Pickering Emulsions Based on Polysaccharides and Biocompatible Particles: A Review of Bio Application, Stabilization and Application

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Abstract
Pickering emulsions (PEs), stabilized by solid particles rather than traditional surfactants, are gaining significant attention due to their superior stability, biocompatibility, and reduced toxicity. This review provides a comprehensive overview of PEs stabilized by Abstract-
polysaccharides and other biocompatible particles, focusing on their formation, stabilization mechanisms, and diverse applications. We explore various methods for PE preparation, including rotor-stator homogenization, high-pressure homogenization, and probe sonication. The critical role of particle characteristics—such as size, wettability, surface charge, and concentration—in dictating emulsion type (O/W or W/O) and stability is examined. The review highlights the use of a wide range of natural biopolymers, including cellulose derivatives (nanocrystals and nanofibrils), chitosan, starch, and proteins like zein, as effective stabilizers. Furthermore, it delves into the expanding applications of these biocompatible PEs in the food industry for active packaging and delivery of bioactive compounds, in pharmaceuticals for topical and transdermal drug delivery, and in cosmetics. While PEs offer considerable advantages, challenges related to production scalability, regulatory approval (e.g., GRAS status for nanocellulose), and long-term performance remain. Future research should focus on optimizing particle modification, exploring novel biopolymer sources, and conducting thorough in vivo studies to fully realize the potential of these advanced colloidal systems

Keywords-Pickering Emulsion, Polysaccharides, Biocompatible Particles, Emulsion Stability, Nanocellulose, Chitosan, Food Applications, Drug Delivery)

Introduction

1.1. Emulsion

Emulsions are mixture compounded two immiscible liquids with one disperse or internal phase in other external or liquid continuous phase. They are heterogeneous and thermodynamically unstable, fasten with molecules of an emulsifying agent and one phase that is deeply distributed in another phase as droplets. Topical emulsions enhance penetration on the skin and improved drug release. Emulsifiers also called as surfactants are substances that form and stabilised food emulsions. Molecular-based emulsifiers, which are surface-active molecules, each of these adsorb onto oil-water interfaces, reduce tension at the interface, and form protective coatings, are typically used for this purpose. Emulsifier molecules cannot prevent emulsion destabilisation in certain environmental conditions like temperature conditions, mechanical treatment, and certain pH, ionic strength. Typically, bioactive molecules are accumulated in dispersed phase by forming tiny molecules with sizes ranging from 1 to 100 μm, remains stabilised by macromolecules or emulsifiers. Nevertheless, the emulsions show thermodynamic instability leads to emulsion coalescence, phase separation or Ostwald ripening, flocculation, disruption via creaming/sedimentation, whose occurrence is mostly determined by characteristics of emulsifier. Scientist have focused on lot of research utilization of plenty of approach for emulsion formation and on-going stabilization where solid particles are used to stabilise emulsion droplets called pickering emulsion.

1.2. Pickering Emulsion (PE)

The term "pickering emulsion" was coined in 1907 in honor of British chemist Spencer Umfreville Pickering. Solid particles are crucial for stabilizing emulsion droplets, acting differently from surfactants in reducing interfacial tension. PE, a surfactant-free emulsion, is stabilized at the interface between two immiscible fluids by colloidal solid particles. The potential of solid particles depends on factors like particle size, shape, concentration, dual wettability, and interactions between the solid particles, oil phase, and water phase. The acquisition of PE involves homogenizing the organic membrane and aqueous phase, resulting in a three-dimensional network of solid particles. Solid particles stabilized by nanoparticles exhibit greater responsiveness and stability compared to surfactant-stabilized emulsions.

1.3. Methods of formation of PE

PE can be obtained by utilising same procedure as used for classic emulsions. Thus, emulsification methods like high-pressure homogenization, and sonication using an ultrasound processor, high-speed homogenization with a rotor-stator can be used to prepare a PE by adding solid particles to the suspension.

1.3.1. Rotor-Stator Homogenization

The well-known technique for preparing PE is the rotor-stator homogenization method, whose stator and rotor make up the homogenizer. The stator which is fixed part of the motor has two stationary primary poles that are DC-excited. The armature winding is installed on the rotating component, which is known as the armature core. This mixer works by means of the blades rotating, which drags the liquid sample to one end of the mixture and expels it quickly through the stator's apertures. The emulsion droplet size is decreased as a result of the acceleration caused by the liquid in the device rotating at a high speed and the shear force acting between the stator and the rotor and high levels of hydraulic cutting. Numerous advantages come with this homogeniser, including low cost, rapidity, ease of operation, and increased energy efficiency. Additionally, the technology is widely applicable in market and is highly flexible.

1.3.2. High-pressure Homogenizer

The continuous emulsification is achieved through the use of high-pressure homogenization method. Among its main parts are high-pressure pumps and homogeneous nozzles. Pre-emulsification is the first step in creating a coarse emulsion. The primary emulsion is then fed through the holes in the high-pressure homogeniser, and its cavitation, turbulence, and shear are used to transform it into a fine emulsion. One of the high-energy techniques for breaking the water and oil phases to produce minute emulsion droplets is high-pressure homogenization. Research has demonstrated that the droplets generated by rotor-stator homogenization are larger than those produced by high-pressure homogenization. Apart from the pressure effect, the length of homogenization time and the pressure applied also affects morphology, droplet size distribution, and size. The aids of high-pressure homogenization include the equipment's capacity to create small, homogeneous drops on a continuous basis. High-pressure homogenization is most broadly used technique for continuous emulsification in the industry, but it is not commonly employed to prepare PEs, probably because its high price and tendency to degrade throughout the process. The resulting emulsion quality can differ from batch to batch and is less repeatable due to agglutinated and highly polydisperse droplets that are usually produced. The majority of high-pressure homogenizers utilises in industrial context to make emulsions are energy-intensive, costly to operate and only able to produce thin, low-viscosity emulsions.

1.3.3. Probe Sonication

Another method for preparing PEs is by using an ultrasonic probe sonicator. Probe sonication generates intense ultrasonic waves that create high shear forces within the sample. These forces can effectively break down immiscible liquids (oil and water) into very fine droplets, promoting the formation of a stable emulsion. solid particles are efficiently dispersed throughout the liquid phase. This is pivotal for creating a stable PE where the particles form a protective layer at the oil-water interface, averting the droplets from coalescing. The oil phase is successfully broken down to petites droplets and stabilizing particles are dispersed by the intense shear pressure. Advantages of utilising probe sonicator include, the ability to control droplet size that influence properties like release rate, viscosity, in-situ synthesis of PE stabilizers within the emulsion itself, offering a streamlined process, and appearance of the final emulsion.

Emulsifying Properties of Natural Polysaccharides

PEs, systems stabilized by solid or colloidal particles, are increasingly used in industries like food, medicine, and cosmetics for material synthesis and nutrient delivery. Proteins and polysaccharides are used as emulsifiers due to their thickening, gelling, and surface activity properties. Energy input increases the adhesion of xanthan gum/lysozyme nanoparticles (XG/Ly NPs), creating a dense interface layer that enhances emulsion stability. Adding xanthan gum significantly increases PEs' stability by stabilizing the oil-water interface and decreasing droplet size. The study highlights the need for more research on XG interactions and long-term stability in various environmental settings. Future research could focus on assessing PEs in specific domains, such as food technology or medicines, to convert laboratory results into real-world applications.

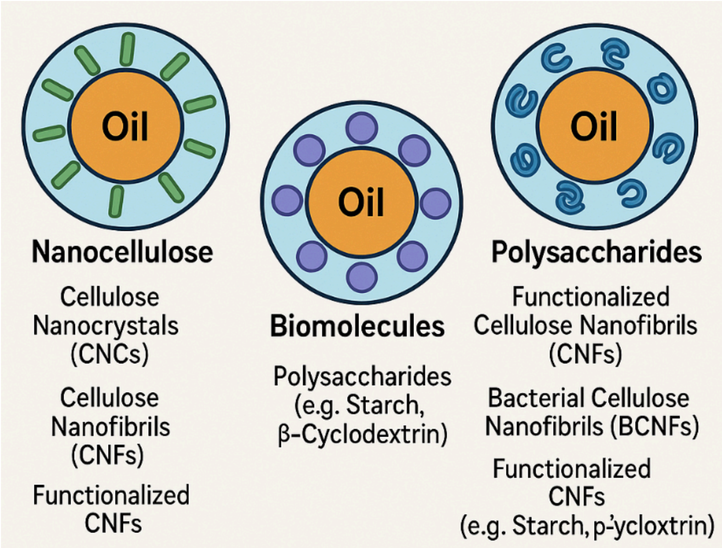

Figure 1. Pickering Emulsions Stabilized by Nanocellulose, Biomolecules, and Polysaccharides

The author discusses the challenges of creating stable polyethylene ether (PEs) with biopolymers due to their hydrophilic nature. Chitosan, a non-toxic and biodegradable biopolymer, is proposed as a promising material for PEs. CH/GA nanoparticles were synthesized as PE stabilizers, showing excellent stability over a two-month storage period. PEs are popular due to their stability and biocompatibility, and can be used in food, cosmetics, medicines, and biological materials. The stability of PEs is influenced by polysaccharides, temperature, ionic strength, and pH.

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Table 1: Pickering Emulsions Stabilized by Nanocellulose, Biomolecules, and Polysaccharides.

Stabilizer Type	Source/Type	Emulsion Type	Stabilization Mechanism	Droplet Size (µm)	Extraction Method & Size Range	Key Applications	References
Cellulose Nanocrystals (CNCs)	Cinnamon, Cardamom, Pineapple Peel	O/W (Oil-in-Water)	Electrostatic	25–50 (Cinnamon)	Acid hydrolysis; 20–60 nm	Antimicrobial packaging, nutraceutical delivery	(Dong, et al. 2021), (Chen, et al. 2019)
Cellulose Nanofibrils (CNFs)	Cardamom, Bacterial cellulose	O/W (Oil-in-Water)	Steric & entropic	30–100 (Cardamom)	Mechanical fibrillation; 2–10 nm diameter, micrometer length	Food, cosmetics, pharmaceutical applications	(He, et al. 2024), (Li, et al. 2020a)
Bacterial Cellulose Nanofibrils (BCNFs)	Bacterial fermentation	O/W (Oil-in-Water)	Steric stabilization	1.42–4.13	Microbial fermentation; 20–150 nm diameter	Food emulsions, low-oil systems	(Zhang, et al. 2022b), (Tan, et al. 2024)
Functionalized CNFs	Modified CNFs (e.g., with cinnamoyl or butyryl groups)	O/W (Oil-in-Water)	Hydrophobic interaction	Not specified	Chemical modification; size varies	Enhanced stability, controlled release systems	(He, et al. 2024), (Uşurelu, et al. 2024)
Polysaccharides (e.g., Starch, β-Cyclodextrin)	Olive oil emulsions	O/W (Oil-in-Water)	Hydrogen bonding	Not specified	Extraction and modification; size varies	Food delivery systems, encapsulation	(Yuan, et al. 2021), (Deng, et al. 2022), (Mahfouzi, et al. 2025)
Functionalized Cellulose Nanofibrils (CNFs)	Cinnamon, Cardamom, Pineapple Peel	O/W (Oil-in-Water)	Electrostatic	25–50 (Cinnamon)	Acid hydrolysis; 20–60 nm	Antimicrobial packaging, nutraceutical delivery	(Uşurelu, et al. 2024), (He, et al. 2024)
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Functionalized CNFs	Modified CNFs (e.g., with cinnamoyl or butyryl groups)	O/W (Oil-in-Water)	Hydrophobic interaction	Not specified	Chemical modification; size varies	Enhanced stability, controlled release systems	(He, et al. 2024), (Silva, et al. 2020)
Polysaccharides (e.g., Starch,	Olive oil emulsions	O/W (Oil-in-Water)	Hydrogen bonding	Not specified	Extraction and modificatio	Food delivery systems,	(Deng, et al. 2022),

β-Cyclodextrin)					n; size varies	encapsulation	(Liu, et al. 2021)
Chitosan–Polysaccharide Complexes	Chitosan and polysaccharides (e.g., pectin)	O/W (Oil-in-Water)	Electrostatic & steric	Not specified	Extraction and complexation; size varies	Nutrient delivery, food formulations	(Cui, et al. 2021; Xu, et al. 2023), (Wan, et al. 2022)
Lignocellulosic Nanocellulose	Apple pomace	O/W (Oil-in-Water)	Steric stabilization	Not specified	Extraction from biomass; size varies	Clean-label emulsions, food applications	(Chen, et al. 2021), (Dai, et al. 2021)
Soy Protein Nanoparticles	Soy protein	O/W (Oil-in-Water)	Adsorption	Not specified	Extraction and nanoparticle formation; size varies	Food emulsions, texture modification	(Yang, et al. 2020), (Zhu, et al. 2018)
Gelatin–Agar Composite Films	Gelatin and agar	O/W (Oil-in-Water)	Gel network formation	Not specified	Gelation and casting; size varies	Active packaging, controlled release systems	(Roy and Rhim 2021)

1.3. Food-related applications

Biopolymer-based packaging films (PEs) are promising alternatives to petroleum-based plastics due to their network structure from molecular interactions. PEs can improve mechanical, barrier, and antibacterial qualities by increasing compatibility of hydrophobic components with hydrophilic matrices. PEs can be stabilized by gelatin nanoparticles, bacterial cellulose, cellulose nanocrystals, and cellulose nanofibrils. Hybrid particles, such as polysaccharide-polysaccharide, protein-polysaccharide, and protein-polyphenol hybrids, also enhance stability and performance.

PEs can be used in various applications, including detecting seafood freshness, prolonging the shelf life of meat and baked items, and preserving fruits and vegetables. However, more research is needed to fully understand the mechanisms of film formation and controlled release of bioactive materials in PE packaging films. To improve the functioning of packing films, future research should focus on regulating the release of bioactive substances in PEs.

In the food, pharmaceutical, and cosmetic industries, plant-derived particles like proteins, polysaccharides, waxes, and lipids can be used as environmentally friendly stabilisers for PEs. These particles improve stability and functionality at oil-water interfaces where they adsorb, potentially producing sustainable products, enhancing emulsion stability, and encapsulating bioactive chemicals. Particle size, surface changes, and environmental factors like pH and ionic strength influence the creation and stability of emulsions made by plant-derived nanoparticles.

Biopolymer-based polyethylene ethers (PEs) offer promising alternatives to petroleum-based plastics, improving compatibility between hydrophobic components and hydrophilic matrices, enhancing mechanical strength, barrier qualities, and bioactive activities. They may reduce food safety risks. Hybrid particles, made up of proteins, polysaccharides, lipids, and phenolic compounds, can enhance emulsion stability, regulate bioactive release, and resist environmental challenges. Physical and chemical processes are used to create PEs, utilizing interactions like hydrophobic, covalent, electrostatic, and hydrogen bonds. Common techniques include complexation with pH and ionic conditions, solvent-anti-solvent exchange, and covalent conjugation via Maillard reactions. Further research is needed on biodegradation, sensory characteristics, and in vivo behavior to enable their use in food and beverage industries. The stability of PEs stabilized by silica nanoparticles is influenced by factors such as hydrophobicity, surface wettability, contact angles near 90°, and strong electrostatic interactions. Further research is needed to fully utilize the potential of hybrid particles in practical applications.

For topical applications, natural stabilisers such as clay minerals and cork bark are more biocompatible and safer than inorganic nanoparticles. Because of its anti-inflammatory and antioxidant qualities, cork bark is a popular choice for cosmetic applications. Clay minerals, such as montmorillonite, are good stabilisers because they are non-toxic, environmentally friendly, and have a large surface area. Although they help stabilise PEs, inorganic nanoparticles like calcium carbonate or silica may be hazardous. Thorough toxicological analyses are required to guarantee topical usage safety. Because of their origin and biocompatibility, natural stabilisers are generally thought to be safer; nevertheless, if inorganic nanoparticles are thoroughly described and their toxicity assessed, they may be just as effective. PEs' mechanical barrier, which improves stability and may improve active ingredient penetration, makes them intriguing for topical and transdermal distribution. Scaling up production and in vivo safety and efficacy investigations, particularly for skin disease therapies, present difficulties, though. In order to maximise the stability and functionality of topical formulations, future viewpoints should concentrate on stimuli-responsive particles, hybrid systems, and sophisticated design techniques.

(Ji and Wang 2023) Nanocellulose is used in food applications. It draws attention to the durability of PEs because of their advantageous qualities, which include biocompatibility, low toxicity, and renewability. Maintaining these emulsions in multi-component food systems under various circumstances is still quite difficult, though. PEs stabilised by nanocellulose exhibit potential for use in a variety of food applications, such as fat replacement, food packaging materials, and bioactive component delivery systems. They improve the encapsulated chemicals' stability and bioavailability, which is essential for functional food items.

PEs with nanocellulose have superior rheological qualities, which makes them appropriate for use in 3D printing. By slowing down lipid digestion, the physical barrier that nanocellulose creates at the oil/water interface may help reduce obesity.

Considering that nanocellulose has not yet been deemed "generally regarded as safe" by the FDA, the study highlights the necessity for additional research on its safety and biological impacts. Limited cytotoxicity and genotoxicity are suggested by toxicological studies; however, case-by-case evaluations are required to address potential safety concerns in food applications.

Future directions include investigating the manufacture of nanocellulose from agricultural waste and creating eco-friendly extraction techniques. For the actual uses of nanocellulose in food systems to advance, this emphasis on sustainability is crucial. A crucial component in food formulations that improves the stability of bioactive substances is nanocellulose. Through irreversible adsorption, it can stabilise PEs, enclosing the bioactive components in a barrier of protection. Additionally, it can work in concert with other stabilisers or bioactive substances like polyphenols to improve stability. Controlled release is made possible by nanocellulose's capacity to modulate emulsions; this is advantageous in food applications where a slow release improves flavour and nutritional value while preserving stability. Additionally, it might lessen the digestion of lipids, guaranteeing the stability of bioactive chemicals that are encapsulated during the digestive process. Furthermore, nanocellulose creates a physical barrier that keeps emulsion droplets from coalescing, which is crucial for preserving the integrity of the emulsion's bioactive ingredients. Because of these characteristics, nanocellulose is a useful component in food compositions that try to efficiently distribute bioactive ingredients. The durability of bioactive substances, particularly in food applications, depends on lipid digestion. Fatty acids are released, and these micelles can contain bioactive substances and increase their bioavailability.

By preventing lipases from interacting with lipids in the stomach environment, the protective barrier that nanocellulose creates in PEs stops breakdown. The stability of the bioactive substances that are encapsulated is preserved by this barrier. Their efficacy can be increased by using nanocellulose to alter the digestion of lipids, enabling a more regulated release. Digestion profiles are also influenced by the kind of lipid that is utilised in emulsions. Medium-chain triglyceride (MCT)-containing emulsions have a higher rate of lipolysis, which affects the stability and bioavailability of lipid-soluble bioactive ingredients. As a result, stabilisers like nanocellulose can improve the stability and bioavailability of bioactive chemicals, which are influenced by lipid digestion. based on nanocellulose Given the frequent changes in pH, temperature, and ionic strength, PEs have stability issues that make it challenging to guarantee reliable performance in a variety of food applications. The FDA has not classified nanocellulose as "generally regarded as safe" (GRAS), which raises safety concerns.

High-pressure homogenisation techniques, in particular, are linked to high energy consumption and operating expenses, which restricts the economic viability and scalability of production. Future studies should concentrate on producing nanocellulose from agricultural waste and by-products, creating environmentally friendly extraction techniques, investigating practical uses such as food delivery and packaging systems, and carrying out uniform safety evaluations. Although the current use of nanocellulose-stabilized PEs has limitations, there is hope for addressing these issues and increasing the range of applications for these emulsions in the food sector in the future.

Sea-buckthorn pulp oil (SBPO) is a valuable fatty acid with potential applications in medicine and cosmetics due to its healing properties. However, its use in these industries is limited by issues such as low bioavailability, oxidation susceptibility, and poor water solubility. A study suggests using bile salt-based vesicles to improve SBPO's stability and distribution for future use in food and cosmetics. The study used various methods to evaluate the formulations' physicochemical characteristics, including dynamic light scattering, electrophoretic light scattering, transmission electron microscopy, atomic force microscopy, multiple light scattering, and attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR).

The stability of colloidal nanocarriers was evaluated during preparation and 30 days after storage at 4°C. The stability was found to be impacted by varying concentrations of SBPO. The study highlighted the importance of monitoring stability while storing colloidal vesicle carriers to ensure their effectiveness.

Bilosomes encapsulated with SBPO at lower concentrations exhibited high stability, highlighting the need for optimizing oil concentration for stable colloidal systems. The study also highlighted the importance of studying the release mechanisms of bioactive compounds in tissue engineering applications and creating natural crosslinking techniques.

Biocompatible porous materials (PEs) have gained attention for their potential as substitutes for block copolymers and conventional surfactants. PEs serve as templates for the production of porous materials, especially for tissue engineering applications, and for the preparation of colloidal capsules for the encapsulation and controlled release of active substances. Future research should focus on in vitro and in vivo investigations, mild crosslinking techniques, controlled structures, and the release and operation of medications or bioactives in tissue engineering applications.

Protein-based particles are ideal for food and tissue engineering due to their biocompatibility, biodegradability, versatility, and tunable properties. They can be combined with different protein types like zein, whey, soy, and gelatin to form protein particles that can be modified through heat-induced aggregation, chemical modification, or complexation. These particles promote cell growth, adhesion, and proliferation. Zein, a hydrophobic protein, is useful for stabilizing emulsions of oil and water. Whey protein is effective as a Pickering emulsifier, preserving encapsulated chemicals and stabilizing emulsions. Gelatin, a collagen-derived protein, performs well as a Pickering emulsifier. High internal phase emulsions (HIPEs) can be stabilized by gelatin nanoparticles, which have stability dependent on pH and concentration. However, the paper lacks a comparison of the antisolvent method and no systematic optimization investigation on variables affecting wettability, charge, and size. Further research on practicality and shelf-life of zein-based PEs could improve their long-term stability and scalability.

2. Conclusion

Pickering emulsions (PEs) stabilized by polysaccharides and other biocompatible particles represent a significant and promising alternative to conventional surfactant-based systems. This review has systematically examined the principles, preparation methods, and diverse applications of these advanced colloidal dispersions.

The use of natural, renewable, and biodegradable materials such as cellulose, starch, chitosan, and various proteins as stabilizers is a key advantage, aligning with the global demand for more sustainable and "clean-label" products in the food, pharmaceutical, and cosmetic industries.The stability and functionality of these emulsions are critically dependent on the intrinsic properties of the stabilizing particles—including their size, surface wettability, charge, and concentration—as well as on environmental factors like pH and ionic strength. As demonstrated, significant research has been dedicated to modifying these biopolymers to optimize their interfacial activity, leading to highly stable emulsions capable of encapsulating and protecting sensitive bioactive compounds.The applications for these biocompatible PEs are vast and continually expanding. In the food sector, they are being developed for fat replacement, enhanced delivery of nutrients and nutraceuticals, and the creation of active packaging films that extend shelf life. In biomedicine, their potential is being realized in targeted drug delivery, vaccine formulations, and as templates for creating porous scaffolds essential for tissue engineering. Furthermore, the absence of synthetic surfactants makes them ideal for gentle and safe cosmetic and topical formulations.Despite the remarkable progress, several challenges must be addressed to facilitate widespread commercial adoption. Key among these are the scalability and cost-effectiveness of nanoparticle production, the need for robust, food-grade modification techniques, and navigating the complex regulatory approval processes for new food and pharmaceutical ingredients.Future research should pivot towards addressing these limitations. Priorities include the development of green and economically viable methods for extracting and modifying biopolymers, perhaps utilizing agricultural byproducts. There is also a critical need for more comprehensive in vivo studies to validate the safety, bioavailability, and controlled-release mechanisms of encapsulated compounds. A deeper understanding of the complex interactions at the oil-water interface and the long-term stability of these systems under real-world conditions will be paramount. Ultimately, continued innovation in this field holds the potential to revolutionize product formulations across numerous industries, paving the way for more effective, sustainable, and healthier consumer products.

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