Green Nanocomposites in Biomedical Applications: An Eco-friendly Approach for Sustainable Healthcare

PranabiniPanda[a], SasmitaNayak[a] and Dilip Kumar Bagal[a,*]

[a]*Department of Mechanical Engg., GCE, Kalahandi, Odisha, India*

[*]Corresponding Author's Email: dilipbagal90@gmail.com

Abstract

Green nanocomposites, a cutting-edge class of materials created by fusing renewable biopolymers with nanoscale reinforcements, show enormous potential for revolutionising biomedical applications due to their sustainable and eco-friendly qualities. The enhanced characteristics, biocompatibility, and biodegradability of these nanocomposites make them appropriate for a variety of biomedical applications. The uses of green nanocomposites in tissue engineering, biosensors, and drug delivery systems are covered in detail in this work. Green nanocomposites have the potential to improve drug delivery, safeguard fragile pharmaceuticals, and enable site-specific and tailored therapy. They are the perfect scaffolds for tissue regeneration in tissue engineering because they have certain mechanical properties that encourage cell attachment and proliferation. Green nanocomposites also provide a flexible framework for the development of sensitive and focused biosensors for the detection of biomolecules with enhanced stability and robustness. Despite these advantages, issues with scalability, biocompatibility, and regulatory approval must be resolved in order to guarantee safe and efficient clinical application. In assessing the toxicity and effect of green nanocomposites, the research also emphasises the significance of safety and environmental factors. The exploration of improved nano-fillers, multifunctional nanocomposites, and intelligent and responsive materials for personalised medicine and diagnostic applications are suggested as future research objectives. Green nanocomposites have the potential to greatly contribute to greener and more sustainable healthcare solutions, revolutionising biomedical processes for a healthier and more environmentally aware future, provided regulatory issues are addressed and the potential is well understood.

Keywords:*Biocompatibility; Drug delivery; Green nanocomposites; Sustainability; Tissue engineering;*

1 Introduction

A completely novel kind of materials called "green nanocomposites" combines biodegradable polymers or natural materials with nanoscale reinforcements made from renewable resources. With the help of these innovative composites, environmental issues will be addressed and sustainable business practises will be promoted in a range of sectors, including biomedical applications.

The search for biocompatible and ecologically friendly materials has recently received increased attention from the biomedical industry. Green nanocomposites provide a tempting option because of their many benefits. They are biodegradable, more ecologically friendly than traditional materials, and could even improve the mechanical and functional qualities of biopolymers. Green nanocomposites have the potential to revolutionise medication delivery, tissue engineering, and biosensing methods in biomedical applications, leading to more environmentally friendly and long-lasting healthcare solutions.

To generate green nanocomposites, a novel material class, biodegradable polymers or natural matrices are mixed with nanoscale reinforcements derived from renewable sources. These minuscule reinforcements, often referred to as nanoparticles or nano-fillers, may be produced using a number of eco-friendly materials, including as cellulose, chitin, lignin, starch, and other biopolymers. In comparison to pure biopolymers, the combination of these renewable components creates a hybrid material with improved mechanical, thermal, and barrier qualities. Green nanocomposites are also biocompatible and biodegradable, which makes them ideal for a variety of biological applications.

Green nanocomposites' salient characteristics include:

1. Enhanced mechanical characteristics and resistance to deformation and fracture are brought about by the incorporation of nano-fillers, which strengthen the nanoscale.

2. Improved thermal stability: Nano-fillers serve as thermal barriers, which lower heat transmission inside the composite and increase its thermal stability.

3. Lessened gas and moisture permeability: By reducing gas and moisture permeability, nano-fillers enable the use of green nanocomposites in applications demanding high barrier performance.

4. Biocompatibility and biodegradability: Green nanocomposites may degrade over time and are intrinsically biocompatible with living tissues, which lessens their environmental effect.

1.1 Types of Green Nanocomposites:

Depending on the kind of matrix and nano-fillers utilised, many forms of green nanocomposites exist. Typical kinds include:

1. Cellulose-based nanocomposites: The matrix is often made of cellulose, a renewable biopolymer that is prevalent in plant cell walls. These composites are often reinforced using nano-fillers made of cellulose, such as cellulose nanofibers (CNFs) or cellulose nanocrystals (CNCs).

2. Nanocomposites comprised of chitin: Chitin is a bio-polymer found in the exoskeletons of insects and crustaceans. It serves as the matrix in these materials. Chitin nanoparticles or nanofibrils are used as nano-fillers to enhance these composites' properties.

3. Starch-based nanocomposites: Starch may be combined with nano-fillers like montmorillonite or other nanoparticles to create starch-based nanocomposites. Starch is a biodegradable matrix material. There are several agricultural sources for starch.

In nanocomposites made from lignin, a byproduct of the pulp and paper industry, the matrix ingredient is lignin. Nano-fillers made from lignin or other renewable sources are utilised to improve the properties of the composites.

1.2 Synthesis Methods for Green Nanocomposites:

Multiple methods must be employed to introduce nano-fillers into the biopolymer matrix with the purpose of produce green nanocomposites. Among the techniques often used are:

1. Solution casting: By means of this method, a solvent is used to disperse a biopolymer matrix and nano-fillers, and the resulting mixture is then cast into a film or other shape. The nanocomposite is then created by evaporating the solvent.

2. Melt blending: To attain a uniform dispersion of the nanoparticles inside the matrix, extruders or mixers are used to combine and melt blend nano-fillers and biopolymer.

3. In-situ polymerization: During the polymerization process, nano-fillers are immediately generated inside the polymer matrix, resulting in a homogenous distribution of nanoparticles.

4. Electrospinning: Nano-fillers are included either during the electrospinning process or post-electrospinning by impregnation. Electrospinning is utilised to build nanofibrous scaffolds from biopolymers.

2 Literature Reviews on Green Nanocomposites in Biomedical Applications

Metallic nanoparticles are utilized in biological uses such as targeted medication delivery and cancer therapy, according to Agbaje et al. (2019) [1]. Focus is placed on the usage of green polymer nanocomposites in a variety of applications, including medical applications, in Adeosun et al. (2012) [2] and Kausar (2020) [3]. Cobalt and cobalt oxide nanoparticles with green synthesis are used in a variety of biological applications, such as wound healing and anti-diabetic characteristics, according to Waris et al. (2021) [4]. The creation of green composites for biomedical applications, including extrusion/injection, compression, and pultrusion methods, is covered by Mann et al. (2019) [5]. The synthesis of nanocomposites for technological advancement, including bimetallic and organic/inorganic polymers, is reviewed by Ringwal et al. (2021) [6] and underlines the benefits of green synthesis techniques, which are economical, environmentally benign, and less harmful to the environment.

The use of green nanomaterials in biological applications including medication delivery and bioimaging is covered in Rawtani et al. (2020) [7]. The state of silicon-enhanced nanocomposites and its applications in a variety of fields, including the healthcare field, are reviewed by Jatoi et al. in 2021 [8]. The possibilities of nanocomposites for application in tissue engineering and load-bearing composites for bone regeneration are discussed by Hule and Pochan (2007) [9]. While Abdullah et al. (2019) [11] emphasises the potential of nano-fillers in sustainable composites for drug delivery and tissue engineering, Avérous and Pollet (2012) [10] explores the use of nanoclay in biodegradable polymers to enhance their qualities. Alkilany et al. (2022) [13] covers the synthesis and biological uses of poly (lactic-co-glycolic acid)-gold nanoparticles, while Turcheniuk et al. (2015) [12] explores the usage of gold-graphene nanocomposites for sensing and photothermal treatment.

Nanocomposites have been used in medication delivery, biosensors, cancer diagnostics, and tissue engineering, according to Heidelberg et al. (2019) [14]. Focus is placed on the potential applications of gold nanoparticle-based composites in tissue engineering, regenerative medicine, targeting, diagnostics, and therapy by Akturk et al. (2019) [15]. Zakaria et al. (2017) [16] discusses the potential of starch nanocomposites for biomedical applications, while Saratale et al. (2018) [17] and Samuel et al. (2022) [18] assess the utilisation of green synthesis methods to develop nanomaterials for biomedical applications. A specific research by Shokrani et al. (2022) [19] on green polymer nanocomposites focuses on skin tissue engineering.

Rashid et al. (2022) [20] discuss the use of green polymer nanocomposites in the packaging and automotive industries, emphasising the biodegradability and environmental friendliness of the materials. Karki et al. (2021) [21] explore the use of nanocomposite and bio-nanocomposite materials in the energy and medical sectors, including drug delivery. The application of green chemistry in the manufacture of drug-loaded nanoparticles is highlighted by Lam et al. (2017) [22] in their discussion of the possible health hazards associated with nanomedicine formulations.

The use of green nanocomposites for energy storage, notably in supercapacitors, is covered by Kausar (2021) [23], and this technology may find utility in biomedical devices.

3 Synthesis and Characterization of Green Nanocomposites

3.1 Green Nanocomposite Synthesis Techniques:

Different synthesis methods that make it easier to incorporate nano-fillers into biopolymer matrices are used to create green nanocomposites. These methods seek to create homogeneous dispersion of nanoparticles, guaranteeing that the resultant composites have improved mechanical, thermal, and barrier characteristics. Among the methods often used to create green nanocomposite materials are:

1. Solution mixing: Using this technique, a stable suspension of nano-fillers is created by dispersing them in an appropriate solvent. The suspension is then combined with the biopolymer matrix, and the combination is agitated to ensure uniform dispersion. A green nanocomposite is then produced once the solvent has been evaporated.

2. Melt extrusion: At high temperatures, melt extrusion includes the direct merging of nano-fillers with the biopolymer matrix. This procedure creates a green nanocomposite with improved characteristics by distributing nanoparticles uniformly throughout the polymer matrix.

3. In-situ polymerization: This method entails polymerizing monomers with nano-fillers present. Consequently, the nano-fillers are absorbed into the expanding polymer chains, creating a green nanocomposite with a network of evenly scattered nanoparticles [24].

4. Electrospinning is a flexible technique for creating nanofibrous scaffolds from biopolymers. By impregnating the polymer after electrospinning or by introducing nano-fillers to the polymer solution before to electrospinning, nano-fillers may be included into the electrospinning process.

3.2 Characterization Techniques for Green Nanocomposites:

Evaluation of the structure, morphology, and characteristics of green nanocomposites requires thorough characterisation. The success of the synthesis process is ensured by using a variety of approaches to ascertain the dispersion and interactions between the nano-fillers and the biopolymer matrix. For characterisation of green nanocomposites, the following methods are often used:

1. Scanning Electron Microscopy (SEM): SEM is used to look at how nanoparticles are distributed throughout the biopolymer matrix and how their surfaces are shaped. It offers high-resolution photographs that provide light on the microstructure of the nanocomposite.Fig. 1 shows high-resolution transmission electron microscopy (TEM) images of recently produced AuNPs (gold nanoparticles). The scale bar indicates the distances as follows: 100 nm, 20 nm, and 5 nm for the first, second, and third images, respectively, and again 100 nm, 20 nm, and 5 nm for the fourth, fifth, and sixth images. These images provide detailed views of the AuNPs, allowing for precise analysis and characterization of their size and morphology.

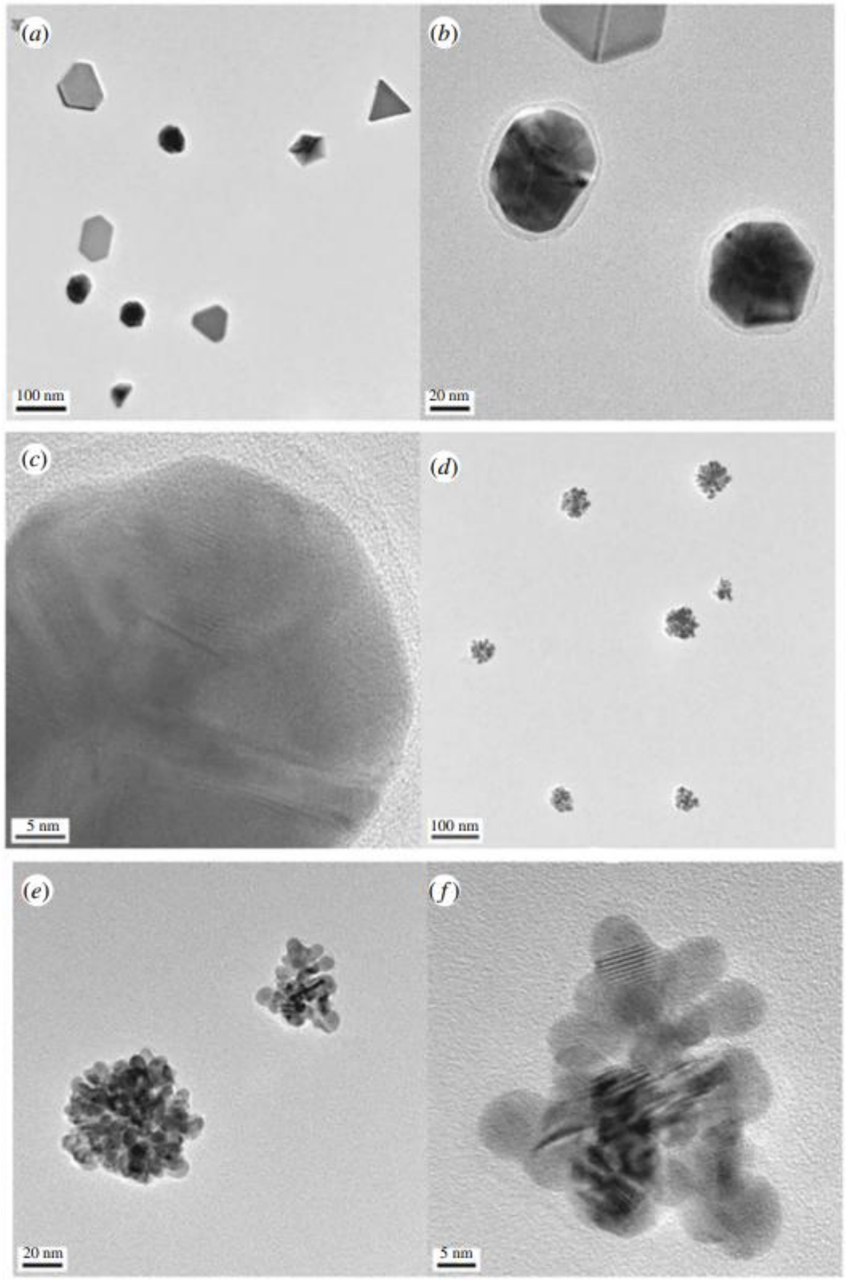

Fig. 1: Images captured by high-resolution transmission electron microscopy of recently produced AuNPs. The scale bar shows the following distances: 100 nm, 20 nm, 5 nm, 100 nm, 20 nm, and 5 nm. [25]

2. Transmission Electron Microscopy (TEM): TEM enables a thorough analysis of the internal structure of the nanocomposite. It offers details on the size, shape, and distribution of nanoparticles at the nanoscale inside the polymer matrix.

3. X-ray Diffraction (XRD): XRD is used to examine the nano-fillers' crystalline structure and the alterations brought about by their integration into the biopolymer matrix. It aids in comprehending the degree of nanoparticle intercalation and dispersion inside the matrix [26].

4. Fourier-Transform Infrared Spectroscopy (FTIR): FTIR is used to examine the chemical interactions that take place between nano-fillers and biopolymer matrices. It aids in determining if the composite has any functional groups or bonds [27].

5. Mechanical Testing: Mechanical testing is used to examine the improvements brought about by nano-fillers by looking at mechanical parameters including tensile strength, modulus, and impact resistance.

6. Thermal analysis: Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) are used to analyse the heat transfer behaviour, crystallinity, and thermal stability of green nanocomposites [28].

7. Testing for Gas Permeability and Water Vapour Permeability: These tests are used to evaluate the green nanocomposites' permeability to gases and water vapour, determining if they are suitable for various biomedical applications.

4 Applications of Green Nanocomposites in Biomedical Applications

4.1 Drug Delivery

Green nanocomposites are interesting prospects for enhancing therapeutic results since they have a number of benefits in drug delivery applications. Some major benefits include:

a. Increased drug loading capacity is made possible by the integration of nano-fillers into the biopolymer matrix, which enables the administration of larger drug concentrations in a smaller dose form.

b. Controlled Release patterns: Drug release patterns that are controlled and maintained may be achieved using green nanocomposites. The addition of nano-fillers may alter the kinetics of medication diffusion and release, prolonging therapeutic benefits and lowering dose frequency.

c. Targeted Delivery: Green nanocomposites may be functionalized to enable precise targeting of medication delivery to the targeted place, reducing systemic adverse effects and enhancing therapeutic effectiveness.

d. Biocompatibility and biodegradability: Green nanocomposites are safe and ecologically friendly drug delivery solutions because they are both biocompatible with living tissues and degradable over time.

e. Stability and Shelf Life: Adding nano-fillers to therapeutic formulations may increase stability and shelf life while preventing drug deterioration and increasing storage times.

4.1.1 Types of Drugs Delivered Using Green Nanocomposites

The ability of green nanocomposites to deliver a variety of medicinal substances, including but not limited to:

a. Small Molecule medications: To improve their efficiency of distribution and lessen toxicity, conventional pharmaceutical medications with low molecular weight might be enclosed inside green nanocomposite carriers.

b. Protein and peptide therapeutics: Green nanocomposites provide a safe haven for delicate protein and peptide medications, maintaining their bioactivity throughout delivery and extending their half-life in the body.

c. Nucleic acid-based treatments: Nanocomposite carriers provide a reliable way to transport mRNA, siRNA, and gene therapies to cells, enabling targeted and site-specific activity.

d. Photodynamic and Photothermal Agents: By incorporating photodynamic or photothermal agents into green nanocomposites, cancer and other disorders may be treated locally using light-triggered treatments.

4.1.2 Challenges in Drug Delivery Using Green Nanocomposites

Despite their potential advantages, a number of challenges still need to be resolved before green nanocomposites may be effectively transformed into effective drug delivery systems.

a. Scalability and Manufacturing Complexity: Producing green nanocomposites on a large scale with consistent qualities may be difficult, demanding efficient synthesis techniques that are both scalable and affordable.

b. A detailed analysis of the possible toxicity and immunological reactions of green nanocomposites is necessary to assure safe clinical application, despite the fact that they are often biocompatible.

c. Targeting Efficiency: Especially in complicated biological contexts, achieving accurate targeting and controlled release at the intended spot continues to be difficult.

d. Regulatory clearance: Thorough safety and effectiveness data must fulfil strict requirements in order for innovative drug delivery systems, including green nanocomposites, to get regulatory clearance.

e. Long-Term Stability: To provide consistent therapeutic effects over time, green nanocomposites should retain their stability and drug release patterns throughout time.

By overcoming these obstacles, green nanocomposites will be successfully incorporated as cutting-edge drug delivery systems, creating new opportunities for efficient and sustainable biomedical treatments.

4.2 Tissue Engineering

Scaffolds made of green nanocomposites are used to enable cell adhesion, proliferation, and tissue regeneration, three-dimensional (3D) scaffolds that replicate the extracellular matrix (ECM) are developed via the process of tissue engineering [29]. Due to their special qualities and environmental friendliness, green nanocomposites have become interesting options for scaffold manufacturing. Green nanocomposite scaffolds provide a bio-inspired milieu that encourages cell development, tissue fusion, and ultimate regeneration. For tissue engineering applications, nano-fillers that are integrated into the biopolymer matrix provide structural support, improve mechanical strength, and improve cellular connections [30]. Fig. 2 displays nanocomposites of green polymers designed for skin tissue engineering.

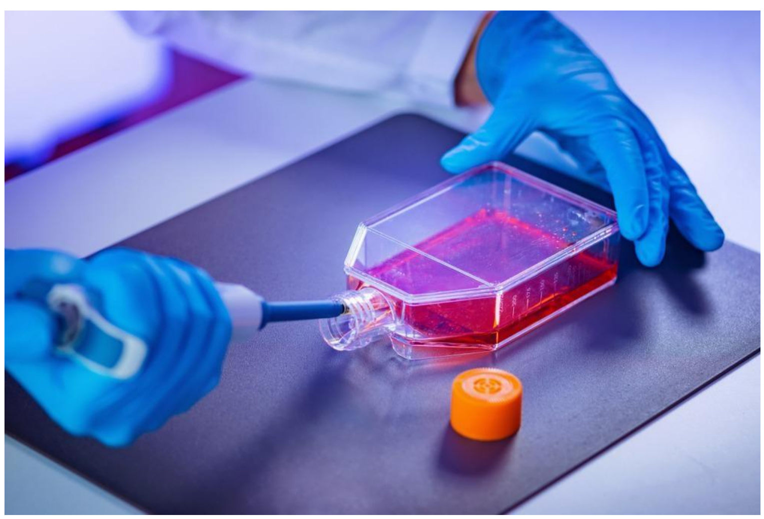

Fig. 2: Nanocomposites of Green Polymers for Skin Tissue Engineering [31]

Green nanocomposites' benefits for tissue engineering Green nanocomposites are ideal for tissue engineering applications since they have a number of benefits.

Improved Biocompatibility: Green nanocomposites' beneficial interactions with cells and tissues are encouraged by their biocompatibility, which reduces unfavourable immune reactions and inflammation.

b. Tailored Mechanical characteristics: The use of nano-fillers enables the mechanical characteristics of green nanocomposite scaffolds to be precisely tailored to meet the demands of various tissues. This improves the mechanical support and structural integrity required for tissue regeneration.

c. regulated Degradation pace: It is possible to design green nanocomposites to decay at a regulated pace, which would be in line with the process of tissue regeneration and would act as temporary support while the new tissue develops.

d. Bioactive Functionalization: To further promote cell attachment, proliferation, and differentiation inside the scaffold, nano-fillers may be functionalized with bioactive compounds, such as growth factors or adhesion peptides.

Green nanocomposites, made from renewable resources, support environmentally friendly tissue engineering techniques by lowering their ecological imprint and negative effects on the environment.

Green nanocomposites: Tissue Engineering Challenges To fully realise the potential of green nanocomposites for tissue engineering, a number of issues must be resolved.

Achieving ideal biodegradation kinetics is important because slow degradation might obstruct tissue regeneration while fast degradation could result in the loss of mechanical integrity.

b. Uniform Dispersion of Nano-Fillers: To prevent any inhomogeneities in the scaffold's structure and characteristics, it is crucial to ensure a uniform dispersion of nano-fillers inside the biopolymer matrix.

c. Cellular Response and Cytotoxicity: In-depth biocompatibility studies are required to gauge how cells react to green nanocomposite scaffolds and spot any possible cytotoxic side effects.

d. Long-term Stability: In order to achieve long-term success, green nanocomposite scaffolds must maintain their structural integrity and mechanical qualities throughout the tissue regeneration process.

e. Scale-up and Manufacturing: For clinical translation, it is essential to develop scalable manufacturing techniques that would result in green nanocomposite scaffolds with predictable features.

The practical implementation of green nanocomposites as scaffold materials will be made possible by collaborative research efforts to overcome these obstacles, promoting the development of tissue engineering and regenerative medicine using sustainable and environmentally friendly methods.

4.3 Biosensors

Green nanocomposites are used to make biosensors. The analytical device known as a biosensor is used to locate and quantify specific biomolecules by combining transducers and biological recognition elements. Green nanocomposites have become enticing materials for the creation of biosensors because of their unique properties and biocompatibility. These nanocomposites may provide a flexible framework for the immobilisation of biomolecules like enzymes, antibodies, or nucleic acids, allowing for the sensitive and precise detection of target analytes. The endurance and sensitivity of biosensors are improved by the addition of nano-fillers to the biopolymer matrix, which makes them ideal for a range of monitoring and diagnostic tasks.

The advantages of green nanocomposites for biosensors Green nanocomposites are a top choice for creating next-generation sensing devices because of their various benefits in biosensor applications.

a. Increased Sensitivity: The high surface area of nano-fillers and their unique physicochemical properties enhance the biomolecules' ability to attach to them, increasing the sensitivity of biosensing.

b. Selectivity and Specificity: Green nanocomposites provide an environment that is regulated and biocompatible for immobilising biomolecules, resulting in excellent specificity and selectivity in detecting target analytes.

c. Stability and Durability: By improving the mechanical and thermal stability of biosensors, nano-fillers improve the stability and lifetime of the sensing apparatus.

d. Portability and Miniaturisation: Green nanocomposites allow for the creation of portable and miniature biosensors that may be used for point-of-care and on-site testing.

Green nanocomposites, which are derived from renewable resources, support sustainability in the creation of biosensors, and their biodegradability assures low environmental effect.Biosensors employing green nanocomposites face challenges. Despite the benefits, there are a number of issues that need to be resolved in order to use green nanocomposites for biosensors:

a. Nanofiller Dispersion: To ensure constant sensor performance and prevent signal fluctuations, uniform nano-filler dispersion within the biopolymer matrix is essential.

b. Biocompatibility and Cytotoxicity: Thorough biocompatibility evaluations are necessary to make sure that green nanocomposites don't impair the functioning of immobilised biomolecules or cause cytotoxic reactions.

c. Signal-to-Noise Ratio: To increase the signal-to-noise ratio and boost the sensitivity of biosensors, it is essential to reduce background noise and non-specific binding interactions.

d. Reproducibility and Standardisation: It is essential to provide standardised manufacturing procedures for biosensors based on green nanocomposites in order to guarantee the consistency and comparability of findings across various platforms.

e. Integration with Transducers: For precise and immediate signal detection, effective integration of green nanocomposite-based biosensors with suitable transducers or readout systems is required.

Researchers may aid in the creation of novel, eco-friendly, and effective sensing technologies for biomedical diagnostics and monitoring by tackling these issues and improving our knowledge of the potential of green nanocomposites in biosensor applications.

5 Safety and Environmental Concerns

5.1 Toxicity of Green Nanocomposites

To guarantee that green nanocomposites are safe and non-toxic in biomedical applications, it is crucial to conduct a safety evaluation. Due to their biodegradability and eco-friendliness, green nanocomposites are often thought to be safer than traditional nanocomposites; nonetheless, thorough toxicity tests must be carried out. The potential toxicity of these materials may be influenced by elements including the kind, concentration, size, and surface functionalization of the nanofiller. In vitro and in vivo studies are required to evaluate cellular reactions, inflammatory responses, and potential long-term effects. Toxicological concerns must be resolved in order to demonstrate the safety of green nanocomposites for use in medical devices, drug delivery systems, and scaffolds for tissue engineering.

5.2 Environmental Impact of Green Nanocomposites

Due largely to their renewable and biodegradable components, green nanocomposites are much more environmentally friendly than conventional nanocomposites. However, throughout their life cycle, green nanocomposites must be carefully considered in terms of their influence on the environment. It is crucial to assess the possible release of nano-fillers during deterioration as well as their impacts on ecosystems. The destiny of nano-fillers in soil and aquatic habitats, possible bioaccumulation, and their impact on creatures other than the targets of the filler should all be studied. Additionally, life cycle analyses (LCAs), which take into account the extraction of raw materials, synthesis procedures, consumption, and disposal, might provide insightful information about the total environmental effect of green nanocomposites.

5.3 Regulatory Considerations for Green Nanocomposites

Regulations and standards must be followed in order to introduce green nanocomposites into biomedical applications. Regulating agencies like the European Medicines Agency (EMA) and the U.S. Food and Drug Administration (FDA) demand thorough safety analyses, preclinical research, and adherence to current Good Manufacturing Practises (cGMP) for medical devices and medications [32, 33]. Through carefully planned research, such as biocompatibility evaluations, in vitro and in vivo toxicity testing, and clinical trials, manufacturers should show the biocompatibility, stability, and effectiveness of green nanocomposites. Additionally, the International Organisation for Standardisation (ISO) criteria for scaffold materials and medical devices should be followed while using green nanocomposites in tissue engineering.

To encourage the appropriate and sustainable integration of green nanocomposites in biomedical applications, it is essential to address safety and environmental issues. Researchers and enterprises may guarantee the secure and environmentally friendly use of green nanocomposites in developing healthcare innovations by performing thorough investigations and adhering to regulatory standards. Additionally, ongoing study in this field will help to maximise the environmental advantages and minimise any hazards connected to these promising materials.

6 Future Scopes and Conclusion

6.1 Future Scopes for Research on Green Nanocomposites

Research efforts to expand the area of green nanocomposites in biological applications may realise their full potential. Future research directions include:

• Advanced Nano-fillers: Investigating brand-new nano-fillers made from sustainable resources that have specific qualities to improve the performance of green nanocomposites in diverse biomedical applications.

• Multifunctional Nanocomposites: To produce adaptable and multifunctional biomedical platforms, different functionality, such as drug delivery, imaging agents, and sensing capabilities, are included into green nanocomposites.

• Biocompatibility Assessment: Carrying out thorough and methodical biocompatibility investigations to guarantee the secure use of green nanocomposites in various biomedical environments.

• Smart and Responsive Nanocomposites: Creating environmentally friendly nanocomposites with stimuli-responsive qualities, such pH or temperature responsiveness, to allow controlled and targeted medication release or tissue regeneration.

• Expansion of in vivo research to examine the long-term behaviour, biodegradation, and tissue integration of green nanocomposites in animal models and ultimately in clinical trials.

• Biodegradable Sensors: advancing the creation of green nanocomposites-based biosensors for real-time biomarker monitoring and disease diagnoses.

6.2 Potential Impact of Green Nanocomposites in Biomedical Applications

Green nanocomposites have the potential to transform biomedical applications by providing environmentally friendly and sustainable solutions to today's most critical healthcare issues:

• Biocompatible and Sustainable Medical Devices: By using green nanocomposites instead of conventional materials, the environmental effect of traditional materials may be reduced.

• Personalised Medicine: The adaptability of green nanocomposites enables the fabrication of customised tissue engineering scaffolds and drug delivery systems, allowing for the customization of treatments to meet the demands of specific patients.

Green nanocomposites provide controlled drug release, tissue engineering platforms, and targeted drug delivery, boosting therapeutic effectiveness and minimising negative effects.

• Point-of-Care Diagnostics: Green nanocomposites-based biodegradable biosensors may provide portable and quick point-of-care diagnostics, enhancing patient access to healthcare in situations with constrained resources.

Green nanocomposites are used in biomedical technologies to lessen their ecological imprint, assist sustainable development, and promote environmentally friendly practises.

6.3 Conclusion and Final Thoughts

Green nanocomposites are a ground-breaking and environmentally friendly method of developing biomedical applications. Green nanocomposites, which combine renewable biopolymers with nanoscale reinforcements, provide improved characteristics, biocompatibility, and biodegradability. They may help create effective and environmentally friendly healthcare solutions by offering significant promise in the areas of medication delivery, tissue engineering, and biosensing.

It's essential to address safety, toxicity, and regulatory issues as research on green nanocomposites continues to reveal its full potential. Thorough research and adherence to regulatory requirements will guarantee the secure introduction of green nanocomposites into clinical settings.

Green nanocomposites, which provide a greener and more sustainable road to better healthcare and a healthier future, are at the forefront of disruptive biomedical technology. Adopting these environmentally friendly materials will transform biomedical procedures and pave the road for ethical and sustainable improvements in healthcare for future generations.

Conflicts of Interest

No financial or commercial transactions that may be seen as a potential conflict of interest occurred throughout the course of the study, according to the authors.

Funding

No financial support is provided for this project.

Acceptance of ethics

None of the authors of this article have conducted any study on people or animals.

Intelligent consent

Each study subject voluntarily provided their informed consent.

References

[1] Agbaje, L., Elegbede, J. A., Akinola, P. O., &Ajayi, V. A. (2019). Biomedical Applications of Green Synthesized-Metallic Nanoparticles: A Review. In Pan African Journal of Life Sciences (Vol. 3, Issue 1, pp. 157–182). Lujosh Ventures Limited. https://doi.org/10.36108/pajols/9102/30(0170)

[2] Adeosun, S. O., Lawal, G. I., Balogun, S. A., &Akpan, E. I. (2012). Review of Green Polymer Nanocomposites. In Journal of Minerals and Materials Characterization and Engineering (Vol. 11, Issue 04, pp. 385–416). Scientific Research Publishing, Inc. https://doi.org/10.4236/jmmce.2012.114028

[3] Kausar, A. (2020). Progress in green nanocomposites for high-performance applications. In Materials Research Innovations (Vol. 25, Issue 1, pp. 53–65). Informa UK Limited. https://doi.org/10.1080/14328917.2020.1728489

[4] Waris, A., Din, M., Ali, A., Afridi, S., Baset, A., Khan, A. U., & Ali, M. (2021). Green fabrication of Co and Co3O4 nanoparticles and their biomedical applications: A review. In Open Life Sciences (Vol. 16, Issue 1, pp. 14–30). Walter de Gruyter GmbH. https://doi.org/10.1515/biol-2021-0003

[5] Mann, G. S., Pal Singh, L., & Kumar, P. (2019). A PEER REVIEW OF THE PROCESSING TECHNOLOGIES AND APPLICATIONS OF GREEN COMPOSITES IN A BIOMEDICAL AREA. In Volume IV Issue VI, June 2019 (Vol. 4, Issue 6, pp. 13–19). Institute of Technical and Scientific Research. https://doi.org/10.30780/ijtrs.v04.i06.002

[6] Ringwal, S., Bartwal, A. S., Semwal, A. R., & Sati, S. C. (2021). Review on Green Synthesized Nanocomposites and Their Biological Activities. In Journal of Mountain Research (Vol. 16, Issue 1). Society for Himalayan Action Research and Development (SHARAD). https://doi.org/10.51220/jmr.v16i1.18

[7] Rawtani, D., Rao, P. K., & Hussain, C. M. (2020). Recent advances in analytical, bioanalytical and miscellaneous applications of green nanomaterial. In TrAC Trends in Analytical Chemistry (Vol. 133, p. 116109). Elsevier BV. https://doi.org/10.1016/j.trac.2020.116109

[8] Jatoi, A. S., Ahmed, S., Muhammad, A., Mubarak, N. M., Mazari, S. A., Abro, R., Memon, A. Q., Shah, A., Anjum, A., & Iqbal, A. (2021). Comprehensive Review on Silicon-enhanced Green Nanocomposites Towards Sustainable Development. In Silicon (Vol. 14, Issue 13, pp. 7383–7398). Springer Science and Business Media LLC. https://doi.org/10.1007/s12633-021-01516-3

[9] Hule, R. A., &Pochan, D. J. (2007). Polymer Nanocomposites for Biomedical Applications. In MRS Bulletin (Vol. 32, Issue 4, pp. 354–358). Springer Science and Business Media LLC. https://doi.org/10.1557/mrs2007.235

[10] Avérous, L., &Pollet, E. (2012). Green Nano-Biocomposites. In Environmental Silicate Nano-Biocomposites (pp. 1–11). Springer London. https://doi.org/10.1007/978-1-4471-4108-2_1

[11] Abdullah, M. A., Nazir, M. S., Tahir, Z., Abbas, Y., Akhtar, M. N., Raza, M. R., & Hussein, H. A. (2019). Processing Aspects and Biomedical and Environmental Applications of Sustainable Nanocomposites Containing Nanofillers. In Sustainable Polymer Composites and Nanocomposites (pp. 727–757). Springer International Publishing. https://doi.org/10.1007/978-3-030-05399-4_25

[12] Turcheniuk, K., Boukherroub, R., &Szunerits, S. (2015). Gold–graphene nanocomposites for sensing and biomedical applications. In Journal of Materials Chemistry B (Vol. 3, Issue 21, pp. 4301–4324). Royal Society of Chemistry (RSC). https://doi.org/10.1039/c5tb00511f

[13] Alkilany, A. M., Rachid, O., Alkawareek, M. Y., Billa, N., Daou, A., & Murphy, C. J. (2022). PLGA-Gold Nanocomposite: Preparation and Biomedical Applications. In Pharmaceutics (Vol. 14, Issue 3, p. 660). MDPI AG. https://doi.org/10.3390/pharmaceutics14030660

[14] Gendelberg, N., Bird, D., &Ravindra, N. M. (2019). Nanocomposites for Biomedical Applications. In Polymer-Based Multifunctional Nanocomposites and Their Applications (pp. 175–199). Elsevier. https://doi.org/10.1016/b978-0-12-815067-2.00007-x

[15] Akturk, O., Erdemli, O., &Tunali, B. C. (2019). Gold nanocomposites for biomedical applications. In Materials for Biomedical Engineering (pp. 485–525). Elsevier. https://doi.org/10.1016/b978-0-12-818431-8.00015-5

[16] Zakaria, N. H., Muhammad, N., & Abdullah, M. M. A. B. (2017). Potential of Starch Nanocomposites for Biomedical Applications. In IOP Conference Series: Materials Science and Engineering (Vol. 209, p. 012087). IOP Publishing. https://doi.org/10.1088/1757-899x/209/1/012087

[17] Saratale, R. G., Karuppusamy, I., Saratale, G. D., Pugazhendhi, A., Kumar, G., Park, Y., Ghodake, G. S., Bharagava, R. N., Banu, J. R., & Shin, H. S. (2018). A comprehensive review on green nanomaterials using biological systems: Recent perception and their future applications. In Colloids and Surfaces B: Biointerfaces (Vol. 170, pp. 20–35). Elsevier BV. https://doi.org/10.1016/j.colsurfb.2018.05.045

[18] Samuel, M. S., Ravikumar, M., John J., A., Selvarajan, E., Patel, H., Chander, P. S., Soundarya, J., Vuppala, S., Balaji, R., &Chandrasekar, N. (2022). A Review on Green Synthesis of Nanoparticles and Their Diverse Biomedical and Environmental Applications. In Catalysts (Vol. 12, Issue 5, p. 459). MDPI AG. https://doi.org/10.3390/catal12050459

[19] Shokrani, H., Shokrani, A., Jouyandeh, M., Seidi, F., Gholami, F., Kar, S., Munir, M. T., Kowalkowska-Zedler, D., Zarrintaj, P., Rabiee, N., & Saeb, M. R. (2022). Green Polymer Nanocomposites for Skin Tissue Engineering. In ACS Applied Bio Materials (Vol. 5, Issue 5, pp. 2107–2121). American Chemical Society (ACS). https://doi.org/10.1021/acsabm.2c00313

[20] Susan, Md. A. B. H., Harun-Ur-Rashid, M., & Imran, A. B. (2023). Green Polymer Nanocomposites in Automotive and Packaging Industries. In Current Pharmaceutical Biotechnology (Vol. 24, Issue 1, pp. 145–163). Bentham Science Publishers Ltd. https://doi.org/10.2174/1389201023666220506111027

[21] Karki, S., Gohain, M. B., Yadav, D., &Ingole, P. G. (2021). Nanocomposite and bio-nanocomposite polymeric materials/membranes development in energy and medical sector: A review. In International Journal of Biological Macromolecules (Vol. 193, pp. 2121–2139). Elsevier BV. https://doi.org/10.1016/j.ijbiomac.2021.11.044

[22] Lam, P.-L., Wong, W.-Y., Bian, Z., Chui, C.-H., &Gambari, R. (2017). Recent advances in green nanoparticulate systems for drug delivery: efficient delivery and safety concern. In Nanomedicine (Vol. 12, Issue 4, pp. 357–385). Future Medicine Ltd. https://doi.org/10.2217/nnm-2016-0305

[23] Kausar, A. (2021). Green Nanocomposites for Energy Storage. In Journal of Composites Science (Vol. 5, Issue 8, p. 202). MDPI AG. https://doi.org/10.3390/jcs5080202

[24] Aykut, Y., &Yurtcan, A. B. (2022). Electrocatalysts Based on Graphene and Its Composites. American Chemical Society. https://doi.org/10.1021/bk-2022-1431.ch007

[25] Kharissova, O. V., Kharisov, B. I., Oliva González, C. M., Méndez, Y. P., &López, I. (2019). Greener synthesis of chemical compounds and materials. In Royal Society Open Science (Vol. 6, Issue 11, p. 191378). The Royal Society. https://doi.org/10.1098/rsos.191378

[26] Chieng, B., Lee, S., Ibrahim, N., Then, Y., & Loo, Y. (2017). Isolation and Characterization of Cellulose Nanocrystals from Oil Palm Mesocarp Fiber. MDPI AG. https://doi.org/10.3390/polym9080355

[27] Prusty, M (Manoranjan). (2006). De-black boxing of reactive blending: an experimental and computational approach. TechnischeUniversiteit Eindhoven. https://doi.org/10.6100/IR612788

[28] Liu, Q., Chen, X., Cao, W., Yang, J., Zhang, W., Ren, Y., … Hu, R. (2017). The synthesis, crystal structure and thermal properties of an energetic compound: the hydrated diazonium salt of 3,6-bis[(1H-1,2,3,4-tetrazol-5-yl)amino]-1,2,4,5-tetrazine. International Union of Crystallography (IUCr). https://doi.org/10.1107/s2053229617014267

[29] Wang, C., & Wang, M. (2017). Electrospun multicomponent and multifunctional nanofibrous bone tissue engineering scaffolds. Royal Society of Chemistry (RSC). https://doi.org/10.1039/c6tb02907h

[30] He, P., Ma, W., Xu, J., Wei, J., Liu, X., Zuo, P., … Zhuang, Q. (2022). Induced Crystallization‐ Controllable Nanoarchitectonics of 3D‐ Ordered Hierarchical MacroporousCo@N‐ Doped Carbon Frameworks for Enhanced Microwave Absorption. Wiley. https://doi.org/10.1002/smll.202204649

[31] https://www.azonano.com/news.aspx?newsID=39095

[32] https://www.qualitymetric.com/about/news/understanding-rare-cancers-using-patient-reported-outcome-measures/

[33] https://biotechsolns.com/regulatory-compliance/