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Nanopolymers in Medical Applications: Advances, Challenges, and Promising Innovations for Healthcare Enhancement

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Abstract

Nanotechnology may change medicine, nanopolymers are versatile and healthy nanomaterials. This study discusses cutting-edge nanopolymer medicinal uses, their successes, challenges, and expected advancements. Nanopolymers are defined and classified first. It involves nanopolymer production and characterization for medical applications. In the following chapters, nanopolymers govern medication release. Nanopolymers in tissue engineering provide promising therapeutic techniques in regenerative medicine, organ transplantation, and tissue repair. Medical imaging contrast agents and biosensors use nanopolymers. Nanopolymers increase cancer therapy efficacy and side effects by targeted drug administration, combination therapies, and imaging-guided treatments. Nanopolymers can transfer genes and modify genomes, making them a useful tool for genetic issues. Nanopolymers boost vaccine and therapeutic immune responses by distributing antigens. Safety and regulation make medical nanopolymers biocompatible and safe. Ethical and environmental factors guide creation and usage. The study covers commercialization, market trends, and key players. It covers nanopolymer integration issues and mainstream medicinal possibilities. Nanopolymer research and tailored nanopolymeric therapeutics are anticipated. "Nanopolymers in Medical Applications: Advances, Challenges, and Promising Innovations for Healthcare Enhancement" finishes with a comprehensive and forward-looking study of nanopolymers' medical revolution. This review advances nanopolymers towards safer, more effective, and patient-centered healthcare.

Keywords

Nanopolymers, Medical applications, Healthcare enhancement, Targeted drug delivery, Biocompatibility

Introduction

Nanotechnology and its impact on medicine

Nanotechnology, which manipulates matter at the atomic or molecular level, has revolutionized medical diagnosis, treatment, and drug delivery [1]. Nanoscale material features enable tailored medication delivery, personalized therapy, and improved medical imaging. Drug effectiveness and side effects are improved using nanoparticles. Nanosensors detect illnesses early and sensitively. Nanotechnology improves tissue engineering, regenerative medicine, and gene therapy, making them potentially curative (Table 1) [2]. Nanomedicine will revolutionize healthcare, bringing precise medicine and better patient outcomes.

Evolution of nanopolymers in medical applications

Nanopolymers in medicine have advanced scientifically and innovatively. Researchers first synthesized and characterized nanopolymers to discover their

Table 1: Different types of nano-polymers used in medical applications.

Type of nanopolymer	Applications in medical field	Examples
Nanoparticles	Drug delivery systems for targeted therapy	Polymeric micelles, Polymeric nanoparticles, Dendrimers
Nanogels	Controlled drug release for tissue regeneration	Crosslinked nanogels, Hydrogels
Nanostructured scaffolds	Tissue engineering and regenerative medicine	Nanofibrous scaffolds, Nanostructured hydrogels
Liposomes	Drug delivery and gene therapy	Cationic liposomes, PEGylated liposomes
Nanofibers	Tissue engineering and wound healing	Electrospun nanofibers, Nanofiber meshes
Dendrimers	Drug delivery and gene therapy	Poly(amidoamine) dendrimers, Poly(propyleneimine) dendrimers
Nanocomposites	Imaging and diagnostic applications	Iron oxide-polymericnanocomposites, Quantum dot-polymeric nanocomposites
Nanocapsules	Drug delivery and controlled release	Polymeric nano-capsules, Inorganic-organic nanocapsules
Nanoparticles with ligands	Targeted drug delivery and cancer therapy	Folate-conjugated nanoparticles, Antibody-targeted nanoparticles
Theranostic nanopolymers	Combined therapeutic and diagnostic applications	Multifunctional polymeric nanoparticles, Imaging-guided nanopolymers

nanoscale characteristics. Nanopolymers improved drug distribution and tailored treatment over time. Tissue engineering enabled tissue regeneration and repair. Nanopolymers as contrast agents improved diagnostic imaging with unparalleled accuracy [3]. Nanopolymers also helped cure cancer, generate vaccines, and treat genes, offering a bright future for nanotechnology in medicine.

Scope and objectives of the nanopolymers in medical applications

"Nanopolymers in Medical Applications" covers the many uses of nanopolymers in healthcare. This book covers nanopolymer fundamentals, synthesis, characterization, and medicinal applications. Drug delivery, tissue engineering, diagnostics, cancer treatment, gene therapy, vaccinations, and infectious illness management are the focus [4]. Responsible development requires safety and regulatory concerns. The book also discusses developing uses, commercial views, and future prospects to help nanopolymers revolutionize healthcare.

Fundamentals of Nanopolymers

Nanopolymers cover nanoscale polymer properties and understanding. Repeating units create chains or networks with unique characteristics in these materials. Nanopolymers' physical and chemical properties vary from 1 to 100 nm [5]. Understanding emulsion polymerization and template-assisted synthesis is crucial. Researchers may analyze morphology, size distribution, and stability using atomic force microscopy and dynamic light scattering. Nanopolymers' adaptability makes them excellent for medication delivery, tissue engineering, and diagnostic imaging.

Nanopolymers: definition, properties, and classification

Nanopolymers are polymers having less than 100 nm dimensions. Their tiny size and high surface-to-volume ratio give them special features. These qualities affect behaviour and applications. Structure, composition, and characteristics classify nanopolymers. Biodegradable, biocompatible, or stimuli-responsive polymers may be straight, branching, or cross-linked [6]. Classifying nanopolymers helps adjust their properties for medicinal applications such medication delivery, tissue engineering, diagnostics, gene therapy, and enhancing healthcare technology.

Synthesis techniques of nanopolymers

Nanopolymer synthesis involves precise control over size, structure, and characteristics. This is accomplished using many methods. Polymerization in an emulsion creates nanoparticles. Template-assisted techniques generate homogeneous nanopolymers via nanoscale cavities in templates. Solution-based methods dissolve polymers or monomers in solvents and precipitate nanoparticles. Polymer solutions are electrospun into nanofibers. In-situ, miniemulsion, and nanoprecipitation are further approaches (Table 2) [7]. Application and nanopolymer characteristics determine the production method.

Characterization methods for nanopolymers

Understanding nanopolymers' structure, size, and characteristics affects their medicinal performance. This requires sophisticated methods. Dynamic light scattering examines particle size distribution in solution, whereas transmission electron microscope images nanopolymers at high resolution. An atomic force microscope measures surface topography and roughness. X-ray diffraction determines crystal and molecular structure. Fourier transform infrared spectrophotometer detects chemical functional groups. Gel permeation chromatography measures molecular weight and distribution. These characterization approaches help researchers optimize nanopolymers for targeted drug administration, diagnostics, and medical advances [6].

Nanopolymers in Drug Delivery

Nanopolymers' unique features have transformed medication delivery. They stabilize, solubilize, and regulate drug release as carriers. Their tiny size enhances cellular uptake and tissue penetration for focused treatment. Nanopolymers may also release drugs at precise places when stimulated. They may also transport various medications for combination therapy and synergy. Drug delivery methods are becoming safer and more effective, resulting in better patient outcomes and fewer adverse effects [5]. Nanopolymers are shaping personalized treatment and transformational healthcare.

Table 2: Different synthesis techniques used for nanopolymers.

Synthesis technique	Description	Applications
Emulsion polymerization	Monomer droplets stabilized in an emulsion	Synthesis of nanopolymer particles with controlled size
Suspension polymerization	Monomer suspension in a non-solvent	Preparation of nanopolymers with specific morphologies
Miniemulsion polymerization	Fine droplets stabilized in a surfactant system	Production of nanoparticles with high monomer conversion
Polymer nanocomposite	Incorporation of nanoparticles into polymer matrix	Reinforcement of polymers for enhanced mechanical properties
Reversible addition-fragmentation chain transfer	Controlled radical polymerization technique	Synthesis of polymers with controlled molecular weight and architecture
Atom transfer radical polymerization	Controlled radical polymerization technique	Production of polymers with well-defined chain ends and structures
Ring-opening polymerization	Opening of cyclic monomers to form polymers	Synthesis of biodegradable polymers and drug carriers
Self-assembly	Spontaneous organization of monomers into nanostructures	Creation of self-assembled nanopolymeric structures
Electrospinning	Electrostatic forces to create nanofibers	Fabrication of nanofiber-based materials for drug delivery
Template-assisted synthesis	Use of templates to create nano-polymeric structures	Production of nanopolymer particles with specific shapes

Nanopolymeric drug carriers: types and applications

Nanopolymeric drug carriers have several uses in medication delivery. Polymeric micelles and nanoparticles stabilize and solubilize weakly soluble medicines, allowing targeted treatment. Site-specific drug delivery is possible with nanogels due to their crosslinked 3D network, which releases pharmaceuticals in response to pH and temperature. Dendrimers, highly branched and well-defined in size and form, may encapsulate pharmaceuticals inside and out for precise drug loading and release [7]. Liposomes, made of lipid bilayers, transport hydrophobic and hydrophilic medicines for cancer treatment and gene delivery. Nanopolymeric carriers may improve medication delivery, effectiveness, adverse effects, and personalized medicine.

Enhancing drug stability and bioavailability

Pharmaceutical development prioritizes medication stability and bioavailability. Nanopolymeric drug carriers enable these goals. Nanocarriers stabilize pharmaceuticals by encapsulating them in their polymeric matrix. Nanocarriers increase bioavailability by improving medication solubility, absorption, and distribution [8]. These carriers also delay medication clearance in the bloodstream. Nanopolymeric drug carriers may enhance medication delivery and patient outcomes by improving therapeutic effectiveness, reducing dose frequency, and reducing adverse effects.

Targeted drug delivery with nanopolymers

Nanopolymers provide accurate, site-specific medication delivery, revolutionizing medicinal therapies. Nanopolymeric carriers may route medicinal molecules to sick cells by recognizing certain molecular markers or receptors. This reduces medication exposure to healthy tissues, lowering off-target negative effects and improving therapeutic effectiveness. Nanopolymers may carry medications to inaccessible areas by crossing biological barriers like the blood-brain barrier [2]. Nanopolymer-targeted medication delivery promises personalized therapy that improves patient outcomes and healthcare quality.

Controlled release systems for improved therapeutic efficacy

Controlled release systems improve therapeutic effectiveness by slowly releasing medicines. These systems deliver medications at exact rates, prolonging therapeutic doses, decreasing adverse effects, and enhancing patient compliance. Due to their biocompatibility and tunability, nanopolymers are excellent controlled release carriers [2]. They adapt medication release kinetics to medical situations and patient demands. Controlled release systems may enhance personalized medicine and patient outcomes in chronic illness management, pain relief, and cancer treatment [9].

Nanopolymers in Tissue Engineering

Nanomaterials for tissue regeneration and repair

Nanopolymers provide novel materials for tissue regeneration and repair, revolutionizing tissue engineering. Nanofibers, nanoparticles, and nanocomposites imitate the extracellular matrix, encouraging cell adhesion, proliferation, and differentiation. They promote tissue development and nanoscale integration, improving biocompatibility and functioning. Nanomaterials in tissue engineering promise bioengineered tissues and organs for regenerative therapy patients (Table 3) [10].

Nanostructured scaffolds for tissue engineering

Tissue engineering requires nanostructured scaffolds. Nanopolymer 3D matrices mimic real tissue, promoting cell adhesion, migration, and tissue development. Their large surface area promotes nutrition and waste exchange, cell development, and tissue regeneration. Nanostructured scaffolds release growth factors and bioactive chemicals to influence cell behavior and tissue formation [11]. Nanopolymers in scaffold design can construct complex tissues and organs, boosting regenerative medicine.

Nanopolymers in organ transplantation and regenerative medicine

Nanopolymers revolutionized organ transplantation and regenerative medicine. Targeted medication delivery using nanopolymeric carriers prevents organ rejection without weakening the immune system. Increased medication absorp-

Table 3: Nanomaterials for tissue regeneration and repair.

Nanomaterial	Description	Applications
Nanofibers	Ultra-thin fibers with nanoscale diameter	Scaffold for tissue engineering, Wound healing
Nanocomposites	Hybrid materials combining different types of nanomaterials	Bone regeneration, Cartilage repair, Tissue scaffolds
Nanogels	Crosslinked nanoscale hydrogels	Controlled drug release, Tissue engineering
Nanoparticles	Small particles in the nanometer size range	Drug delivery, Targeted therapy, Tissue regeneration
Nanostructured surfaces	Surface modifications promoting cell adhesion	Implant coatings, Tissue regeneration
Nanofibrous membranes	Porous membranes with nanofiber structure	Skin regeneration, Tissue engineering
Nanoceramics	Ceramic materials in the nanoscale size range	Bone tissue engineering, Dental implants
Nanocomposite hydrogels	Hybrid hydrogels with nanoscale fillers	Soft tissue engineering, Drug delivery
Nanocarriers	Nanoparticles or nanovesicles for controlled drug delivery	Localized drug release, Tissue repair

tion at the transplanting site reduces systemic negative effects. Nanopolymers also provide a supportive milieu for transplanted cells and tissues to develop and integrate [12]. Nanopolymers may improve organ transplants and regenerative therapy, giving patients hope.

Diagnostic Applications of Nanopolymers

Nanopolymers as contrast agents in medical imaging

Magnetic resonance imaging, computed tomography, and ultrasound contrast agents use nanopolymers. Their special features allow accurate tissue and organ imaging with greater contrast and resolution. Functionalized nanopolymers may target biomarkers for better imaging and early disease diagnosis. Biocompatibility and adjustable surface chemistry provide safe and effective body transport [13]. Nanopolymer-based contrast agents might improve medical imaging and disease diagnosis and monitoring.

Enhancing sensitivity and specificity in diagnostics

Diagnostic tests benefit from nanopolymers. Nanopolymers with particular ligands or antibodies may specifically collect disease-specific biomarkers. Diagnostic testing has fewer false positives and negatives. Nanopolymeric systems may amplify signals and detect low-concentration analytes. Diagnostic advances offer early illness identification, quick intervention, and better patient outcomes.

Nanopolymeric biosensors for early disease detection

Nanopolymeric biosensors can accurately detect disease-specific proteins. Nanopolymers immobilize recognition components like antibodies or aptamers that selectively bind target analytes in these biosensors. Nanopolymeric biosensors create signals for speedy and accurate illness diagnosis. Point-of-care testing allows early illness identification even in resource-limited situations due to its miniaturization and portability [14]. Nanopolymeric biosensors might revolutionize healthcare by enabling early therapies and better disease control.

Nanopolymers in Cancer Therapy

Targeting cancer cells with nanopolymeric therapeutics

Nanopolymers target cancer cells while protecting healthy tissues. Functionalized nanopolymers may target cancer-specific biomarkers on cell surfaces to deliver drugs. Treatment effectiveness, systemic toxicity, and adverse effects are improved [15]. Targeted nanopolymeric therapies can adapt cancer therapy to specific patients and tumors.

Combination therapies and synergistic effects

Nanopolymeric carrier-based cancer therapy combinations have shown promise. Nanopolymers may improve treatment results by co-delivering numerous medicines. This method reduces tumor recurrence, treatment resistance, and therapeutic response [16]. Nanopolymeric carriers may co-deliver imaging agents and medicines, allowing real-time treatment effectiveness monitoring and therapeutic choices.

Theranostic nanopolymers for imaging-guided cancer treatment

Nanopolymeric carrier-based cancer therapies are promising. Nanopolymers can co-deliver several drugs to enhance therapy. This lowers cancer recurrence, treatment resistance, and response. Nanopolymeric carriers may co-deliver imaging agents and drugs for real-time treatment effectiveness monitoring and therapeutic options [17].

Nanopolymers in Gene Therapy

Nanocarriers for efficient gene deliverys

Nanopolymers may transport genes efficiently. Gene transfer requires nanocarriers to safeguard fragile gene cargo, boost cellular absorption, and escape endosomes. Surface changes enhance gene delivery to targeted cells by targeting particular cells [18]. Nanopolymeric gene carriers may safely and effectively deliver therapeutic genes for genetic disorders and other illnesses.

Genome editing using nanopolymers

Nanopolymers provide precise DNA manipulation in genome editing. Nanopolymers can deliver CRISPR-Cas9 to cells. Nanopolymeric gene-editing methods efficiently insert, delete, or modify genes with little off-target consequences [19, 20]. Nanopolymers enhance gene therapy by controlling the release and protection of editing components.

CRISPR-Cas9 technology and nanopolymeric vectors

CRISPR-Cas9 gene-editing requires nanopolymeric vectors. These vectors protect CRISPR- Cas9 components during delivery, improve cellular absorption, and efficiently edit target DNA. Nanopolymers may contain targeting ligands or imaging agents for precise gene editing and real-time monitoring. CRISPR-Cas9 technology with nanopolymeric vectors might revolutionise genetic disease treatment and personalized medicine [21].

Nanopolymers in Vaccines and Immunotherapy

Nanovaccine design and antigen delivery

Nanovaccines and antigen delivery using nanopolymers seem promising. Vaccines using nanopolymeric carriers may induce a strong and tailored immune response. These carriers prevent antigen degradation, boost immune cell presentation, and maintain release, improving vaccination effectiveness. Nanopolymers target antigens to particular immune cells, improving immunogenicity and immunological memory. Nanopolymer nanovaccines may prevent infectious illnesses and boost cancer-fighting immune responses (Table 4) [22].

Immunomodulatory effects of nanopolymers

Nanopolymers modulate immunological responses. Their nanoscale size and surface features impact immune cell activation, maturation, and function. Nanopolymers may alter cytokine production, antigen presentation, and inflammatory responses. Effective vaccinations, targeted medicines, and immunotherapies require understanding and using immunomodulatory effects. Nanopolymers' immunomodulation may improve disease management and treatment results.

Nanopolymeric adjuvants for enhanced vaccine responses

Modern vaccinations boost immunity using nanopolymeric adjuvants. These adjuvants boost the immune system when coupled with antigens. Nanopolymers deliver antigens and adjuvants slowly, prolonging immunological activation. They target antigen-presenting cells to boost vaccination effectiveness. Nanopolymeric adjuvants engage both innate and adaptive immune responses, making vaccine formulation flexible. Using these adjuvant qualities might lead to powerful vaccinations and cancer immunotherapies.

Nanopolymers for infectious disease management

Nanopolymers have transformed infectious disease diagnosis, treatment, and prevention. Nanopolymeric biosensors and imaging agents enable early identification and containment of infectious pathogens in diagnostics. Nanopolymers help target and limit antimicrobial agent release, improving therapeutic effectiveness and minimizing antibiotic resistance. Nanopolymers may be used to create antimicrobial coatings and materials that prevent disease development and transmission. Nanopolymer-adjuvanted vaccines boost immune responses, improving infection protection [23]. In resource-limited environments, nanopolymers help produce point-of-care testing and portable devices. Nanopolymers might solve global health problems by tackling infectious illnesses from several aspects.

Safety and Regulatory Considerations

Medical nanopolymer development and use need safety and regulatory issues. Patient safety requires nanopolymer biocompatibility and toxicity testing. In vitro and in vivo preclinical research is needed to understand their biological interactions and long-term consequences. Nanopolymers' body bioaccumulation and dispersion must be studied. For product consistency and safety, regulatory agencies need nanopolymer characterization, production, and stability data. Product quality and uniformity need strict good manufacturing practice compliance. Clinical studies need informed consent and ethical conduct. Researchers, business, and regulatory authorities must work together to set nanopolymer-based medical product standards. Safety and regulatory procedures will build

Table 4: Nanovaccine design and antigen delivery.

Nanovaccine design and antigen delivery	Description	Applications
Polymeric nanoparticles	Nanoparticles capable of encapsulating antigens and adjuvants	Targeted delivery of antigens to antigen-presenting cells, Enhanced immune response
Lipid-based nanovaccines	Lipid-based carriers delivering antigens and immune-stimulating components	Efficient presentation of antigens to immune cells, Potent immune activation
Nanogels	Stimuli-responsive nanogels with	Antigen-loading capabilities
Inorganic nanoparticles	Inorganic	Materials engineered for antigen delivery
VLP-based nanovaccines	Virus-like	Particles presenting antigens for immune recognition
Dendrimer-based nanovaccines	Dendrimers	Carrying multiple antigen copies and adjuvants
Nanofibers	Nanofiber-based delivery systems for antigens and immune modulators	Sustained antigen release, Enhanced immune activation
Hybrid nanovaccines	Combination of nanomaterials for synergistic vaccine effects	Multi-stage immune stimulation, Improved vaccine efficacy
mRNA based nanovaccines	Encapsulated mRNA encoding antigens for intracellular delivery	Induction of antigen-specific immunity, Potential for rapid vaccine development
Virus-based nanovaccines	Repurposed virusesas antigen delivery carriers	Strong immune response, Mimicry of natural infection for immunity induction

medical community trust and enable nanopolymer incorporation in healthcare.

Future Directions and Emerging Applications

Promising nanopolymer research areas

Medical nanopolymer research seems promising. Smart nanopolymers that release drugs on demand in response to illness signals are promising. Bioactive nanopolymers that promote tissue regeneration and immunological regulation enable novel regenerative medicine and immunotherapies. Biodegradable and biocompatible nanopolymers provide sustainable and safe medicinal operations [24, 25]. Nanopolymers as carriers for nucleic acids, gene editing, and RNA interference may advance gene treatments. Interdisciplinary research will open nanopolymer uses that might revolutionize healthcare.

Integration of nanopolymers in personalized medicine

Nanopolymers might revolutionize personalized treatment. Patient-specific medication delivery systems offer accurate dosing and treatment regimens, enhancing therapeutic results. Nanopolymers' capacity to encapsulate therapeutic chemicals and target certain cell types allows patient-specific combination therapy [26, 27]. Nanopolymers' non-invasive and precise diagnostic applications enable early intervention and individualized treatment strategies. Nanopolymers' flexibility and versatility will help personalized medicine revolutionize medical practice and save lives.

Nanopolymers and the future of medical innovations

Nanopolymers might revolutionize medicine. Their unique characteristics and tunability allow medication delivery, tissue engineering, diagnostics, and gene therapy advancements. Multifunctional nanopolymeric systems with medicinal, imaging, and targeting functions will revolutionize precision medicine and theranostics. Nanopolymers' capacity to overcome biological barriers and reach difficult anatomical regions would enable revolutionary therapies for untreatable disorders. Nanopolymers are projected to play an increasingly important role in global health concerns, personalized medicine, and patient-centered healthcare delivery as research continues.

Conclusion

In conclusion, nanopolymers have transformed medical applications, delivering many breakthroughs, solving problems, and promising healthcare improvements. Nanoscale polymeric materials have revolutionized medication delivery by offering targeted and controlled release mechanisms, boosting therapeutic effectiveness, and reducing adverse effects. Nanopolymers have helped tissue regeneration and repair in tissue engineering, enabling regenerative medicine and organ transplantation. Their work in diagnostics, cancer treatment, gene therapy, vaccines, and infectious disease management has enabled personalized medicine and precise therapies. These advances raise issues including nanopolymer safety and biocompatibility, regulatory concerns, and responsible development. However, academics, business, and regulators can overcome these obstacles and bring nanopolymers into mainstream medicine. Smart nanopolymers, bioactive nanomaterials, and personalized medicine integration are intriguing future research fields. Nanopolymers might provide a patient-centered healthcare system with better results and quality of life. "Nanopolymers in Medical Applications: Advances, Challenges, and Promising Innovations for Healthcare Enhancement" guides researchers, clinicians, and policymakers towards responsible and transformative nanopolymer use to improve healthcare for humanity.

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Conflict of Interest

None.

References

1. Adeyemi SB, Akere AM, Orege JI, Ejeromeghene O, Orege OB, et al. 2023. Polymeric nanoparticles for enhanced delivery and improved bioactivity of essential oils. *Heliyon* 9(6): e16543. https://doi.org/10.1016/j.heliyon.2023.e16543
2. Noma SAA. 2023. Investigation of improved uricase release and kinetic parameters through dual affected responsive nanopolymers. *Process Biochem* 113: 52-58. https://doi.org/10.1016/j.procbio.2023.06.003
3. Zheng Z, Zhu S, Lv M, Gu Z, Hu H. 2022. Harnessing nanotechnology for cardiovascular disease applications-a comprehensive review based on bibliometric analysis. *Nano Today* 44: 101453. https://doi.org/10.1016/j.nantod.2022.101453
4. Zhao J, Zhang C, Wang W, Li C, Mu X, et al. 2022. Current progress of nanomedicine for prostate cancer diagnosis and treatment. *Biomed Pharmacother* 155: 113714. https://doi.org/10.1016/j.biopha.2022.113714
5. Saiyad M, Shah N. 2022. Nanopolymers in drug delivery system. *Mater Today Proc* 67: 25-30. https://doi.org/10.1016/j.matpr.2022.05.019
6. Yadav A, Kujur A, Kumar A, Singh PP, Gupta V, et al. 2020. Encapsulation of *Bunium persicum* essential oil using chitosan nanopolymer: preparation, characterization, antifungal assessment, and thermal stability. *Int J Biol Macromol* 142: 172-180. https://doi.org/10.1016/j.ijbiomac.2019.09.089
7. Banerjee A, Ray SK. 2021. Synthesis of chitosan grafted polymethyl methacrylate nanopolymers and its effect on polyvinyl chloride membrane for acetone recovery by pervaporation. *Carbohydr Polym* 258: 117704. https://doi.org/10.1016/j.carbpol.2021.117704
8. Jain S, Dongare K, Nallamothu B, Dora CP, Kushwah V, et al. 2022. Enhanced stability and oral bioavailability of erlotinib by solid self nano emulsifying drug delivery systems. *Int J Pharm* 622: 121852. https://doi.org/10.1016/j.ijpharm.2022.121852
9. Li Z, Veeraraghavan VP, Mohan SK, Bolla SR, Lakshmanan H, et al. 2020. Apoptotic induction and anti-metastatic activity of eugenol encapsulated chitosan nanopolymer on rat glioma C6 cells via alleviating the MMP signaling pathway. *J Photochem Photobiol B Biol* 203: 111773. https://doi.org/10.1016/j.jphotobiol.2019.111773
10. He X, Zhu Y, Ma B, Xu X, Huang R, et al. 2022. Bioactive 2D nanomaterials for neural repair and regeneration. *Adv Drug Deliv Rev* 187: 114379. https://doi.org/10.1016/j.addr.2022.114379
11. Tucker BS, Aliakbarshirazi S, Vijayan VM, Thukkaram M, De Geyter N, et al. 2021. Nonthermal plasma processing for nanostructured biomaterials and tissue engineering scaffolds: a mini review. *Curr Opin Biomed Eng* 17: 100259. https://doi.org/10.1016/j.cobme.2020.100259

12. Li D, Liu Y, Wu N. 2022. Application progress of nanotechnology in regenerative medicine of diabetes mellitus. *Diabetes Res Clin Pract* 190: 109966. https://doi.org/10.1016/j.diabres.2022.109966
13. Gao J, Yang P, Li H, Li N, Liu X, et al. 2023. Advances in anti-tumor research based on bionic micro-nano technology. *J Drug Deliv Sci Technol* 86: 104674. https://doi.org/10.1016/j.jddst.2023.104674
14. Sargazi S, Siddiqui B, Qindeel M, Rahdar A, Bilal M, et al. 2022. Chitosan nanocarriers for microRNA delivery and detection: a preliminary review with emphasis on cancer. *Carbohydr Polym* 290: 119489. https://doi.org/10.1016/j.carbpol.2022.119489
15. Noah NM, Ndangili PM. 2023. Polymeric Nanosystems for Neurological Therapeutics. In Hasnain MS, Nayak AK, Aminabhavi TM (eds) Polymeric Nanosystems Theranostic Nanosystems. Academic Press, pp 723-759.
16. Wang H, Qiao C, Guan Q, Wei M, Li Z. 2023. Nanoparticle-mediated synergistic anticancer effect of ferroptosis and photodynamic therapy: novel insights and perspectives. *Asian J Pharm Sci* 18(4): 100829. https://doi.org/10.1016/j.ajps.2023.100829
17. Kukkar D, Kukkar P, Kumar V, Hong J, Kim KH, et al. 2021. Recent advances in nanoscale materials for antibody-based cancer theranostics. *Biosens Bioelectron* 173: 112787. https://doi.org/10.1016/j.bios.2020.112787
18. Pourmadadi M, Ostovar S, Ruiz-Pulido G, Hassan D, Souri M, et al. 2023. Novel epirubicin-loaded nanoformulations: advancements in polymeric nanocarriers for efficient targeted cellular and subcellular anticancer drug delivery. *Inorg Chem Commun* 155: 110999. https://doi.org/10.1016/j.inoche.2023.110999
19. Solanki R, Shankar A, Modi U, Patel S. 2023. New insights from nanotechnology in SARS-CoV-2 detection, treatment strategy and prevention. *Mater Today Chem* 29: 101478. https://doi.org/10.1016/j.mtchem.2023.101478
20. Rádis-Baptista G, Campelo IS, Morlighem JÉR, Melo LM, Freitas VJ. 2017. Cell-penetrating peptides (CPPs): from delivery of nucleic acids and antigens to transduction of engineered nucleases for application in transgenesis. *J Biotechnol* 252: 15-26. https://doi.org/10.1016/j.jbiotec.2017.05.002
21. Ljubimov VA, Ramesh A, Davani S, Danielpour M, Breunig JJ, et al. 2022. Neurosurgery at the crossroads of immunology and nanotechnology. New reality in the COVID-19 pandemic. *Adv Drug Deliv Rev* 181: 114033. https://doi.org/10.1016/j.addr.2021.114033
22. Goradel NH, Nemati M, Bakhshandeh A, Arashkia A, Negahdari B. 2023. Nanovaccines for cancer immunotherapy: focusing on complex formation between adjuvant and antigen. *Int Immunopharmacol* 117: 109887. https://doi.org/10.1016/j.intimp.2023.109887
23. Ahmad A, Gulraiz Y, Ilyas S, Bashir S. 2022. Polysaccharide based nano materials: health implications. *Food Hydrocoll Healh* 2: 100075. https://doi.org/10.1016/j.fhfh.2022.100075
24. Selvarajan L, Venkataramanan K, Senthilkumar TS. 2023. Experimental investigation and optimization of EDM performance measures of $MoSi_2$-SiC intermetallic ceramic composite using RSM with regression equations. *Silicon* 15: 1747-1769. https://doi.org/10.1007/s12633-022-02093-9
25. Rajaguru K, Karthikeyan T, Vijayan V. 2020. Additive manufacturing–state of art. *Mater Today Proc* 21: 628-633. https://doi.org/10.1016/j.matpr.2019.06.728
26. Venkatraman V, Sugumar S, Sekar S, Viswanathan S. 2019. Environmental effect of CI engine using microalgae biofuel with nano-additives. *Energy Sources Part A Recovery Util Environ Effects* 41(20): 2429-2438. https://doi.org/10.1080/15567036.2018.1563250
27. Vijayan V, Kumar SA, Gautham S, Masthan MM, Piraichudan N. 2021. Design and analysis of prosthetic foot using additive manufacturing technique. *Mater Today Proc* 37: 1665-1671. https://doi.org/10.1016/j.matpr.2020.07.195