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Non-Spherical Polymeric Nanoparticles: Synthesis and Applications

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ABSTRACT

Non-spherical polymeric nanoparticles have emerged as a promising functional materials due to their distinctive physicochemical properties and enhanced performance in various applications. Advances in synthesis techniques now allow precise control over particle morphology, enabling the production of polymeric nanoparticles in various morphologies such as rods, discs, and ellipsoids. This review aims to provide a comprehensive overview of synthesis techniques for producing non-spherical polymeric nanoparticles, highlighting their potential advantages over spherical particles. Key findings include the impact of morphology on drug delivery, food packaging, and agricultural efficiency, with non-spherical structure showing improved performance in targeted delivery, uptake, and interaction with biological and environmental systems. Through comparative analysis, this review provide insight into the selection of suitable synthesis methods for specific applications, laying a foundation for further research and industrial applications.

Keywords: polymer, nanoparticles, non-spherical, morphology, nanocarriers

1. INTRODUCTION

In the past fes decades, polymeric nanoparticles have gained great attention, due to their potential uses in wide range of applications, including food, catalysis, cosmetic, and biomedical[1-3]. It is define as particulate dispersion or solid particles with size in the range of 10-1000 nm [4]. Polymeric nanoparticles have unique properties which can meet various applications and industrial needs. The properties of polymeric nanoparticles can be modified depending on the particular application.

Based on previous studies, nanoparticles morphology has significant effect in the applications' effectiveness and overall success. It has been reported that differences biological behaviours were observed between spherical and non-spherical nanoparticles on *in vivo* studies [5]. Non-spherical polymeric nanoparticles can be found in the form of rods, worm-like micelles, vesicles, and large compound micelles (Fig. 1)[6].

Drug loading capacities, biodistribution and cellular uptake in drug delivery application were affecting by morphology and the size of polymeric nanoparticles [7]. Therefore, the synthesis process of polymeric nanoparticles to obtain specific morphology for particular applications has become an important aspect in nanotechnology research area.

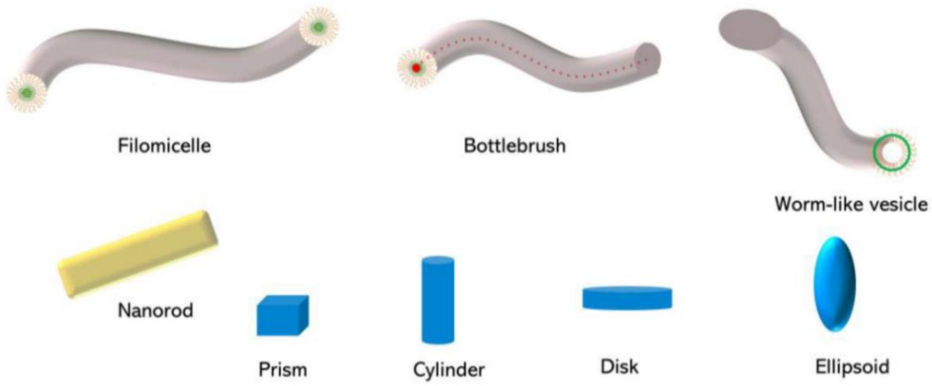

Figure 1. Non-spherical polymeric nanoparticles in various morphologies [6]

Synthesis of non-spherical polymeric nanoparticles can be conducted by direct polymerization of monomers or modification of preformed polymers. Emulsion polymerization, dispersion polymerization, mini-emulsion polymerization, and micro-emulsion polymerization have been used to synthesis polymeric nanoparticles. Preformed polymers mostly modified into nanoparticles via solvent evaporation, dialysis, salting-out, and supercritical fluid technology. Another approach to prepare nanoparticles of various morphology is self-assembly of amphiphilic block copolymers. Each technique still try to resolve the challenge for nanoparticles assembly in order to obtain various morphologies, including to achieve narrow size distribution, which will determine the effectiveness and advantages during usage.

2. SYNTHESIS OF NON-SPHERICAL POLYMERIC NANOPARTICLES

2.1 Synthesis of nanoparticles via direct polymerization

2.1.1 Emulsion polymerization

Emulsion polymerization has been widely used to synthesis polymeric nanoparticles due to its ability to produce stable colloidal dispersions with controlled particle sizes, typically in the range of 50 to 500 nm [8]. This method involves the polymerization of monomers dispersed in an aqueous phase, stabilized by surfactants or emulsifiers, under the influence of an initiator (Fig. 2). The process begins by emulsifying hydrophobic monomers such as styrene or methyl methacrylate in water with the help of surfactants to form micelles. Water-soluble initiators, such as potassium persulfate (KPS), then generate free radicals in the aqueous phase, initiating polymerization within the micelles where the monomer concentration is highest.

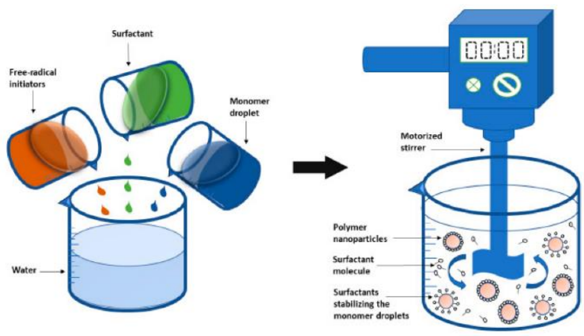

Figure 2. Schematic representation of the emulsion polymerization technique [9].

As the polymerization progresses, monomer molecules from the larger monomer droplets continuously diffuse into the growing polymer particles within the micelles [8]. This micellar nucleation mechanism leads to the formation of uniform and stable polymer nanoparticles. The size and stability of the resulting nanoparticles can be finely tuned by adjusting the surfactant concentration, the type of initiator, the monomer-to-water ratio, and the reaction temperature. Emulsion polymerization offers high polymerization rates and yields due to the compartmentalization effect, where each micelle acts as a nanoreactor, limiting termination reactions and enhancing monomer conversion.

To achieve non-spherical shapes, several strategies have been developed that alter the thermodynamic and kinetic pathways of particle formation [10]. One common approach is the incorporation of crosslinkers at controlled concentrations and specific stages during polymerization, which can restrict the mobility of the growing polymer chains and lock the particles into asymmetric shapes [11]. Additionally, employing phase separation within droplets—by using monomer mixtures with different solubility or reactivity—can lead to various morphologies such as rods, ellipsoids, or vesicles morphologies. This is often facilitated by surfactants and co-solvents that stabilize intermediate forms.

Another method involves the use of external stimuli, such as shear forces, electric fields, or temperature gradients, which can influence the orientation of polymer chains and phase boundaries during polymerization [12]. Template-assisted emulsion polymerization is also becoming interesting to apply, where pre-formed non-spherical templates or nano-confinement within a particular shape guide the morphology of the resulting particles [13]. Furthermore, post-polymerization deformation, where spherical nanoparticles are swollen and then deformed under heat or mechanical force before being "frozen" into shape by crosslinking, allows for precise morphological control.

2.1.2 Dispersion polymerization

Dispersion polymerization is a versatile technique for synthesizing polymeric nanoparticles, particularly within the size range of 50–1000 nm [14]. In this process, monomers are initially soluble in a continuous phase, usually an organic solvent or water, while the resulting polymer becomes insoluble and precipitates out as the polymerization proceeds. Stabilizers, often steric stabilizers such as polyvinylpyrrolidone (PVP) or graft copolymers, are essential in this system to prevent aggregation of the growing polymer particles, leading to well-dispersed colloidal particles. For instance, the schematic of preparation polymeric nanoparticles via dispersion polymerization have shown in Figure 3.

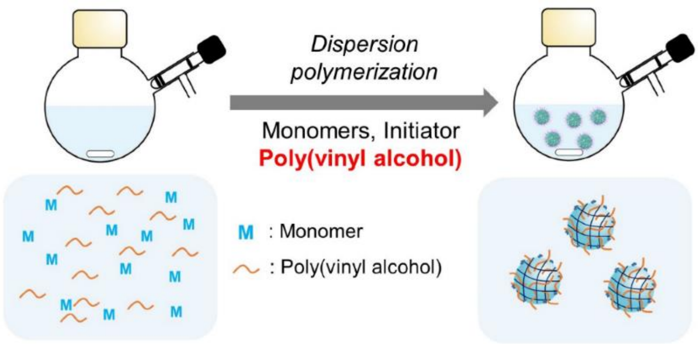

Figure 3. Schematic of synthesis of polymeric nanoparticles via dispersion polymerization [15].

Non-spherical morphology can be obtained by modified process variables such as monomer type, solvent polarity, initiator concentration, polymerization kinetics, and the design of stabilizers or surfactants [16]. For example, incorporating functional comonomers that introduce anisotropic interactions, or selectively controlling the rate of polymer growth in different directions, can drive the formation of rods, ellipsoids, or dumbbell-shaped nanoparticles.

Additionally, post-polymerization modifications or templating methods can be employed to tailor the shape of nanoparticles. For instance, seeded dispersion polymerization using non-spherical seed nanoparticles, or employing reactive surfactants that favor certain morphologies, has been shown to produce non-spherical structures [17]. Temperature and solvent quality also play critical roles; a poor solvent environment for the forming polymer can induce directional aggregation and non-spherical growth. Recent advances also utilize block copolymer self-assembly and in-situ crosslinking strategies to maintain anisotropic shapes during and after polymerization.

2.1.3 Mini-emulsion polymerization

Unlike conventional emulsion polymerization, miniemulsion systems are stabilized kinetically through the use of surfactants and costabilizers, enabling the formation of nanodroplets that serve as individual reaction sites [18]. These nanodroplets, typically ranging from 50 to 500 nm in diameter, are formed by high-shear techniques such as ultrasonication or high-pressure homogenization. The presence of a hydrophobe compound helps to suppress Ostwald ripening, preserving the initial droplet size and ensuring the formation of uniform nanoparticles [19]. The schematic process of miniemulsion polymerization has shown in Figure 4 below.

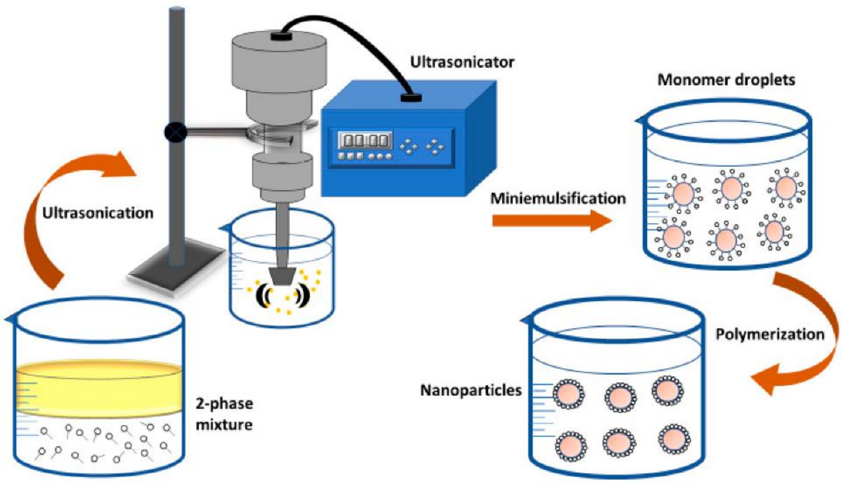

Figure 4. Schematic representation of miniemulsion polymerization [9].

The synthesis of non-spherical polymeric nanoparticles via miniemulsion polymerization often involves the adjustment of reaction parameters, monomer types, and the introduction of non-spherical-inducing agents [16]. For example, the use of crosslinking monomers or polymerization under constrained conditions can lead to morphological variations from the typical spherical shape. Furthermore, the incorporation of rigid comonomers—such as liquid crystalline or block copolymer components—can promote phase separation or directional growth, resulting in rod-like, disk-shaped, or ellipsoidal particles.

Another strategy to achieve non-spherical shapes is to perform polymerization in the presence of deformable templates or to induce internal phase separation during polymerization. By adjusting the compatibility between different monomers or adding solvents that partly soluble in certain polymer bond, it is possible to create Janus, or other non-spherical structures [20]. The surfactant concentration and type also play a critical role; surfactants can influence the interfacial tension and rigidity of the droplet boundary, subtly directing the shape evolution of growing polymer particles.

2.1.4 Micro-emulsion polymerization

The formation of non-spherical polymeric nanoparticles via microemulsion polymerization typically relies on the varied of several key parameters, including the surfactant type and concentration, the monomer composition, the aqueous-to-oil phase ratio, and the polymerization conditions (such as temperature and initiator type). The shape of the resulting nanoparticles mostly facilitated by the use of block copolymer surfactants or templating agents that direct the assembly of monomer units into specific morphologies before or during polymerization [21].

Furthermore, the use of crosslinkers and functional co-monomers can further promote shape control by introducing rigidity or phase separation within the growing particle. For example, the incorporation of a rigid comonomer or selective crosslinking along a particular axis can lead to the elongation or flattening of particles, resulting in non-spherical geometries. Similarly, polymerization within asymmetric microdomains of the microemulsion—such as rod-shaped or lamellar micelles—can directly template the formation of elongated or flattened particles. The schematic diagram of microemulsion polymerization is given below (Fig. 5).

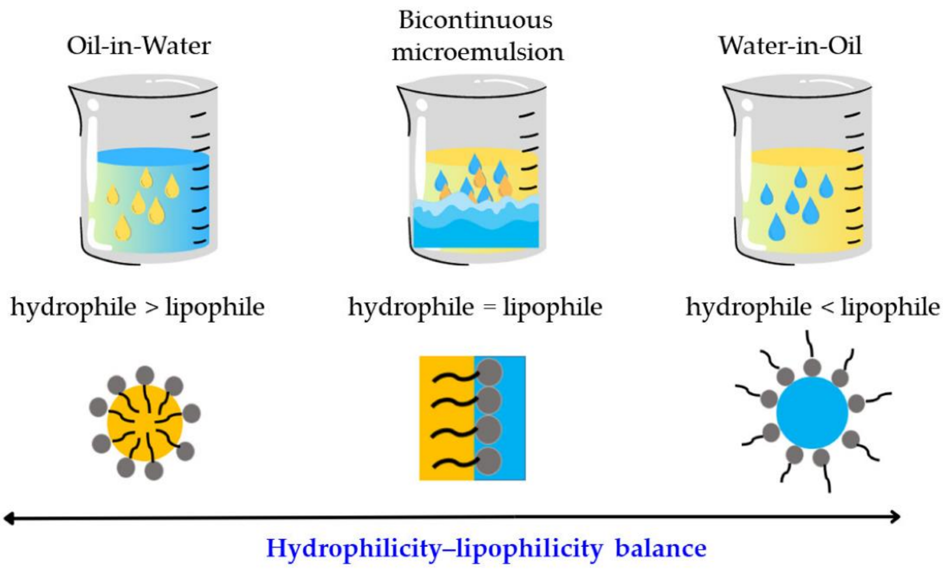

Figure 5. Schematic diagram of microemulsion polymerization in different configuration [22].

2.2 Synthesis of nanoparticles from preformed polymer

2.2.1 Solvent evaporation

The solvent evaporation technique is a widely adopted method for the preparation of polymeric nanoparticles, especially when targeting controlled drug delivery applications. In the conventional solvent evaporation approach, a hydrophobic polymer is first dissolved in a volatile organic solvent such as dichloromethane (DCM) or ethyl acetate [23]. This polymer solution may also include a therapeutic agent or functional additive. The organic phase is then emulsified into an aqueous phase containing a surfactant or stabilizer, such as polyvinyl alcohol (PVA), under high-shear conditions to form an oil-in-water (O/W) emulsion. Upon evaporation of the organic solvent, typically under reduced pressure or continuous stirring, the polymer precipitates to form solid nanoparticles (Fig. 6).

To obtain non-spherical nanoparticles, researchers often introduce specific shape-directing factors during the emulsification or solvent evaporation stages [16]. One approach involves modulating the interfacial tension between the organic and aqueous phases by tuning the surfactant concentration or using block copolymers with shape-inducing properties [24]. Another strategy includes mechanical or microfluidic deformation, where the emulsion droplets are stretched or flowed through constrictive geometries, causing them to harden into rod-like, ellipsoidal, or disk-shaped particles as the solvent evaporates [25]. The viscosity of the polymer solution, solvent evaporation rate, and polymer molecular weight also significantly influence the final particle morphology.

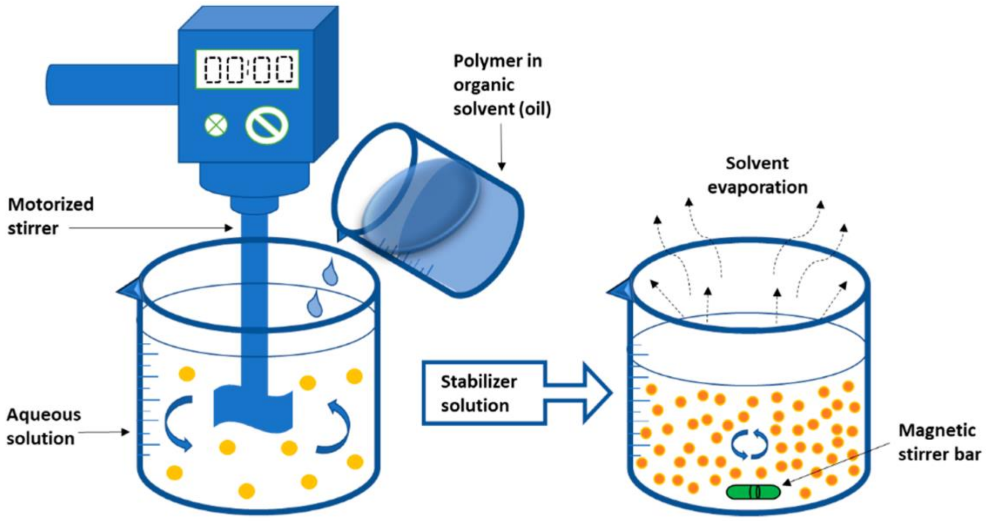

Figure 6. Schematic process of solvent evaporation method [9].

Nanoprecipitation coupled with rapid solvent removal can trap polymers in metastable shapes before they collapse into spheres, especially when polymer chains have limited mobility due to high glass transition temperatures or rapid solidification. Such kinetically frozen structures can be stabilized further by chemical crosslinking or by designing polymers with self-assembly behavior.

2.2.2 Dialysis

Dialysis is a method that leverages the differential permeability of semi-permeable membranes to remove small molecules, such as solvents, surfactants, or unreacted monomers, from a polymeric solution. In the context of preparing non-spherical polymeric nanoparticles, dialysis serves a dual role: it not only purifies the nanoparticle dispersion but can also drive the self-assembly or structural rearrangement of polymer chains into non-spherical morphologies [26].

The preparation typically begins with the dissolution of amphiphilic block copolymers or specially designed polymers in a good solvent, often an organic solvent such as dimethylformamide (DMF) or tetrahydrofuran (THF) [26]. These solvents enable the polymers to remain molecularly dispersed. The polymer solution is then placed into a dialysis bag and immersed in a non-solvent, typically water, which acts as a selective anti-solvent (Fig. 7). As dialysis progresses, the organic solvent diffuses out of the bag while water diffuses in, slowly altering the solvent polarity around the polymer molecules. This gradual solvent exchange induces self-assembly of the polymer into nanoparticles.

To direct the formation of non-spherical morphologies—such as rods, worms, or vesicles—several factors can be tuned. These include the polymer composition (e.g., the ratio of hydrophilic to hydrophobic blocks), the rate of solvent exchange, polymer concentration, and temperature. For instance, block copolymers with a longer hydrophobic segment often promote the formation of elongated structures. Moreover, slow solvent exchange during dialysis favors the thermodynamically preferred morphology, which may differ from the kinetically trapped spherical form seen in rapid mixing methods.

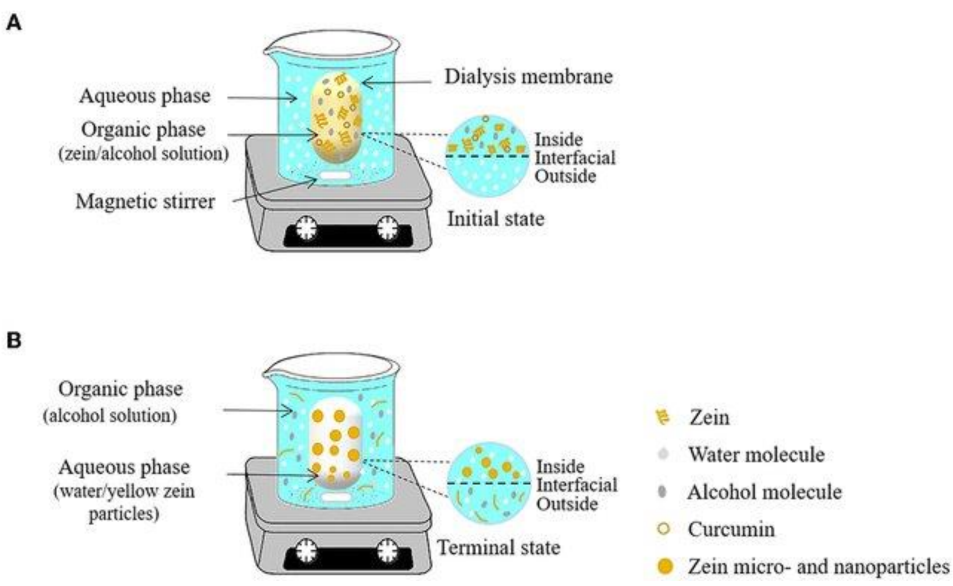

Figure 7. Schematic process of dialysis method to form zein micro-and nanoparticles [27].

One of the key advantages of dialysis over other nanoparticle formation techniques, such as nanoprecipitation, is the high degree of control it offers over nanoparticle morphology and internal structure [26]. This control makes it especially useful for preparing non-spherical polymeric nanoparticles intended for drug delivery, imaging, or nanoreactor applications, where shape can significantly influence biodistribution, cellular uptake, and functionality.

2.2.3 Salting-out

Salting-out method provides a useful approach due to its relatively mild processing conditions, scalability, and ability to tune particle shape by manipulating formulation and process parameters. In this method, a water-miscible organic solvent—commonly acetone or ethanol—dissolves the desired polymer, such as poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), or polylactic acid (PLA) [28]. This organic phase is then emulsified into an aqueous phase containing a high concentration of an inorganic salt, such as magnesium chloride or sodium chloride, under controlled stirring or homogenization. The presence of salt reduces the miscibility of the organic solvent with water and forces phase separation. Upon dilution with additional water (or through dialysis), the organic solvent diffuses into the aqueous phase, and the polymer precipitates to form nanoparticles. The schematic diagram of salting out method to obtain nanoparticles is presented in Figure 8.

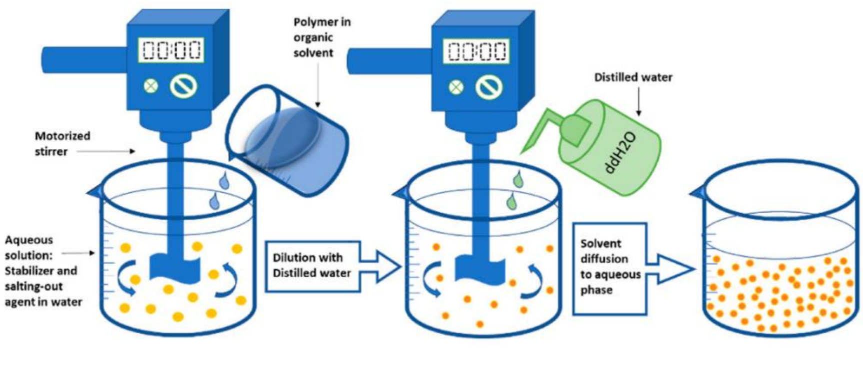

Figure 8. Schematic diagram of salting out method [9].

To generate non-spherical nanoparticles—such as rods, discs, or ellipsoids—the method must be precisely tuned. These include adjusting the polymer concentration, the type and concentration of salts, the solvent-to-nonsolvent ratio, and the shear rate during emulsification [29]. For instance, high shear forces during the emulsification step may elongate the polymer droplets before solidification, leading to anisotropic shapes. Moreover, using block copolymers or incorporating surfactants with anisotropic interaction properties can also drive the formation of non-spherical particles by modulating the interfacial energy [30].

2.2.4 Supercritical fluid technology

Supercritical fluid (SCF) technology has emerged as a promising and green method for the preparation of polymeric nanoparticles, especially when targeting non-spherical morphologies. Unlike traditional techniques that often require high amounts of organic solvents or harsh processing conditions, SCF methods—particularly those involving supercritical carbon dioxide (scCO_2)—offer a more environmentally friendly alternative due to the tunable properties of the supercritical phase. By adjusting parameters such as temperature, pressure, and flow rates, it is possible to control particle nucleation and growth dynamics, enabling the production of nanoparticles with tailored sizes and shapes [31]. The schematic process of supercritical fluid technology to prepare nanoparticle is shown in Figure 9.

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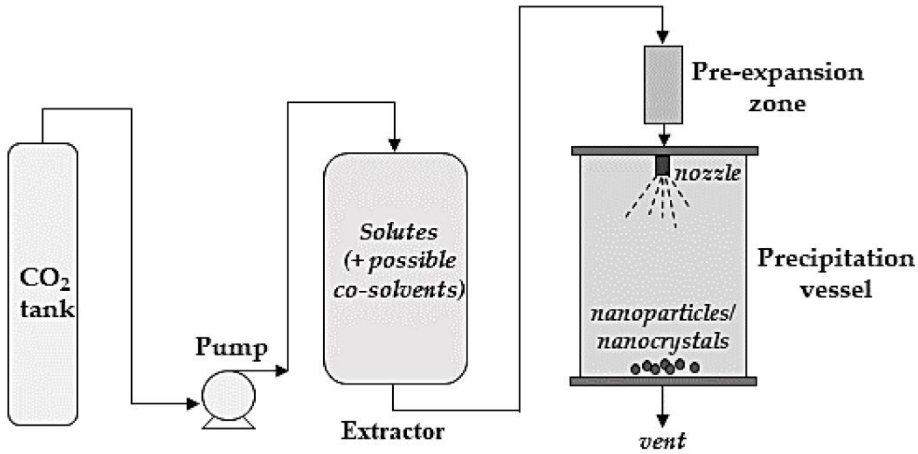

Figure 9. Schematic process of nanoparticle synthesis in the presence of supercritical fluid [32].

One of the key advantages of using supercritical fluids lies in their unique combination of gas-like diffusivity and liquid-like solvating power. This allows for efficient penetration into polymer matrices and rapid precipitation upon expansion or depressurization. Non-spherical nanoparticles, such as rods, discs, or ellipsoids, can be engineered through SCF technology by manipulating factors such as polymer type, concentration, nozzle geometry, and the rate of depressurization [33]. The asymmetric growth of polymer chains during rapid phase changes is often responsible for the formation of non-spherical geometry. Such shapes are increasingly desirable for biomedical applications—particularly in drug delivery—where non-spherical particles can demonstrate improved cellular uptake, prolonged circulation times, and enhanced targeting efficiency due to their unique hydrodynamic and surface interaction properties.

Furthermore, SCF-based synthesis allows for the encapsulation of sensitive bioactives—such as proteins, nucleic acids, or small-molecule drugs—under mild conditions, preserving their structural integrity and bioactivity [34]. This is particularly beneficial when creating complex nanocarriers where shape and function are tightly linked. As research advances, the integration of SCF technology with templating methods or flow-assisted fabrication is anticipated to further enhance the precision and scalability of non-spherical polymeric nanoparticle production, positioning it as a key player in next-generation nanomedicine and advanced materials science.

2.2.5 Self-assembly block copolymers

Block copolymers consist of two or more chemically distinct polymer blocks covalently bonded together. Due to their amphiphilic nature, these copolymers spontaneously organize into a variety of nanostructures in selective solvents, driven by the minimization of interfacial energy between incompatible segments and the surrounding medium [35]. This self-assembly process can be precisely tuned to generate nanoparticles with controlled sizes, shapes, and internal morphologies.

To obtain non-spherical polymeric nanoparticles—such as rods, worms, vesicles, or disks—various factors must be considered during the self-assembly process. These include the relative block lengths (i.e., the volume fraction of each segment), the choice of solvent, the concentration of the copolymer, and the method of self-assembly (e.g., solvent-switch, film rehydration, or nanoprecipitation) [36]. For instance, increasing the volume fraction of the hydrophobic block or manipulating the packing parameter can drive the formation of elongated or flattened morphologies instead of traditional spherical micelles. Solvent polarity and evaporation rate also significantly affect the kinetics and thermodynamics of micelle formation, further influencing particle shape. The example process of self-assembly method to form nanoparticles is shown in Figure 10.

Advanced techniques such as solvent-switch self-assembly and polymerization-induced self-assembly (PISA) have expanded the toolbox for producing non-spherical nanoparticles [38]. In solvent-switch methods, the block copolymer is first dissolved in a good solvent for both blocks, followed by the gradual addition of a selective solvent to trigger micellization. This gradual transition allows finer control over morphology. In PISA, polymerization of the core-forming block occurs in situ, often under aqueous conditions, leading to the formation of anisotropic particles at high solid content and under scalable conditions. By fine-tuning the polymerization kinetics and composition, a wide array of non-spherical nanostructures can be efficiently accessed.

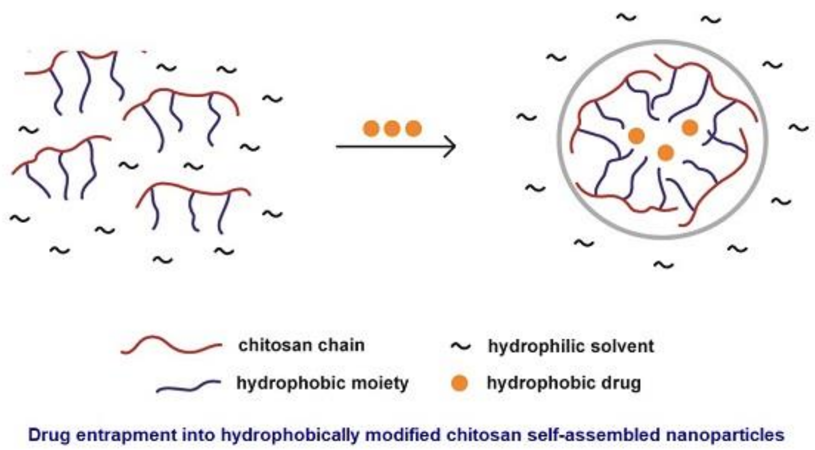

Figure 10. Self-assembly process of synthesis of chitosan nanoparticles for drug delivery application[37].

A comparison of the synthesis techniques for non-spherical polymeric nanoparticles is presented in Table 1. This comparison highlights the advantages and disadvantages of each method in terms of complexity, scalability, morphology control, and suitability for various applications.

Table 1. Comparison of Different Synthesis Methods for Non-Spherical Polymeric Nanoparticles

Method	Advantages	Limitations
Emulsion Polymerization	High yield, narrow size distribution, scalable production	Requires surfactants, sensitive to formulation and temperature changes
Dispersion Polymerization	Good control over particle size and shape, flexible solvent use	Requires suitable stabilizers, sensitive to solvent quality
Mini-emulsion Polymerization	Enables fine control of shape, effective encapsulation	High shear required, complex formulation
Micro-emulsion Polymerization	Excellent control over morphology, narrow particle distribution	High surfactant concentration, limited scalability
Solvent Evaporation	Simple and widely used, compatible with drug loading	Involves organic solvents, limited shape control without extra steps
Dialysis	Precise morphology control, mild conditions	Time-consuming, not easily scalable
Salting-out	Cost-effective, suitable for drug delivery systems	Difficult to control shape without additives
Supercritical Fluid	Green technology, effective encapsulation of sensitive compounds	Requires specialized equipment and high-pressure operations
Block Copolymer Self-Assembly	High tunability of shape and functionality	Complex synthesis, sensitive to block ratio and solvent polarity

3. NON-SPHERICAL POLYMERIC NANOPARTICLES APPLICATIONS

3.1 Food processing and packaging technology

Non-spherical polymeric nanoparticles (NPs) are gaining increasing attention in the food industry due to their unique structural characteristics, which offer advantages over traditional spherical nanoparticles. These anisotropic shapes—such as rods, ellipsoids, discs, and fibers—enable enhanced interactions with biological surfaces and improved stability in complex food matrices. Their shape-dependent behavior influences not only their physical properties, such as diffusion and aggregation, but also their functionality in food processing and packaging applications [39].

In food packaging, non-spherical polymeric NPs can be engineered to create films with superior mechanical strength, barrier properties, and active functionalities like antimicrobial or antioxidant activity [40]. For example, rod-shaped polymeric NPs can align within polymer matrices to form percolation networks that enhance gas barrier performance and reduce oxygen permeability. These characteristics are vital for extending shelf life and maintaining the nutritional quality of packaged foods. Additionally, anisotropic NPs can be loaded with active compounds—such as essential oils, vitamins, or preservatives—and incorporated into packaging materials for controlled release, providing active protection during storage. For instance, cellulose nanoparticles (in form of cellulose nanocrystals and cellulose nanofbers) have been employed to encapsulate essential oil, enhancing its antimicrobial effectiveness in active food packaging [41].

Non-spherical nanoparticles offer novel solutions for delivery systems in food processing application [40]. Their non-spherical geometry can improve mucosal adhesion and penetration in the gastrointestinal tract, making them ideal for oral delivery of bioactives. Rod-like or worm-like NPs, for instance, have shown prolonged residence time and slower release rates, which can be leveraged for encapsulating flavors, enzymes, or probiotics. The ability to control the shape of polymeric NPs also allows for precise tuning of their interaction with food components, enhancing their compatibility and performance in complex formulations.

3.2 Drug delivery and medical applications

Non-spherical PNPs offer improved cellular internalization and prolonged retention within specific tissues as drug carrier [42]. For example, rod-shaped nanoparticles exhibit enhanced margination toward blood vessel walls and demonstrate superior accumulation in tumor tissues compared to their spherical equivalents [5]. Paclitaxel-loaded rod-shaped PLGA nanoparticles have shown improved accumulation in tumor tissues and enhanced anticancer activity [43]. Similarly, worm-like micelles based on PEG-b-PCL copolymers have demonstrated superior blood circulation time for doxorubicin delivery [44]. This makes them suitable carriers for anticancer drugs, allowing for higher therapeutic efficacy with reduced systemic toxicity. Additionally, their elongated structure provides a larger surface area for drug loading and functionalization with targeting ligands, further improving site-specific delivery [45].

Diagnostics also benefit from the anisotropic properties of non-spherical PNPs. Their shape influences how they scatter or absorb light and how they respond to external stimuli, which is advantageous in imaging techniques such as optical coherence tomography, photoacoustic imaging, and magnetic resonance imaging [16]. By engineering the shape and composition of these nanoparticles, researchers can fine-tune their contrast properties to achieve more sensitive and accurate detection of diseases.

In tissue engineering, non-spherical polymeric nanoparticles are used to mimic the fibrous architecture of natural extracellular matrices [46]. Their elongated shapes can influence cell behavior, promoting cell adhesion, alignment, and differentiation—essential factors in tissue regeneration. Furthermore, they can be embedded in scaffolds to deliver bioactive molecules in a controlled and sustained manner, enhancing the regeneration process.

3.3 Agricultural applications

The controlled morphology of non-spherical polymeric nanoparticles can be tailored to optimize interactions with specific plant components. For example, rod-like particles may align more effectively with elongated plant cells, enhancing penetration and systemic movement [47]. Moreover, the increased surface area-to-volume ratio of non-spherical shapes can facilitate higher loading capacities for pesticides, fertilizers, or genetic materials [48]. This allows for sustained and controlled release profiles, reducing the frequency of application and minimizing environmental runoff or non-target exposure.

In the context of crop protection and growth enhancement, these advanced carriers can be engineered to respond to environmental stimuli—such as pH, temperature, or enzymatic activity—within plant tissues. This responsiveness allows for on-demand release of active ingredients, further improving the precision and efficacy of treatment [49]. Additionally, non-spherical polymeric nanoparticles can be functionalized with ligands or peptides to target specific plant pathogens or tissues, enhancing selectivity and reducing adverse effects on beneficial microorganisms or surrounding ecosystems. A practical example includes the use of polycaprolactone (PCL)-based ellipsoidal nanoparticles for entrapping essential oils from Zanthoxylum rhoifolium (Rutaceae) as pesticide [50].

The adoption of non-spherical polymeric nanoparticles in agriculture holds great promise, yet it also requires a deeper understanding of their interactions with complex plant systems. Ongoing research is focused on optimizing synthesis methods, evaluating biocompatibility, and assessing long-term environmental impacts. As these technologies mature, they are expected to contribute significantly to sustainable agriculture by improving crop yield, reducing agrochemical use, and promoting eco-friendly farming practices.

4. CONCLUSION

This review aimed to examine recent advancements in the synthesis and application of non-spherical polymeric nanoparticles. Through analysis of multiple synthesis strategies, we highlighted how morphology control enhances nanoparticle performance across domains. Key findings underscore that rod-shaped, worm-like, and ellipsoidal nanoparticles often demonstrate superior drug delivery efficiency, prolonged circulation, and targeted interactions. In food systems, non-spherical NPs contribute to improved mechanical and barrier properties, while in agriculture, they support sustainable delivery of active agents. By comparing the strengths and limitations of synthesis approaches and offering real-world application examples, this review provides a foundational guide for researchers and industry stakeholders aiming to tailor nanoparticle morphology for specific performance outcomes.

As research progresses, non-spherical polymeric nanoparticles are expected to play an increasingly critical role in developing efficient, sustainable, and multifunctional systems for both industrial and biomedical applications.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the author(s).

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Sri Agustina: Conceptualization, Supervision, Writing – Original Draft. **Hadi Wahyudi**: Resources, Writing – Review & Editing. **Marta Pramudita**: Literature review, Writing – Review & Editing **Alia Badra Pitaloka**: Literature review, Writing – Review & Editing.

REFERENCES

[1] C. Adhikari, "Polymer nanoparticles-preparations, applications and future insights: A concise review," *Polymer-Plastics Tecnol. and Mat*., vol. 60, no. 18, pp. 1996-2024, 2021, https://doi.org/10.1080/25740881.2021.1939715

[2] A. Wasilewska, M. Bielicka, U. Klekotka, B. Kalska-Szostko, "Nanoparticle applications in food–a review," *Food Funct*., vol. 14, no. 6, pp. 2544-2567, 2023, doi: 10.1039/d2fo02180c

[3] D. Nunes, S. Andrade, M. J. Ramalho, J. A. Loureiro, and M. C. Pereira, "Polymeric nanoparticles-loaded hydrogels for biomedical applications: A systematic review on in vivo findings," *Polymers*, vol. 14, no. 5, p. 1010, 2022, https://doi.org/10.3390/polym14051010

[4] P. Patel, N. Vyas, M. Raval, "Safety and toxicity issues of polymeric nanoparticles: A serious concern," *Nanotech. in Medicine: Toxicity and Safety*, pp. 156-173, 2021.

[5] P. Lagarrigue, F. Moncalvo, and F.Cellesi, "Non-spherical polymeric nanocarriers for therapeutics: the effect of shape on biological systems and drug delivery properties," *Pharmaceutics*, vol. 15, no. 1, p. 32, 2022, https://doi.org/10.3390/pharmaceutics15010032

[6] P. Lagarrigue, F. Moncalvo, and F. Cellesi, "Non-spherical Polymeric Nanocarriers for Therapeutics: The Effect of Shape on Biological Systems and Drug Delivery Properties," *Pharmaceutics*, vol. 15, no. 1, p. 32, 2023, https://doi.org/ 10.3390/pharmaceutics15010032

[7] W. Zhang et al., "Effects of morphology and size of nanoscale drug carriers on cellular uptake and internalization process: a review," *RSDC Adv.*, vol. 13, no. 1, pp. 80-114, 2023.

[8] S. Sahoo et al., "Preparation of polymeric nanomaterials using emulsion polymerization," *Adv. in Mat. Sci. and Eng*., vol. 2021, no. 1, p. 1539230, 2021.

[9] T. Pulingam, P. Foroozandeh, J.-A. Chuah, and K. Sudesh, "Exploring Various Techniques for the Chemical and Biological Synthesis of Polymeric Nanoparticles," *Nanomaterials*, vol. 12, no. 3, p. 576, 2022. https://doi.org/10.3390/nano12030576

[10] J. Zhang et al., "Polymeric non-spherical coarse microparticles fabricated by double emulsion-solvent evaporation for simvastatin delivery," *Colloids and Surfaces B: Biointerfaces*, vol. 199, p. 111560, 2021.

[11] C. J. Marsden et al., "Crosslinked p (MMA) particles by RAFT emulsion polymerisation: tuning size and stability," *Polymer Chem.*, vol. 13, no. 28, pp. 4124-4135, 2022.

[12] A. M. Doerr, J. M. Burroughs, S. R. Gitter, X. Yang, A. J. Boydston, and B. K. Long, "Advances in polymerizations modulated by external stimuli," *ACS Catalysis*, vol. 10, no. 24, pp. 14457-14515, 2020.

[13] M. Pérez-Page et al., "Template-based syntheses for shape controlled nanostructures," *Adv. in Colloid and Interface Sci.*,vol. 234, pp. 51-79, 2016.

[14] R. J. C. Arshady, "Suspension, emulsion, and dispersion polymerization: A methodological survey," *Colloid and Polymer Sci.*, vol. 270, pp. 717-732, 1992.

[15] Y. Kitayama, S. Takigawa, and A. Harada, "Effect of Poly(Vinyl Alcohol) Concentration and Chain Length on Polymer Nanogel Formation in Aqueous Dispersion Polymerization," *Molecules*, vol. 28, no. 8, p.

3493, 2023, https://doi.org/ 10.3390/molecules28083493

[16] A. Patil, S. Dyawanapelly, P. Dandekar, and R. Jain, "Fabrication and characterization of non-spherical polymeric particles," *J. of Phar. Innovation*, vol. 16, pp. 747-758, 2021.

[17] N. Sudjaipraparat, C. Kaewsaneha, S. Nuasaen, and P. Tangboriboonrat, "One-pot synthesis of non-spherical hollow latex polymeric particles via seeded emulsion polymerization," *Polymer*, vol. 121, pp. 165-172, 2017. https://doi.org/10.1016/j.polymer.2017.06.024

[18] F. J. Schork, Y. Luo, W. Smulders, J. P. Russum, A. Butté, and K. Fontenot, "Miniemulsion polymerization," *Polymer Particles*, pp. 129-255, 2005.

[19] M. Y. Koroleva and E. V. Yurtov, "Ostwald ripening in macro-and nanoemulsions," *Russian Chem. Reviews,* vol. 90, no. 3, p. 293, 2021, **DOI** 10.1070/RCR4962.

[20] L. Koch, S. Botsch, C. Stubenrauch, "Emulsion templating: Unexpected morphology of monodisperse macroporous polymers," *J. of Colloid and Interface Sci.* vol. 582, pp. 834-841, 2021, https://doi.org/10.1016 /j.jcis. 2020. 08.106

[21] F. M. Pavel, "Microemulsion polymerization," *J. of Dispersion Sci. and Tech.,* vol. 25, no. 1, pp. 1-16, 2004, https://doi.org/10.1081/DIS-120027662

[22] Z. Ait-Touchente et al., "Exploring the Versatility of Microemulsions in Cutaneous Drug Delivery: Opportunities and Challenges," *Nanomaterials*, vol. 13, no. 10, p. 1688, 2023.

[23] S. A. Chaudhary, D. M. Patel, J. K. Patel, and D. H. Patel, "Solvent emulsification evaporation and solvent emulsification diffusion techniques for nanoparticles," in Emerging technologies for nanoparticle manufacturing: *Springer Cham*., 2021, pp. 287-300.

[24] N. R. Visaveliya and J. M. Köhler, "Emerging structural and interfacial features of particulate polymers at the nanoscale," *Langmuir*, vol. 36, no. 44, pp. 13125-13143, 2020.

[25] S. Guha, and A. B. Jindal, "An insight into obtaining of non-spherical particles by mechanical stretching of micro-and nanospheres," *J. of Drug Delivery Sci and Technol.* vol. 59, p. 101860, 2020, https://doi.org/10.1016/j.jddst.2020.101860

[26] J. P. Rao and K. E. Geckeler, "Polymer nanoparticles: Preparation techniques and size-control parameters," *Progress in Polymer Sci.*, vol. 36, no. 7, pp. 887-913, 2011, https://doi.org/10.1016/j.progpolymsci.2011.01.001

[27] X. Yan, M. Li, X. Xu, X. Liu, and F. Liu, "Zein-based nano-delivery systems for encapsulation and protection of hydrophobic bioactives: A review," *Frontiers*, vol. Volume 9 - 2022, 2022-September-28 2022.

[28] B. Nagavarma, H. K. Yadav, A. Ayaz, L. Vasudha, and H. Shivakumar, "Different techniques for preparation of polymeric nanoparticles-a review," *Asian J. of Pharm. and Clin. Res.,* vol. 5, no. 3, pp. 16-23, 2012.

[29] S. R. Jitta and L. Kumar, "Salting out and ionic gelation manufacturing techniques for nanoparticles," in Emerging Technologies for Nanoparticle Manufacturing: Springer, 2021, pp. 129-165.

[30] T. Pulingam, P. Foroozandeh, J.-A. Chuah, and K. J. N. Sudesh, "Exploring various techniques for the chemical and biological synthesis of polymeric nanoparticles," *Nanomaterials*,vol. 12, no. 3, p. 576, 2022.

[31] K. Byrappa, S. Ohara, and T. Adschiri, "Nanoparticles synthesis using supercritical fluid technology–towards biomedical applications," *Advanced Drug Delivery Reviews*, vol. 60, no. 3, pp. 299-327, 2008. https://doi.org/10.1016/j.addr.2007.09.001

[32] P. Franco and I. De Marco, "Nanoparticles and Nanocrystals by Supercritical CO2-Assisted Techniques for Pharmaceutical Applications: A Review," *Applied Sci*., vol. 11, no. 4, p. 1476, 2021, https://doi.org/10.3390/app11041476

[33] T. Adschiri and A. J. T. Yoko, "Supercritical fluids for nanotechnology," *The J. of Supercritical Fluids*, vol. 134, pp. 167-175, 2018, https://doi.org/10.1016/j.supflu.2017.12.033

[34] B. Esmaeili, J. Chaouki, and C. Dubois, "Nanoparticle encapsulation by a polymer via in situ polymerization in supercritical conditions," *Polymer Eng. and Sci*., vol. 52, no. 3, pp. 637-642, 2012.

[35] J. P. Patterson, M. P. Robin, C. Chassenieux, O. Colombani, and R. K. O'Reilly, "The analysis of solution self-assembled polymeric nanomaterials," *Chem. Society Reviews*, vol. 43, no. 8, pp. 2412-2425, 2014.

[36] A. K. Boal, F. Ilhan, J. E. DeRouchey, T. Thurn-Albrecht, T. P. Russell, and V. M. Rotello, "Self-assembly of nanoparticles into structured spherical and network aggregates," *Nature*, vol. 404, no. 6779, pp. 746-748, 2000.

[37] J. P. Quiñones, H. Peniche, and C. Peniche, "Chitosan Based Self-Assembled

Nanoparticles in Drug Delivery," *Polymers*, vol. 10, no. 3, p. 235, 2018, DOI: 10.3390/polym10030235

[38] W. J. Zhang, C. Y. Hong, and C. Y. Pan, "Polymerization-induced self-assembly of functionalized block copolymer nanoparticles and their application in drug delivery," *Macromolecular and Rapid Comm.*, vol. 40, no. 2, p. 1800279, 2019.

[39] S. M. Hegde et al., "Nanomaterials in Food System Application: Biochemical, Preservation, and Food Safety Perspectives," in *Application of Nanotechnology in Food Science, Processing and Packaging: Springer*, 2022, pp. 17-30.

[40] P. Chauhan, E. S. Chauhan, and P. Singh, "A Review of Nanotechnology Applications in Food Processing, Packaging, and Preservation," *Adv. in Res.*, vol. 25, no. 6, pp. 427-441, 2024.

[41] S. Sharma, L. Mulrey, M. Byrne, A. K. Jaiswal, and S. Jaiswal, "Encapsulation of essential oils in nanocarriers for active food packaging," *Food*, vol. 11, no. 15, p. 2337, 2022, https://doi.org/10.3390/foods11152337

[42] E. A. Simone, T. D. Dziubla, and V. R. Muzykantov, "Polymeric carriers: role of geometry in drug delivery," *Expert Opin Drug Deliv*., vol. 5, no. 12, pp. 1283-1300, 2008.

[43] M. Xu et al., "Preparation and optimization of poly (lactic-co-glycolic acid) rod-shaped particles in nano size range for paclitaxel delivery," *Front Bioeng. Biotechnol.*, vol. 10, p. 1103990, 2022.

[44] S. H. Ahmad Shariff, W. K. Wan Abdul Khodir, S. Abd Hamid, M. S. Haris, and M. W. Ismail, "Poly(caprolactone)-b-poly(ethylene glycol)-Based Polymeric Micelles as Drug Carriers for Efficient Breast Cancer Therapy: A Systematic Review," *Polymers*, vol. 14, no. 22, p. 4847, 2022, https://doi.org/10.3390/polym14224847

[45] N. Kapate, J. R. Clegg, and S. Mitragotri, "Non-spherical micro-and nanoparticles for drug delivery: Progress over 15 years," *Adv. Drug Delivery Reviews*, vol. 177, p. 113807, 2021.

[46] P. Li et al., "Evolution and recent progress of non-spherical chiral micro-and nanoparticles: preparation, design, and advanced applications," *Polymer Chem*., 2024.

[47] S. J. Parkinson et al., "Polymer nanoparticles pass the plant interface," *Nature*, vol. 13, no. 1, p. 7385, 2022.

[48] M. Pascoli, P. J. Lopes-Oliveira, L. F. Fraceto, A. B. Seabra, H. C. Oliveira, , "State of the art of polymeric nanoparticles as carrier systems with agricultural applications: a minireview," *Energy, Ecology and environment*, vol. 3, pp. 137-148, 2018.

[49] A. Sikder, A. K. Pearce, S. J. Parkinson, R. Napier, and R. K.. O'Reilly, "Recent trends in advanced polymer materials in agriculture related applications," *ACS Appl. Polymer Mat*., vol. 3, no. 3, pp. 1203-1217, 2021.

[50] S. Shakiba, C. E. Astete, S. Paudel, C. M. Sabliov, D. F. Rodrigues, and S. M. Louie, "Emerging investigator series: polymeric nanocarriers for agricultural applications: synthesis, characterization, and environmental and biological interactions," *Environmental Sci.: Nano*, vol. 7, no. 1, pp. 37-67, 2020.