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NANOPOLYMERIZATION IN PHARMACEUTICS: A REVOLUTION IN DRUG DELIVERY AND TARGETING

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ABSTRACT

The emergence of nanotechnology has transformed the pharma industry, with novel solutions to centuries-old issues of drug delivery and therapeutic targeting. Of these, nanopolymerization-a method of fabricating polymeric nanostructures with nanometer-scale control over size, composition and function-has become a revolutionary strategy. This review discusses the concept of nanopolymerization, elucidating its methodology, classes of nanopolymers and mechanisms of drug loading and release. Particular focus is given to its various applications in oral, parenteral, mucosal and transdermal delivery methods, gene therapy and vaccine delivery. The capability to integrate passive as well as active targeting strategies into nanopolymeric systems has further contributed to site-specific delivery, minimized systemic toxicity and enhanced therapeutic effectivity. Recent progress, such as FDA-approved products, combination therapy and stimuli-responsive or "smart" systems, reveal the translational value of nanopolymerization in theranostics and personalized medicine. Nonetheless, safety concerns, high-volume manufacturing and regulatory approval are still the main challenges to clinical translation. This article concludes that nanopolymerization is a huge step ahead in the design of future drug delivery systems and ongoing research in this field is set to bridge the gap between the innovation being discovered in the laboratory and care for patients.

KEYWORDS

Nanopolymerization, Theranostic, Drug delivery and Targeting.

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INTRODUCTION

Background of drug delivery challenges

Contemporary pharmaceutics is always confronting a number of major drawbacks of conventional drug delivery systems. Low solubility of most newly discovered drug candidates results in low bioavailability after oral administration, whereas the rapid metabolic degradation, brief half-life, and harsh physiological conditions decrease the drug effective concentration at the target site[1,2]. Moreover, the absence of drug specificity in distribution frequently leads to side effects and accordingly, more doses are needed to obtain therapeutic efficacy[3,4].

Emergence of Nanotechnology in Pharmaceutics

In response to the above challenges, nanotechnology has emerged as a significant innovation in drug formulation. Nanocarriers have been developed that can improve solubility, protect labile drugs from degradation, prolong circulation time, and sometimes cross biological barriers such as the blood-brain barrier[5,6]. Polymeric nanoparticles, in particular, offer turnable chemical and physical properties (size, surface charge, polymer composition) which enable better control over drug delivery behavior[4,7].

Rationale for Nano polymerization in Drug Delivery

Nano polymerization refers to the fabrication of polymers at the nanoscale-whether via polymerizing monomers in situ, self-assembly of polymeric blocks, or by creating polymeric matrices or shells around drug molecules. The use of polymerization in nanoparticle systems allows for precise control over structural features relevant to drug delivery: for example, particle size, porosity, functional groups for targeting, degradability, and stimuli-responsive behavior[5,4]. This controlled manufacture can enhance drug loading efficiency, sustain release kinetics, reduce off-target effects and improve targeting to diseased tissues, making nanopolymerization an appealing paradigm for next-generation drug delivery platforms.

Concept of Nanopolymerization

Definition and Principles

Nano polymerization is a term that describes polymer synthesis methods and processes that yield polymeric architectures on the nanometre level (e.g., nanoparticles, nanospheres, nanovesicles, nanogels) or that utilize polymerization to induce nanoscale self-assembly (i.e., nanostructure formation in situ in the course of polymer growth). Controlled/living polymerization methods (e.g., atom transfer radical polymerization, ATRP) and controlled chain-transfer procedures (e.g., RAFT) are frequently employed to achieve narrowly dispersed polymer chains, block structures, and exact end-group chemistries that facilitate further nanoscale structuration and functionalization[8]. Concurrently, polymerization-induced self-assembly (PISA) exploits the amphiphilic growth of a solvophobic block from a solvophilic macro-RAFT (or derivative) macroinitiator in a way that the developing block becomes insoluble and auto-assembles spontaneously into nanoparticles as the polymerization proceeds-uniting synthesis and assembly in one pot and allowing for high solid-content production of nano-objects[9]. The two paradigms-precision (controlled polymerization) and concurrent assembly (PISA)-constitute the conceptual foundation of nanopolymerization in pharmaceutical nanoplatform design[8,9].

Types of Nanopolymerization Techniques (Emulsion, Interfacial, Self-Assembly)

A variety of techniques are applied to produce polymeric nanomaterials for drug delivery; they can broadly be grouped into:

Methods that polymerize monomers in dispersed phases (e.g., emulsion, miniemulsion, suspension polymerization),

Approaches that form nanoparticles from pre-formed polymers (e.g., nanoprecipitation, solvent-displacement, double-emulsion)

In-situ polymerization/assembly approaches such as PISA and interfacial polymerization[10,11].

Emulsion/miniemulsion polymerization enables formation of polymer particles where monomer droplets act as nanoreactors and is compatible with hydrophobic monomers; interfacial polymerization forms thin polymer shells at liquid–liquid interfaces (useful for core-shell particles and nanocapsules).

Nanoprecipitation (solvent-shifting) is a low-energy bottom-up method to make polymer nanoparticles from pre-formed polymers and is widely used for encapsulating hydrophobic drugs-recent developments include flash and microfluidic nanoprecipitation to improve reproducibility and control at scale[11,10]. PISA (described above) and other chain-growth techniques (photo-initiated or thermally initiated RAFT/ATRP variants) allow direct production of defined nano-objects with tunable morphologies (spheres, worms, vesicles) while often enabling functionalization and cross-linking during polymerization[10,11].

Advantages over conventional polymerization

Architectural control

Controlled/living polymerizations yield narrow polydispersity and block architectures that guide self-assembly and drug loading.

One-pot assembly

PISA integrates polymer synthesis and nanoparticle formation in a single scalable step with fewer purification needs.

Morphology tenability

Block length, solvent, polymerization degree and concentration allow tailoring of micelles, worms, or vesicles.

In situ functionalization

Reactive handles and cross-linking chemistries enable stability enhancement and targeting without extra steps.

Improved encapsulation

Higher drug-loading efficiency compared to conventional multi-step processing.

Predictable release

Controlled architectures offer more reliable and tunable release kinetics.

Stimuli-responsiveness

Direct access to smart carriers responsive to pH, temperature, or biological triggers.

Multifunctionality

Simplified routes to carriers with combined therapeutic and targeting functions.

Biodegradable vs. Non-Biodegradable Systems

Biodegradable nanopolymers (e.g., PLGA, PLA, polycaprolactone, many natural polymers) degrade via hydrolysis or enzymatic pathways into small molecules that can be metabolized or excreted, reducing long-term accumulation risk and often obviating the need for surgical removal of implanted materials[12,13]. Biodegradable carriers have been extensively studied for sustained release, vaccine delivery, and depot formulations due to their tunable degradation kinetics and generally favorable safety profiles in preclinical and clinical studies[12,13].

Non-biodegradable polymers (for example, certain cross-linked acrylates, polystyrene, and some high-molar-mass polyethylene derivatives) can provide exceptional stability, mechanical robustness, and prolonged structural integrity, which may be useful for long-lived implants, diagnostic devices, or where slow non-degrading matrices are specifically required. However, concerns about long-term persistence, chronic inflammatory responses, and regulatory hurdles limit their use in many systemic drug-delivery applications; thus, the design trade-off between durability and safety is a central consideration[13,14]. Design considerations: for systemic and injectable delivery, biodegradable polymers remain the dominant choice; non-biodegradable systems retain niche roles (e.g., certain implantable devices or external patch supports) and when used, require careful assessment of biostability and clearance[13,14].

Stimuli-Responsive Nanopolymers

Stimuli-responsive (or “smart”) nanopolymers change their physico-chemical properties in response to environmental triggers-pH, temperature, redox potential, enzymes, light, or magnetic fields-and can therefore provide on-demand drug release or site-specific activation[15,16]. pH-sensitive polymers that exploit the acidic microenvironment of tumors or endo/lysosomal compartments are widely used to trigger release of anticancer drugs or nucleic acids selectively at the disease site[16].

Other approaches use enzyme-responsive linkers (e.g., matrix metalloproteinases in tumor stroma), redox-sensitive disulfide bonds (exploiting higher intracellular glutathione), or thermo-responsive polymers (e.g., PNIPAM derivatives) for local controlled release. These systems can be engineered via nanopolymerization techniques to embed responsive motifs directly into the polymer backbone or as pendant groups, enabling precise spatial and temporal control of payload release while minimizing systemic exposure[15-18]. Clinical outlook: stimuli-responsive nanopolymers hold high translational promise for improving therapeutic index and enabling combination theranostic functions, but robustness, reproducibility of trigger response and safety of stimuli (e.g., heating, light penetration) remain active areas of research[15-18].

Mechanisms of drug loading and release

Encapsulation strategies and drug loading

Encapsulation involves physically entrapping or locating a drug in the polymer matrix, carrier core, or nanogel network without forming chemical bonds. One of the approaches to boost loading is polymer and drug co-precipitation, which supports nanoparticle formation in which the drug is loaded throughout (in core and on surface), occasionally resulting in high drug loading (up to ~60-70 wt%) as well as high encapsulation efficiencies (often >90%) if salt concentration, solubility of drug/polymer and precipitation rate are well optimized[25]. Another method is drug-polymer conjugation (covalent bonding) or grafting of drug molecules onto polymer backbones; this method is possible to achieve delayed release, control of release kinetics with high accuracy

Release Kinetics: Diffusion, Degradation, Swelling

Drug release from nanopolymeric systems is governed by multiple mechanisms, often in combination. Diffusion is significant when the drug is small, water-soluble, and not strongly bound; the drug diffuses through water-filled pores or through the polymer matrix to the external medium[19].

Polymer degradation (bulk or surface erosion) plays a major role for biodegradable systems like PLGA, PLA, PCL and polyanhydrides; the rate depends on molecular weight, crystallinity, polymer composition and environmental conditions (pH, enzymes)[20].

Swelling-controlled release is important in hydrogels or nanogels, where polymer network swelling allows water ingress which enables diffusion and possibly polymer chain motion; in stimuli-responsive systems, swelling may vary with external trigger (e.g., temperature, pH) altering release rate[21].

Surface Conjugation and Functionalization

Surface conjugation refers to attaching functional molecules (antibodies, peptides, targeting ligands, polymers) to the surface of nanopolymers, which can influence both drug release (by hindering or modulating diffusion) and targeting. For example, antibody fragment conjugation to PLGA-PEG nanoparticles via maleimide-thiol or carbodiimide chemistries improves targeting efficiency and the choice of conjugation method influences orientation and functional exposure of the ligand, which in turn affects cellular uptake and possibly release profiles[22]. Also, reactive handles can be designed or tailored on surfaces of polymer nanoparticles to allow covalent conjugation of biomolecules and modulate their density; such conjugation may impose additional diffusion barriers or steric hindrance affecting drug release[23].

Applications in drug delivery

Oral drug delivery

Oral delivery remains one of the most appealing administration routes due to its non-invasiveness and patient compliance. However, physiological barriers such as low pH in the stomach, digestive enzymes, mucosal barriers and first-pass metabolism limit efficacy of many drugs. Polymeric nanoparticles have been engineered to overcome these obstacles via mucoadhesive biopolymers (e.g., chitosan, alginate), polymers targeted to specific intestinal cell types (e.g., M cells) and through protective encapsulation to avoid degradation[24,25]. For example, chitosan derivatives have been used to enhance intestinal absorption of peptides and PLGA nanoparticles coated with targeting ligands show promise in oral vaccination models[24,25].

Parenteral (IV, IM) Delivery

Parenteral delivery allows direct systemic circulation and is essential for drugs that are poorly absorbed orally. Nanopolymers used in IV/IM formulations often exploit PEGylation or surface engineering to prolong circulation time, reduce opsonization, and target specific tissues (e.g., tumor, liver). In Recent Advances in Micro- and Nano-Drug Delivery Systems Based on Natural and Synthetic Biomaterials (2023), synthetic biodegradable polymers (e.g., PLGA, PLA) are combined in nano-formulations for chemotherapy delivery and vaccine adjuvant systems, using both IV and IM routes, with improvements in biocompatibility and payload retention noted[25]. Another example includes nanoemulsion-based systems adjusted for IV administration, which have been optimized for stability and sustained release of hydrophobic drugs, reducing dosing frequency and improving therapeutic index[26].

Mucosal and transdermal routes

Mucosal (nasal, pulmonary, buccal, vaginal) and transdermal delivery routes avoid first-pass metabolism, often offer rapid onset or localized action and can improve patient comfort.

Transdermal applications

Recent reviews highlight the use of polymeric nanoparticles (e.g., PLGA, chitosan), nanofibers, nanogels, nanoemulsions and natural polysaccharides to improve skin permeation, achieve controlled release, and reduce irritation[27]. For example, PLGA NPs loaded into transdermal films or hydrogels have shown deeper penetration into skin layers and sustained release over multiple hours without causing skin inflammation[27].

Mucosal routes

Polymeric nanocarriers, especially those using mucoadhesive polymers such as chitosan or its derivatives, are used for nasal or buccal administration (e.g., for vaccines or for systemic delivery of peptides) to exploit high permeability and rich vasculature. Studies show that using nanoparticles targeting transcytosis pathways (e.g., M cells) can significantly increase systemic uptake[24].

Gene delivery and vaccines

Nanopolymeric carriers provide major advantages for gene delivery (siRNA, mRNA, DNA) and vaccine delivery. By protecting nucleic acids from nuclease degradation, facilitating cellular uptake, endosomal escape and enabling co-delivery of adjuvants, these systems improve efficacy.

A recent review of micro and nano-drug delivery systems (2023) describes the use of PLGA, hyaluronic acid and ceramide materials in nanoparticle formulations for anti-tumor therapies, including vaccine delivery platforms, demonstrating improved immune responses and targeting via surface functionalization[25].

Nanoemulsion-based systems also have been adapted for vaccine antigen delivery, especially for mucosal administration, enhancing immunogenicity while reducing adjuvant-related toxicity, by careful tuning of emulsion droplet size, surface charge and polymer or surfactant composition[26].

Targeting strategies enabled by nanopolymerization

Passive targeting (enhanced permeability and retention effect)

Passive targeting exploits the leaky vasculature and poor lymphatic drainage typical of solid tumors to allow nanoparticles to accumulate in the tumor interstitium; this is the so-called EPR (Enhanced Permeability and Retention) effect. Nanopolymeric carriers sized between ~10-200nm, with “stealth” surface properties (e.g., PEGylation) often show prolonged circulation and enhanced tumor accumulation via EPR[5,3]. For example, polymeric micelles of poly(N-isopropylacrylamide)-block-poly(ε-caprolactone) have been shown to passively target lung tissue after systemic delivery, based on their size and physiochemical features (without active ligands)[28]. However, passive targeting alone often results in variable accumulation due to heterogeneity of tumor vasculature, interstitial pressure and particle clearance by the mononuclear phagocyte system (MPS)[3,29].

Active targeting (ligand-mediated, antibody/peptide conjugation)

Active targeting refers to modifying the surface of nanopolymeric carriers with ligands-small molecules, peptides, aptamers, or antibodies-that bind specifically to receptors overexpressed on target diseased cells, enabling enhanced uptake through receptor-mediated endocytosis, and improving specificity beyond what passive EPR allows[30]. Recent advances include using ligands such as folic acid, RGD peptides, cetuximab (anti-EGFR antibody), hyaluronic acid for CD44 targeting, etc., in polymeric nanomicelles and nanocarriers, yielding increased tumor cell uptake and better therapeutic index compared with non-targeted counterparts[3]. One example: nanomicelles built from maleimide-terminated PEG-PCL loaded with a photothermal agent and decorated with cetuximab showed targeted binding and photothermal effect in EGFR-overexpressing colorectal cancer cells[3].

Multifunctional/theranostic nanopolymers

A growing trend is incorporation of both therapeutic and diagnostic (imaging, radionuclide, contrast) functions into single polymeric nanocarriers-theranostics-that can deliver drug while enabling imaging or monitoring of delivery, release, or treatment effect. For instance, A Proof-of-Concept Study on the Theranostic Potential of ^{177}Lu-Labeled Biocompatible Covalent Polymer Nanoparticles showed that ^177Lu-radiolabeled PEGylated covalent polymer nanoparticles accumulated in tumor sites in a 4T1 breast cancer model, enabled imaging via SPECT/CT and showed significant antitumor efficacy including tumor cure in some animals[31]. Another example: polymeric nanogels being developed for dual functions of imaging agent incorporation as well as therapeutic payload, leveraging the high functional group density, swelling behaviour and biocompatibility of nanogels to integrate diagnostic modalities with controlled drug release[32].

These multifunctional systems often combine passive and active targeting, stimuli-responsive release after specific triggers and diagnostic readouts (MRI, SPECT, fluorescence) to monitor biodistribution or therapy progression.

Recent advances and case studies

Advances in stimuli-responsive nanopolymeric systems

Recent research highlights the development of multistimuli-responsive nanopolymers capable of releasing drugs in response to more than one environmental cue (pH, temperature, redox, or enzymes), enhancing selectivity and therapeutic efficacy. For instance, dual pH/redox-responsive PLGA PEG nanoparticles have demonstrated enhanced cytotoxicity in tumor models while sparing normal cells due to triggered intracellular drug release[33,34]. Similarly, thermo/pH-responsive poly (N-isopropylacrylamide-co-acrylic acid) nanogels have been developed for controlled release of anticancer agents, showing improved tumor suppression *in vivo*[35].

Clinical and preclinical case studies

Case Study 1: PLGA Nanoparticles in Cancer Therapy

PLGA nanocarriers encapsulating doxorubicin have shown strong preclinical efficacy. PEGylation and folic acid functionalization improved tumor targeting, resulting in greater cytotoxicity than non-targeted systems. Pharmacokinetic data confirmed extended circulation and reduced cardiotoxicity compared with free doxorubicin[36].

Case Study 2: Nanogels for vaccine delivery

Poly(N-vinylcaprolactam)-based nanogels have been investigated as intranasal carriers for influenza vaccines. Preclinical studies demonstrated stronger mucosal immunity, sustained antibody titers, and lower antigen dose requirements. Their high water content and adjustable cross-linking supported rapid dendritic cell uptake and prolonged antigen release[37].

Case Study 3: Theranostic polymeric nanoparticles

Polymeric theranostic systems combining drug delivery and imaging have shown promise in breast cancer models. Near-infrared fluorescent nanoparticles loaded with paclitaxel enabled simultaneous tumor imaging and therapy, achieving enhanced tumor accumulation through EPR effects and active targeting, highlighting the potential of integrated diagnostic–therapeutic nanocarriers[38].

Challenges and future directions

Despite these promising advances, challenges remain. Translational barriers include scale-up synthesis reproducibility, long-term biocompatibility, regulatory approval complexity, and heterogeneity in human tumors that can reduce EPR efficacy[39]. Future directions focus on personalized nanomedicine, integrating AI-driven design of polymeric structures, combination therapy platforms, and multimodal theranostics, which can enhance therapeutic index and monitor treatment in real time[40].

Safety, Toxicity and Regulatory Perspectives

Biocompatibility and Immunogenicity

The biocompatibility of nanopolymeric drug delivery systems is paramount to ensure their safe application in clinical settings. These systems must interact with biological tissues without eliciting adverse reactions such as toxicity, immunogenicity, or thrombogenicity. Polymeric nanoparticles (NPs), particularly those made from biodegradable materials like poly(lactic-co-glycolic acid) (PLGA) and chitosan, have demonstrated favorable biocompatibility profiles in various *in vitro* and *in vivo* studies[12]. However, the immunogenicity of these systems can be influenced by factors such as particle size, surface charge and the presence of surface-modifying agents.

Scale-Up and manufacturing challenges

The transition of nanopolymeric drug delivery systems from laboratory-scale synthesis to large-scale manufacturing presents several challenges. One of the primary concerns is the reproducibility of nanoparticle characteristics, such as size distribution, surface morphology and drug encapsulation efficiency, which can vary significantly during scale-up processes[41]. Additionally, the selection of appropriate manufacturing techniques is critical. Methods like solvent evaporation, nanoprecipitation, and emulsification-solvent diffusion are commonly employed; however, each has its limitations regarding scalability, solvent use and process control. Furthermore, ensuring the sterility and stability of the final product is crucial, necessitating the implementation of stringent quality control measures and adherence to good manufacturing practices (GMP).

Regulatory Guidelines for Nanopolymeric Drugs

Regulatory frameworks for nanopolymeric drug delivery systems are evolving to address the unique properties and potential risks associated with nanomaterials. In India, the Department of Biotechnology (DBT) has developed the "Guidelines for Evaluation of Nanopharmaceuticals," which provide comprehensive guidelines covering aspects such as preclinical safety, stability testing, and clinical evaluation of nanopharmaceuticals[42]. These guidelines emphasize the need for thorough characterization of nanomaterials, including their physicochemical properties, biological interactions, and potential toxicity profiles. Additionally, they advocate for the application of risk-based approaches to assess the safety and efficacy of nanomedicines, considering factors such as exposure levels, route of administration, and the intended therapeutic application.

Future Directions and Emerging Trends

Personalized Nanomedicine

Personalized nanomedicine aims to tailor nanopolymeric drug delivery systems to individual patient characteristics, including genetic profile, disease phenotype and drug metabolism. By integrating patient-specific biomarkers, polymeric nanoparticles can be customized in terms of size, surface chemistry and drug payload, maximizing therapeutic efficacy while minimizing side effects. This approach is particularly promising in oncology, where tumor heterogeneity significantly impacts treatment response. Computational modeling and AI-driven design are increasingly employed to predict optimal nanoparticle formulations for individual patients.

Integration with artificial intelligence and machine learning

Artificial intelligence (AI) and machine learning (ML) are transforming the design and optimization of nanopolymeric systems. ML algorithms can predict nanoparticle stability, drug release kinetics and biodistribution based on polymer chemistry, particle size and surface characteristics, significantly accelerating the development pipeline.

Multi-Functional and multi-drug delivery platforms

Emerging nanopolymeric systems are increasingly designed for co-delivery of multiple drugs or combination therapies, allowing synergistic effects and overcoming drug resistance. For example, dual-drug loaded PLGA-PEG nanoparticles for co-delivery of chemotherapeutic agents have demonstrated superior tumor suppression in preclinical models compared to single-drug systems. Similarly, multifunctional platforms integrating drug delivery, imaging and targeting in a single polymeric nanoparticle (“theranostic” systems) are under active development, promising real-time monitoring of therapy and enhanced precision medicine.

Environmentally and biologically responsive polymers

The next generation of nanopolymeric systems will increasingly exploit stimuli-responsive polymers that respond to pH, redox potential, temperature, enzymes, or external triggers (light, ultrasound) to achieve site-specific drug release. These “smart polymers” reduce systemic toxicity and improve drug bioavailability at target sites. Research is also focusing on biodegradable and environmentally sustainable polymers to minimize long-term accumulation and toxicity risks[14].

Regulatory and translational considerations

Future trends emphasize alignment of nanopolymeric drug design with regulatory expectations. Standardization of characterization methods, reproducible scale-up protocols and comprehensive safety assessment will be critical for clinical translation. Collaborative frameworks between academia, industry, and regulatory bodies are expected to streamline approval pathways, making personalized and advanced nanopolymer-based therapeutics more accessible.

Types of nanopolymers used in pharmaceutics

Table No.1: Natural vs. Synthetic Nanopolymers

S.No	Feature	Natural Polymers (Polysaccharides and Proteins)	Synthetic Polymers (Polyesters, PEG derivatives, Acrylics)
1	Examples	Chitosan, Alginate, Gelatin, Dextran	PLGA, PLA, PGA, PEG derivatives, Polyacrylates
2	Key Properties	Biocompatible, biodegradable, biointeractive	Chemically tunable, reproducible, stable
3	Special Features	Mucoadhesive (chitosan), gentle gelation (alginate), bioadhesion	Precise control over degradation rate, molecular weight and surface chemistry
4	Formulations Possible	Nanoparticles, hydrogels, polyelectrolyte complexes	Micelles, vesicles, solid nanoparticles, block copolymer assemblies
5	Drug Release	Controlled release with low toxicity	Programmable release via degradation and architecture
6	Advantages	Excellent biocompatibility, natural biofunctionality, low immunogenicity	High tunability, reproducibility, stealth properties (PEGylation), regulatory approval (PLGA, PEG)
7	Limitations	Batch variability, limited mechanical strength, possible immunogenicity	May require organic solvents, less biointeractive, costlier synthesis
8	Best Suited For	Mucosal, oral, wound-healing, topical delivery	Injectable, systemic, long-circulating drug delivery
9	Hybrid Use	Often combined with synthetics (e.g., PLGA–chitosan, PEG–polysaccharides) to merge advantages	Frequently blended with natural polymers for improved biofunctionality

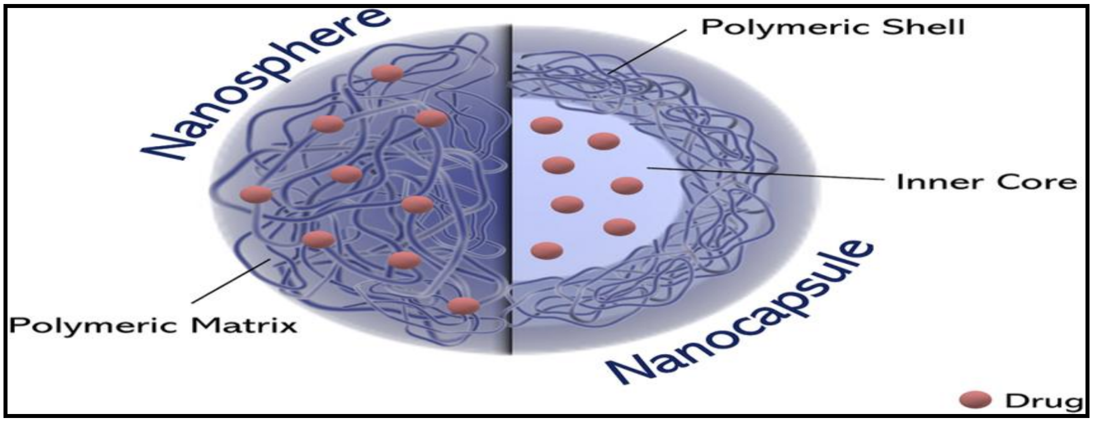

Figure No.1: Nanopolymerization

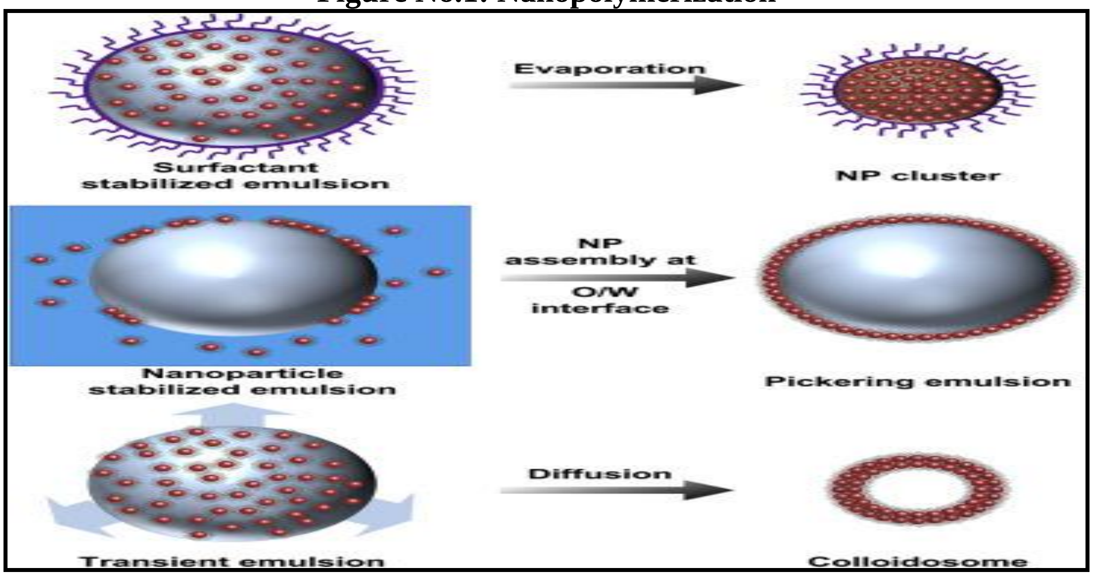

Figure No.2: Emulsion based Nano polymerization

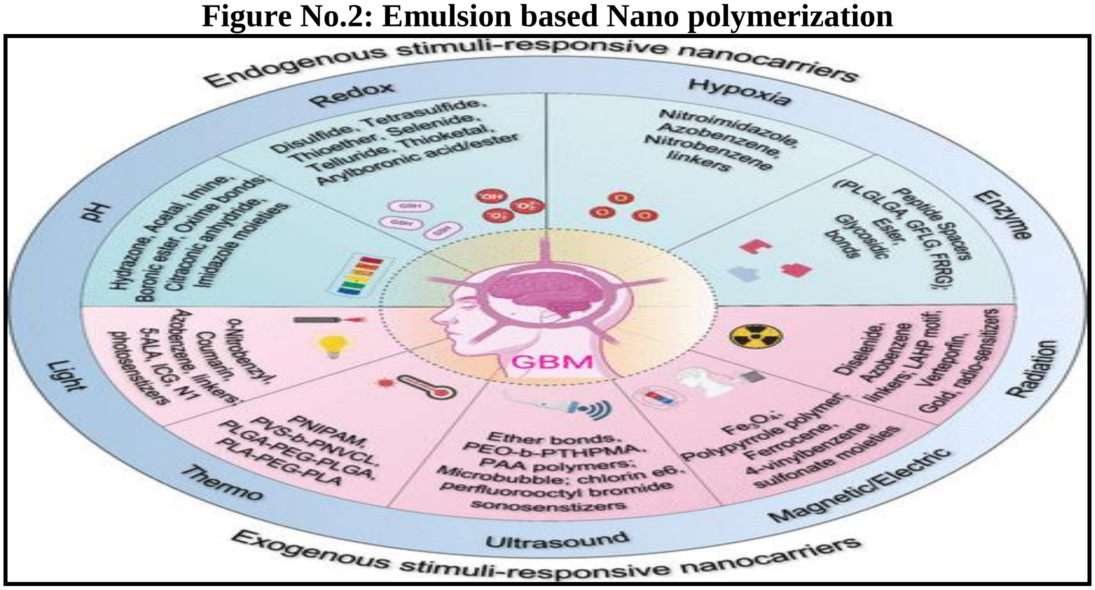

Figure No.3: Stimuli response Nanocarriers

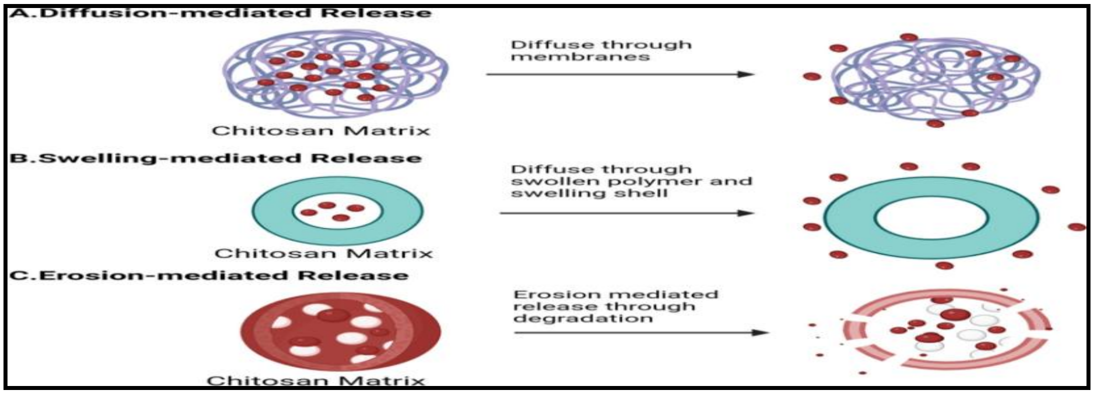

Figure No.4: Kinetics of Nanocarriers

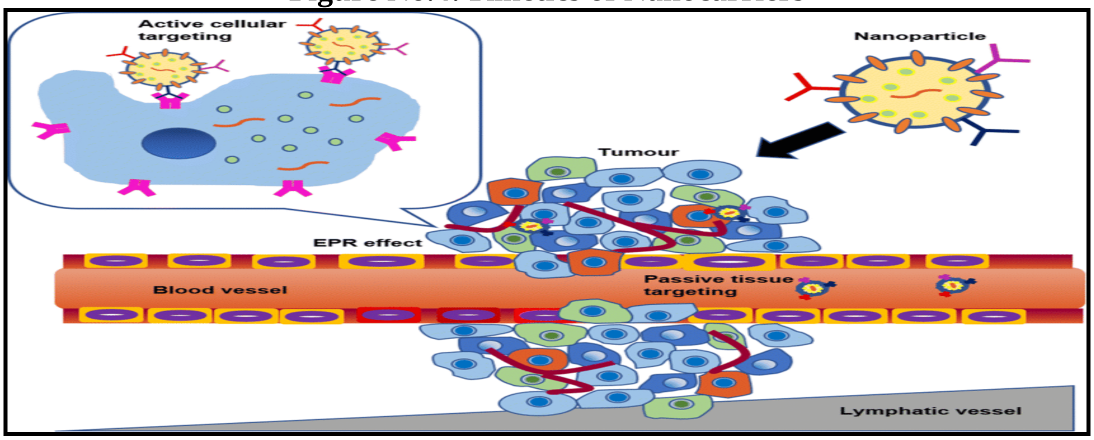

Figure No.5: Active and passive targeting nanocarriers

CONCLUSION

Nanopolymerization has emerged as a transformative approach in pharmaceutics, enabling the design of highly versatile and efficient drug delivery systems. Through the development of biodegradable, biocompatible and stimuli-responsive polymeric nanocarriers, researchers have been able to overcome traditional limitations of drug administration, including poor solubility, rapid metabolism, low bioavailability and off-target toxicity. Both passive and active targeting strategies have demonstrated substantial improvements in therapeutic efficacy, while multifunctional and theranostic nanopolymers integrate drug delivery with diagnostic capabilities, allowing for real-time monitoring of treatment outcomes. Applications span oral, parenteral, transdermal, mucosal, gene and vaccine delivery, highlighting the broad adaptability of nanopolymeric systems. Recent advances in personalized nanomedicine, AI-assisted formulation design, and multi-drug co-delivery platforms illustrate the growing sophistication of these technologies, promising higher precision and individualized therapy. Concurrently, attention to safety, immunogenicity, scale-up challenges and evolving regulatory frameworks ensures that nanopolymeric drugs can transition effectively from preclinical studies to clinical applications. Looking forward, the integration of smart polymers, environmentally responsive systems and multifunctional theranostic platforms represents a future where drug delivery is not only more effective but also safer, tailored, and dynamically monitored. Overall, nanopolymerization is revolutionizing pharmaceutical sciences, offering a new paradigm for targeted, controlled, and efficient therapeutics that could significantly enhance patient outcomes across a wide spectrum of diseases.

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CONFLICT OF INTEREST

We declare that we have no conflict of interest.

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