Green Synthesis of Fe and Ag Nanoparticles: A Systematic Review with Emphasis on Biomedical and Environmental Applications

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Abstract

The green synthesis of metallic nanoparticles is a sustainable alternative to conventional chemical and physical methods, it has significant advantages like environmental compatibility, cost-effectiveness, and biocompatibility. This systematic review is a critical look at the current research on green synthesis of iron (Fe) and silver (Ag) nanoparticles, especially for biomedical and environmental applications. The review analyzes the synthesis protocols, characterization techniques, the mechanistic pathways, and where they can be applied and it also highlights the challenges and limitations in the current methodologies. Our analysis reveals that green synthesis approaches are promising, but there are big gaps in standardisation, scalability, and also the long-term stability of the synthesized nanoparticles is not good. The paper concludes with recommendations for future research and we really need more rigorous comparative studies to prove that green synthesis methods are better than conventional approaches.

Keywords: Green synthesis, Iron nanoparticles, Silver nanoparticles, Biomedical applications, Environmental remediation, Sustainability

1. Introduction

But the conventional synthesis methods for these nanoparticles use a lot of toxic chemicals, high energy, and make hazardous by-products, raising very serious concerns about their environmental and health implications.

This approach is supposed to align with the principles of green chemistry, which wants to design chemical processes that minimize environmental impact and maximize efficiency. Green synthesis of nanoparticles has advantages. Reduced toxicity, lower energy requirements, and you get more biocompatible materials.

Despite all the research on green synthesis methods, their remains a significant lack of systematic reviews that critically evaluate how effective they are. Most reviews just focus on one synthesis method or one application, they don't give a comprehensive analysis of the field. This gap in literature is a big problem. Especially since there is increasing commercial interest in green-synthesized nanoparticles and we need evidence to make good decisions.

The present review wants to address this critical knowledge gap. By providing a systematic analysis of green synthesis methodes for Fe and Ag nanoparticles. With particular emphasis on their biomedical and environmental applications. The review has a critical perspective, looking at both the successes and limitations of current approaches and identifying areas where more research is needed right away.

2. Methodology

This systematic review was conducted by following the Proffered Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive literature search was done using multiple electronic databases, PubMed, Web of Science, Scopus, and Google Scholar. The search strategy was a combination of keywords. Things like "green synthesis," "iron nanoparticles," "silver nanoparticles," "biomedical applications," "environmental remediation," and "plant extract synthesis."

The inclusion criteria was: (1) peer-reviewed articles published from 2019 to 2022, (2) studies about green synthesis of Fe or Ag nanoparticles, (3) articles that reported bomedical or enviornmental applications, and (4) had to be in English. The exclusion criteria was: (1) conference abstracts, (2) review articles without their own data, (3) studies on other metalic nanoparticles, and (4) articles that were only about conventional synthesis methods.

Initial screening got us 1,247 articles, 342 met the inclusion criteria after we screened the title and abstract. After a full-text review, 156 articles were picked for detailed analysis. Data extraction was performed on them, focusing on synthesis methods, characterization techniques, what they were used for, and the outcomes.

3. Green Synthesis Aproaches

3.1 Plant-Based Synthesis

Plant-based synthesis is the most studied approach for green synthesis of metallic nanoparticles. The method works because of phytochemicals like phenols, flavonoids, terpenoids, and alkaloids, which are the reducing and stabilizing agents, so the plant is doing all the work for you. For silver nanoparticles, plant extracts are really good at reducing Ag^+ ions to metallic silver, and it just happens at room temperature.

The synthesis mechanism involves the metal ions complexing with plant metabolites, then they are reduced to zero-valent metal atoms which then grow into nanoparticles, however its hard to standardize. The exact mechanistic pathways are not really understood, and because the synthesis conditions are so different in every study it's hard to make a standard protocol. This is a big limitation that hurts the reproducibility and scalability of plant-based synthesis methods.

But if you look critically at these studies there are problems. First, most of them don't even characterize the plant extract enough, so we have no idea what phytochemicals are actually making the nanoparticles. Second, the synthesis parameters like temperature, pH, and how long the reaction is are all over the place, even for the same plant. This just proves that we don’t understand the synthesis mechanism and we need to standardize things.

3.2 Microbial Synthesis

Microbial synthesis of nanoparticles with bacteria, fungi, and algae is popular now. Because microorganisms can make uniform nanoparticles and you can control the size and shape. The process is you expose the microorganisms to metal salt solutions, and then they bio transform the metal ions into nanoparticles with enzymes.

Bacterial synthesis of silver nanoparticles is done with *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa*. The mechanism is they release enzymes like nitrate reductase which reduce the metal ions. But, microbial synthesis has challenges, it takes a long time, purification is complicated, and you need sterile conditions, which is a hassle.

For iron nanoparticles, microbial synthesis is good, but the zero-valent iron nanoparticles are hard to make this way because iron is so reactive and wants to oxidize, which is a major limitation for using it for cleaning the environment. So it’s not as useful as you’d think.

3.3 Biopolymer-Mediated Synthesis

Using natural biopolymers like chitosan for nanoparticle synthesis is another green approach. These biopolymers are both reducing agents and stabilizing matrices, so they should give better control over nanoparticle size and shape than just crude plant extracts.

Chitosan-mediated synthesis of silver nanoparticles has been studied a lot. The amino groups in chitosan coordinate the metal ions and the hydroxyl groups help reduce them. The nanoparticles you get are stable and biocompatible, so they're good for biomedical stuff. But the process often needs high temperatures and long reaction times, which isn't really that "green" if you think about it.

4. Characterization Techniques and Challenges

4.1 Structural Characterization

Characterization of green-synthesized nanoparticles. It relies on the usual techniques like XRD, TEM, SEM, and DLS. These tell you about particle size, shape, and structure. But there are challenges.

A big challenge is the organic stuff from the biological sources, it interferes with the results. Like, plant extracts can make organic coatings on the nanoparticles, you might not even see them in TEM images. Also organic impurities mess up XRD patterns, so you can’t be sure about the crystalline phase.

Another problem is no one has a standard way to prepare samples for characterization. Everyone washes, dries, and stores their nanoparticles differently, so you get inconsistent properties. This makes it impossible to compare results from different studies. It is a major problem for science.

4.2 Chemical Composition Analysis

Figuring out the exact chemical composition is a significant challenge. You use techniques like XPS and EDS, but the results are hard to interpret because of all the organic compounds from the biological source.

The oxidation state of iron in green-synthesized iron nanoparticles is especially hard to know for sure. Many studies say they made zero-valent iron nanoparticles, but when you look with XPS you see iron oxides. This is a big deal because for environmental remediation, you need the zero-valent iron for it to work. So people might be claiming things that aren't completely true.

5. Bomedical Applications

5.1 Antimicrobial Activity

The antimicrobial properties of green-synthesized silver nanoparticles are very well studied, lots of reports show they work against bacteria, fungi, and viruses. The mechanism is probably the release of silver ions, which kill the cells.

But, a critical analysis of the studies shows flaws. A lot of them use really high concentrations of nanoparticles that you could never use in real life. Also, most studies only use lab strains of bacteria not real pathogens from a clinic, so you don't know if it would actually work in a person. It is probably not as good as they say.

5.2 Drug Delivery Systems

Green-synthesized nanoparticles are promising for drug delivery because they're biocompatible. Silver nanoparticles have been used for cancer drugs, and iron nanoparticles for targeted delivery with magnets.

The biocompatibility is always said to be a big advantage, but there are hardly any real toxicity studies. Mostly just in vitro cell viability assays. Which don't really tell you about in vivo toxicity. We need long-term toxicity studies to see if these things are actually safe for people.

7. Critical Analysis and Limitations

7.1 Reproducibility and Standardization Issues

One of the biggest challenges for green synthesis is reproducibility. And standardization. The biological materials are just too different from each other, which leads to nanoparticles with inconsistent properties. It's a huge problem with plant extracts, because the plant's age, where it grew, and how you extracted it changes everything.

Without standard protocols, you can't compare results. It also stops it from being used commercially. Many papers don't even describe their synthesis conditions well enough so you can't even try to reproduce it. This lack of reproducibility is bad for the credibility of green synthesis.

7.2 Scalability Challenges

Almost all green synthesis studies are just lab scale. Small volumes, batch processes. Nobody has really looked at scaling these methods up to industrial levels. Scaling up is hard. You have to keep the quality consistent, mix everything right, and what do you do with all the biological waste? The economics is also a question. People say its cost-effective. But is it? The cost of getting the plants, quality control, and waste management might make it just as expensive as the old ways.

7.3 Mechanistic Understanding

We've done all this research but we still don't really know how green synthesis works. The biological materials are so complex you can't pinpoint what is making the nanoparticles. This lack of understanding means we probably can't ever optimize the synthesis properly. We are just guessing. The kinetics of how the nanoparticles form and grow is also not characterized, so controlling size and shape is just luck. This knowledge gap is a huge barrier.

8. Future Perspectives and Recommendations

8.1 Standardization and Protocol Development

We need to develop standardized protocols. It should be a priority. We just need everyone to agree on one way to do it. These protocols should say exactly how to prepare the biological material, the synthesis conditions, and how to characterize it. We should make reference materials so we can compare results between labs. International collaboration is key, everyone should get together and make some rules.

9. Conclusion

So, the green synthesis of iron and silver nanoparticles is a promising approach for making nanomaterials sustainably for biomedicine and environmental remediation, however, critical analysis of the current literature shows big limitations that must be addressed before these methods are a real alternative to conventional synthesis. The main problem is the lack of reproducibility and standardization, it's the biggest barrier. Because the biological materials are all different and there are no standard protocols, the nanoparticle properties are all over the place.

The mechanistic understanding is also poor. Which stops us from designing better synthesis. And we don't know if we can even scale it up for industry, it might be too expensive.

But even with these problems, green synthesis is better for the environment and makes more biocompatible particles. So we should keep researching it. Future research needs to focus on making standard protocols, understanding the mechanisms, and doing proper toxicity tests. Collaboration between everyone, academics, industry, and government, is the only way this will work. The field of green synthesis is still young, but it has a lot of potential. It is very important for the future of our planet.

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