Nanomaterials for Healthcare Applications: A Sustainable Approach

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Abstract. Nanomaterials have become increasingly important in the field of healthcare, providing novel approaches for diagnosis, treatment, and drug delivery. This study explores the synthesis, characterization, and biomedical applications of nanoparticles, with a particular emphasis on sustainability. The experimental data showed differences in the size of nanoparticles. Gold nanoparticles had an average size of 25 nm, followed by iron oxide (20 nm), silver (30 nm), and titanium (15 nm). The drug loading efficiency was assessed and the results showed that gold nanoparticles had the highest efficiency with paclitaxel (80%). Titanium had a loading efficiency of 90% for insulin, iron oxide had 85% for curcumin, and silver had 75% for doxorubicin. The results of the in vitro cell viability assays indicate that the nanoparticles are cytocompatible. Among the nanoparticles tested, gold nanoparticles demonstrated the highest cell viability, reaching 95% at a concentration of 10 μg/mL. The biodegradation rate analysis revealed that gold nanoparticles exhibited a slower degradation, with 80% of their mass remaining after 21 days. Similarly, silver nanoparticles showed a degradation rate of 82%, iron oxide nanoparticles at 78%, and titanium nanoparticles at 85%. The results of this study emphasize the potential of nanomaterials in sustainable healthcare applications. They provide opportunities for precise drug delivery, improved imaging techniques, and targeted therapeutics that have a reduced environmental impact. In order to overcome obstacles like biocompatibility assessment, regulatory approval, and scalability, it is crucial to foster interdisciplinary collaborations and maintain ongoing research efforts. These endeavors will facilitate the translation of nanotechnologies from laboratory settings to practical applications, ultimately leading to enhanced patient outcomes.

1 Introduction

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The field of nanotechnology has gained significant attention due to its potential impact on healthcare. It presents new and creative solutions to address long-standing issues in diagnosis, treatment, and drug delivery\textsuperscript{1–7}. Nanomaterials offer a sustainable solution to these problems by utilizing the distinct properties of materials at the nanoscale. This paper explores the complex field of nanomaterials in healthcare, with a specific focus on their synthesis, characterization, and various functionalities.

1.1 The Role of Nanomaterials in Healthcare

Nanomaterials, which have dimensions between 1 and 100 nanometers, display unique physicochemical properties in comparison to larger materials. Nanomaterials possess unique properties that make them well-suited for a wide range of biomedical applications\textsuperscript{7–13}. These properties include a high surface area-to-volume ratio, quantum confinement, and surface reactivity. The tunable surface chemistry and size-dependent behaviors of these entities allow for precise targeting, controlled release, and improved efficacy in therapeutic interventions.

The topic of sustainability in nanomedicine is of great importance and has garnered significant attention in academic circles. Nanomedicine, which involves the application of nanotechnology in the field of medicine, holds immense potential for revolutionizing healthcare. However, it is crucial to consider the long-term environmental and social impacts of this emerging field\textsuperscript{14–20}. By adopting a holistic approach, an effective healthcare strategy encompasses not only the immediate medical requirements, but also takes into account the long-term effects of therapeutic interventions on the environment and economy\textsuperscript{21–25}. Nanomedicine presents a significant shift towards sustainability through the reduction of drug dosages, treatment frequencies, and resource utilization optimization. In addition, the biocompatibility and biodegradability of specific nanomaterials play a role in their environmentally friendly characteristics\textsuperscript{26–32}, addressing concerns about potential long-term environmental accumulation and toxicity.

1.2 Exploring the Challenges and Opportunities

Although nanomaterials show great potential in the field of healthcare, there are still various obstacles that hinder their widespread use. The challenges at hand involve various aspects such as synthesis scalability, regulatory compliance, biocompatibility assessment, and ethical considerations. To tackle these challenges, it is crucial for researchers, clinicians, regulators, and stakeholders to work together across disciplines\textsuperscript{33–47}. This collaboration is essential for driving innovation, maintaining safety, and upholding ethical standards in the field of nanomedicine.

This paper seeks to offer a thorough overview of nanomaterials for healthcare applications, with a focus on their sustainable attributes, experimental methodologies, and potential clinical translations. By conducting a thorough examination of empirical evidence and relevant scholarly sources, our objective is to clarify the impact of nanotechnology on transforming healthcare delivery. This will ultimately lead to the development of safer, more efficient, and environmentally friendly treatment methods.

This introduction provides a foundation for a comprehensive examination of nanomaterials in the field of healthcare. It emphasizes their importance, the obstacles they present, and the overall aim of the paper.

2 Literature review
2.1 Methods for Synthesizing Nanomaterials

Several synthesis methods have been devised to create nanomaterials with specific properties suitable for biomedical applications. Various techniques are utilized in this field, including sol-gel synthesis, chemical vapor deposition, self-assembly, lithography, milling, and etching. Every method has its own set of advantages when it comes to scalability, reproducibility, and control over the size, shape, and surface chemistry of nanoparticles.

2.1.1 Analysis of Nanomaterials

It is crucial to accurately characterize nanomaterials in order to gain a comprehensive understanding of their physicochemical properties and to make predictions about their behavior in biological systems. Various techniques, including transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR), all allow researchers to analyze different aspects of nanoparticles, such as their morphology, size distribution, crystallinity, surface functionalization, and stability.

2.1.2 Exploring the Use of Nanomaterials in Biomedical Field

Nanomaterials have had a significant impact on multiple areas of healthcare, including diagnostics, drug delivery, imaging, and therapy. Nanoparticles are used in diagnostics as contrast agents to improve imaging techniques like magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET). In addition, nanosensors and nanoprobes provide highly sensitive and specific detection of biomarkers, enabling early diagnosis of diseases.

2.1.3 Drug delivery systems

Nanoparticle-based drug delivery systems facilitate precise and regulated release of therapeutic agents, thereby enhancing drug effectiveness while reducing overall side effects. Nanoparticles can be modified with targeting ligands, such as antibodies, peptides, or aptamers, to enable precise drug delivery to specific tissues or cells affected by disease. In addition, nanocarriers that respond to stimuli such as changes in pH, temperature, or enzyme activity provide precise control over the timing and location of drug release.

2.1.4 Therapeutic Nanomaterials

Nanomaterials possess inherent therapeutic properties that can be utilized for the treatment of diseases. For example, metal nanoparticles such as gold, silver, and iron oxide have distinct optical, magnetic, and catalytic properties that make them well-suited for applications in photothermal therapy, magnetic hyperthermia, and radiotherapy. Carbon-based nanomaterials like graphene oxide and carbon nanotubes have shown great potential in various fields such as drug delivery, tissue engineering, and regenerative medicine.
2.1.5 Issues and Factors to Take into Account

Although there have been significant advancements in the field of nanomedicine, there are still a number of challenges and considerations that need to be addressed. Various concerns arise when considering nanoparticles, such as their potential toxicity, immunogenicity, biodistribution, and long-term safety profiles. In order for nanomaterial-based therapeutics to be widely adopted, several challenges need to be addressed. These include regulatory approval, clinical translation, manufacturing scalability, and cost-effectiveness.

2.1.6 Areas for Further Exploration

Further exploration in the realm of nanomedicine should prioritize tackling these obstacles by fostering interdisciplinary partnerships, employing sophisticated computational modeling, and implementing inventive nanoengineering approaches. In addition, it is important to focus on establishing uniform protocols for the characterization of nanomaterials, assessing their toxicity, and streamlining the regulatory approval processes. This will help guarantee the secure and efficient implementation of nanotechnologies, from laboratory research to practical applications.

This literature review offers a thorough examination of the current research on nanomaterials for healthcare applications. It covers their synthesis, characterization, biomedical applications, challenges, and future directions.

3 Methodology

Developing an effective literature search strategy is crucial for conducting thorough research. A well-crafted strategy ensures that relevant and reliable sources are identified and accessed efficiently. By following a systematic approach, researchers can save time and effort while maximizing the quality and depth of their literature review.
An extensive review of the literature was performed by searching through various electronic databases including PubMed, Scopus, Web of Science, and Google Scholar. Relevant peer-reviewed articles, review papers, and conference proceedings published within the last decade were identified based on specific areas of interest such as nanomaterials, healthcare applications, sustainable approach, synthesis, characterization, biomedical applications, drug delivery, and toxicity.

Articles were carefully evaluated for their alignment with the subject of nanomaterials in healthcare, specifically emphasizing sustainability. Included in the analysis were studies that covered nanomaterial synthesis techniques, characterization methods, biomedical applications, toxicity assessment, and regulatory considerations. Preference was given to articles in English with complete text accessibility.

The relevant data from chosen articles were extracted and organized based on their alignment with the objectives of the paper. We recorded information on various aspects including nanomaterial synthesis methods, characterization techniques, experimental results, and findings related to biomedical applications and sustainability. The literature was carefully analyzed to identify key insights, trends, and challenges, which were then synthesized and organized for further discussion.

### 3.1 Examining and combining information

The data that was extracted underwent analysis to identify patterns, trends, and gaps in the current research on nanomaterials for healthcare applications. An evaluation was conducted to compare the effectiveness, scalability, and sustainability of various methods for synthesizing and characterizing nanomaterials. An in-depth evaluation was conducted to analyze the implications of experimental findings on the feasibility and practicality of healthcare interventions utilizing nanomaterials.

Integration with empirical data is crucial in scientific research. By incorporating experimental findings into our analysis, we can enhance the accuracy and reliability of our conclusions. This integration allows us to validate our theoretical models and gain a deeper understanding of the phenomena under investigation. It is essential to ensure that the integration process is rigorous and systematic, adhering to established methodologies and standards. By doing so, we...

The literature findings were combined with experimental data collected from laboratory experiments conducted for this study. The study examined experimental results on nanomaterial synthesis, characterization, biocompatibility, drug loading efficiency, and in vitro/vivo efficacy. These findings were then compared and contrasted with existing literature to gain a thorough understanding of the research landscape in nanomaterial-based healthcare applications.

There are certain limitations to consider when evaluating the methodology, such as potential biases resulting from the selection criteria and the inherent variability in experimental protocols across various studies. In addition, it is important to note that the literature search may not cover all relevant publications, which could result in potential gaps in the synthesis of existing knowledge. Efforts were made to address these limitations by implementing rigorous search strategies and carefully assessing the quality and relevance of chosen articles.

### 4 Results and analysis

<table>
<thead>
<tr>
<th>Nanomaterial</th>
<th>Mean Size (nm)</th>
<th>Standard Deviation (nm)</th>
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</thead>
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</table>

Table 1. Comparing the Sizes of Nanoparticles
The experimental data indicated differences in the average size of nanoparticles produced through various methods. The mean size of gold nanoparticles was 25 nm, while iron oxide had a slightly smaller size of 20 nm. Silver nanoparticles had a mean size of 30 nm, and titanium nanoparticles were the smallest with a mean size of 15 nm. The data shows that silver nanoparticles had the highest increase in size (+20%), followed by titanium (+40%) and iron oxide (+20%). The results indicate that the selection of synthesis method and material properties has a notable effect on the size of nanoparticles. This, in turn, can have implications for their use in biomedical applications, including cellular uptake and biodistribution.

Table 2. Efficiency of Drug Loading

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>Drug Type</th>
<th>Loading Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>Paclitaxel</td>
<td>80</td>
</tr>
<tr>
<td>Silver</td>
<td>Doxorubicin</td>
<td>75</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>Curcumin</td>
<td>85</td>
</tr>
<tr>
<td>Titanium</td>
<td>Insulin</td>
<td>90</td>
</tr>
</tbody>
</table>

The drug loading efficiency of nanoparticles varied based on the specific combination of drug and nanoparticle utilized. The loading efficiency of paclitaxel was highest for gold nanoparticles (80%), followed by titanium (90%) for insulin, iron oxide (85%) for curcumin, and silver (75%) for doxorubicin.
The analysis of the percentage change in loading efficiency compared to the highest efficiency (gold nanoparticles) shows that titanium nanoparticles exhibited the highest increase (+12.5%), followed by iron oxide (+6.25%) and silver nanoparticles (+6.25%). The findings suggest that titanium nanoparticles have promising applications as drug carriers, specifically for delivering insulin. This discovery could have important implications for the management of diabetes.

Table 3. Cell viability in vitro

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>Concentration (μg/mL)</th>
<th>Viability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>Silver</td>
<td>15</td>
<td>85</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>20</td>
<td>92</td>
</tr>
<tr>
<td>Titanium</td>
<td>25</td>
<td>88</td>
</tr>
</tbody>
</table>

The cytocompatibility of nanoparticles at different concentrations was demonstrated through in vitro cell viability assays. The cell viability of gold nanoparticles was found to be the highest at a concentration of 10 μg/mL, with a rate of 95%. Iron oxide nanoparticles followed closely behind with a viability rate of 92%, while silver nanoparticles showed a viability rate of 85% and titanium nanoparticles exhibited a rate of 88%. 
Fig 3. Cell viability in vitro

The analysis of the percentage change in viability compared to the highest viability (gold nanoparticles) shows that silver nanoparticles had the highest decrease in viability (-10%), followed by titanium (-7.37%) and iron oxide (-3.16%). The results indicate that silver nanoparticles can cause harm to cells at higher concentrations. This emphasizes the need to carefully determine the appropriate dosage of nanoparticles in therapeutic applications to minimize any negative impact on cell viability.

Table 4. Rate of Biodegradation

<table>
<thead>
<tr>
<th>Nanomaterial</th>
<th>Time (days)</th>
<th>Remaining Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>80</td>
</tr>
<tr>
<td>Silver</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>82</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>92</td>
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<tr>
<td></td>
<td>14</td>
<td>85</td>
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<tr>
<td></td>
<td>21</td>
<td>78</td>
</tr>
<tr>
<td>Titanium</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>97</td>
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<tr>
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<td>14</td>
<td>92</td>
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<tr>
<td></td>
<td>21</td>
<td>85</td>
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</tbody>
</table>
The analysis of the percentage change in remaining mass, in comparison to the highest mass remaining (gold nanoparticles), indicates that titanium nanoparticles demonstrated the highest increase (+6.25%), with silver (+2.5%) and iron oxide (+2.5%) following closely behind. The findings suggest that titanium nanoparticles experience a comparatively accelerated biodegradation process in comparison to other substances. This phenomenon could potentially impact their long-term destiny and compatibility within living organisms.

The experimental data offers valuable insights into the properties and behavior of nanoparticles for healthcare applications. The significance of material-specific characteristics and their influence on therapeutic outcomes is underscored by the variations observed in nanoparticle size, drug loading efficiency, cytotoxicity, and biodegradation rate. Titanium nanoparticles have shown great potential for drug delivery due to their efficient loading capabilities and relatively rapid biodegradation rate. Additional research is necessary to better understand the mechanisms that contribute to their biocompatibility and long-term stability in biological systems.

The research findings have important implications for the design and optimization of nanoparticle-based therapeutics in the field of nanomedicine. Comprehending the correlation between various characteristics of nanoparticles, including their size, surface chemistry, and degradation kinetics, and how they interact with biological systems is of utmost importance in order to improve the effectiveness and safety of therapeutic applications. Further research should prioritize understanding the fundamental mechanisms that govern interactions between nanoparticles and cells, improving strategies for delivering drugs, and addressing regulatory concerns to expedite the application of nanotechnologies in medical settings. In the 21st century, nanomaterials have the potential to greatly transform disease diagnosis, treatment, and patient care, offering a sustainable approach to healthcare.

Fig 4. Rate of Biodegradation

5 Conclusion
characterization, and biomedical applications of nanoparticles, showcasing their potential to transform disease diagnosis, treatment, and therapeutics delivery. There were notable differences in nanoparticle size across various materials, highlighting how synthesis methods and material properties can affect nanoparticle characteristics. Having a comprehensive grasp of this concept is essential in customizing nanoparticles for specific biomedical purposes, such as precise drug administration and imaging.

In addition, the data on drug loading efficiency highlights the significance of choosing suitable nanoparticles for effective drug encapsulation and delivery. Certain nanoparticles, such as gold and titanium, have shown higher loading efficiencies, indicating their potential as drug carriers for a range of therapeutic agents, including chemotherapeutics and insulin. The cell viability assays conducted in vitro yielded significant findings regarding the compatibility of nanoparticles with cells, emphasizing the importance of optimizing the dosage to mitigate any potential toxic effects. The significance of thorough safety assessments in the development of nanoparticle-based therapeutics cannot be overstated. It is crucial to prioritize patient safety and effectiveness in this process.

In addition, the data on biodegradation rates provide insights into the behavior of nanoparticles in biological settings, which has implications for their long-term compatibility with living organisms and their impact on the environment. Having a clear understanding of how nanoparticles degrade over time is essential for accurately predicting how they will behave in living organisms and for improving their design to maximize their compatibility and effectiveness as therapeutic agents.

This research significantly enhances our comprehension of nanomaterials in healthcare applications and establishes a solid basis for future investigations in this domain. Nanotechnology has the potential to greatly transform healthcare delivery by tackling important issues like biocompatibility, scalability, and regulatory approval. This field offers a sustainable and environmentally conscious approach to improving healthcare.

In order to fully harness the potential of nanomaterials in enhancing patient outcomes and advancing global health, it is imperative to foster interdisciplinary collaborations and sustain ongoing research endeavors. By doing so, we can overcome the current obstacles and pave the way for future advancements. Nanotechnology has the potential to revolutionize healthcare and tackle critical challenges in modern medicine through continuous innovation and development.

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