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POLYMERIC NANOPARTICLES: AN OVERVIEW OF PREPARATION, CHARACTERIZATION, APPLICATIONS, AND FUTURE PERSPECTIVES

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ABSTRACT: Polymeric nanoparticles (NPs) are tiny particles with a size between 10 and 1000 nm, with the ability to contain or have active substances surface-adsorbed onto the polymeric core. Both nanospheres and nano capsules are under the umbrella of "nanoparticles," which are distinguished by the morphological organization. For the targeted delivery of medications used to treat a variety of disorders, polymeric NPs have demonstrated considerable promise. We go through the most popular techniques for creating and characterizing polymeric NPs, the effectiveness of the active ingredient's connection with the polymeric core, and in vitro release mechanisms in this review. Due to their adaptability and broad range of features, polymeric nanoparticles have recently gained more potential usage as carriers for a variety of pharmaceuticals in therapeutic applications. Due to the drawbacks of conventional pharmacological therapy, there will be a higher risk of unpleasant responses. These days, nanoparticles are becoming more and more significant since they enable activity at specific locations. These nanoparticles enable the precise targeting of different cells or receptors. Cellular absorption and Internalization are both regulated in a number of different ways.

INTRODUCTION: The drug is dissolved, entrapped, encapsulated, or linked to a nanoparticle matrix in the form of polymeric nanoparticles (PNPs), which range in size from 10 to 1000 nm and are made from biocompatible and biodegradable polymers. Depending on the method of preparation, nanospheres and nano-capsules can be created. In Nano capsules, the drug is physically and evenly distributed throughout the matrix. Still, in nanospheres, the drug is contained within a hollow that is surrounded by a special polymer membrane.

With applications in medicine, biotechnology, and environmental technology, the field of polymeric nanoparticles (PNPs) is expanding quickly. PNPs are appealing drug delivery systems because some PNP methods (eg, emulsion polymerization) can be complex. The carriers are designed to deliver medications to certain targets¹.

Polymer-based nanoparticles effectively carry drugs, proteins, and DNA to target cells and organs. Their nanoscale size enables effective cell membrane penetration and circulatory stability. Polymers are extremely helpful components when building various molecular patterns that can be combined to create distinctive nanoparticle shapes with various potential medical applications. Over the past two decades, a number of techniques for producing PNPs have been developed. These techniques are divided into three categories based

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on how the particle is formed: through a polymerization reaction, directly from a macromolecule or pre-made polymer, or through an ionic gelation technique².

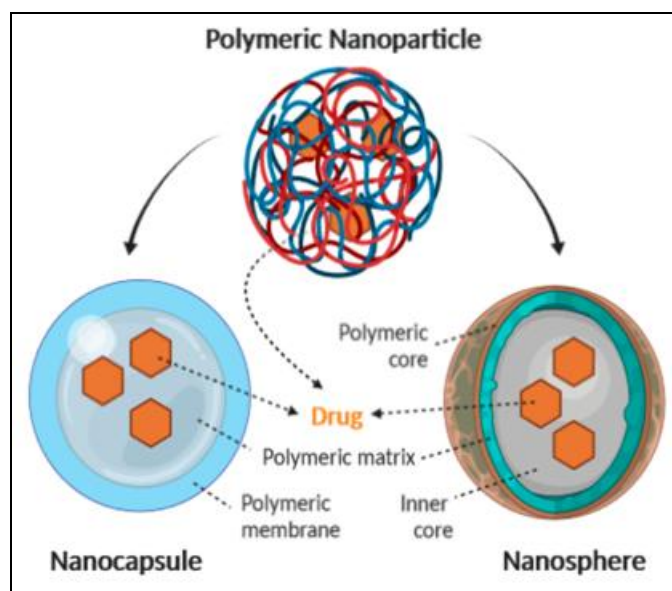


FIG. 1: STRUCTURE OF A NANOCAPSULE AND A NANOSPHERE

Method of Preparation of Polymeric Nanoparticles: Depending on the intended use, different polymeric nanoparticles are created using different processes. Polymerization and drug dispersion in prepared polymers are the two most common processes for producing PNPs in drug delivery methods. There are advantages to polymerization processes, such as precise control over the size, architecture, and functionality of nanoparticles. The release-defining properties, chemical make-up, charge, hydrophilicity/hydrophobicity, swelling/deswelling ability, reactivation, and pH dependence/independence can all have an impact on the choice of polymer³.

Methods for the preparation of nanoparticles from the dispersion of preformed polymer:

- ❖ Solvent evaporation
- ❖ Nanoprecipitation
- ❖ Emulsification/solvent diffusion
- ❖ Salting out
- ❖ Dialysis
- ❖ Supercritical fluid technology (SCF)

Methods for the preparation of nanoparticles from the polymerization of monomers:

- ❖ Emulsion
- ❖ Mini emulsion
- ❖ Micro emulsion
- ❖ Interfacial polymerization
- ❖ Controlled/Living radical polymerization (C/LRP)

Ionic Gelation or Coacervation of Hydrophilic Polymers:

Solvent Evaporation: The first technique created to create polymeric NPs from a premade polymer was solvent evaporation. In order to produce nanospheres using this approach, an oil-in-water (o/w) emulsion must first be prepared. The process begins with creating an organic phase, which consists of a polar organic solvent in which the polymer is dissolved, and the active ingredient (such as a medication) is added through dissolution or dispersion. Chloroform and dichloromethane are frequently Utilized, albeit more so in the past. They have been replaced by ethyl acetate, which exhibits a superior toxicological profile and is more appropriate for biomedical applications, due to its toxicity⁴.

The preparation of an aqueous phase containing a surfactant, such as polyvinyl acetate (PVA), is also common. The organic solution is treated by high-speed homogenization or ultrasonication after being emulsified in the aqueous phase using a surfactant. This results in a dispersion of nanodroplets. The polymer solvent evaporates while being allowed to diffuse into the continuous phase of the emulsion, resulting in a suspension of NPs.

When utilizing more non-polar to moderately polar solvents, such as dichloromethane and chloroform, for example, the solvent is either slowly evaporated under reduced pressure or by continuous magnetic stirring at ambient temperature. The nanoparticles can then be cleaned, recovered by centrifugation, and freeze-dried for prolonged storage after the solvent has evaporated⁵.

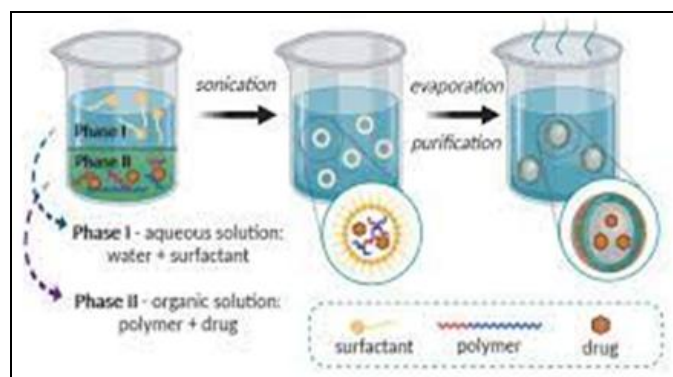


FIG. 2: SCHEMATIC REPRESENTATION OF THE SOLVENT EVAPORATION METHOD

Nanoprecipitation: This procedure, also known as the solvent displacement procedure, calls for two miscible solvents. A polymer that has been dissolved in an organic miscible solvent, such as Acetone or acetonitrile. They are easily eliminated by evaporation because they are immiscible in water. The basis of this method is the interfacial deposition of a polymer once the organic solvent is displaced from a lipophilic solution to the aqueous phase. The polymer is dissolved in an intermediate polarity water-miscible solvent, and this solution is dropped-wise or at a regulated rate sequentially into an aqueous solution while being stirred. The nanoparticles form instantly to escape the water molecules as a result of the rapid spontaneous diffusion of the polymer solution into the aqueous phase. The polymer precipitates as nano capsules or nanospheres as the solvent diffuses from the nanodroplets. While adding the organic phase to the aqueous phase is customary, the technique can also be reversed without negatively impacting the creation of nanoparticles. Although their presence is not necessary to ensure the creation of

nanoparticles, surfactants can typically be added to the process to maintain the stability of the colloidal suspension. The resultant nanoparticles typically have a narrow size distribution and a well-defined size, which distinguishes them from those made by the emulsification solvent evaporation process ⁶.

One of the most well-liked and repeatable methods for laboratory drug encapsulation is nanoprecipitation. It is founded on the use of a non-solvent, which must be miscible with the solvent but is insoluble for the drug and polymer, and a solvent in which the polymer and drug are soluble. Following contact between the two solutions, a spontaneous diffusion of the polymer-drug solution occurs in the direction of the non-solvent, resulting in simultaneous polymer precipitation and API encapsulation. Nanoprecipitation is typically used to produce NPs with a low polydispersity index and a size range of 100 to 300 nm ⁷. The water, whether or not it contains a stabilizer, is employed as a non-solvent, and the most used solvents are ethanol, acetone, and tetrahydrofuran. Solvent type, polymer concentration, solvent/non-solvent ratio, non-solvent addition flow rate, and stirring rate are frequently examined for process optimization. One of the most often used techniques for creating PLGA NPs is nanoprecipitation. The efficiency of the mixture and the precipitation can make the scale-up problematic, despite the fact that it is fairly reproducible at the laboratory scale. Because they enable better control of the factors involved in precipitation processes and can generate the formulations on a medium scale, microreactors have thus been Utilized to aid the process ⁸.

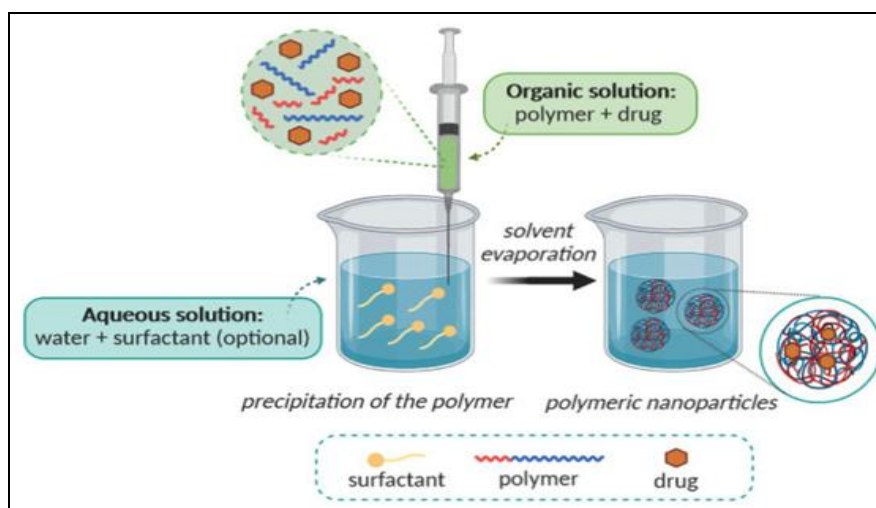


FIG. 3: SCHEMATIC REPRESENTATION OF THE NANOPRECIPITATION METHOD

Emulsification/Solvent Diffusion: This technique involves creating an o/w emulsion between an aqueous solution containing a surfactant and a somewhat water-miscible solvent containing a polymer and medicament. This emulsion's internal phase is made up of a somewhat hydro-miscible organic solvent, like benzyl alcohol or ethyl acetate, that has already been saturated with water to provide an initial thermodynamic equilibrium

between the two phases at room temperature⁹. Colloidal particles are created as a result of solvent diffusion from the dispersed droplets into the external phase, which is caused by the following dilution with a high amount of water. Usually, this process is used to create nanospheres, but if a small amount of oil (such as triglycerides: C6, C8, C10, C12) is added to the mixture, nano capsules can also be created¹⁰.

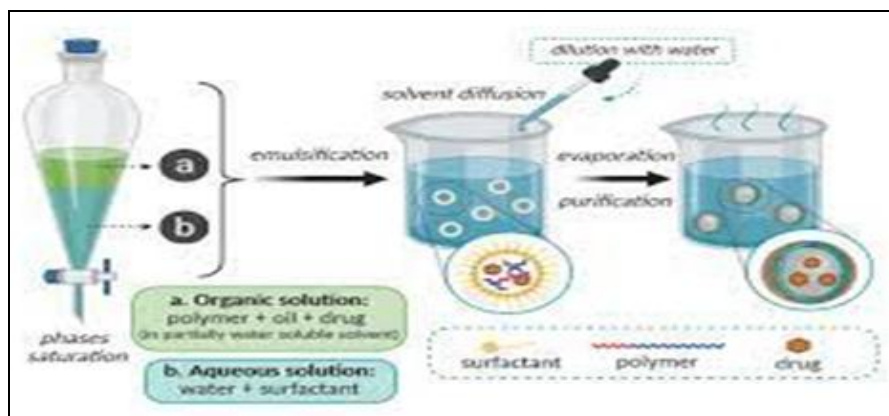


FIG. 4: SCHEMATIC REPRESENTATION OF THE EMULSIFICATION/SOLVENT DIFFUSION METHOD

Salting out: The separation of a water miscible solvent from an aqueous solution is the basis for the salting-out effect. You can think of the salting-out method as a modification of the emulsification/solvent diffusion method. The salting-out agent (electrolytes such as magnesium chloride, calcium chloride, and magnesium acetate, or non-electrolytes like sucrose) and a colloidal stabilizer like polyvinylpyrrolidone or hydroxyethyl cellulose are used to emulsify the polymer and medication after being first dissolved in acetone. In order to improve acetone penetration into the aqueous phase, this oil/water emulsion is thinned out with just enough water or aqueous solution to produce nanospheres¹¹. The

effectiveness of the drug's encapsulation can be significantly impacted by the salting-out agent, so it should be carefully chosen. The solvent and salting-out agent are both removed via cross-flow filtration. The process used to create PLA, or poly (methacrylic acid), nanospheres is highly effective and simple to scale up. Reduced protein encapsulant stress is the main advantage of salting out. When processing heat-sensitive materials, salting out may be advantageous since it doesn't call for a temperature rise. The most notable limitations are the extensive nanoparticle cleaning operations and the restricted use to lipophilic drugs¹².

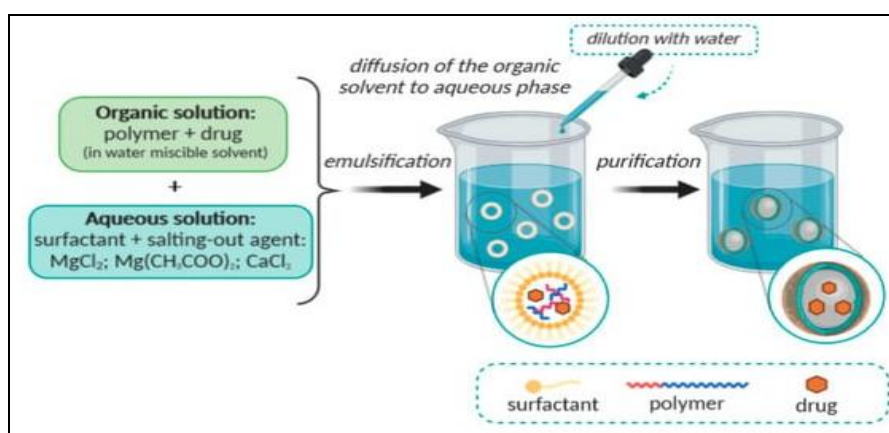


FIG. 5: SCHEMATIC REPRESENTATION OF THE SALTING-OUT METHOD

Dialysis: The creation of the dialysis procedure served as the culmination of efforts to investigate a nanoparticulate framework free of surfactants. The dialysis approach is one of the most often used methods because of its many benefits, including its ease of use and effectiveness in producing polymeric nanoparticles with a uniform size distribution. Dialysis offers a straightforward, practical method for producing tiny, homogenous

PNPs that is free of surfactants¹³. The dialysis tube is filled with a polymer that has been dissolved in an organic solvent and has a specific molecular weight cut-off. Due to a reduction in solubility and the onset of homogeneous nanoparticle suspensions, the withdrawal of the solvent from inside the film causes vanguard polymer buildup. The polymer solvent used affects the nanoparticles' morphology and size¹⁴.

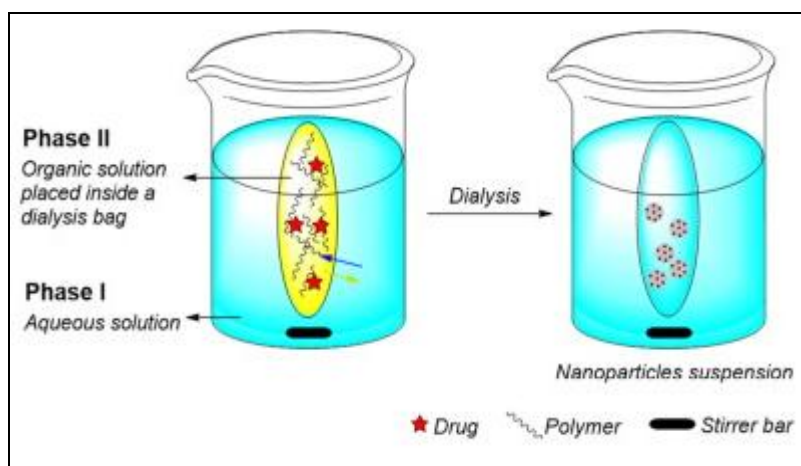


FIG. 6: SCHEMATIC REPRESENTATION OF THE DIALYSIS METHOD

Supercritical Fluid Technology (SCF): It should be emphasized that the techniques covered in the previous sections call for the use of organic solvents and surfactants, both of which pose risks to human health and the environment. On the other hand, if solvent contaminants from the original solvent are still present in the drug-loaded PNPs, they become toxic and may cause the drug to break down in the polymer matrix.

Another difficulty is coming up with accurate, adaptable production techniques for nanomedicines that could be easily scaled up. Research efforts have been focused on developing environmentally sound PNP production techniques in order to address these obstacles¹⁵. A SCF is a fluid that has been heated and compressed above its critical pressure (Pc) and temperature (Tc) (Pc). Its physicochemical characteristics in these circumstances fall between a gas and a liquid. This is a novel state of matter where the fluid has the density and solvating properties of a liquid while also behaving like a gas. The most popular SCF is supercritical carbon dioxide (scCO₂) because it possesses moderate critical conditions, is plentiful, affordable, non-flammable, nontoxic, and environmentally safe¹⁶.

Methods for the Preparation of Nanoparticles from the Polymerization of Monomers:

Emulsion Polymerization: One of the quickest methods for producing nanoparticles is polymerization, which may be categorized into two forms depending on whether an organic or an aqueous continuous phase is utilized. Monomer dispersion into an emulsion or suspension is mastery of the continuous organic phase process, as in Inverse microemulsion or any nonsolvent¹⁷. If enough energy is applied, the monomer can also be changed into an initiating radical. When this radical monomer strikes another monomer, the chain propagates, and phase separation and the formation of solid particles can happen before or after termination. In the beginning, surfactants and other soluble polymers were used to prevent the particles from clogging during the polymerization process. However, this procedure is no longer used because dangerous chemicals were used at various stages¹⁸.

Mini-emulsion Polymerization: For mini-emulsion polymerization processes, free radical producers (initiators) and radical polymerizable monomers, dispersion media (often water), surfactants, and organic solvents. The emulsion polymerization medium is typically deionized

water. A 50–500 nm homogeneous emulsion or settling scatterings of monomer nanodroplets are used in the mini-emulsion polymerization process¹⁹. Under constant mixing, an organic solvent containing an initiator and a dissolver is combined with a watery stage containing surfactant and water. This results in a conventional emulsion. A high-energy mechanical source, like an ultrasonicator, is used to create nanodroplets. During the mechanical unsetting process, the monomer beads rapidly change in size until they finally find a balancing state with a negligible attainable nano-molecule size of²⁰.

Micro-emulsion Technique: In a microemulsion, a water-solvent initiator is added to a miniaturised-scale emulsion fluid that contains a volatile organic solvent and monomer and has been thermodynamically tuned. The surfactant-containing water is added, and as soon as it is, the polymerization process begins. This process depends on a substantial amount of surfactant framework, which reduces interfacial tension to almost zero²¹. These emulsions can be made by combining two immiscible oil/water phases; ultrasonication is not necessary. Additionally, due to the usage of a considerable amount of surfactant, nanoparticles are completely submerged in surfactant. The resulting particles are between 5 and 50 nm in size. This method can be used to create polymer nanoparticles with a variety of morphologies, such as core-shell, hollow spherical, moonlike, etc²².

Interfacial Polymerization: A general preparation method for getting PNPs is interfacial polymerization. Polymerization in steps is another name for it. In this method, the two miscible liquid phases' interfacial region serves as the site of polymerization. This method can be used to create a variety of polymer nanoparticles, including ultra-thin films, nano capsules, and nanofibers²³. Liquid-solid interfaces, liquid-liquid interfaces, and liquid-in-liquid emulsion interfaces are among the many types of interfacial polymerization that exist. Two immiscible (consistent and dispersed) fluid phases of two reactive monomers are scattered. The immiscible stages' interfacial limit is where the response occurs. Momentarily, the latex nanoparticles scatter in the fluid stage. Several polymers, including polyaniline (PANI),

polypyrene (PPy), poly (3,4-ethylenedioxythiophene), and polythiophene (PTh), have been developed²⁴.

Controlled or Living Radical Polymerization (C/LRP): Using the aforementioned polymerization techniques, radical polymerization courses introduced new methodologies to PNPs that had been obtained. This is among the most helpful techniques for making polymers. It entails the polymer undergoing free radical generation, which can be produced in several ways, for example, by adding an initiator. Particularly in the context of emulsion polymerization, radical polymerization takes place in a continuous or dispersed framework and is sustained by the ongoing expansion of free radical components²⁵.

The profitable component of the plan is to adjust the polymer's key features, resulting in the creation of PNPs with the appropriate molecular size and size distribution, design, and utility. Numerous radical polymerization techniques have been proposed in the literature, including nitroxide-mediated polymerization, atom transfer radical polymerization, and currently developed reversible addition and fragmentation transfer chain polymerization²⁶.

Ionic Gelation or Coacervation of Hydrophilic Polymers: Polymeric nanoparticles are created using biodegradable hydrophilic polymers like chitosan, gelatin, and sodium alginate. Ionic gelation is a technique developed by Calvo and colleagues for creating nanoparticles of hydrophilic chitosan²⁷. The method of ionic gelation was used to create chitosan nanoparticles that were loaded with dexamethasone sodium phosphate in their study. Chitosan, a diblock co-polymer of ethylene oxide or propylene oxide (PEO-PPO), and poly anion sodium tripolyphosphate are the two aqueous phases combined in the method. In this method, the negatively charged tripolyphosphate and the positively charged amino group of chitosan interact to produce nanometre-sized coacervates. In contrast to ionic gelation, which takes place when a substance changes from a liquid to a gel as a result of ionic interaction circumstances at room temperature, coacervates are produced when two aqueous phases interact electrostatically²⁸.

Characterization of Polymeric Nanoparticles:

Morphology: The size and shape of polymeric NPs have been extensively studied using scanning and transmission electron microscopy (SEM and TEM). To undertake the NPs' morphology analysis, they are typically paired with cryofracture techniques. The commonly used TEM can measure the thickness of the nano capsule wall, distinguish between nano capsules and nanospheres, and distinguish between them. Nano capsules are created by wrapping an oily core in a thin (5 nm) polymeric envelope, as opposed to nanospheres, which have a spherical shape and a solid polymeric structure²⁹. Atomic force microscopy (AFM) has also been utilized to describe the surface morphology of polymeric NPs. It offers high-resolution data in three formats. It can also discern surface details at the atomic level and in nanometric dimensions. By using this method, a complex topography on the nanoparticles' surfaces has been seen, and by examining sample slices, the existence of tiny cavities and pores has also been made clear³⁰.

Particle Size Distribution: The average diameter of polymeric NPs produced using various techniques might range from 100 to 300 nm. The size distribution should be unimodal, and the polydispersity should be as low as possible (preferably, close to zero). It is also possible to obtain particles with dimensions between 60 and 70 nm or even less than 50 nm. The most often used methods for measuring nanoparticle size are dynamic (DLS) and static (SLS) light scattering, while TEM, SEM, and AFM are also frequently employed. Depending on the technique, different sizes can be measured; for instance, electron microscopy shows a particle separated from its surroundings, whereas DLS enables measurement of the hydrodynamic radius of suspended particles³¹. Additionally, because it can measure larger sizes, DLS is a crucial addition to TEM. Observing variations in particle size distribution can provide details on the aggregation state of a nanoparticle in solution. Many factors, including the qualitative and quantitative composition, can affect the size of polymeric NPs. For instance, when producing nano capsules, the type of oil used as the core can affect the particle diameter because of variations in viscosity, hydrophobicity, or interfacial tension between the various liquid phases.

The amount of medicine may result in larger particles with a wider size distribution, which can also affect the nanoparticles' average diameter³².

Chemical Composition and Crystal Structure:

The idea of atomic absorption, which states that ground-state electrons of atoms can leap to an excited state by absorbing a given amount of energy from light with a particular wavelength, is the basis for one of the most widely used ensemble techniques, atomic absorption spectroscopy. The sample mass concentration can be determined by comparing the signal with calibration standards at known concentrations, since the amount of energy absorbed depends on the type and quantity of atoms in the light path. Time-of-flight mass spectrometry (TOFMS), which involves ionizing small to large organic analytes into the gas phase with minimal fragmentation and their subsequent separation/detection using a time-of-flight mass spectrometer, is one method used to determine the chemical composition of a single particle³³. A nanoparticle's arrangement of constituent atoms can either be amorphous or structured into a crystal form. In most cases, Powder X-ray diffraction (PXRD) or selective area electron diffraction using a transmission electron microscope are methods for determining structure. While single particles can be used for electron diffraction, a gram of material must be supplied for X-ray diffraction³⁴.

Molar Mass Distribution of the Polymer:

Determining the polymer's molar mass distribution can reveal details about the formulation's impact on the polymerization process, the occurrence of chemical interactions between the drug and the polymer, as well as the polymer's degradation. Size-exclusion chromatography is the method most frequently employed to determine the polymer molar mass distribution (SEC). Additionally, static light scattering (SLS) has been utilized to assess the amount of light that the polymeric NPs scatter³⁵.

Surface Area and Chemistry: The surface area of the NPs is significant because it affects reactivity and surface interactions with ligands. Surface area is measured using various techniques. Adsorption of an inert gas, such as N₂, under various pressure circumstances results in the formation of a monolayer of gas coverage, which is used to directly estimate the surface area of the

nanoparticle. The "total surface area" is inversely proportional to the number of gas molecules required to create a monolayer and the cross-sectional area of the adsorbate gas molecule. Due to the gas's ability to bind to internal pores and crevices, this approach is also used to assess the morphology of porous materials³⁶. The elemental or molecular chemistry of a particle surface is referred to as surface chemistry. Due to their increased area-to-volume ratio, nanoparticles have a higher percentage of atoms on their surfaces, where they are in direct contact with solvents and have an impact on how other molecules interact with them. Some nanoparticles, like nano capsules, have a core-shell structure in which the atoms on the exterior surface and the inside core are unlike. The surface chemistry of nanoparticles can be characterized using a variety of methods, such as secondary ion mass spectroscopy and X-ray photoelectron spectroscopy³⁷.

Zeta Potential: The surface charge of the particles is represented by the zeta potential, which is affected by changes in the interface with the dispersing medium, changes brought on by the dissociation of functional groups on the particle's surface, or by the adsorption of ionic species present in the aqueous dispersion medium, as well as the solvation effect. The zeta potential is estimated from the electrophoretic mobility of particles in a particular solvent, and this parameter is evaluated using Doppler techniques to quantify the particle velocity as a function of voltage. The major elements of polymeric NPs are phospholipids, poloxamers, and polymers, and when included in formulations, they have the power to alter the zeta potential. For the colloidal solution to be physicochemically stable, a relatively high zeta potential value, defined as $|30 \text{ mV}|$, is necessary because strong repulsive forces tend to prevent aggregation due to sporadic collisions with nearby nanoparticles³⁸. Zeta potential measurements help understand the way that medications bind to nanoparticles. Understanding the loading of albumin into nanospheres made from chitosan and a diblockcopolymer of ethylene oxide and propylene oxide required the use of the zeta potential (PEO-PPO). We have noticed how the zeta potential values are impacted by the composition of the various formulations. Thus, by adding surfactants or other coatings to the surface

of NPs, such as poly-ethylene-glycol (PEG) of varied molecular weights, the zeta potential of NPs can be adjusted for a particular application³⁹.

pH of Suspension: Monitoring pH as a function of time allows for the collection of pertinent data regarding the stability of nanoparticulate suspensions. For instance, a change in pH could be a sign of polymer breakdown, suggesting alterations in particle surface protonation. In a study, it was discovered that suspensions of nano capsules and nanospheres had less molar mass after six months of storage, which led to a drop in the pH of these formulations. However, depending on how hydrophobic the polymer is, the rapid reduction in pH values of suspensions can be due to both the ionization of carboxylic groups present in the polymer, which releases protons into the surrounding media⁴⁰.

Stability of Polymeric NPs Suspensions: Because the sedimentation process is sluggish for submicrometric particles and further slowed down by the Brownian movement, colloidal suspensions typically do not phase separate until a few months after preparation. The processes of particle agglomeration and sedimentation, however, might take place gradually. The adsorption of active molecules onto the surface of the nanoparticles and the presence of adsorbed surfactants are two aspects that can affect the stability of colloidal suspensions. Particle size, zeta potential, polymer molar mass distribution, drug content, and pH are a few physicochemical variables that can be used to track the stability of polymeric colloidal suspensions⁴¹. However, issues with low physicochemical stability, especially lengthy storage periods, can limit the commercial utilization of polymeric NPs dispersed in aqueous fluids. Particle aggregation, chemical stability of the polymer, drugs, or other raw materials utilized in the manufacture of NPs, as well as the early release of the active ingredient, are the key drawbacks. In addition, it's critical to stress that preservatives are necessary for liquid dosage forms because they are susceptible to microbial growth. Drying techniques like lyophilization (freeze-drying) or spray drying are typically advised in order to postpone or prevent these physicochemical and microbiological issues. Lyophilization, which involves evaporating water, has been used

extensively for drying suspensions of nanospheres⁴².

Determination of the Drug Association: Due to their small size, which makes it challenging to distinguish the free fraction of the drug from the associated fraction, determining the amount of drug associated with nanoparticles is particularly complicated. Ultracentrifugation is a separation method that is frequently employed. After centrifugation, the free medication that is present in the suspension is found in the supernatant. The complete dissolving of a portion of the nanoparticles in an appropriate solvent often yields the whole drug concentration⁴³. Consequently, the difference between the concentrations of total and free drug is used to compute the drug concentration associated with the nanoparticles. Another technique that has been applied is ultrafiltration-centrifugation, which uses a membrane to separate a portion of the colloidal suspension from the dispersion aqueous phase. The ultrafiltrate is used to measure the free drug concentration, and the drug fraction bound to the nanostructures is derived by deducting the total and free concentrations⁴⁴.

Pharmaceutical In-vitro Release Kinetics: Drug release from polymeric nanoparticles has been characterized by techniques such as diffusion from dialysis bags and separation based on ultracentrifugation, low-pressure filtration, or ultrafiltration-centrifugation. Previous research has shown that the drug release from nanospheres typically takes the shape of an exponential (first order), which may be because the drug diffuses from the polymeric matrix to the environment or because the polymeric matrix erodes, releasing the drug. The medicine contained in the oily nucleus of the nano capsule would potentially be released from this vesicular structure upon diffusion through the polymeric wall, presenting zero-order kinetics⁴⁵.

Applications of Nanoparticulate Delivery Systems:

Nanoparticle as Drug Delivery Systems: Due to physiological hurdles that cellular mechanisms confront, drug resistance at the target level commonly restricts the use of pharmacological drugs. Additionally, many medications have low bioavailability, poor solubility, and are swiftly

eliminated from the body by the reticuloendothelial system. Furthermore, dose-dependent side effects frequently limit the efficiency of other medications, such as chemotherapeutic medicines⁴⁶.

Gastrointestinal Tract: The GI and Skin are other entrance points. It is well established that cellular trafficking, post-translocation processes, and diffusion and accessibility through mucus, initial contact with enterocytes, all affect the rates of particle uptake in the gastrointestinal system. The quicker the particles could diffuse through the GI secretion to reach the target organ, the smaller their diameter. Intestinal enterocytes Nanoparticles can go to the bloodstream after GI tract absorption and disperse throughout the body. Targeting techniques use specific binding to ligands or receptors and nonspecific adsorptive mechanisms to enhance the interaction of nanoparticles with adsorptive sites (enterocytes and M-cells of Peyer's patches) in the GI tract. Cell-specific carbohydrates are visible on the surface of enterocytes and M cells, and they can act as drug-binding sites for nanoparticles⁴⁷.

Brain: The blood-brain barrier (BBB), which regulates the transit of endogenous and exogenous substances and serves the neuroprotective function, makes the brain one of the least accessible organs for the delivery of medications. Drugs that bind to the surface-modified poly (butyl cyanoacrylate) (PBCA) nanoparticles may be able to pass the BBB and reach the brain⁴⁸.

Tumor Cell Targeting: Anticancer medications, which often have wide distribution, are harmful to both healthy and cancerous cells. Miniaturizing the delivery systems so that they are significantly smaller than their targets is therefore necessary for precise medication release into highly specific targets. Personalized medicine, which minimizes the treatment's impact on other locations while optimizing its therapeutic benefit, is now a possibility because of the application of nanotechnology in drug molecule targeting to the site of action. The fact that these particles are so small allows them to pass through various barriers, tiny capillaries, and individual cells to accomplish this purpose⁴⁹.

Respiratory Tract: The respiratory tract is one of the most common entrance points for nanoparticles.

Nanoparticles could get past the typical phagocytic defenses in the respiratory tract, enter the bloodstream, and possibly even reach the central nervous system. For the delivery of medicinal chemicals, aerosol therapy employing nanoparticles as drug carriers is becoming more and more important. Due to non-invasive administration through inhalation aerosols, avoiding first-pass metabolism, direct delivery to the site of action for the treatment of respiratory diseases, and the availability of a significant surface area for local drug action and systemic drug absorption, the lung is an appealing target for drug delivery⁵⁰.

Nanoparticles for Gene Delivery: Nanoparticles containing plasmid DNA may also be used as efficient sustained-release gene delivery agents because they may quickly transition from the lysosomal degradation compartment to the cytoplasmic compartment. According to Hedley et al., nanoparticles may continuously release DNA upon intracellular uptake and endosomal escape. After intracellular uptake and endosomal escape, nanoparticles might release DNA at a steady rate, leading to permanent gene expression. By using PLGA nanoparticles that express therapeutic genes like bone morphogenic protein, this gene delivery method could be used to facilitate bone repair⁵¹.

Nanoparticles for Diagnosis and Bioimaging: There are several molecular imaging methods, including optical imaging (OI) and magnetic resonance imaging (MRI), and it has been reported that imaging of biological specimens in vitro and in vivo can be done using MRI, ultrasonic imaging, positron emission tomography, and other techniques. Bioimaging technologies are being advanced by the present development of luminous and magnetic nanoparticles. Luminescent nanoprobes for OI and magnetic nanoparticles for MRI are two separate types of nanoparticles that have been extensively employed for imaging. Additionally, dual-mode nanoparticles are available for simultaneous OI and MRI imaging⁵².

Future Perspectives: Applications for polymer-based nanomedicine are numerous and have a long history. The transition from lab-scale proof of concept research to reproducible, with precisely controlled physicochemical features and high-yield manufacture of practical nanomaterials, is likely

one of the most significant problems related to nanoparticles. This is a crucial element that is frequently overlooked in the literature. Additionally, certain nanomaterials will never be tested in human studies. If the key characteristics that make a polymer suitable for biological use (biodegradable, stable, non-cytotoxic, and well defined) and the regulatory requirements for clinical trials were taken into consideration, this may be somewhat overcome. The designed polymer also needs to be affordable to manufacture as a nanomedicine. Numerous techniques have been widely used to create PNPs. The size distribution is typically fairly wide, and the mean particle size isn't necessarily ideal for applications involving medication delivery. The most researched techniques use emulsion-based systems. Longer periods of sonication exposure are known to cause surfactant degradation due to radicals that develop during the thermal decomposition of water. As an alternative, nanoprecipitation has rapidly gained attention in the literature in recent years.

CONCLUSION: Since various medications and macromolecules (such as proteins, peptides, vaccines, hormones, and genes) can be delivered *via* these systems, polymeric NPs have demonstrated promising potential for diagnostic and therapeutic applications for a variety of disorders. The usage of NPs has been linked to improvements in bioavailability, stability, solubility, cellular permeability, absorption, biodistribution, and targeting to particular locations. Additionally, they can provide the formulation through more practical means, improving patient compliance. The basics of the most popular preparation techniques mentioned in the literature, as well as the natural and synthetic polymers that are available to prepare polymeric NPs. It was shown that the method and materials utilized to create the NPs may have an impact on the particle size, size distribution, surface charge, drug loading, and drug release, all significant factors to take into account during the development. To make it easier for these formulations to reach the market, innovation in recent decades has primarily concentrated on enhancing current techniques and using approaches that enable the reproducible manufacture of vast numbers of particles.

Polymeric NPs are anticipated to fulfill the needs of appropriate drug delivery systems to consistently improve therapeutics and diagnosis.

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REFERENCES:

1. Wu S, Neto E, Matos AP, Jafari A, Kozempel J, Silva YJ, Larrea C, Alves Junior S, E. Junior, F. Alexis and R. Oliveira: Radioactive polymeric nanoparticles for biomedical application. *Drug Deliv* 2020; 27: 1544–1561.
2. Ahmad MZ, Mohammed AA, Algahtani MS, Mishra A and Ahmad J: Nanoscale topical pharmacotherapy in the management of psoriasis: Contemporary research and scope. *J Funct Biomater* 2023; 14: 1–19.
3. B. Mukherjee, B. Paul, A. Hoque, R. Sen, S. Chakraborty, A. Chakraborty, Polymeric nanoparticles as tumor-targeting theranostic platform, *Design Appli.* (2023) 217.
4. S.R. Pasika, R. Bulusu, B.V. Rao, N. Kommineni, P.K. Bolla, S.G. Kala, C. Godugu, Nanotechnology for biomedical applications, *Nanomaterials* (2023) 297–327.
5. E. Rostami, Recent achievements in sodium alginate-based nanoparticles for targeted drug delivery, *Polym. Bull.* 9 (2022) 6885–6904.
6. Z. Cheng, M. Li, R. Dey, Y. Chen, Nanomaterials for cancer therapy: Current progress and perspectives, *J Hematol. Oncol.* 14 (2021) 1–27.
7. G. Amoabediny, F. Haghiralsadat, S. Naderinezhad, M.N. Helder, E. Kharanaghi, J. Arough, B. Doulabi, Overview of preparation methods of polymeric and lipid-based (niosome, solid lipid, liposome) nanoparticles, *Int. J. Polym. Mater. Polym. Biomater.* 6 (2018) 383–400.
8. R.R. Wakaskar, Role of nanoparticles in drug delivery encompassing cancer therapeutics, *Int. J. Drug Dev. Res.* 3 (2017) 1–17.
9. C.R. Oliveira, D. Almeida, F.F. Padilha, R.R. Souza, R.L. Uniar, Polymeric nanoparticles for the treatment of prostate cancer-technological prospecting and critical analysis, *Recent Patents Nanotechnol.* 17 (2023) 8–14.
10. B. Begines, T. Ortiz, M. Aranda, G. Martínez, M. Merinero, F. Arias, A. Alcudia, Polymeric nanoparticles for drug delivery: recent developments and prospects, *Nanomaterials* 10 (2020) 1403.
11. F. Din, W. Aman, I. Ullah, O.S. Qureshi, O. Mustapha, S. Shafique, A. Zeb, Effective use of nanocarriers as drug delivery systems for the treatment of selected tumors, *Int. J. Nanomed.* 12 (2017) 7291.
12. D.B. Viana, M. Gaedke, N.M. Leao, A. Boker, D.C. Soares, U. Glebe, M.L. Tebaldi, Hybrid protein-polymer nanoparticles based on P (NVCL-co-DMAEMA) loaded with cisplatin as a potential anti-cancer agent, *J. Drug Deliv Sci. Technol.* 79 (2023), 103995.
13. E.A. Madawi, A.R. Jayoush, M. Qalaji M, H.E. Thu, S. Khan, M. Sohail, A. Mahmood, Z. Hussain, Polymeric nanoparticles as tunable nanocarriers for targeted delivery of drugs to skin tissues for treatment of topical skin diseases, *Pharmaceut* 15 (2023) 657.
14. D. Bennet, S. Kim, Polymer nanoparticles for smart drug delivery, *Appl. Nanotechnol. Drug Delivery.* 25 (2014) 8.
15. H. Amani, H. Arzaghi, M. Bayandori, A.S. Dezfouli, H. Toroudi, A. Shafiee, L. Moradi, Controlling cell behavior through the design of biomaterial surfaces: a focus on surface modification techniques, *Adv. Mat. Int.* 13 (2019) 1900572.
16. M.S. Bami, M.A. Estabragh, P. Khazaeli, M. Ohadi, G. Dehghannoudeh, pH-responsive drug delivery systems as intelligent carriers for targeted drug therapy: Brief history, properties, synthesis, mechanism, and application, *J. Drug Deliv. Sci. Technol.* 19 (2021), 102987.
17. J. Kleynhans, M. Sathekege, T. Ebenhan, Obstacles and recommendations for clinical translation of nanoparticle system-based targeted alpha-particle therapy, *Materials* 17 (2021) 4784.
18. S. Kumaresan, S. Vaiyapuri, J.H. Kang, N. Dubey, G. Manivasagam, K.D. Yun, S. W. Park, Additive-manufactured zirconia- bio-ceramics for biomedical applications.
19. E. Avcu, F.E. Bastan, M. Guney, Y.Y. Avcu, M.A. Rehman, A.R. Boccaccini, Biodegradable polymer matrix composites containing graphene-related materials for antibacterial applications, *Acta Biomater.* (2022) 31.
20. E.R. Radu, S.I. Voicu, T.V.K. Hakur, Polymeric membranes for biomedical applications, *Polymers* 15 (2023) 619.
21. V.A. Spirescu, C. Chircov, A.M. Grumezescu, E. Andronescu, Polymeric nanoparticles for antimicrobial therapies: an up-to-date overview, *Polymers* 5 (2021) 724.
22. A. Arun, P. Malraut, A. Laha, H. Luo, S. Ramakrishna, Collagen nanoparticles in drug delivery systems and tissue engineering, *Appl. Sci.* 23 (2021) 11369.
23. P.K. Sehgal, A. Srinivasan, Collagen-coated microparticles in drug delivery, *Expert Opin. Drug Deliv.* 7 (2009) 687–695.
24. R. Sarvari, M. Nouri, S. Agbolaghi, L. Roshangar, A. Sadrghighi, A.M. Seifalian, P. Keyhanvar, A summary on non-viral systems for gene delivery based on natural and synthetic polymers, *Int. J. Polym. Mat. Polym. Biomater.* 4 (2022) 246–265.
25. B.E. Abdelmalek, J. Estaca, A. Sila, O. Alvarez, M.C. Guillen, S. Ellouz, M. A. Ayadi, A. Bougatef, Characteristics and functional properties of gelatin extracted from squid (*Loligo vulgaris*) skin, *Food Sci. Technol.* 65 (2016) 924–931.
26. D. Sleep, Albumin and its application in drug delivery, *Expert Opin. Drug Deliv.* 12 (2015) 793–812.
27. E. Kianfar, Protein nanoparticles in drug delivery: animal protein, plant proteins and protein cages, albumin nanoparticles, *J. Nanobiotechnol* 19 (2021) 159.
28. A. Loureiro, G. Azoia, C. Gomes, A.A. Paulo, Albumin-based nanodevices as drug carriers, *Curr. Pharmaceut. Design* 10 (2016) 1371–1390.
29. P.O. Boamah, J. Onumah, W.O. Aduguba, K.G. Santo, Application of depolymerized chitosan in crop production, *Int. J. Biol. Macromol.* 4 (2023), 123858.
30. W. Tang, J. Wang, H. Hou, Y. Li, J. Wang, J. Fu, L. Lu, D. Gao, Z. Liu, F. Zhao, X. Gao, Application of chitosan and its derivatives in medical materials, *Int. J. Biol. Macromol.* 12 (2023), 124398.
31. H. Singh, V. Kumar, Cellulosic nanowhiskers: preparation and drug delivery application, *Curr. Drug Deliv.* 10 (2021) 1426–1434.

32. P. Simonak, Doctoral dissertation, Masaryk University, Faculty of Economics and Administration.
33. P. Zarrintaj, S. Manouchehri, Z. Ahmadi, M.R. Saeb, A.M. Urbanska, D.L. Kaplan, M. Mozafari, Agarose-based biomaterials for tissue engineering, *Carbohydr Polymers* 1 (2018) 66–84.
34. E. Montes, Dextran: sources, structures, and properties, *Polysaccharides* 3 (2021) 554–565.
35. J. Varshosaz, Dextran conjugates in drug delivery, *Expert Opin. Drug Deliv.* 5 (2012) 509–523.
36. N. More, M. Avhad, S. Utekar, A. More, Polylactic acid (PLA) membrane—significance, synthesis, and applications, *Polym. Bull.* 2 (2023) 1117–1153.
37. C.R. Devi, R. Ray, S. Koduri, A.K. Moharana, D. Ts, Clinical equivalence of polyglycolic acid suture and polyglactin 910 suture for subcutaneous tissue closure after cesarean delivery: a single-blind randomized study. *Medical devices, Evid. Res.* 31 (2023) 27–36.
38. O.A. Oladipo, S.L. Lebelo, T.A. Msagati, Nanocarrier design–function relationship. The prodigious role of properties in regulating biocompatibility for drug delivery applications, *Chem-Biol Inter.* 31 (2023), 110466.
39. V.J. Mkhabela, S.S. Ray, Poly (ε-caprolactone) nanocomposite scaffolds for tissue engineering: a brief overview, *J. Nanosci. Nanotechnol.* 14 (2014) 535–545.
40. Y. Bae, K. Kataoka, Intelligent polymeric micelles from functional poly (ethylene glycol)-poly (amino acid) block copolymers, *Adv. Drug Deliv. Rev.* 10 (2009) 768–784.
41. S.H. Boddu, P. Bhagav P, P.K. Karla, S. Jacob, M.D. Adatiya, D.M. Dhameliya, K. M. Ranch, A.K. Tiwari, Polyamide/poly (amino acid) polymers for drug delivery, *J. Funct. Biomater.* 4 (2021) 58.
42. L. Shi, J. Zhang, M. Zhao, S. Tang, X. Cheng, W. Zhang, W. Li, X. Liu, H. Peng, Q. Wang, Effects of polyethylene glycol on the surface of nanoparticles for targeted drug delivery, *Nanoscale* 24 (2021) 10748–10764.
43. A. Bunker, Poly (ethylene glycol) in drug delivery, why does it work, and can we do better? All-atom molecular dynamics simulation provides some answers, *Phys. Procedia* 34 (2012) 24–33.
44. L. Navarro, N. Ceaglio, I. Rintoul, Structure and properties of biocompatible poly (glycerol adipate) elastomers modified with ethylene glycol, *Polymer* 8 (2017) 625–632.
45. A. Shikanov, B. Vaisman, S. Shikanov, A.J. Domb, Efficacy of poly (sebacic acid- co-ricinoleic acid) biodegradable delivery system for intratumoral delivery of paclitaxel, *Biomater. Korean Social Biomat.* 4 (2010) 1283–1291.
46. T.S. Gaaz, A.B. Sulong, M.N. Akhta, A.A. Kadhum, A.B. Mohamad, A.A. Amri, Properties and applications of polyvinyl alcohol, halloysite nanotubes and their nanocomposites, *Molecules* 12 (2015) 22833–22847.
47. F. Danhier, E. Ansorena, J.M. Silva, R. Coco, A. Breton, V. Preat, PLGA-based nanoparticles. An overview of biomedical applications, *J. Control. Rel.* 2 (2012) 505–522.
48. H.K. Makadia, S.J. Siegel, Poly lactic-co-glycolic acid (PLGA) as biodegradable controlled drug delivery carrier, *Polymers* 3 (2011) 1377–1397.
49. P. Gentile, V. Chiono, I. Carmagnola, P.V. Hatton, An overview of poly (lactic-co-glycolic) acid (PLGA)-based biomaterials for bone tissue engineering, *Int. J. Mole Sci.* 15 (2014) 3640–3659.
50. A. Zielinska, F. Carreiro, A.M. Oliveira, A. Neves, B. Pires, D.N. Venkatesh, A. Durazzo, M. Lucarini, P. Eder, A.M. Silva, A. Santini, Polymeric nanoparticles production, characterization, toxicology and ecotoxicology, *Molecules* 16 (2020) 3731.
51. A.A. Elrahman, F.R. Mansour, Targeted magnetic iron oxide nanoparticles preparation, functionalization and biomedical application, *J. Drug Deliv. Sci. Technol.* 52 (2019) 702–712.
52. B.S. Mahmoud, A.H. Amri, C. Conville, Polymeric nanoparticles for the treatment of malignant gliomas, *Cancers* 12 (2020) 175.

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