IOSR Journal of Applied Chemistry (IOSR-JAC)
e-ISSN: 2278-5736.Volume 19, Issue 3 Ser. I (March. 2026), PP 23-31
www.iosrjournals.org

Decoding Polymeric Nanoparticles: Modern Characterization Approaches

Parveen Kumari, Pawan Kumar
Associate Professor, Department Of Chemistry, S.D. (PG) College, Panipat.
Associate Professor, Department Of Zoology, I.B. (PG) College, Panipat.

Abstract
Polymeric nanoparticles (PNPs) are versatile colloidal carriers (1–1000 nm) that encapsulate or adsorb active agents within nanospheres or nanocapsules, enabling targeted delivery, controlled release, and enhanced bioavailability. This review synthesizes current production methods such as nanoprecipitation, emulsification–solvent evaporation, salting-out, dialysis, and supercritical fluid techniques highlighting their relative advantages for scalability, encapsulation efficiency, and payload stability. It surveys key characterization tools, including dynamic light scattering (DLS), transmission and scanning electron microscopy (TEM/SEM), atomic force microscopy (AFM), zeta-potential analysis, Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and X-ray diffraction (XRD), and explains how these techniques inform particle size distribution, morphology, surface chemistry, crystallinity, thermal behavior, and drug polymer interactions. The review also examines metrics of performance association/encapsulation efficiency, loading capacity, and in vitro release kinetics and links formulation variables to release mechanisms (diffusion, degradation, swelling, and erosion). Given growing clinical and industrial interest, toxicological and ecotoxicological considerations are discussed, emphasizing nanoparticle biodistribution, cellular uptake, oxidative stress, and environmental persistence, alongside gaps in standardized safety testing and regulation. Finally, the paper outlines future priorities: green and scalable synthesis, robust in-vitro or in-vivo correlation models, advanced multimodal characterization, and harmonized safety and lifecycle assessments to accelerate responsible translation of polymeric nanoparticles into therapeutic and environmental applications.

Keywords: *Polymeric nanoparticles, drug delivery, therapeutic potential, nanomedicine, toxicology, etc.*

Date of Submission: 16-03-2026 Date of Acceptance: 26-03-2026

I. Introduction

Polymeric nanoparticles (PNPs) constitute a versatile class of colloidal carriers with sizes typically ranging from 1 to 1000 nm, capable of encapsulating or adsorbing therapeutic, diagnostic, or functional payloads within nanospheres or nanocapsules [1][2][3]. Their small size and tunable surface chemistry permit enhanced cellular uptake, prolonged circulation, and controlled release profiles, which together improve therapeutic index and reduce off-target toxicity in a wide range of biomedical applications, including oncology, infectious disease, and central nervous system disorders [4]. Advantages of polymeric NPs as drug carriers include their potential use for controlled release, the ability to protect drug and other molecules with biological activity against the environment, improve their bioavailability and therapeutic index Key production methods notably nanoprecipitation, emulsification solvent evaporation, salting-out, dialysis, and supercritical fluid techniques offer complementary trade-offs between encapsulation efficiency, particle uniformity, solvent use, and scalability, and recent process intensification strategies (e.g., flash nanoprecipitation) have improved reproducibility and size control for hydrophobic payloads[5][6].

Comprehensive characterization is essential to predict in-vivo behavior and regulatory acceptance. Dynamic light scattering (DLS) and zeta-potential measurements provide rapid metrics of hydrodynamic size and colloidal stability, while TEM/SEM and AFM reveal core morphology and surface topology; spectroscopic and thermal methods (FTIR, DSC, XRD) elucidate drug–polymer interactions, crystallinity, and thermal stability, which directly influence release kinetics and shelf life. Integrating orthogonal techniques yields robust particle fingerprints that correlate with encapsulation efficiency, loading capacity, and release mechanisms (diffusion, degradation, swelling, erosion) [7][8].

Performance metrics such as encapsulation efficiency (EE) and drug loading are highly formulation-dependent: polymer type, molecular weight, solvent selection, and process parameters (mixing rate, surfactant concentration, polymer: drug ratio) can shift EE and release profiles substantially [9][10]. Recent studies demonstrate that optimized nanoprecipitation and electrohydrodynamic mixing can maximize EE for hydrophobic drugs, while supercritical fluid methods reduce residual solvent and improve payload stability for

sensitive actives [11][12].

As clinical and industrial interest grows, toxicological and ecotoxicological considerations have become central [13]. Evidence indicates that nanoparticle biodistribution, cellular internalization pathways, and oxidative-stress responses depend on size, surface charge, and degradation products; environmental persistence and potential trophic transfer also require lifecycle level assessment. Regulatory guidance and standardized testing protocols are still evolving, creating an urgent need for harmonized assays that link in-vitro endpoints to in-vivo outcomes [14].

This review synthesizes contemporary production strategies and characterization workflows, links formulation variables to functional performance, and highlights safety and sustainability priorities. Emphasis is placed on green and scalable synthesis, multimodal characterization, and in-vitro or in-vivo correlation (IVIVC) frameworks to accelerate responsible translation of polymeric nanoparticles into therapeutic and environmental applications [15][16][17].

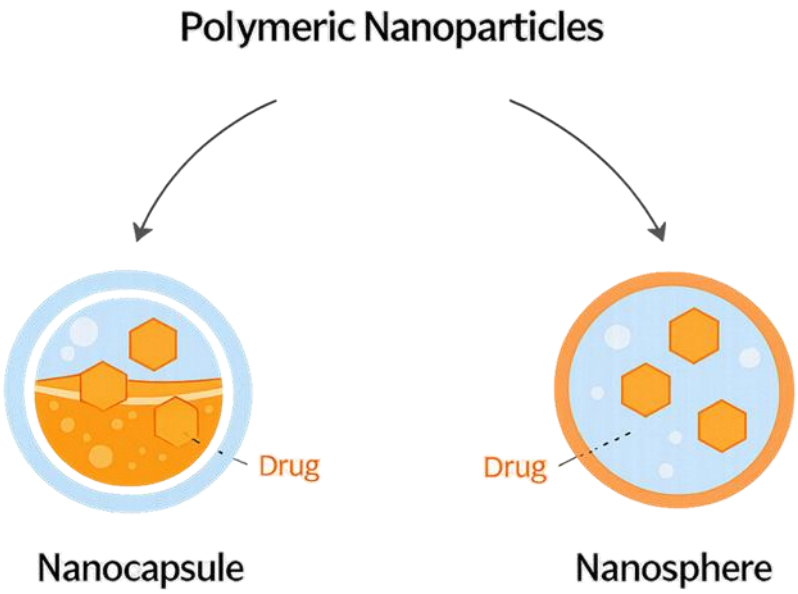

Figure 1: Structure of nanocapsules and nanospheres

Characterization of Polymeric Nanoparticles

Polymeric nanoparticles (PNPs) exhibit a wide range of physical properties including variations in composition, concentration, size, shape, surface charge, crystallinity, and dispersion state that critically influence their biological behavior and functional performance. To achieve comprehensive characterization, researchers employ a suite of analytical techniques tailored to assess these parameters. Commonly used methods include electron microscopy (e.g., TEM and SEM) for morphological analysis, dynamic light scattering (DLS) or photon correlation spectroscopy (PCS) for particle size distribution and polydispersity, near-infrared spectroscopy for chemical profiling, electrophoresis for surface charge and mobility, and chromatographic techniques for purity and drug polymer interaction studies [18]. Together, these tools provide a multidimensional understanding of nanoparticle structure, stability, and functionality, which is essential for optimizing formulation and ensuring reproducibility in therapeutic applications [[19]. Polymeric NPs characterization is very important, in terms of its applicability, but also to ascertain issues concerning nanotoxicology and exposure assessment in workplaces, which are important to assess their health and safety hazards, as well as to control manufacturing processes [20].

II. Morphology

Scanning and transmission electron microscopy (SEM and TEM) are widely employed to characterize the size and shape of polymeric nanoparticles (NPs). These techniques are often coupled with cryofracture methods to enable detailed morphological analysis. Among them,

Table 1: Characterization Techniques for Polymeric Nanoparticles

Technique	Key Information Provided	Strengths	Limitations	Typical Applications
Atomic Force Microscopy (AFM)	Surface morphology, roughness, particle height, mechanical properties	High-resolution 3D imaging; works in ambient or liquid environments; minimal sample prep	Limited field of view; slower imaging; tip artifacts possible	Differentiating nanospheres vs. nanocapsules; studying drug release surface changes
Transmission Electron Microscopy (TEM)	Internal structure, crystallinity, particle size	Ultra-high resolution; reveals internal morphology and polymer–drug distribution	Requires thin samples; vacuum environment; possible sample damage	Visualizing nanocapsule cores; drug distribution inside polymer matrices
Scanning Electron Microscopy (SEM)	External morphology, particle shape, surface texture	High resolution; wide field of view; rapid imaging	Requires conductive coating; vacuum environment; limited internal detail	Assessing particle uniformity, aggregation, and surface topology
Dynamic Light Scattering (DLS)	Hydrodynamic size, polydispersity index (PDI)	Rapid, non-destructive; suitable for colloidal suspensions	Sensitive to aggregates; assumes spherical particles; provides average size only	Routine size distribution analysis; monitoring stability in suspension

TEM is particularly valuable, as it can differentiate between nanocapsules and nanospheres and also determine the thickness of the nanocapsule wall [21]. Nanospheres have a spherical shape, with a solid polymeric structure, whereas nanocapsules are formed by a thin (about 5 nm) polymeric envelope around the oily core. Another technique that has been used to characterize the surface morphology of polymeric NPs is atomic force microscopy (AFM) and others shown in table [22]. It provides information with high resolution in three dimensions, and in a nanometric scale, while it is also able to resolve surface details at an atomic level [23]. Application of this technique revealed a complex surface topography of the nanoparticles. Furthermore, analysis of sample cross-sections indicated the presence of small cavities and pores within the structure [6].

Particle Size Distribution

Polymeric nanoparticles typically range from 100–300 nm in size. An ideal system shows low polydispersity with a unimodal distribution. Smaller particles (60–70 nm or <50 nm) can also be produced depending on the synthesis method [24]. The nanoparticle size can be measured by using different techniques, the most commonly used being the dynamic (DLS) and static (SLS) light scattering, but TEM, SEM and AFM are also oftenly used [25]. Size measurements vary depending on the technique used. Electron microscopy provides direct images of isolated particles, while dynamic light scattering (DLS) measures the hydrodynamic radius of particles in suspension. DLS complements TEM by detecting larger sizes and offering insight into nanoparticle aggregation in solution through changes in size distribution [26]. The size of polymeric nanoparticles is affected by several factors, including their qualitative and quantitative composition. For instance, in nanocapsules, the nature of the core oil plays a key role in determining particle diameter, as variations in viscosity, hydrophobicity, and interfacial tension between phases influence particle formation. Additionally, higher drug loading can increase the average particle size and lead to a broader size distribution [6][7].

Table 2: Particle Size Distribution of Polymeric Nanoparticles

Aspect	Details
Typical Size Range	100–300 nm (mean diameters); smaller particles ~60–70 nm or even <50 nm can be obtained depending on method.
Desired Distribution	Low polydispersity (ideally near zero); unimodal size distribution preferred for reproducibility and stability.
Dynamic Light Scattering (DLS)	Measures hydrodynamic radius of particles in suspension; rapid, non-destructive; detects aggregation state. Limitation: assumes spherical particles, sensitive to polydispersity.
Static Light Scattering (SLS)	Provides complementary size distribution data; useful for larger particles; less sensitive to small aggregates compared to DLS.
Transmission Electron Microscopy (TEM)	High-resolution imaging of isolated particles; reveals internal morphology. Limitation: sample preparation in vacuum; may not represent hydrated state.
Scanning Electron Microscopy (SEM)	External morphology and surface texture; wide field of view. Limitation: requires conductive coating; no hydrodynamic information.
Atomic Force Microscopy (AFM)	Surface morphology and particle height; works in ambient or liquid environments. Limitation: slower imaging, limited field of view.
Factors Influencing Size	Polymer composition and concentration (affects viscosity and matrix formation). Nature of oil in nanocapsules (viscosity, hydrophobicity, interfacial tension). Drug loading amount (higher drug content may increase particle diameter and broaden distribution).

Chemical Composition And Crystal Structure

Chemical composition refers to the atomic elements of which a nanoparticle is composed, as well as compounds native or formed functional groups, and it can be measured in an ensemble or single-particle elemental analysis method. One of the most common ensemble techniques used is atomic absorption spectroscopy which is based on the principle of atomic absorption, where ground state electrons of the atoms jump to an excited state by absorbing a certain quantity of energy from light at a specific wavelength [27]. The absorbed energy depends on the type and number of atoms in the light path, allowing sample mass concentration to be determined by comparison with calibration standards. Time-of-flight mass spectrometry (TOFMS) is commonly used to analyze the chemical composition of single particles by ionizing analytes with minimal fragmentation and separating them based on their time of flight [28]. The atomic arrangement within a nanoparticle can be either crystalline or amorphous, depending on its synthesis conditions and material composition. To determine crystal structure, researchers commonly use powder X-ray diffraction (XRD) and selected area electron diffraction (SAED) via transmission electron microscopy (TEM). XRD is ideal for bulk analysis but typically requires milligram to gram-scale quantities of sample material. In contrast, SAED enables single-particle crystallographic analysis, making it especially valuable for characterizing nanoscale domains and heterogeneous samples where material availability is limited [29][30][31].

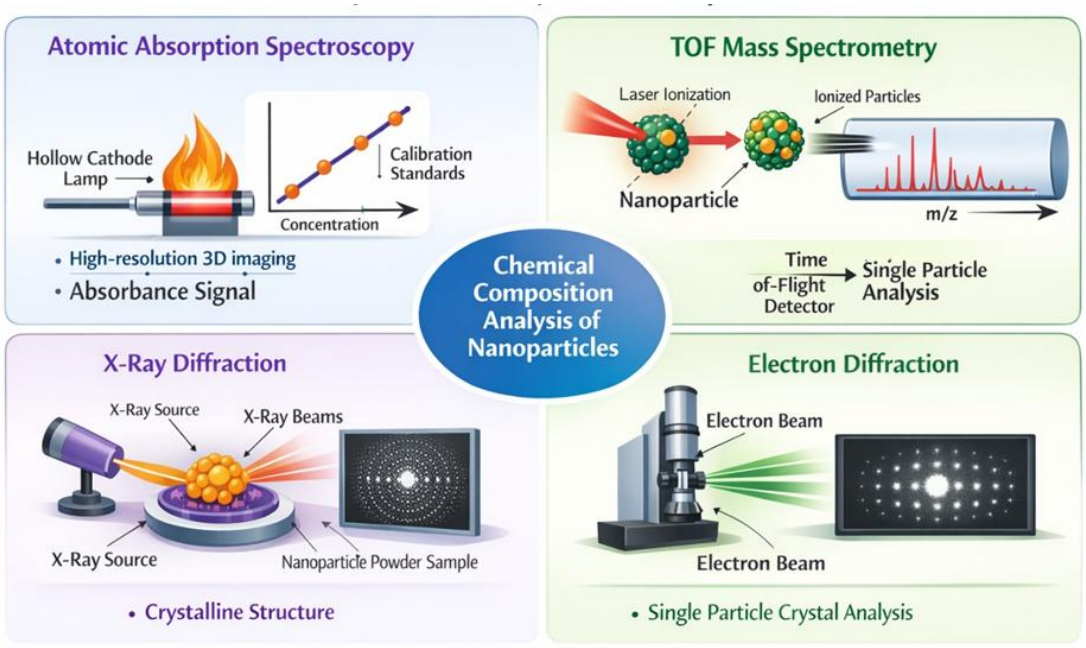

Figure 2: Chemical composition and analysis of nanoparticle.

Molar Mass Distribution of the Polymer

Determining the molar mass distribution of the polymer after preparation helps assess how formulation components affect the polymerization process, identify possible interactions between the drug and polymer, and evaluate any degradation of the polymer matrix]32]. The most commonly used technique for determining the polymer molar mass distribution is size-exclusion chromatography (SEC) [33][34]. In addition to dynamic techniques, static light scattering (SLS) has been employed to evaluate the intensity of light scattered by polymeric nanoparticles. Unlike DLS, which measures fluctuations in scattered light over time to determine particle size in suspension, SLS analyzes the angular distribution of scattered light to infer structural and compositional attributes. This method offers valuable insights into particle uniformity and aggregate formation, especially when used alongside other optical and imaging techniques [26].

Surface Area and Chemistry

The surface area of nanoparticles is important as it affects their reactivity and interactions with ligands. Various techniques assess different aspects of surface area. A direct method involves measuring the adsorption of an inert gas (e.g., N_2) onto the particle surface under controlled pressures to form a monolayer coverage [35]. The number of gas molecules that is necessary to form a monolayer and the cross-sectional area of the adsorbate gas molecule is related to the "total surface area". This method is also used to evaluate morphology of porous materials, as the gas also binds to internal pores and crevices [36]. Surface chemistry refers to the elemental or molecular chemistry of a particle surface. For nanoparticles, a higher proportion of atoms are on their surfaces,

(due to higher area/volume ratio) and these atoms are in direct contact with solvents and influence their interactions with other molecules [37]. Some nanoparticles, such as nanocapsules have a core-shell structure, in which the outer surface atoms are different from those of the interior core. Multiple techniques are available to characterize nanoparticle surface chemistry, for example X-ray photoelectron spectroscopy and secondary ion mass spectroscopy [38].

Table 3: Surface Characterization Techniques for Nanoparticles

Technique	Principle	Sample Requirement	Strengths	Limitations	Applications
Gas Adsorption (BET Method)	Adsorption of inert gas (e.g., N_2) to form a monolayer; calculates surface area from gas uptake	Requires bulk powder sample (mg–g scale)	Provides total surface area including pores; widely standardized	Cannot distinguish external vs. internal surfaces; requires dry samples	Measuring surface area, porosity, morphology of porous nanoparticles
X-ray Photoelectron Spectroscopy (XPS)	Measures binding energies of photoelectrons emitted by surface atoms	Requires thin films or nanoparticle coatings	Elemental composition and chemical states of outermost layers (~5–10 nm)	Surface-sensitive only; requires vacuum; limited depth profiling	Surface chemistry, oxidation states, ligand binding
Secondary Ion Mass Spectrometry (SIMS)	Bombards surface with ions, analyzes ejected secondary ions	Requires solid sample; minimal preparation	High sensitivity; detects trace elements and functional groups	Destructive; complex spectra; requires calibration	Molecular and elemental surface chemistry, functional group analysis
Electron Microscopy (TEM/SEM/AFM)	Imaging with electron or atomic probes	Small sample amounts; TEM requires thin sections	Direct visualization of morphology, topology, roughness	Limited chemical info; requires vacuum (TEM/SEM); slower imaging (AFM)	Morphology, surface texture, nanoparticle aggregation, roughness

Zeta Potential

The zeta potential (ζ) reflects the surface charge of the particles, which is influenced by changes in the interface with the dispersing medium, due to the dissociation of functional groups on the particle's surface or due to the adsorption of ionic species present in the aqueous dispersion medium as well as the solvation effect [39]. The zeta potential of nanoparticles is typically determined using Doppler based techniques that measure particle velocity under an applied electric field. From this velocity, the electrophoretic mobility of the particles in a given solvent is calculated, which is then used to derive the zeta potential. This parameter provides critical insight into colloidal stability and particle solvent interactions [31][40]]. Phospholipids, poloxamers, and polymers are the main components of polymeric NPs and, once present in formulations, are capable of influencing the zeta potential. A relatively high zeta potential value, considered as |± 30 mV|, is important for good physicochemical stability of the colloidal suspension, as large repulsive forces tend to prevent aggregation due to occasional collisions with adjacent nanoparticles [31]. The zeta potential determination is useful in elucidating the mechanism of association of drugs with nanoparticles [39][41]. The zeta potential of NPs can thus be tailored for a specific application, by introducing surfactants or other coatings onto the NPs surface, such as poly-ethylene-glicol (PEG) of varying molecular weights [21][42].

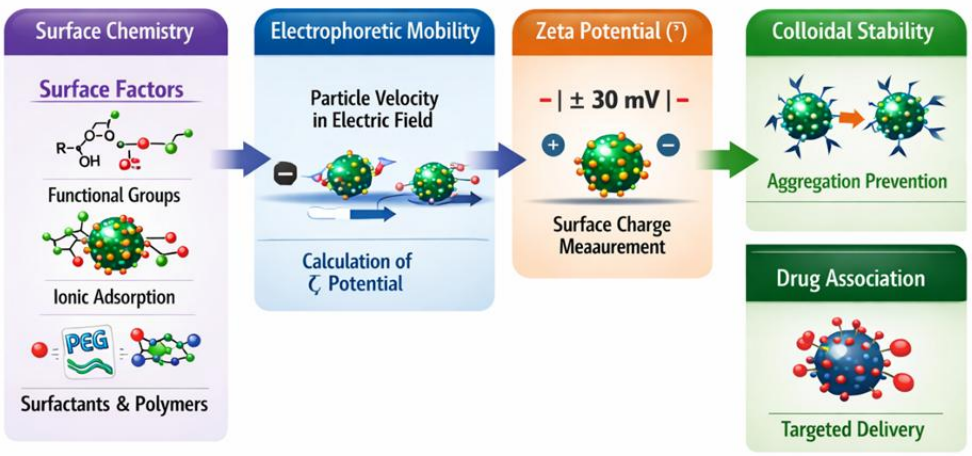

Figure3: Zeta potential and nanoparticles.

pH of Suspensions

Monitoring pH over time provides valuable insights into the stability of nanoparticulate suspensions. Fluctuations in pH may signal polymer degradation, often linked to changes in surface protonation. For instance, Calvo et al. reported a decline in molar mass and pH in nanocapsule and nanosphere formulations after six months of storage. Short-term pH drops can also result from the ionization of carboxylic groups within the polymer, releasing protons into the medium an effect influenced by the polymer's hydrophobicity [7]. Moreover, pH directly affects the zeta potential and thus the electrostatic stability of the formulation. Given its role in surface charge modulation and colloidal behavior, pH monitoring is essential for understanding nanoparticle interactions and long-term formulation integrity [43].

Stability of Polymeric NPs Suspensions

Colloidal suspensions typically resist phase separation for several months because submicrometric particles sediment slowly and Brownian motion counteracts settling. Nevertheless, particle **agglomeration** and eventual **sedimentation** can develop over time, leading to gradual loss of homogeneity and stability [44]. Several factors can influence the stability of colloidal suspensions, such as the adsorption of active molecules on the surface of the nanoparticles and the presence of adsorbed surfactants. Some physicochemical parameters that can be used to monitor the stability of polymeric colloidal suspensions are particle size, zeta potential, polymer molar mass distribution, drug content, and pH [45]. However, industrial application of polymeric NPs dispersed in aqueous media can be limited due to problems of low physicochemical stability, in prolonged storage periods [46]. The main limitations are the particle aggregation, the polymer chemical stability, the drug, or other raw materials used during NPs production and also the premature release of the active substance. In addition, it is important to emphasize that liquid dosage forms are prone to microbial proliferation with the need to add preservatives [47]. In order to delay or avoid these physicochemical and microbiological problems, drying, such as lyophilization (freeze-drying) or spray drying is usually recommended. Lyophilization consists of removing water through sublimation and has been widely used for drying nanosphere suspensions [48]. Spray drying offers an alternative to lyophilization for stabilizing nanoparticles formed from solid lipids. The process atomizes the liquid feed into fine droplets that enter a drying chamber where hot air operated in co-current, counter-current, or mixed flow rapidly removes solvent, yielding dry solid particles. The dried material is then separated and collected as fine powders, granules, or agglomerates, improving storage stability and handling compared with liquid suspensions [49][50].

Determination of the Drug Association

Determining the fraction of drug associated with nanoparticles is challenging because the small particle size complicates separation of free and bound drug [51]. A common approach is ultracentrifugation: after centrifugation, the free drug is quantified in the supernatant, while the total drug is measured by fully dissolving a portion of the nanoparticle sample; the associated drug is obtained by subtracting the free concentration from the total [52][53]. An alternative is ultrafiltration-centrifugation, which uses a membrane to separate part of the aqueous phase from the colloidal suspension; the free drug is measured in the ultrafiltrate and the associated fraction is again calculated as the difference between total and free drug concentrations [52]. According to published studies, several factors may influence the amount of drug associated with nanostructured systems, such as: physicochemical characteristics of the drug, pH of the medium, NPs surface characteristics or nature of the polymer, the amount of drug added to the formulation, the order of addition of drug to the formulation (before or after the formation of nanostructures), nature of the oil used (in the case of nanocapsules), as well as the type of surfactant adsorbed to the polymeric surface [54][55][56]. Altering the surface properties of nanoparticles can influence the rate of drug adsorption, even at the same initial drug concentration. This factor is crucial for controlling and prolonging drug release. Hence, studying the drug adsorption isotherm is important, as it reveals how the drug is distributed on the nanoparticle surface and its binding capacity [55]. In nanospheres, drugs may be dissolved, dispersed within the polymer matrix, or adsorbed onto the surface. In contrast, nanocapsules are designed to enhance the loading of lipophilic drugs, which are typically encapsulated within an oily core surrounded by a polymeric shell [7].

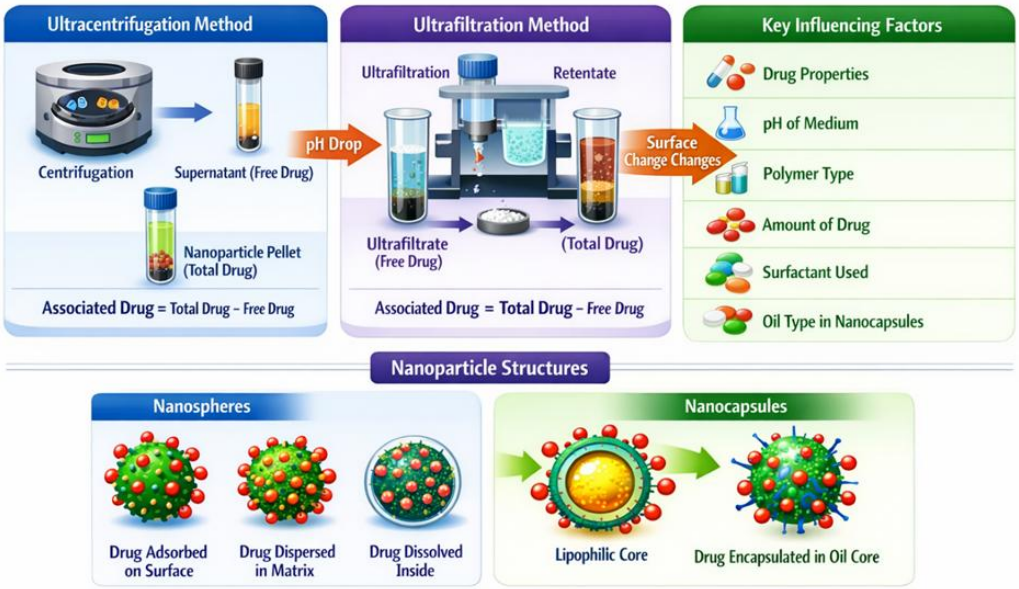

Figure 4: Drug association with nanospheres and nanocapsules.

Pharmaceutical In Vitro Release Kinetics

Drug release from polymeric nanoparticles is governed by several mechanisms, often acting concurrently: desorption of drug from particle surfaces, erosion of the polymeric matrix, diffusion of drug through a nanosphere matrix or across the polymeric shell of nanocapsules, or combinations of diffusion and erosion [31][1].

Common in vitro methods to characterize release include dialysis (diffusion from dialysis bags) and separation-based approaches such as ultracentrifugation, low-pressure filtration, and ultrafiltration-centrifugation [57]. For nanospheres, release profiles frequently follow an exponential (first-order) pattern, consistent with drug diffusion out of the polymer matrix and/or matrix erosion [31][58]. In contrast, when a drug is dissolved in the oily core of a nanocapsule, release is controlled by diffusion through the polymeric wall and can approximate zero-order kinetics [59].

Calvo et al. observed that release profiles from nanocapsules resembled those from nanoemulsions, suggesting that, in some systems, the polymeric shell may not significantly impede release; instead, release is dominated by the partitioning of drug between the oil droplets and the external aqueous phase [42].

III. Conclusions

Polymeric nanoparticles (PNPs) offer a versatile platform for drug delivery, where formulation choices (polymer type and molar mass, solvent and process parameters, core oil and surfactant selection, drug loading and order of addition) and production methods (nanoprecipitation, emulsification, supercritical fluids, etc.) critically determine encapsulation efficiency, particle size and uniformity, surface chemistry, and release behavior; comprehensive, orthogonal characterization (DLS, zeta potential, TEM/SEM/AFM, spectroscopic and thermal analyses) combined with validated separation methods (ultracentrifugation, ultrafiltration, dialysis) is essential to quantify drug association and in vitro release while avoiding artefacts, and stability challenges for aqueous dispersions (aggregation, polymer degradation, premature release, microbial growth) often necessitate drying strategies (lyophilization or spray drying) and careful monitoring of size, PDI, zeta potential, polymer molar mass, drug content, and pH to ensure reproducible performance and safe translation “Polymeric nanoparticles (PNPs) constitute a versatile class of colloidal carriers with sizes typically ranging from 1 to 1000 nm, capable of encapsulating or adsorbing therapeutic, diagnostic, or functional payloads within nanospheres or nanocapsules.

References:

[1]. Soppimath, K.S.; Aminabhavi, T.M.; Kulkarni, A.R.; Rudzinski, W.E. Biodegradable Polymeric Nanoparticles As Drug Delivery Devices. J. Control. Release 2001, 70, 1–20.

[2]. Cano, A.; Ettcheto, M.; Chang, J.H.; Barroso, E.; Espina, M.; Kuhne, B.A.; Barenys, M.; Auladell, C.; Folch, J.; Souto, E.B.; Et Al. Dual-Drug Loaded Nanoparticles Of Epigallocatechin-3-Gallate (EGCG)/Ascorbic Acid Enhance Therapeutic Efficacy Of EGCG In A Appswe/PS1dE9 Alzheimer’s Disease Mice Model. J. Control. Release 2019, 301, 62–75.

[3]. Cano, A.; Sánchez-López, E.; Ettcheto, M.; López-Machado, A.; Espina, M.; Souto, E.B.; Galindo, R.; Camins, A.; García, M.L.; Turowski, P. Current Advances In The Development Of Novel Polymeric Nanoparticles For The Treatment Of Neurodegenerative Diseases. Nanomed. (Future Med.) 2020.

[4]. Owens III, D.E.; Peppas, N.A. Opsonization, Biodistribution, And Pharmacokinetics Of Polymeric Nanoparticles. Int. J. Pharm. 2006, 307, 93–102.
[5]. Schaffazick, S.R.; Pohlmann, A.R.; Dalla-Costa, T.; Guterres, S.L.S. Freeze-Drying Polymeric Colloidal Suspensions: Nanocapsules, Nanospheres And Nanodispersion. A Comparative Study. Eur. J. Pharm. Biopharm. 2003, 56, 501–505.
[6]. Lee K. K. H., Khan F. F. N., Cosby L. C., Et Al., Polymer Concentration Maximizes Encapsulation Efficiency In Electrohydrodynamic Mixing Nanoprecipitation, Frontiers In Nanotechnology, 2021.
[7]. Le M., Characterization Techniques For Nanomaterials: A Comprehensive Review, Journal Of Materials Science And Nanomaterials, 2024.
[8]. Gobena S. T., Woldeyonnes A. D., A Review Of Synthesis Methods And Characterization Techniques Of Polymer Nanocomposites, Discover Materials, 2024.
[9]. Padhi S., Behera A., Cellular Internalization And Toxicity Of Polymeric Nanoparticles, In Environmental Chemistry For A Sustainable World, Springer, 2022.
[10]. Zielińska A., Carreiró F., Oliveira A. M., Et Al., Polymeric Nanoparticles: Production, Characterization, Toxicology And Ecotoxicology, Molecules, 2020.
[11]. Zhang C., Pansare V. J., Prud'homme R. D., Flash Nanoprecipitation Of Polystyrene Nanoparticles, Soft Matter, 2012.
[12]. Günday, C.; Anand, S.; Gencer, H.B.; Munafò, S.; Moroni, L.; Fusco, A.; Donnarumma, G.; Ricci, C.; Hatir, P.C.; Türeli, N.G. Ciprofloxacin-Loaded Polymeric Nanoparticles Incorporated Electrospun Fibers For Drug Delivery In Tissue Engineering Applications. Drug Deliv. Transl. Res. 2020, 10, 706–720.
[13]. Moncalvo, F.; Martinez Espinoza, M.I.; Cellesi, F. Nanosized Delivery Systems For Therapeutic Proteins: Clinically Validated Technologies And Advanced Development Strategies. Front. Bioeng. Biotechnol. 2020, 8, 89.
[14]. Froiio, F.; Ginot, L.; Paolino, D.; Lebaz, N.; Bentaher, A.; Fessi, H.; Elaissari, A. Essential Oils-Loaded Polymer Particles: Preparation, Characterization And Antimicrobial Property. Polymers 2019, 11, 1017.
[15]. Jawahar, N.; Meyyanathan, S. Polymeric Nanoparticles For Drug Delivery And Targeting: A Comprehensive Review. Int. J. Health Allied Sci. 2012, 1, 217.
[16]. Reis, C.P.; Neufeld, R.J.; Ribeiro, A.J.; Veiga, F.; Nanoencapsulation, I. Methods For Preparation Of Drug-Loaded Polymeric Nanoparticles. Nanomed. Nanotechnol. Biol. Med. 2006, 2, 8–21.
[17]. Bennet, D.; Kim, S. Polymer Nanoparticles For Smart Drug Delivery. In Application Of Nanotechnology In Drug Delivery; Intechopen: London, UK, 2014; Volume 8.
[18]. Silva, A.M.; Alvarado, H.L.; Abrego, G.; Martins-Gomes, C.; Garduno-Ramirez, M.L.; Garcia, M.L.; Calpena, A.C.; Souto, E.B. In Vitro Cytotoxicity Of Oleanolic/Ursolic Acids-Loaded In PLGA Nanoparticles In Different Cell Lines. Pharmaceutics 2019, 11, 362.
[19]. Carbone, C.; Martins-Gomes, C.; Pepe, V.; Silva, A.M.; Musumeci, T.; Puglisi, G.; Furneri, P.M.; Souto, E.B. Repurposing Itraconazole To The Benefit Of Skin Cancer Treatment: A Combined Azole-DDAB Nanoencapsulation Strategy. Colloids Surf. B Biointerfaces 2018, 167, 337–344.
[20]. Doktorovova, S.; Souto, E.B.; Silva, A.M. Nanotoxicology Applied To Solid Lipid Nanoparticles And Nanostructured Lipid Carriers—A Systematic Review Of In Vitro Data. Eur. J. Pharm. Biopharm. 2014, 87, 1–18.
[21]. Bohrey, S.; Chourasiya, V.; Pandey, A. Polymeric Nanoparticles Containing Diazepam: Preparation, Optimization, Characterization, In-Vitro Drug Release And Release Kinetic Study. Nano Converg. 2016, 3, 1–7.
[22]. Andreani, T.; Kiill, C.P.; De Souza, A.L.R.; Fangueiro, J.F.; Doktorovová, S.; Garcia, M.L.; Gramião, M.P.D.; Silva, A.M.; Souto, E.B. Effect Of Cryoprotectants On The Reconstitution Of Silica Nanoparticles Produced By Sol–Gel Technology. J. Therm. Anal. Calorim. 2015, 120, 1001–1007.
[23]. Mathurin, J.; Pancani, E.; Deniset-Besseau, A.; Kjoller, K.; Prater, C.B.; Gref, R.; Dazzi, A. How To Unravel The Chemical Structure And Component Localization Of Individual Drug-Loaded Polymeric Nanoparticles By Using Tapping AFM-IR. Analyst 2018, 143, 5940–5949.
[24]. Hickey, J.W.; Santos, J.L.; Williford, J.-M.; Mao, H.-Q. Control Of Polymeric Nanoparticle Size To Improve Therapeutic Delivery. J. Control. Release 2015, 219, 536–547.
[25]. Brar, S.K.; Verma, M. Measurement Of Nanoparticles By Light-Scattering Techniques. Trac. Trends Anal. Chem. 2011, 30, 4–17.
[26]. Carvalho, P.M.; Felício, M.R.; Santos, N.C.; Gonçalves, S.; Domingues, M.M. Application Of Light Scattering Techniques To Nanoparticle Characterization And Development. Front. Chem. 2018, 6, 237.
[27]. Mourdikoudis, S.; Pallares, R.M.; Thanh, N.T. Characterization Techniques For Nanoparticles: Comparison And Complementarity Upon Studying Nanoparticle Properties. Nanoscale 2018, 10, 12871–12934.
[28]. Lu, M.; Yang, X.; Yang, Y.; Qin, P.; Wu, X.; Cai, Z. Nanomaterials As Assisted Matrix Of Laser Desorption/Ionization Time-Of-Flight Mass Spectrometry For The Analysis Of Small Molecules. Nanomaterials 2017, 7, 87.
[29]. Yang, Y.; Jiang, Y.; Xu, J.; Yu, J. Conducting Polymeric Nanoparticles Synthesized In Reverse Micelles And Their Gas Sensitivity Based On Quartz Crystal Microbalance. Polymer 2007, 48, 4459–4465.
[30]. Dazon, C.; Witschger, O.; Bau, S.; Fierro, V.; Llewellyn, P.L. Nanomaterial Identification Of Powders: Comparing Volume Specific Surface Area, X-Ray Diffraction And Scanning Electron Microscopy Methods. Environ. Sci. Nano 2019, 6, 152–162.
[31]. Zielin´Ska, A.; Ferreira, N.R.; Feliczak-Guzik, A.; Nowak, I.; Souto, E.B. Loading, Release Profile And Accelerated Stability Assessment Of Monoterpenes-Loaded Solid Lipid Nanoparticles (SLN). Pharm. Dev. Technol. 2020, 25, 1–13.
[32]. Doncom, K.E.; Blackman, L.D.; Wright, D.B.; Gibson, M.I.; O'Reilly, R.K. Dispersity Effects In Polymer Self-Assemblies: A Matter Of Hierarchical Control. Chem. Soc. Rev. 2017, 46, 4119–4134.
[33]. Podzimek, S. Light Scattering, Size Exclusion Chromatography And Asymmetric Flow Field Flow Fractionation: Powerful Tools For The Characterization Of Polymers, Proteins And Nanoparticles; John Wiley & Sons: Hoboke, NJ, USA, 2011.
[34]. Stals, P.J.; Gillissen, M.A.; Paffen, T.F.; De Greef, T.F.; Lindner, P.; Meijer, E.; Palmans, A.R.; Voets, I.K. Folding Polymers With Pendant Hydrogen Bonding Motifs In Water: The Effect Of Polymer Length And Concentration On The Shape And Size Of Single-Chain Polymeric Nanoparticles. Macromolecules 2014, 47, 2947–2954.
[35]. Mansfield, E.; Kaiser, D.L.; Fujita, D.; Van De Voorde, M. Metrology And Standardization For Nanotechnology: Protocols And Industrial Innovations; John Wiley & Sons: Hoboke, NJ, USA, 2017.
[36]. Dumitriu, S.; Popa, V. Polymeric Biomaterials: Medicinal And Pharmaceutical Applications; CRC Press: Boca Raton, FL, USA, 2013; Volume 2.
[37]. Baer, D.R.; Engelhard, M.H.; Johnson, G.E.; Laskin, J.; Lai, J.; Mueller, K.; Munusamy, P.; Thevuthasan, S.; Wang, H.; Washton, N. Surface Characterization Of Nanomaterials And Nanoparticles: Important Needs And Challenging Opportunities. J. Vac. Sci. Technol. A Vac. Surf. Film. 2013, 31, 050820.
[38]. Simonet, B.M.; Valcarcel, M. Monitoring Nanoparticles In The Environment. Anal. Bioanal. Chem. 2009, 393, 17–21.

[39]. Honary, S.; Zahir, F. Effect Of Zeta Potential On The Properties Of Nano-Drug Delivery Systems-A Review (Part 1). Trop. J. Pharm. Res. 2013, 12, 255–264.
[40]. Ostolska, I.; Wis´Niewska, M. Application Of The Zeta Potential Measurements To Explanation Of Colloidal Cr 2 O 3 Stability Mechanism In The Presence Of The Ionic Polyamino Acids. Colloid Polym. Sci. 2014, 292, 2453–2464.
[41]. Zielin´Ska, A.; Ferreira, N.R.; Durazzo, A.; Lucarini, M.; Cicero, N.; Mamouni, S.E.; Silva, A.M.; Nowak, I.; Santini, A.; Souto, E.B. Development And Optimization Of Alpha-Pinene-Loaded Solid Lipid Nanoparticles (SLN) Using Experimental Factorial Design And Dispersion Analysis. Molecules 2019, 24, 2683.
[42]. Doktorovova, S.; Santos, D.L.; Costa, I.; Andreani, T.; Souto, E.B.; Silva, A.M. Cationic Solid Lipid Nanoparticles Interfere With The Activity Of Antioxidant Enzymes In Hepatocellular Carcinoma Cells. Int. J. Pharm. 2014, 471, 18–27
[43]. Calvo, P.; Remunan-Lopez, C.; Vila-Jato, J.L.; Alonso, M. Novel Hydrophilic Chitosan-Polyethylene Oxide Nanoparticles As Protein Carriers. J. Appl. Polym. Sci. 1997, 63, 125–132.
[44]. González, A.E. Colloidal Aggregation Coupled With Sedimentation: A Comprehensive Overview. Adv. Colloid Sci. 2016, 211.
[45]. Kamiya, H.; Gotoh, K.; Shimada, M.; Uchikoshi, T.; Otani, Y.; Fuji, M.; Matsusaka, S.; Matsuyama, T.; Tatami, J.; Higashitani, K. Characteristics And Behavior Of Nanoparticles And Its Dispersion Systems. In Nanoparticle Technology Handbook; Elsevier: London, UK, 2008; Pp. 113–176.
[46]. Lazzari, S.; Moscatelli, D.; Codari, F.; Salmona, M.; Morbidelli, M.; Diomede, L. Colloidal Stability Of Polymeric Nanoparticles In Biological Fluids. J. Nanoparticle Res. 2012, 14, 920.
[47]. Heinz, H.; Pramanik, C.; Heinz, O.; Ding, Y.; Mishra, R.K.; Marchon, D.; Flatt, R.J.; Estrela-Lopis, I.; Llop, J.; Moya, S. Nanoparticle Decoration With Surfactants: Molecular Interactions, Assembly, And Applications. Surf. Sci. Rep. 2017, 72, 1–58.
[48]. Abdelwahed, W.; Degobert, G.; Stainmesse, S.; Fessi, H. Freeze-Drying Of Nanoparticles: Formulation, Process And Storage Considerations. Adv. Drug Deliv. Rev. 2006, 58, 1688–1713.
[49]. Ziaee, A.; Albadarin, A.B.; Padrela, L.; Femmer, T.; O'Reilly, E.; Walker, G. Spray Drying Of Pharmaceuticals And Biopharmaceuticals: Critical Parameters And Experimental Process Optimization Approaches. Eur. J. Pharm. Sci. 2019, 127, 300–318.
[50]. Wanning, S.; Sueverkruep, R.; Lamprecht, A. Pharmaceutical Spray Freeze Drying. Int. J. Pharm. 2015, 488, 136–153.
[51]. De Jong, W.H.; Borm, P.J. Drug Delivery And Nanoparticles: Applications And Hazards. Int. J. Nanomed. 2008, 3, 133.
[52]. Wallace, S.J.; Li, J.; Nation, R.L.; Boyd, B.J. Drug Release From Nanomedicines: Selection Of Appropriate Encapsulation And Release Methodology. Drug Deliv. Transl. Res. 2012, 2, 284–292.
[53]. Bohnert, T.; Gan, L.-S. Plasma Protein Binding: From Discovery To Development. J. Pharm. Sci. 2013, 102, 2953–2994.
[54]. Patra, J.K.; Das, G.; Fraceto, L.F.; Campos, E.V.R.; Del Pilar Rodriguez-Torres, M.; Acosta-Torres, L.S.; Diaz-Torres, L.A.; Grillo, R.; Swamy, M.K.; Sharma, S. Nano Based Drug Delivery Systems: Recent Developments And Future Prospects. J. Nanobiotechnol. 2018, 16, 71.
[55]. Khan, I.; Saeed, K.; Khan, I. Nanoparticles: Properties, Applications And Toxicities. Arab. J. Chem. 2019, 12, 908–931.
[56]. Grumezescu, A.M. Nano-And Microscale Drug Delivery Systems: Design And Fabrication; William Andrew: Norwich, NY, USA, 2017.
[57]. Shen, J.; Burgess, D.J. In Vitro Dissolution Testing Strategies For Nanoparticulate Drug Delivery Systems: Recent Developments And Challenges. Drug Deliv. Transl. Res. 2013, 3, 409–415.
[58]. Lee, J.H.; Yeo, Y. Controlled Drug Release From Pharmaceutical Nanocarriers. Chem. Eng. Sci. 2015, 125, 75–84.
[59]. Fu, Y.; Kao, W.J. Drug Release Kinetics And Transport Mechanisms Of Non-Degradable And Degradable Polymeric Delivery Systems. Expert Opin. Drug Deliv. 2010, 7, 429–444.