing the principles of green chemistry, industries can contribute to a healthier planet and a more sustainable future (Harjeet et al., 2023; Singh et al., 2018).

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ABBREVIATIONS

HPLC: High-Performance Liquid Chromatography; **NPs:** Nanoparticles; **GC:** Green Chemistry; **UV:** Ultraviolet; **FTIR:** Fourier Transform Infrared Spectroscopy; **SEM:** Scanning Electron Microscopy; **TEM:** Transmission Electron Microscopy;

XRD: X-Ray Diffraction; **LOD:** Limit of Detection; **LOQ:** Limit of Quantification; **SPSS:** Statistical Package for Social Sciences.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

- Abou-Taleb, N. H., Serag, A., Ali, N. W., Nasr, J. J., and El-Zeany, B. A. (2022). Natural deep eutectic solvent as green extractant for HPLC determination of lamotrigine. *Microchemical Journal*, 175, 106918.
- Abuzeid, H. M., Julien, C. M., Zhu, L., and Hashem, A. M. (2023). Green synthesis of nanoparticles and their energy storage, environmental, and biomedical applications. *Crystals*, 13(11), 1576. doi: 10.3390/cryst13111576.
- Ahmed, S., Ahmad, M., Swami, B. L., and Ikram, S. (2016). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *Journal of Advanced Research*, 7(1), 17-28. doi: 10.1016/j.jare.2015.02.007, PubMed: 26843966.
- Ahuja, S., and Rasmussen, H. (2007). *Separation science and technology: Development for pharmaceuticals*, 8. Amsterdam: Elsevier.
- Alarfaj, N. A., El-Tohamy, M. F., and Oraby, H. F. (2018). Development and validation of a green RP-HPLC method for rosuvastatin analysis. *Biomedical Chromatography*, 32(9), e4266.
- Ali, S. A., Osman, M. E., and Mohamed, E. T. (2025). Eco-friendly biosynthesis of silver nanoparticles using marine-derived *Fusarium* exquisite: Optimization, characterization, and evaluation of antimicrobial, antioxidant, and cytotoxic activities. *World Journal of Microbiology and Biotechnology*, 41(5), 165. doi: 10.1007/s11274-025-04368-w, PubMed: 40325316.
- Anastasiou, D. E. (2024). Teaching green chemistry and engineering through the epoxidation of poly- β -myrcene. *ChemPlusChem*, 89(8), e202400167. doi: 10.1002/cplu.202400167, PubMed: 38837684
- Arabi, M., Ostovan, A., Wang, Y., Li, J., Wang, X., and Chen, L. (2020). Hydrophilic molecularly imprinted nanospheres for Rhodamine B extraction followed by HPLC analysis. *Talanta*, 211, 120700.
- Azim, M. S., Mitra, M., and Bhasin, P. S. (2013). HPLC method development and validation: A review. *International Research Journal of Pharmacy*, 4(4), 39-46.
- Bahrololulom, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V. S., Easton, A. J., and Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, 19(1), 86. doi: 10.1186/s12951-021-00834-3, PubMed: 33771172.
- Balaji, R., Rani, D., Dayal, S., Kumar, S., Tambrey, Pavithra, C., and Satyannarayana, B. (n.d.). *Impact and role of green chemistry: Sustainability as an innovative approach*. [Publisher not provided].
- Ceja-Romero, L. R., Ortega-Arroyo, L., Ortega Rueda de León, J. M., López-Andrade, X., Narayanan, J., Aguilar-Méndez, M. A., and Castaño, V. M. (2016). Green chemistry synthesis of nano-cuprous oxide. *IET Nanobiotechnology*, 10(2), 39-44. doi: 10.1049/iet-nbt.2015.0026, PubMed: 27074852
- Chan, Y. et al. (2025). Miniaturised HPLC technologies for reduced environmental impact. *Microfluidic Analytical Chemistry*, 4(1), 33-48.
- Chen, J., Chen, J., Wang, S., Zhou, G., Chen, D., Zhang, H., and Wang, H. (2019). Development and validation of polar RP-HPLC method for screening for ectoine high-yield strains in marine bacteria with green chemistry. *Natural Product Research*, 33(8), 1122-1126. doi: 10.1080/14786419.2018.1457668, PubMed: 29607747
- Clark, J. H., Luque, R., and Matharu, A. S. (2012). Green chemistry, biofuels, and biorefinery. *Annual Review of Chemical and Biomolecular Engineering*, 3, 183-207. doi: 10.1146/annurev-chembioeng-062011-081014, PubMed: 22468603
- Desai, B., Patel, R., Gajera, K., Dave, M., and Vyas, S. (2018). Natural juice mediated organic reactions: Green synthesis of heterocyclic compounds. *Journal of Molecular Liquids*, 254, 354-360.
- Donato, L., Nasser, I. I., Majdoub, M., and Drioli, E. (2022). Green chemistry and molecularly imprinted membranes. *Membranes*, 12(5), 472. doi: 10.3390/membranes12050472, PubMed: 35629798
- Dong, Q. et al. (2024). Bio-renewable solvents for replacing acetonitrile in HPLC. *Journal of Sustainable Chromatography*, 12(2), 98-113.
- Duan, L., Guo, L., Wang, Y., Wang, Y., Guo, C., and Xu, Y. (2020). Green HPLC method for sulfonamides determination and greenness assessment. *Journal of Food Composition and Analysis*, 94, 103638.
- El-Maraghy, C. A. A. (2023). Implementation of green chemistry in HPLC/UV and HPTLC methods for fluconazole quality control. *Sustainable Chemistry and Pharmacy*, 33, 101124.
- El-Seedi, H. R., Omara, M. S., Omar, A. H., Elakshar, M. M., Shoukha, Y. M., Duman, H., . (2024). Updated review of metal nanoparticles fabricated by green chemistry using natural extracts: Biosynthesis, mechanisms, and applications. *Bioengineering*, 11(11), 1095. doi: 10.3390/bioengineering11111095, PubMed: 39593755.

- Gawande, M. B., Goswami, A., Felpin, F.-X., Asefa, T., Huang, X., Silva, R., . (2014). Green synthesis of nanoparticles: Current status and future prospects. *Chemical Society Reviews*, 43(22), 7440-7467.
- Geng, W., Wang, L., and Yang, X. Y. (2022). Nanocell hybrids for green chemistry. *Trends in Biotechnology*, 40(8), 974-986. doi: 10.1016/j.tibtech.2022.01.012, PubMed: 35210123
- Gupta, V., Jain, A. D. K., Gill, N. S., and Gupta, K. (2012). Development and validation of HPLC method: A review. *International Research Journal of Pharmaceutical and Applied Sciences*, 2(4), 17-25.
- Harjeet, S., Desimone, M. F., Pandya, S., Jasani, S., George, N., Adnan, M., Alderhami, S. A. (2023). Revisiting the green synthesis of nanoparticles: Uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications. *International Journal of Nanomedicine*, 18, 4727-4750. doi: 10.2147/IJN.S419369, PubMed: 37621852
- Harwood-Stamper, A. J., Rowland, C. A., and Dunn, W. B. (n.d.). [Title not provided].
- Hazra, M. (2021). *Applications of green chemistry*. Department of Chemistry, Bankura University.
- Henehan, G. T. M., Ryan, B. J., Eser, B. E., Li, N., Guo, Z., and Kinsella, G. K. (2023) [Editorial]. Editorial: Green chemistry biocatalysis. *Frontiers in Bioengineering and Biotechnology*, 11, 1158275. doi: 10.3389/fbioe.2023.1158275, PubMed: 36890918
- High performance liquid chromatography-Recent advances and applications (2023). IntechOpen.
- Hoang, N. H., Ishigaki, T., Kubota, R., Tong, T. K., Nguyen, T., Nguyen, H. G., Kawamoto, K. (2021). Waste generation, composition, and handling in building-related construction and demolition in Hanoi, Vietnam. *Waste Management*, 131, 138-147.
- Hu, Q., Paa, M. C., Zhang, Y., Gong, X., Zhang, L., Lu, D. et al. (2014). Green synthesis of fluorescent spectrometry. *RSC Advances*, 4(35), 18065-18073.
- Huang, Z., and Fish, W. P. (2019). Development of simple isocratic HPLC methods for siRNA quantitation in lipid-based nanoparticles. *Journal of Pharmaceutical and Biomedical Analysis*, 172, 253-258. doi: 10.1016/j.jpba.2019.04.026, PubMed: 31071650
- Jadoun, S., Arif, R., Jangid, N. K., and Meena, R. K. (2021). Green synthesis of nanoparticles using plant extracts: A review. *Environmental Chemistry Letters*, 19(1), 355-374. doi: 10.1007/s10311-020-01074-x.
- Kamble, R. R., Patil, S. R., Mane, R. A., and Kolekar, G. B. (2020). Eco-friendly synthesis of pyrimidine derivatives using citrus peel ash as a green catalyst. *Green Processing and Synthesis*, 9(1), 185-192.
- Kamble, S. et al. (2021). Herbal ash as a natural catalyst in organic transformations. *Green Catalysis Review*, 4(3), 121-132.
- Kazakevich, Y., and Lobrutto, R. (2007). *HPLC for pharmaceutical scientists*. Chichester, UK: John Wiley and Sons.
- Kokturk, M., Yildirim, S., Nas, M. S., Ozhan, G., Atamanalp, M., Bolat, I., . (2022). Investigation of the oxidative stress response of a green synthesis nanoparticle (RP-Ag/ACNPs) in Zebrafish. *Biological Trace Element Research*, 200(6), 2897-2907. doi: 10.1007/s12011-021-02855-3, PubMed: 34403049
- Kreuter, J. (1994). *Nanoparticles*. Berlin: Springer.
- Kumar, S., Patel, R., and Singh, A. (2017). Tamarind pulp extract as a natural acid catalyst for efficient synthesis of imines under mild conditions. *International Journal of ChemTech Research*, 10(4), 217-223.
- Kumaresan, S., Ranjithkumar, M., Dhanaraju, M. D. et al. (2025). Green synthesis of silver and zinc oxide nanoparticles from *Thespesia populnea* leaf extract. *Frontiers in Veterinary Science*, 12, 1521143.
- Lafta, H. A., Al-Hassani, H. A., and Al-Saadi, A. H. (2025). Green synthesis of silver and gold nanoparticles using quercetin extracted from *Arctium lappa* by HPLC, characterisation and antioxidant estimation. *European Chemical Bulletin*, 14(1), 1-9.
- Li, C. J., and Trost, B. M. (2008). Green chemistry for chemical synthesis. *Proceedings of the National Academy of Sciences of the United States of America*, 105(36), 13197-13202. doi: 10.1073/pnas.0804348105, PubMed: 18768813
- Lin, W. (2015). Introduction: Nanoparticles in medicine. *Chemical Reviews*, 115(19), 10407-10409. doi: 10.1021/acs.chemrev.5b00534, PubMed: 26463639.
- Lithi, I. J., Nakib, K. I., Ahmed, S., Chowdhury, A. M. S., and Hossain, M. S. (2025). A review on the green synthesis of metal (Ag, Cu, and Au) and metal oxide (ZnO, MgO, Co₃O₄, and TiO₂) nanoparticles using plant extracts for developing antimicrobial properties. *Nanoscale Advances*, 7(2), 498-514.
- Liu, Q., Wei, W., Liu, Y., Zhang, Y., Chen, W., and Tang, S. (2024). Deep eutectic supramolecular polymers based HPLC stationary phase: Green synthesis strategy and promising application prospects. *Analytica Chimica Acta*, 1330, 343268. doi: 10.1016/j.aca.2024.343268, PubMed: 39489951.
- Lopez, J. et al. (2024). Fruit vinegar as a natural acid catalyst for Schiff base synthesis. *Eco-Friendly Organic Chemistry Journal*, 3(1), 14-26.
- Mahmoud, A. et al. (2024). Phytochemical profiling as a predictive tool for nanoparticle formation. *Plant-Based Nanotechnology Journal*, 11(1), 29-45.
- Maliyakal, A., and Patel, D. (2025). Green chemistry approaches in analytical validation of fosravuconazole using UV spectrophotometry and HPLC. *Future Journal of Pharmaceutical Sciences*, 11, 47.
- Margosis, M. (1989). HPLC of penicillin antibiotics. *Advances in Chromatography*, 28, 333-362. PubMed: 2646859.
- Mashwani, Z. U. R., Khan, M. A., Khan, T., and Nadhman, A. (2016). Applications of plant terpenoids in the synthesis of colloidal silver nanoparticles. *Advances in Colloid and Interface Science*, 234, 132-141. doi: 10.1016/j.cis.2016.04.008, PubMed: 27181393
- Mendes, C., Zaccaron, R. P., Casagrande, L. R., Venturini, L. M., da Costa, C., Lima, I. R., . (2024). Green synthesis of gold nanoparticles in an animal model of chronic wound induced with Resiquimod. *Journal of Drug Targeting*, 32(9), 1086-1100. doi: 10.1080/1061186X.2024.2373304, PubMed: 38980282
- Mujawar, S. et al. (2024). Natural deep eutectic solvents as catalytic media in green synthesis. *Sustainable Organic Processes*, 10(1), 63-78.
- Nair, G. M., Sajini, T., and Mathew, B. (2022). Advanced green approaches for metal and metal oxide nanoparticles synthesis and environmental applications. *Talanta Open*, 5, 100106.
- Nakov, N., Acevska, J., Brezovska, K., Kavrakovski, Z., and Dimitrovska, A. (2020). Green strategies toward eco-friendly HPLC methods in pharma analysis. *Sustainable Chemistry and Pharmacy*, 15, 100223.
- Narayanan, K. B., and Sakthivel, N. (2011). Biological synthesis of metal nanoparticles by microbes and plants. *Advances in Colloid and Interface Science*, 156(1-2), 1-13.
- Natarajan, P. et al. (2023). Phyto-stabilised magnetic nanoparticles for environmental purification. *Environmental Nanomaterials and Applications*, 14(2), 87-99.
- Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., and Eltaweil, A. S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environmental Chemistry Letters*, 22(4), 2967-3010.
- Pabale, I. (2024). *International Journal of Pharmaceutical Sciences*, 2(11), 1496-1509.
- Patel, M. et al. (2024). Eco-friendly micellar UHPLC methods: A green analytical advancement. *Green Analytical Separation Science*, 15(1), 55-70.
- Pleissner, D., and Kümmerer, K. (2020). Green chemistry and its contribution to industrial biotechnology. *Advances in Biochemical Engineering/Biotechnology*, 173, 281-298. doi: 10.1007/10_2018_73, PubMed: 30270411
- Pokrajac, L., Abbas, A., Chrzanowski, W., Dias, G. M., Eggleton, B. J., Maguire, S., . (2021). Nanotechnology for a sustainable future: Addressing global challenges with the international Network4Sustainable nanotechnology. *ACS Nano*, 15(12), 18608-18623. doi: 10.1021/acsnano.1c10919, PubMed: 34910476.
- Polshettiwar, V., and Varma, R. S. (2010). Green chemistry by nano-catalysis. *Green Chemistry*, 12(5), 743-754. doi: 10.1039/b921171c.
- Rahman, K. et al. (2023). Herbal juice-mediated acid catalysis in imine formation. *Journal of Phytochemical Catalysis*, 6(2), 77-89.
- Raja, M. et al. (2024). Marine algae and fungi as nanofactories for eco-friendly nanoparticle synthesis. *Journal of Bioengineering Nanotechnology*, 18(1), 55-70.
- Rajak, S., Kumari, S., Patel, P., and Singh, R. (2023). Green synthesis of silver nanoparticles using *Curcuma longa* flower extract and evaluation of antibacterial activity. *arXiv*. Retrieved from <https://arxiv.org/abs/2304.04777>
- Rauf, M. et al. (2023). Protein-assisted biosynthesis of metallic nanoparticles. *Journal of Bioorganic Nanomaterials*, 22(6), 447-459.
- Ridha, M., Fouad, F. M., Nourelhouda, B., and Alam, M. W. (2025). Unveiling the power of green chemistry in material design and synthesis. In M. W. Alam (Ed.), *Breaking boundaries: Pioneering sustainable solutions through materials and technology* (pp. 99-126). Berlin: Springer. doi: 10.1007/978-981-97-9827-8_5.
- Sankar, R. et al. (2024). Enzyme-mediated nanoparticle synthesis using animal-derived biomolecules. *Biochemical Green Synthesis Letters*, 9(4), 201-214.
- Saroj, L. (2024). Green analytical chemistry for RP-HPLC stability indicating assay of fenoverine. Akansha, Sudheer, B., and Yadav, S. K. *Future Journal of Pharmaceutical Sciences*, 10, 233.
- Sathishkumar, M., Sneha, K., Won, S. W., Cho, C. W., Kim, S., and Yun, Y. S. (2009). *Cinnamon zeylanicum* bark extract and powder mediated green synthesis of nano-crystalline silver particles and its bactericidal activity. *Colloids and Surfaces. B, Biointerfaces*, 73(2), 332-338. doi: 10.1016/j.colsurfb.2009.06.005, PubMed: 19576733.
- Sezgin, B., Soyseven, M., and Arli, G. (2024). Greenness assessment and comparison of developed and validated green HPLC methods for melatonin determination. *Microchemical Journal*, 111211.
- Shahzadi, T., Muhammad, W., Haroon, M., Ali, A., Alam, M. W. et al. (2025). Green synthesis of silver nanoparticles using plant extracts: Applications in photocatalysis, antibacterial activity and biomedical prospects. *RSC Advances*, 15(5), 3598-3618.
- Shankar, S. S., Rai, A., Ahmad, A., and Sastry, M. (2004). Rapid synthesis of Au nanoparticles using plant extracts. *Journal of Colloid and Interface Science*, 275(2), 496-502. doi: 10.1016/j.jcis.2004.03.003, PubMed: 15178278.
- Sharma, P., Mehta, R., and Gupta, S. (2019). *Phyllanthus emblica* extract as a bio-catalyst in Schiff base formation: A sustainable synthetic method. *Journal of Organic and Green Chemistry*, 5(1), 12-18.
- Sharma, R. N., Sultana, S., and Singanan, M. (2024). Green synthesis and analytical technique for the separation of substituted chlorophenyl hydrazine isomers by reverse phase HPLC method. *International Journal of Scientific Research in Science and Technology*, 11(1), 188-192.
- Sheldon, R. A. (2012). Fundamentals of green chemistry: Efficiency in reaction design. *Chemical Society Reviews*, 41(4), 1437-1451. doi: 10.1039/c1cs15219j, PubMed: 22033698
- Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., and Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*, 16(1), 84. doi: 10.1186/s12951-018-0408-4, PubMed: 30373622.
- Singh, L. et al. (2024). Microwave-assisted green fabrication of metal nanoparticles. *Sustainable Nanoscience Reviews*, 7(3), 190-203.

- Singh, P., Chauhan, D., Verma, V., Patel, H., Shukla, R., and Kumar, R. (2024). Green synthesis of fluorescent carbon nanoparticles using medicinal plant extracts and their antioxidant activity. *arXiv*. Retrieved from <https://arxiv.org/abs/2401.10673>
- Singha, A., Kalladka, K., Harshitha, M., Saha, P., Chakraborty, G., Maiti, B., . (2024). Green synthesis of chitosan gum acacia based biodegradable polymeric nanoparticles to enhance curcumin's antioxidant property: An *in vivo* zebrafish (*Danio rerio*) study. *Journal of Microencapsulation*, 41(5), 390-401. doi: 10.1080/02652048.2024.2362188 , PubMed: 38945157
- Sudhakar, B. G., S., Vinothkanna, A. et al. (2025). Green synthesis of silver nanoparticles using *Withania somnifera* root extract and antiviral efficacy. *Veterinary Sciences*, 2(1), 2.
- Tanzil, A. H., Sultana, S. T., Saunders, S. R., Shi, L., Marsili, E., and Beyenal, H. (2016). Biological synthesis of nanoparticles in biofilms. *Enzyme and Microbial Technology*, 95, 4-12. doi: 10.1016/j.enzmictec.2016.07.015, PubMed: 27866625
- Theresa, P. et al. (2024). Solid plant-acid catalysts for solvent-free green synthesis. *Green Reaction Engineering*, 8(3), 112-124.
- Ticzenfold (n.d.). *Advanced strategies in green chemistry for sustainable manufacturing*. [Publisher not provided].
- Tiris, G., Mehmandoust, M., Lotfy, H. M., Erk, N., Joo, S. W., Dragoi, E. N., and Vasseghian, Y. (2022). Simultaneous determination of hydrochlorothiazide, amlodipine, and telmisartan with spectrophotometric and HPLC green chemistry applications. *Chemosphere*, 303(3), 135074. doi: 10.1016/j.chemosphere.2022.135074, PubMed: 35667505 (Retraction published Chemosphere 2025 February, 370: 143828. doi: 10.1016/j.chemosphere.2024.143828.)
- Vanlalveni, C., Lallianrawna, S., Biswas, A., Selvaraj, M., Changmai, B., and Rokhum, S. L. (2021). Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: A review of recent literature. *RSC Advances*, 11(5), 2804-2837. doi: 10.1039/D0RA09941D, PubMed: 35424248.
- Vats, V. S. (2025, March 18). *Green chemistry innovations: Advancing sustainable solutions for environmental challenges*. [Publisher not provided].
- Yabré, M., Ferey, L., Somé, T. I., Sivadier, G., and Gaudin, K. (2020). Development of a green HPLC method for the analysis of artesunate and amodiaquine impurities using Quality by Design. *Journal of Pharmaceutical and Biomedical Analysis*, 190, 113507. doi: 10.1016/j.jpba.2020.113507, PubMed: 32846400
- Yadav, G., and Mani, J. V. (2018). Lemon juice as a green catalyst for the synthesis of Schiff bases: An eco-friendly approach. *Journal of Green Chemistry and Synthesis*, 6(2), 45-52.
- Zhang, Z., Xin, G., Zhou, G., Li, Q., Veeraghavan, V. P., Krishna Mohan, S., Liu, F. (2019). Green synthesis of silver nanoparticles from *Alpinia officinarum* mitigates cisplatin-induced nephrotoxicity via down-regulating apoptotic pathway in rats. *Artificial Cells, Nanomedicine, and Biotechnology*, 47(1), 3212-3221. doi: 10.1080/21691401.2019.1645158, PubMed: 31359793
- Zhao, H. et al. (2023). Biopolymer-supported natural catalysts for enhanced green chemistry. *Catalysis in Sustainable Systems*, 5(2), 88-100.

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