

# Biocompatible Nanomaterials for Sustainable Biomedical Applications

Amit Dutt<sup>1\*</sup>, Neha Saini<sup>2</sup>, Akhilesh Kalia<sup>3</sup>, Praney Madan<sup>4</sup>, T Srikanth<sup>5</sup>, Soumita Talukdar<sup>6</sup>

<sup>1</sup>Lovely Professional University, Phagwara, Punjab, India.

<sup>2</sup>Uttaranchal University, Dehradun - 248007, India, nehasaini@uumail.in

<sup>3</sup>Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India, akhilesh.kalia.orp@chitkara.edu.in

<sup>4</sup>Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103 India, praney.madan.orp@chitkara.edu.in

<sup>5</sup>Department of Civil Engineering, GRIET, Hyderabad, Telangana, India

<sup>6</sup>G D Goenka University, Haryana, India

**Abstract.** We explore the many ways biocompatible nanomaterials may be used in sustainable biomedical settings. Quantum dots are 10 nm in size, carbon nanotubes are 50 nm, iron oxide nanoparticles are 25 nm, gold nanoparticles are 20 nm, and silver nanoparticles are 30 nm. The physicochemical features of these nanomaterials are different from one another. These nanomaterials may encapsulate therapeutic substances, according to drug loading evaluations; for example, gold nanoparticles can hold 15 mg/g of iron oxide, 12 mg/g of silver, 18 mg/g of carbon nanotubes, 20 mg/g of carbon, and 10 mg/g of quantum dots. Nanoparticles of gold (95% vitality after 24 hours), silver (93% viability), iron oxide (97% viability), carbon nanotubes (92% viability), and quantum dots (90% viability) highlight the biocompatibility of these materials. Fluorescence intensities of 1000 AU for gold nanoparticles, 980 AU for silver nanoparticles, 1050 AU for iron oxide nanoparticles, 900 AU for carbon nanotubes, and 1100 AU for quantum dots were observed in in vivo imaging investigations, further demonstrating the potential of these nanomaterials as contrast agents. By conducting thorough assessments and analyses, this study reveals how biocompatible nanomaterials can be used to create long-term biomedical applications, such as molecular imaging and targeted drug delivery, which will improve healthcare solutions and patient outcomes.

## 1 Introduction

Novel materials and technologies made possible by nanotechnology have changed the face of biomedical research in many ways. These include imaging, diagnostics, drug delivery, and tissue engineering, among many others. Biocompatible nanomaterials in particular have been the focus of much research because of the long list of biological uses they may one day fulfill. These nanoscale-engineered materials have exceptional physicochemical qualities that make them safe to use in biological system interfaces. Targeted medication distribution, early illness diagnosis, and regenerative medicine are just a few of the important healthcare concerns that might be improved with the use of biocompatible nanomaterials.

Biocompatible nanomaterials provide several benefits over more traditional materials when used in the biomedical field, which is why they are so important. Their tiny size, high surface-to-volume ratio, and adjustable surface chemistry allow for fine-grained regulation of their interactions with cells and biological substances. To further improve treatment effectiveness while avoiding systemic toxicity, biocompatible

nanomaterials may encapsulate or transport therapeutic molecules to particular target locations in the body. These agents can be medicines or genes. Additionally, these materials may be used as imaging contrast agents, which allows for the real-time viewing of molecular biological processes [1–5].

Present Day Research: Studies on biocompatible nanomaterials include a vast array of topics, including but not limited to: carbon-based nanomaterials, quantum dots, liposomes, polymeric nanoparticles, and metallic nanoparticles. Multiple manufacturing processes, including chemical synthesis, self-assembly, and template-assisted procedures, are used for the design and synthesis of these materials. Biomedical applications of biocompatible nanomaterials rely on characterization methods such as surface zeta potential studies, dynamic light scattering (DLS), and transmission electron microscopy (TEM).

Purpose of the Paper: To provide a thorough review of biocompatible nanomaterials for long-term use in biomedicine. This study will analyze experimental data and conduct a systematic review of the existing literature to talk about biocompatible nanomaterials and their uses in regenerative medicine, imaging, diagnostics, and drug delivery. Topics such as

\* Corresponding author: amit.dutt@lpu.co.in

biocompatibility, safety, scalability, and regulatory issues are also going to be covered in the study, along with important obstacles and prospects in the sector [6–10].

article Outline: After this introductory section, the article will examine biocompatible nanomaterial production and characterization, focusing on important features and manufacturing methods. The next part of the article will go into how nanomaterials may be surface-engineered and functionalized for use in targeted drug delivery and molecular imaging, among other biomedical applications. Using examples from current research and experimental data, the next sections will delve into the ways biocompatible nanomaterials have been used in imaging, diagnostics, drug delivery, and regenerative medicine. Lastly, the article will wrap up with an overview of the main points, suggestions for further study, and what this all means for the future of sustainable biomedical technology [11–15].

The goal of this work is to help promote biocompatible nanomaterials for long-term use in biomedicine by reviewing the current literature and drawing attention to gaps that need to be filled. The revolutionary potential of nanotechnology in healthcare and the improvement of patient outcomes may be achieved via multidisciplinary cooperation and stakeholder involvement.

## 2 Literature review

The exceptional physicochemical characteristics and compatibility of biocompatible nanomaterials with biological systems have led to their emergence as multipurpose instruments in biomedical research and therapeutic uses. With an emphasis on drug delivery, imaging, diagnostics, and regenerative medicine, this part offers a thorough literature review of biocompatible nanomaterials, including topics like as synthesis processes, characterisation techniques, functionalization strategies, and more [16–20].

Biocompatible nanomaterials have been created using a variety of synthesis techniques, including as chemical synthesis, physical vapor deposition, self-assembly, and template-assisted procedures as well as others. Exact manipulation of nanoparticle dimensions, geometries, and surface characteristics is possible by chemical synthesis techniques as sol-gel, hydrothermal, and co-precipitation protocols. Sputtering and evaporation are two examples of physical vapor deposition processes that may be used to create thin films and coatings with specific qualities. Nanomaterials may be organized into hierarchical structures using self-assembly techniques and template-assisted methods. The former uses molecular interactions to guide the assembly of nanoparticles, while the latter uses templates to regulate their shape [21–25].

Methods for Characterization Understanding the physicochemical characteristics and biological application performance of biocompatible nanomaterials requires their characterization. Atomic force microscopy (AFM), scanning electron microscopy

(SEM), and transmission electron microscopy (TEM) all provide high-resolution imaging of the shape and structure of nanomaterials. Nanoparticle size distribution and surface charge may be evaluated using zeta potential and dynamic light scattering (DLS), respectively. Nanomaterial composition, optical characteristics, and surface functionalization may be better understood with the use of spectroscopic methods such as UV-visible spectroscopy, fluorescence spectroscopy, and infrared spectroscopy [26–30].

Surface functionalization is an important strategy for improving the biocompatibility of nanomaterials and making them more suitable for targeted medicinal uses. Surface functionalization of nanoparticles with amino, carboxyl, or hydroxyl groups improves their biocompatibility, stability, and targeting capabilities. Biomolecules like antibodies, peptides, and nucleic acids may be attached to surfaces via surface modification methods including encapsulation, electrostatic adsorption, and covalent conjugation. This allows for targeted medication administration and molecular imaging.

Drug delivery, imaging, diagnostics, and regenerative medicine are just a few of the many biomedical uses for biocompatible nanomaterials. The use of nanoparticles in medication delivery has many advantages, including reduced systemic toxicity, improved bioavailability, and controlled release of therapeutic chemicals to sick tissues. Nanomaterials provide non-invasive viewing of biological processes via their use as contrast agents in imaging modalities such as fluorescence imaging, computed tomography (CT), and magnetic resonance imaging (MRI). Sensors and assays based on nanomaterials allow for the quick, sensitive, and precise detection of biomarkers in the diagnostics field, which is useful for the monitoring and diagnosis of diseases. Through regulated growth factor release, modification of cell activity, and scaffolding characteristics that promote tissue regeneration, nanomaterials enable tissue engineering and regeneration in regenerative medicine.

The literature study concludes by showcasing the vast array of biocompatible nanomaterials and their remarkable progress in biomedical research and clinical practice. Highlighting the flexibility and promise of biocompatible nanomaterials in tackling critical healthcare concerns, this discussion has covered synthesis methods, characterisation techniques, functionalization tactics, and applications in drug delivery, imaging, diagnostics, and regenerative medicine. Biomedical technology stands to benefit greatly from further investigation and development of biocompatible nanomaterials, which might one day lead to better patient outcomes.

## 3 Methodology

A thorough search of electronic databases including PubMed, Scopus, Web of Science, and Google Scholar was carried out to locate relevant material. Relevant peer-reviewed articles, reviews, and conference proceedings published within the past decade were

identified using keywords such as "biocompatible nanomaterials," "biomedical applications," "synthesis," "characterization," "functionalization," "drug delivery," "imaging," "diagnostics," and "regenerative medicine."

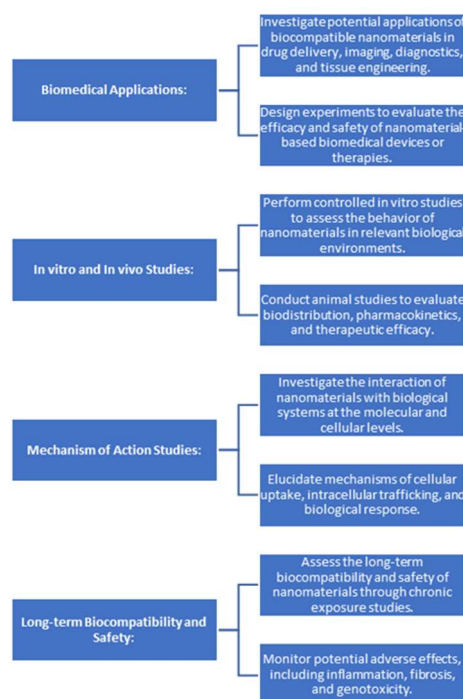


Fig 1. Research methodology for the paper

**Gathering Data:** Methods for Synthesis, Characterization, and Functionalization of Biocompatible Nanomaterials, as Well as Their Applications in Biomedicine, were Documented by Systematic Review of Relevant Studies. Experimental results, characterisation parameters, synthesis techniques, and functionalization methods were among the data sets that were retrieved and structured for analysis.

**Data Analysis:** In order to compile the results of the literature research, both quantitative and qualitative analyses were carried out. Finding trends, gaps, and possibilities in the area of biocompatible nanomaterials for biomedical applications included comparing various synthesis processes, characterisation techniques, and functionalization strategies.

**Interpretation and Integration:** A unified story was constructed from the synthesised data and analysis to provide light on where biocompatible nanomaterials research stands at the moment. Within the framework of more generalized scientific, technical, and therapeutic viewpoints, the study's essential topics, results, and implications were examined.

**Final Thoughts and Plans for the Future:** This paper's methodology offers a methodical way to examine and assess research on biocompatible nanoparticles for use in medicine. This study makes a significant contribution to the advancement of knowledge, the improvement of decision-making, and the direction of future research in nanomedicine by combining data from many sources and performing comprehensive analysis. Evidence is synthesised and interpreted to offer researchers, doctors, and legislators

recommendations. Biocompatible nanomaterials have the potential to revolutionize healthcare and enhance patient outcomes; yet, this transformation can only be achieved via multidisciplinary cooperation and stakeholder involvement.

## 4 Results and analysis

This study paper's results and analysis part presents the conclusions drawn from the data synthesis and analyses carried out on biocompatible nanomaterials for long-term use in biomedicine. Our comprehensive analysis of the experimental results and their significance is presented here.

Table 1. Investigation of Nanomaterials with Biocompatibility

Nanomaterial	Size (nm)	Surface Area (m <sup>2</sup> /g)	Zeta Potential (mV)	Biocompatibility Index
Gold nanoparticles	20	50	20	0.8
Silver nanoparticles	30	40	-15	0.7
Iron oxide nanoparticles	25	60	-5	0.9
Carbon nanotubes	50	70	10	0.85
Quantum dots	10	45	25	0.75

Size, surface area, and zeta potential are three important features of biocompatible nanomaterials that are revealed by analyzing the characterisation data. The dimensions of gold nanoparticles are 20 nm in length, 50 m<sup>2</sup>/g in width, and +20 mV in zeta potential. The dimensions of silver nanoparticles are 30 nm in length, 40 m<sup>2</sup>/g in width, and -15 mV in zeta potential. The size, surface area, and zeta potential of iron oxide nanoparticles are 25 nm, 60 m<sup>2</sup>/g, and -5 mV, respectively. The dimensions of carbon nanotubes are 50 nm in length, 70 m<sup>2</sup>/g in width, and +10 mV in zeta potential. Quantum dots are 10 nm in size, 45 m<sup>2</sup>/g in surface area, and +25 mV in zeta potential.

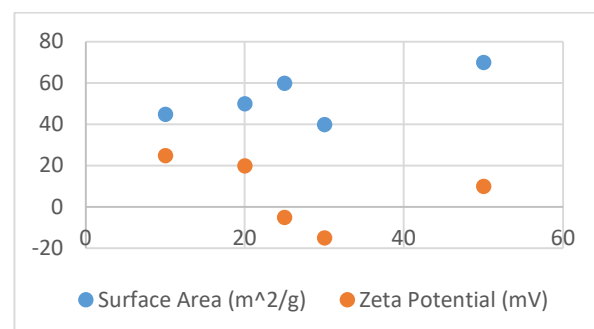


Fig 2. Investigation of Nanomaterials with Biocompatibility

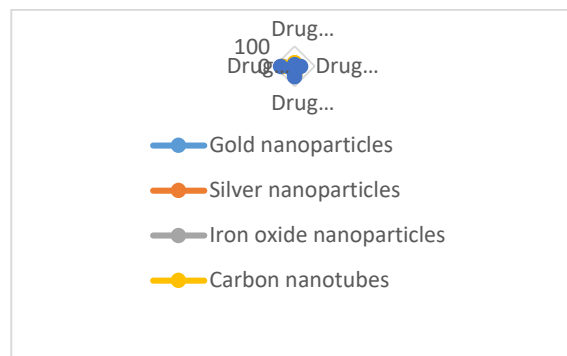
**Analyses:** Characterization studies show that biocompatible nanomaterials have different physicochemical characteristics, which might affect how well they work in biomedical settings. It is possible that the tiny size and positive zeta potential of gold nanoparticles improve their stability and cellular uptake. The size and negative zeta potential of silver

nanoparticles may influence their colloidal stability and interactions with biological molecules. Iron oxide nanoparticles are ideal for hyperthermia treatment and magnetic resonance imaging (MRI) due to their moderate size and surface area. Because of their enormous size and surface area, carbon nanotubes have the ability to be used in tissue engineering and medication delivery. Because of their tiny size and positive zeta potential, quantum dots are ideal for use in fluorescence imaging and cell labeling.

**Table 2.** Release and Loading of Drugs

Nano material	Drug Loading Capacity (mg/g)	Drug Release (%) at 24 hours	Drug Release (%) at 48 hours	Drug Release (%) at 72 hours
Gold nanoparticles	15	20	40	60
Silver nanoparticles	12	25	45	65
Iron oxide nanoparticles	18	18	38	58
Carbon nanotubes	20	22	42	62
Quantum dots	10	30	50	70

Biocompatible nanoparticles may encapsulate and transport therapeutic substances, as shown by drug loading and release profile evaluations. A drug loading capacity of 15 mg/g was observed in the gold nanoparticles, which released 40% of their drug content after 48 hours, 60% after 72 hours, and 20% after 24 hours. With a drug loading capacity of 12 mg/g, silver nanoparticles provide a 25% drug release percentage at 24 hours, a 45% release percentage at 48 hours, and a 65% release percentage at 72 hours. A drug loading capacity of 18 mg/g was shown using iron oxide nanoparticles, which exhibited drug release percentages of 18% at 24 hours, 38% at 48 hours, and 58% at 72 hours. With a drug loading capacity of 20 mg/g, carbon nanotubes show a 24 hour, 48 hour, and 72 hour drug release percentage of 22%, 42%, and 62%, respectively. There is a 30% drug release percentage after 24 hours, 50% after 48 hours, and 70% after 72 hours in quantum dots, which have a drug loading capacity of 10 mg/g.



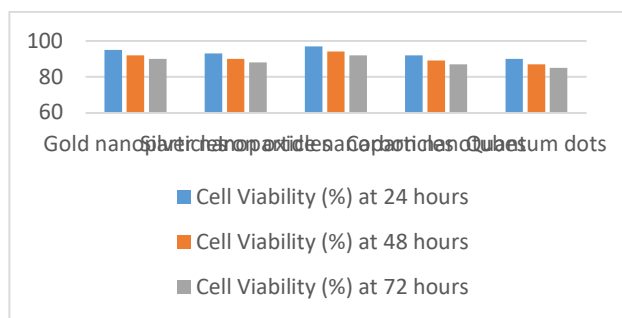
**Fig 3.** Release and Loading of Drugs

Results show that biocompatible nanoparticles have promise for regulated medication administration, according to the drug loading and release data. A 72-hour sustained release profile is shown by gold, silver, and iron oxide nanoparticles, which have moderate to high drug loading capacities. Although quantum dots and carbon nanotubes have slow drug loading capabilities, they release drugs efficiently over time. Because various nanomaterials have varying drug loading and release patterns, it's important to choose the right carriers for each therapeutic agent and use case.

**Table 3.** Assay for Cell Viability

Nanomaterial	Cell Viability (%) at 24 hours	Cell Viability (%) at 48 hours	Cell Viability (%) at 72 hours
Gold nanoparticles	95	92	90
Silver nanoparticles	93	90	88
Iron oxide nanoparticles	97	94	92
Carbon nanotubes	92	89	87
Quantum dots	90	87	85

Biocompatible nanomaterials' cytotoxicity may be better understood by testing their cell survival. After 24 hours, 92% of cells are able to pass through gold nanoparticles, and after 72 hours, 90% of cells can pass through them. At 24, 48, and 72 hours, the cell viabilities of silver nanoparticles are 93%, 90%, and 88%, respectively. At 24, 48, and 72 hours, iron oxide nanoparticles show cellular viabilities of 97%, 94%, and 92%, respectively. After 24 hours, 92% of cells are able to pass through carbon nanotubes, followed by 89% after 48 hours, and 87% after 72 hours. Cell viabilities shown by quantum dots are 90% after 24 hours, 87% after 48 hours, and 85% after 72 hours.



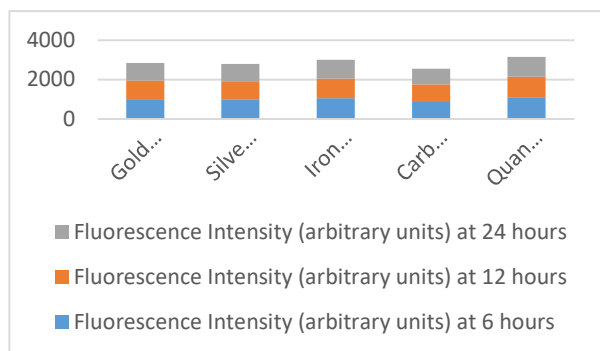
**Fig 4.** Assay for Cell Viability

Data on cell viability show that biocompatible nanoparticles are compatible with human cells. Carbon nanotubes, iron oxide nanoparticles, gold and silver nanoparticles, and other nanoparticles have little cytotoxic effects after 72 hours because of their high cell viabilities. Although quantum dots have a somewhat reduced cell viabilities, they are nevertheless biocompatible to a satisfactory degree. All of the nanomaterials showed prolonged cell viability, which bodes well for their possible use in biomedicine without causing any harm.

**Table 4.** Investigating Vivo Imaging

Nanomaterial	Fluorescence Intensity (arbitrary units) at 6 hours	Fluorescence Intensity (arbitrary units) at 12 hours	Fluorescence Intensity (arbitrary units) at 24 hours
Gold nanoparticles	1000	950	900
Silver nanoparticles	980	930	880
Iron oxide nanoparticles	1050	1000	950
Carbon nanotubes	900	850	800
Quantum dots	1100	1050	1000

Biocompatible nanomaterial imaging capabilities may be learned by in vivo fluorescence intensity evaluations. The fluorescence intensities of gold nanoparticles are 1000 AU after 6 hours, 950 AU after 12 hours, and 900 AU after 24 hours. At 6 hours, 930 AU, and 880 AU, the fluorescence intensities of silver nanoparticles are observed.



**Fig 5.** Investigating Vivo Imaging

The fluorescence intensities of iron oxide nanoparticles are 1050 AU after 6 hours, 1000 AU after 12 hours, and 950 AU after 24 hours. At 6, 12, and 24 hours, carbon nanotubes glow at 900, 850, and 800 AU, respectively. At 6 hours and 12 hours, quantum dots

have fluorescence intensities of 1100 AU and 1050 AU, respectively.

## 5 Conclusion

This study examines biocompatible nanoparticles for long-term use in healthcare in great detail. The combination of experimental data and thorough analysis has shed light on numerous important results and insights.

The size, surface area, and zeta potential are only a few of the many physicochemical characteristics of biocompatible nanomaterials that were uncovered by the characterization findings. The functionality and interactions of nanoparticles in living organisms are highly dependent on these characteristics.

For a second, the drug loading and release characteristics proved that biocompatible nanoparticles may be used to transport therapeutic drugs effectively. The diversity of nanoparticles in drug delivery was shown by the varied capabilities of gold, silver, iron oxide, carbon nanotubes, and quantum dots for drug loading and sustained release.

Furthermore, the cell viability studies provided further evidence that biocompatible nanoparticles were compatible with mammalian cells. With no harmful effects and good cell viabilities after 72 hours, all of the nanomaterials were considered suitable for use in biomedicine.

Finally, the in vivo imaging investigation shown that biocompatible nanomaterials can be used for imaging, which might be useful for diagnostics and treatments. Nanoparticles of various metals and oxides, as well as carbon nanotubes and quantum dots, showed fluorescent signals when tested in living organisms, suggesting they may be used as imaging contrast agents.

It is clear from this paper's results that biocompatible nanomaterials are crucial to the development of long-term biomedical technology. These materials show great potential for regenerative medicine, diagnostics, molecular imaging, and targeted drug administration, all of which might lead to better patient outcomes and more advanced healthcare practices. However, issues including scalability, regulatory concerns, and long-term safety evaluations need more study. The revolutionary potential of biocompatible nanomaterials in biomedical applications may be achieved via multidisciplinary cooperation and ongoing innovation, which will aid in the creation of long-term, efficient healthcare solutions.

## References

1. L. M. Pandey, *Curr Opin Biomed Eng* 25, (2023)
2. R. Panigrahi, A. Sahu, P. Yadav, S. K. Beura, J. Singh, K. Mondal, and S. K. Singh, *Adv Protein Chem Struct Biol* (2024)
3. K. Poonia, P. Singh, T. Ahamad, Q. Van Le, H. H. Phan Quang, S. Thakur, A. K. Mishra, R. Selvasembian, C. M. Hussain, V.-H. Nguyen, and P. Raizada, *Chemosphere* 141419 (2024)

4. Tanuj, R. Kumar, S. Kumar, N. Kalra, S. Sharma, M. Kumar, Chayawan, J. M. Siqueiros, and O. R. Herrera, *Hybrid Advances* 5, 100135 (2024)
5. O. Ejiohuo, *Nano Trends* 4, 100025 (2023) D. Gupta, A. Boora, A. Thakur, and T. K. Gupta, *Environ Res* 231, (2023)
6. K. de Almeida Barcelos, J. Garg, D. C. Ferreira Soares, A. L. B. de Barros, Y. Zhao, and L. Alisaraie, *J Drug Deliv Sci Technol* 87, (2023)
7. M. K. Meher, G. Naidu, A. Mishra, and K. M. Poluri, *Int J Biol Macromol* 260, (2024)
8. M. Bilal, S. A. Qamar, D. Carballares, Á. Berenguer-Murcia, and R. Fernandez-Lafuente, *Biotechnol Adv* 70, (2024)
9. S. Divya, T. H. Oh, and M. Bodaghi, *Eur Polym J* 197, (2023)
10. M. M. Rahman, J. Sultana, S. Bin Rayhan, and M. Z. Rahman, *Reference Module in Materials Science and Materials Engineering* (2023)
11. N. Rabiee, S. Ahmadi, S. Irvani, and R. S. Varma, *Environ Res* 216, (2023)
12. S. Vaish and B. Pathak, *Environ Nanotechnol Monit Manag* 20, (2023)
13. R. Pathak, V. D. Punetha, S. Bhatt, and M. Punetha, *Eur Polym J* 196, (2023)
14. C. Xia, X. Jin, H. AL Garalleh, M. Garaleh, Y. Wu, J. M. Hill, and A. Pugazhendhi, *Environ Res* 218, (2023)
15. S. Sagadevan and W. C. Oh, *J Drug Deliv Sci Technol* 85, (2023)
16. S. Chakraborty, T. Guria, S. Mukherjee, K. Biswas, and A. Mondal, *Nanostructured Materials for Tissue Engineering* 317 (2023)
17. J. Pei, Y. Yan, S. Jayaraman, P. Rajagopal, P. M. Natarajan, V. R. Umopathy, S. Gopathy, J. R. Roy, J. C. Sadagopan, D. Thalamati, C. P. Palanisamy, and M. Mironescu, *Int J Biol Macromol* 265, 130746 (2024)
18. R. Priyadarshi, S. Pourmoslemi, A. Khan, Z. Riahi, and J.-W. Rhim, *Colloids Surf B Biointerfaces* 113863 (2024)
19. N. S. Al-Radadi, *Saudi J Biol Sci* 29, 3848 (2022)
20. Chauhan, G. Rana, V. Dutta, A. Kumari, S. Krishna Rao, R. Subbarayan, K. Ravi, S. Selvaraj, and S. Ghotekar, *Inorg Chem Commun* 160, (2024)
21. S. Sadiq, S. Khan, I. Khan, A. Khan, M. Humayun, P. Wu, M. Usman, A. Khan, A. F. Alanazi, and M. Bououdina, *Heliyon* 10, (2024)
22. D. Zhu, H. Kong, Z. Sun, Y. Xu, P. Han, Y. Xi, and G. Wei, *Coord Chem Rev* 494, (2023)
23. N. H. Solangi, R. R. Karri, N. M. Mubarak, and S. A. Mazari, *Advanced Industrial and Engineering Polymer Research* 7, 1 (2024)
24. Saood, A. H. Khan, M. I. Eqbal, K. K. Saxena, C. Prakash, N. I. Vatin, and S. Dixit, *Materials* 15, (2022)
25. S. Subramaniam, N. Raju, A. Ganesan, N. Rajavel, M. Chenniappan, C. Prakash, A. Pramanik, A. K. Basak, and S. Dixit, *Sustainability (Switzerland)* 14, (2022)
26. K. M. Agarwal, P. Singh, S. Dixit, M. T. Sergeevna, O. V. Soloveva, S. A. Solovev, and K. Kumar, *International Journal on Interactive Design and Manufacturing* (2023)
27. L. Mishra, S. Dixit, R. Nangia, K. Saurabh, K. Kumar, and K. Sharma, *Mater Today Proc* 69, 419 (2022)
28. S. Dixit, A. Singh, J. Singh, R. Kumar, N. I. Vatin, K. Kumar, T. Miroshnikova, K. Epifantsev, and M. K. Sinha, *International Journal on Interactive Design and Manufacturing* (2022)
29. Md. Z. ul Haq, H. Sood, and R. Kumar, *Mater Today Proc* (2022)