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Pickering Emulsions: An Emerging Clean-label Emulsion Technology and its Applications in the Food Industry

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Authors' contributions

This work was carried out in collaboration among all authors. Author DM designed the study and wrote original draft of the manuscript. Authors GA and SD edited the manuscript and collected data. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Pickering emulsions, stabilized by solid particles instead of traditional surfactants, have garnered significant attention for their potential applications in the food industry. This review explores the fundamental principles, and provides a comprehensive overview of the mechanisms behind the stabilization of Pickering emulsions, with theories on the adsorption of solid particles at the oil-water interface mechanisms, significant parameters affecting the stability of emulsion such as wettability, particle size, shape, surface charge, etc. Additionally, various preparation methodologies for creating Pickering emulsions, including high-energy and low-energy methods are mentioned. Their key applications in beverages, dairy products, sauces, dressings, packaging, and preservation are

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highlighted along with a brief description of how they enhance texture, stability, and product performance is reported. Their advantages, particularly the role in creating stable, natural, and clean-label food products and challenges for their commercial applications been discussed. Being a novel approach in emulsion technology. Pickering emulsions are the active area for research for developing sustainable emulsions for the food industry.

Keywords: Pickering emulsions; colloidal particles; wettability; low fat products; food industry.

1. INTRODUCTION

Emulsion is a dispersion system made of two immiscible liquids, where one phase gets dispersed as microscopic droplets in another phase. When emulsion droplets collide with neighbouring droplets on Brownian movement, they tend to merge, which results in thermodynamically unstable system and because of molecular incompatibility, they rapidly undergo phase separation (Zhang et al., 2023). On mechanical agitation, the two distinct phases can form a dispersion system, however it is unstable. So, they essentially need an emulsifying agent to attain long-term stability to form a thermodynamically stable system (Chen et al., 2020).

Creating emulsions is easy but making them stable for longer periods is difficult task. Thickening agents, stabilizers, and commonly emulsifiers are employed to prevent, or at least postpone, the separation which may eventually cause emulsions to break down thus making emulsions kinetically unstable (Berton-Carabin & Schroën, 2015). Emulsifying agent comes in board range of surface-active agents. Ionic surfactants, non-ionic surfactants, and amphiphilic biopolymers are included in molecular surfactants usually used as conventional emulsifiers. However few of them may affect the health, causing irritation to skin, allergic reactions, loss of moisture in the epidermis, hemolytic activity etc. thus limiting their application in food and other industries (Chen et al., 2020; De Carvalho-Guimarães et al., 2022).The current world strives for a type of emulsion system that is stabilized by food grade and organic particles over surfactants stabilized conventional emulsions due to good recovery qualities, low toxicity, and cost (Rayees et al., 2024).There are new requirements on food industries as consumers' awareness increases about healthy products, safety, and sustainability. The major demands are

1) Safe products
2) Reduction of artificial additives or ingredients
3) Nutrient foods rich in bioactive compounds

Pickering emulsions are one such solution to meet the demands, which provide stability devoid of surfactants (Øye et al., 2023).

2. PICKERING EMULSION

Pickering emulsion is a form of emulsion where emulsifiers are colloidal particles or solid particles (Pickering particles) instead of surfactants that adhere at the oil-water interface. These particles produce a coating that stops oil droplets from aggregating by getting anchored at the oil-water interface constantly. It can withstand flocculation, coagulation, droplet aggregation, and Ostwald ripening. The proper interaction of the droplets and particles at the interface ensures an irreversible physical barrier formed by particles They have a 'Surfactant-free' character which sets them apart from conventional emulsions (Rayees et al., 2024).

3. BACKGROUND

Pickering emulsions have been known since the pioneering work of Walter Ramsden (1903) and S.U. Pickering (1907). Emulsions stabilized by solid particles wetted by both liquids are known as Pickering emulsions, named after Pickering, who noted that oil droplets in emulsions coated with a film of solid particles smaller than oil droplets might prevent them from destabilizing. The creation and behavior of particle-stabilized surfaces in model systems have been studied in great detail over the years since its discovery. However, only recently has the possible use of so-called Pickering emulsions in food been examined with renewed interest when papers were published demonstrating that various kinds of dispersed particles of biological origin are useful for stabilizing Pickering emulsions (Berton-Carabin & Schroën, 2015). In the discipline of food emulsions, Pickering emulsions have drawn substantial interest and related publications have been rising over the past few decades compared to Food nano-emulsions and Food double emulsions (Øye et al., 2023).

4. MECHANISM

Surfactants adsorb at the two-phase interface in a thermal equilibrium state between desorption and adsorption in case of conventional emulsions. Very rapid adsorption of molecular emulsifiers during the homogenization process, i.e. they actively adsorb and desorb from interface under the drive of thermal motion which results in destabilization of emulsions. However, in the case of Pickering emulsions solid particles adsorb slowly but irreversibly at the interface resulting in a greater requirement of thermal energy for undergoing Brownian movement by particles and high desorption energy. But target emulsion droplets must have a minimum size of one order of magnitude higher than the colloidal particles used for stabilization (Zhao et al., 2024). The stability mechanism of Pickering emulsions can be explained through the theory of solid particle interface film and the three-dimensional viscoelastic particle network mechanism (Chen et al., 2020).

4.1 Theory of Solid Particle Interface Film

Through both steric hindrance and mechanical barrier property, they strongly prevent the Coalescence (large droplets) and Ostwald ripening as particles encircle oil droplets forming a densely packed layer (either single or multiple layers) (Zhao et al., 2024). The thicker the adsorbed particle layer, the higher the coalescence stability and the lower the coalescence rate. As the size of the colloidal particles decreases, the specific surface area of emulsion droplets increases ensuring more stability of emulsion. Hence, emulsions with smaller droplets are frequently more stable in form (Liang & Tang, 2013). The rheology and shear properties of the interface film improve as the particle creates a physical barrier film that can prevent droplets from touching and aggregating each other (Chen et al., 2020). Furthermore, an electrostatic repulsion between the droplets, created by charged colloidal particles can also prevent the droplets from aggregating. Compared to larger ones, smaller droplets are more resistant to gravitational separation and aggregation (Yan et al., 2020).

4.2 Theory of Network Mechanism by Three-Dimensional Viscoelastic Particle

The 3D network structure of particle aggregation may be formed around the droplets coated by particles in the continuous phase, thereby hindering their mobility. This mechanism is based on sufficient interparticle attraction and an adequate high concentration of solid particles that are not adsorbed (Zhao et al., 2024). A depletion process that relies on the existence of non-adsorbing polymers in the continuous phase can also sustain Pickering emulsions. When non-adsorbing polymer molecules are present in high enough concentrations to promote the flocculation of the emulsion droplets and colloidal particles in the Pickering emulsion, an osmotic stress is produced (Yan et al., 2020). The rate of migration of particles and the merger of droplets as the viscosity of the emulsion of emulsion increases with 3D structure thus avoiding the destabilization of the emulsion and aggregation of droplets (Chen et al., 2020).

5. MAJOR PARAMETERS THAT DETERMINE THE STABILITY OF EMULSION

"Emulsion stability" refers to an emulsion's capacity to tolerate variations in its physicochemical properties over time. Emulsions may exhibit instability processes such as phase separation, flocculation, coalescence (large droplets), and gravitational separation (sedimentation). The stability of its physical characteristics, including size, structure, morphology, rheology, and others over a period defines the emulsion's ability to maintain stability (Rayees et al., 2024).

In the food sector, Pickering emulsions are probably complicated colloidal dispersions made up of polymers, solid particles, and emulsion droplets. The stability and functional performance of the colloidal particles are expected to be affected by their size, concentration, and wettability as well as the properties of the water and oil phases and the oil-water ratio. Additionally, environmental and emulsification conditions will have a major impact on the production and stability of Pickering emulsions (Yu et al., 2023). Some of the important parameters which determine the stability are

5.1 Wettability

To preserve structural integrity and provide efficient attachment of particles at the interface, particle solubility is essential (Cheng et al., 2024). Dual wettability, or partial wetting of solid particles by both phases, is necessary for the solid particles to be adsorbed at the oil–water interface during the production of a Pickering emulsion. Adsorption of solid particles reduces the driving force for particle transfer by increasing the oil–water interfacial area and decreasing energy of particles for Brownian movement (De Carvalho-Guimarães et al., 2022). A particle needs to be wettable in order to function at the oil-water interface. The contact angle between the particle and the interface can be utilized to determine how wettable the solid particles employed in Pickering emulsion (Rayees et al., 2024).

Wettability affects the type of emulsion that is created and is measured by the contact angle, whereas hydrophobicity, which is dependent on the oil–water interface contact angle, has a significant impact on the adsorption of a particle at the interface. Direct measurement of contact angle, captive drop method, gel trapping technique (GTT) etc are used for measuring contact angle (Low et al., 2020). But generally, Young's equation can be used to determine θ where θ is the three-phase contact angle of solid particles which is an essential characteristic for describing their wettability (Zhao et al., 2024).

$$\cos\theta = (\gamma_{so} - \gamma_{sw}) / \gamma_{ow}$$

γ_{so} is solid particle-oil interfacial tension
γ_{sw} is solid particle-water interfacial tension
γ_{ow} is oil-water interfacial tension, respectively

Particle-stabilized emulsions can be categorized as,

1) Oil-in-water (O/W) emulsions: hydrophilic particles stabilizers (e.g., silica, clay) with a contact angle in the range of 15° < θ <90° (measured through the water phase).
2) Water-in-oil (W/O) emulsions: hydrophobic particles are stabilizers (e.g., carbon black) with a contact angle in the range of 90° < θ < 165° (Dickinson, 2010).

If the wetting contact angle is between 30 and 150 degrees, where the particle desorption energy is many orders of magnitude more than the thermal energy of Brownian motion, the Pickering emulsion will exhibit irreversible adsorption features (Xiao et al., 2016).Ideally, particles with a θ around 90◦ have a near neutral wettability at the O/W interface and are more appropriate for the fabrication of stable Pickering emulsions (Dickinson, 2010).When two phases completely moisten the particles, they stay scattered in one phase and are unable to form an emulsion. The wettability of the particles may be fine-tuned in a number of ways by altering their topology or surface functional groups (chemical anchoring or physical adsorption) (Gonzalez Ortiz et al., 2020).

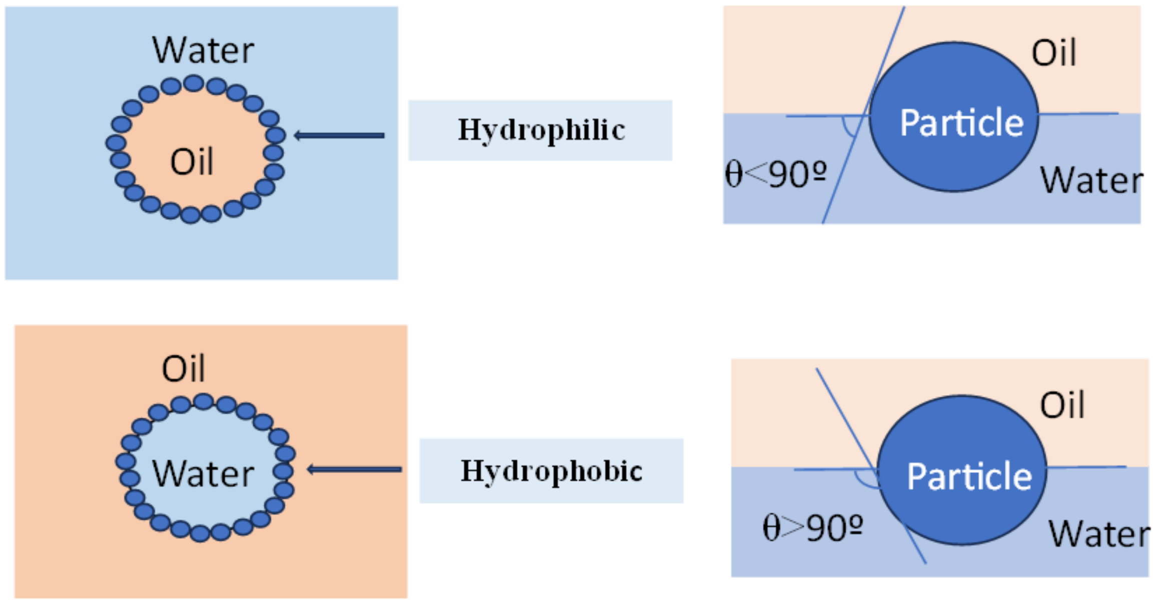

Fig. 1. Schematic representation of oil/water and water /oil Pickering emulsion

5.2 Particle Concentration

The particle concentration has a significant impact on the emulsion stability and average droplet size. Since solid particles cannot function as emulsifiers until they are adsorbed at the oil-water interface, the stability of the emulsion tends to grow proportionately with the concentration of the particle. The existence of too many particles inhibits coalescence because they adhere to and stabilize the liquid-liquid interface. Interestingly, particles that escape from a droplet can adsorb to another surface at the same time, linking two droplets with a shared particle monolayer. Coalescence is avoided because of this arrangement and maintains the equilibrium contact angle on both sides of the bridging particles. But in certain situations, a rise in particles concentration only results in an excess particle in one phase, therefore this is not a general principle for emulsion stability (Gonzalez Ortiz et al., 2020).

5.3 Solid Particle

The characteristics of solid particles greatly influence the Pickering emulsions' stability, type (O/W or W/O), shape, and characteristics (Yang et al., 2017). The preparation begins with choosing the right solid particles, which need to have suitable wettability properties so that they efficiently adsorb at the oil-water interface and can stabilize the interface by decreasing the interfacial tension b/w two phases as there exists the balance of hydrophobicity and hydrophilicity. These colloidal substances, which can range from inorganic materials to organic compounds act as a barrier to avoid the coalescence of oil droplets (Cheng et al., 2024). Shape, stability, categorization, and attributes of Pickering emulsions are all majorly influenced by the qualities of solid particles (Rayees et al., 2024).

Solid particles must have the following characteristics to be used as a stabilizer for Pickering emulsion: (i) they must be partially wettable by both the continuous and dispersed phases of the system while maintaining their insoluble nature in either phase; (ii) their surface charge must not be excessively high to the point where they repel one another rather than firmly adhering to the interfaces between the two immiscible liquids; and (iii) their size must be significantly smaller than the intended emulsion size (Low et al., 2020).

Commonly the solid particles used are silica, clay, hap, magnetic nanoparticles, chitosan (CS), cyclodextrin (CD), nanotubes, and some food-grade stabilizers such as starch, soy protein, and zein protein, etc. The nanomaterials used to create Pickering emulsion fall into three categories: Janus Colloidal Particles (JCPs), Microspheres, and Microcapsules (Yang et al., 2017). Because of the higher aspect ratio of anisotropic particles, several researchers believed that the desorption energy value, capillary force, and interfacial layer may all be increased by them to produce more stable emulsion systems. Various asymmetrical structures, such as ellipsoids, nanofibrils, nanocages, plated forms, nanotubes, and others, can exhibit distinct Pickering emulsion stability mechanisms (Rayees et al., 2024). Nanoparticle-stabilized Pickering emulsions have become highly adaptable due to their exceptional stability. The emulsion droplet is more stable under a range of experimental settings, and the emulsion can be readily demulsified after extraction methods, especially if the nanoparticles are magnetic based on the requirement (De Carvalho-Guimarães et al., 2022).

Numerous studies have demonstrated that complexing with other substances can modify particles to increase their hydrophobicity, which gives PEs additional stability, especially against a range of biochemical and environmental conditions where a single-moiety particle (such as a protein-based particle) might degrade (Nimaming et al., 2023).

5.4 Surface Charge, pH, and Salt Concentration

The adsorption of charged particles on the emulsion surfaces is usually because of the droplet charge in Pickering emulsions. Several environmental conditions, including pH, ionic strength, and chemical interactions, can affect particles' surface charge (McClements, 2015). The stability of a colloidal dispersion, which is heavily reliant on the quantity of surface charge, can be investigated by measuring the zeta potential (Zp) of the particle suspension. It is essential for both the colloidal properties of solid particles and the adsorption of solid particles onto the interfaces between two immiscible liquids.

Solid particles with a high Zp tend to separate from one another rather than firmly adhere to the o/w surfaces. When Zp is reduced to a low-charged zone, the colloidal particles aggregate, strengthening the particles' network in the continuous phase and enhancing emulsion stability (Low et al., 2020). In many studies to regulate the stability of Pickering emulsions, changes in pH or salt concentration are employed (Albert et al., 2019). It was found that by adding salts and varying pH, surface charge density was reduced resulting less requirement of CNC's (Cellulose Nanocrystals) to form a stable emulsion. Just by adding 3 mM Na^+ or 1 mM or less Ca^{+2} to a CNC suspension, the amount of CNC (Cellulose Nanocrystals) was reduced by 30% to stabilize 2 mL of Canola oil (Varanasi et al., 2018).

5.5 Dimensions of Pickering Particles

In essence, the Pickering particulate's dimensions determine two important characteristics of the final emulsion that will be generated: (i) the emulsion's stability and (ii) the size of the emulsion droplets (Low et al., 2020). The detachment energy is provided by

$\Delta E = \gamma_{OW} \pi R^2_{sphere}(1 - |\cos\theta|)^2$ (Binks & Lumsdon, 2000)

It can be inferred that the detachment energy varies linearly with 1-|cosθ| for discs and rods and quadratically with 1-|cos θ| for spheres. This indicates that, in comparison to spherical particles, more energy would be needed to desorb disc and rod-like Pickering particles from a liquid-liquid interface (Vis et al., 2015). It depicts that even non-spherical particles have better emulsification properties. The size of the particles also influences the size of the droplets that are created during emulsification; the size of the droplets reduces as the size of the stabilizing particles increases (Low et al., 2020). The relationship between the diameter of emulsion droplet and Pickering particles as follows: $r_e=4\varphi_d r_p/\varphi_p$ where r_e and r_p are the radius of emulsion droplets and Pickering particles respectively whereas φ_d and φ_p are the volume fraction of dispersed phase and particles respectively. This relationship states that, for a constant volume fraction of dispersed phase and Pickering particles, the emulsion droplets should enlarge in proportion to the Pickering particle radius (Binks & Lumsdon, 2001). Generally, the size of the particle selected for Pickering stabilization should be at least one order of magnitude smaller than the droplet size required to create a stable emulsion (Varanasi et al., 2018).

6. CLASSIFICATION

Pickering emulsions can be systematically classified based on various attributes such as

- The type of stabilizing particles that are used, which affect the emulsion's properties- it can be inorganic, organic, or natural biological materials.
- The volume fraction of the dispersed phase, which determines the emulsion's structure and applications – involves High Internal Phase Emulsions (HIPEs) having more than 74% of dispersed phase volume and Low Internal Phase Emulsions (LIPEs) having a smaller portion of the dispersed phase
- The functional properties that determine its interactions and suitability to industry- include different stimuli-responsive properties
- The Continuous phase of emulsion - Oil in water and water in oil (Cheng et al., 2024).

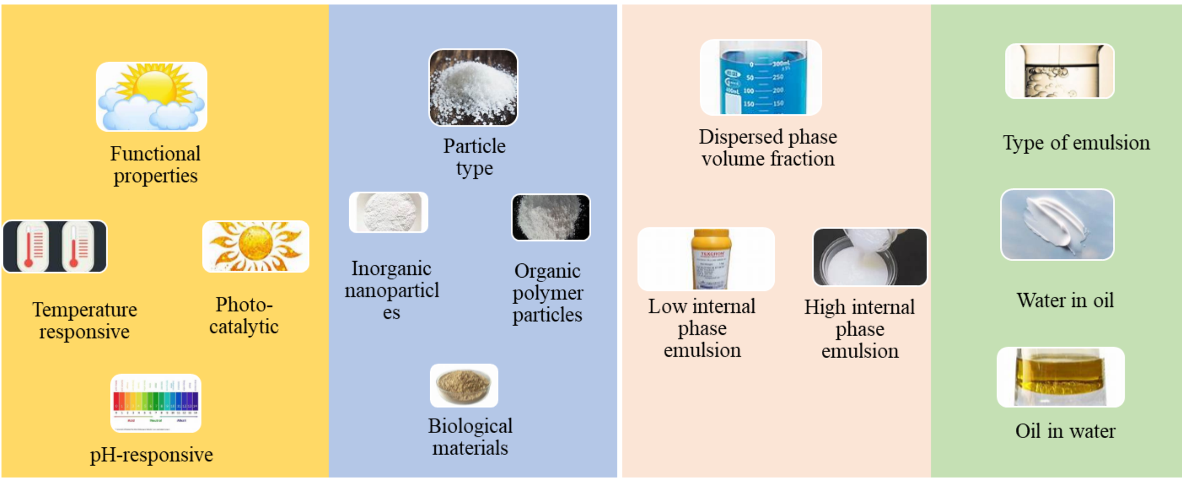

Fig. 2. Classification of Pickering emulsions

7. DEGRADATION OF PICKERING EMULSION

Like other colloidal systems, Pickering emulsions can degrade over time as a result of a number of physical, chemical, and biological causes. It is essential to comprehend the mechanisms of Pickering emulsion deterioration to optimize their design for long-term stability and effectiveness.

7.1 Physical Degradation

Although the solid particles in Pickering emulsions usually create a steric barrier that inhibits this merging, insufficient particle coverage or poor adhesion can undermine this barrier, making the droplets susceptible to coalescence and emulsion instability (Cheng et al., 2024). Additionally, when the same amount of water and oil is mixed, an emulsion for long-term stability will be preferentially created; but, if the ratio is too high, the emulsion will suffer phase separation and become unstable against coalescence due to its non-preferred nature (Gonzalez Ortiz et al., 2020). Differences in internal pressure cause Ostwald ripening. Though it is less frequent in Pickering emulsions, it can nevertheless happen if the continuous phase can partially dissolve the dispersed phase. The stability and homogeneity of the emulsion may be affected over time by the formation of larger droplets at the expense of smaller ones due to the slow diffusion of molecules (Cheng et al., 2024).

7.2 Chemical Degradation

Lipid hydroperoxides and transition metal ions interacting close to the droplet surfaces is the primary source of lipid oxidation in many foods based on emulsions (McClements & Decker, 2000). Emulsions containing chemically sensitive substances, such as bioactive chemicals or polymer stabilizers, may undergo hydrolysis. The emulsified structure may decompose as a result of these compounds undergoing chemical interactions with water in an acidic or basic environment (Tercki et al., 2023). Emulsions with sensitive bioactive compounds or unsaturated oils are vulnerable to oxidative degradation. Oxygen exposure can lead to the development of unwanted chemicals that compromise the emulsion's stability, flavour, and nutritional value, shortening its shelf life and decreasing its overall efficacy (Cheng et al., 2024).

7.3 Biological Degradation

Since emulsions can provide a suitable habitat for bacteria, yeast, or mold, particularly if they include nutrients and are maintained in circumstances that are favourable to these microorganisms, microbial spoilage is a serious issue. Such microbial development may change the emulsion's physical stability, jeopardizing its efficacy, and safety and possibly rendering it inappropriate for its intended use (Wang et al., 2024).

8. CRITERIA

Emulsion having desired stability can achieved only when these two main criteria are successfully fulfilled:

1. Formulation
2. Efficient emulsification process

Though formulation mainly affects the long-term stability of the emulsion, the process also matters since the shear rate of the emulsification process often governs the droplet size of solid particles (Pickering particles) (Chevalier & Bolzinger, 2013).

9. PREPARATION OF PICKERING EMULSION

Methods for the preparation of PE can be categorized into High-energy and Low-energy methods. Where High-energy methods are more suitable for industrial application which produces emulsion by using a high shear rate. Whereas in low-energy methods physical-chemical properties of raw materials' properties play a significant role in droplet formation (Gauthier & Capron, 2021). Steric repulsion is a frequent barrier that prevents particle adsorption when polymer-functionalized particles are used as stabilizers. Mechanical forces like high shear mixing, high-pressure homogenization, or sonication can be used to overcome it (Köhler et al., 2010; Larson-Smith & Pozzo, 2012).

9.1 High-Energy Processes

Because of their poor binding kinetics, particles at surfaces typically take a long time to equilibrate when little or no external energy is supplied (Wu & Ma, 2016). To create stable Pickering emulsions, particle emulsifiers must often be driven to the interfaces using a lot of external energy. Rotor-stator homogenization, high-pressure homogenization, ultrasonic

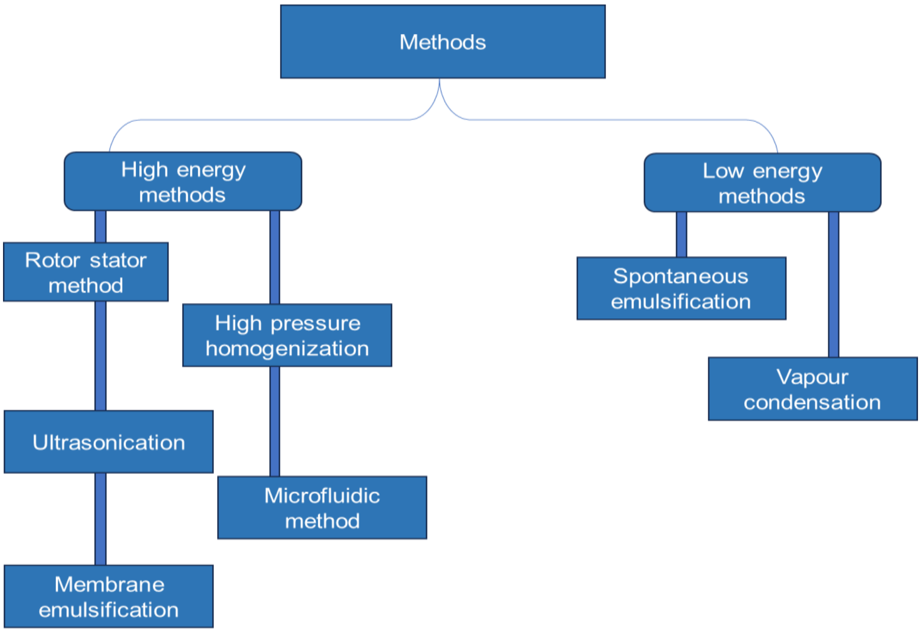

Fig. 3. Preparation methods for Pickering emulsion

emulsification, microfluidic emulsification, and membrane emulsification are among the many emulsification techniques that can be used for preparing Pickering emulsions (Gauthier & Capron, 2021).

Ultrasonication: It is a green technology that uses low-frequency sound waves, commonly above 16 kHz (ranging between 20 and 80 kHz) for diffusing one phase into another using (Pandita et al., 2024). Because it can both emulsify and force particle adsorption onto droplet interfaces, sonication is a useful technique in Pickering emulsion formation (Lee et al., 2008).

The ultrasonic probe is most frequently used to form Pickering emulsions. By transferring sonication energy to the surrounding sample, the probe primarily uses cavitation and ultrasonic forces to induce emulsification. The primary factors affecting the droplet size are the emulsification time, ultrasonic frequency, and amplitude (Albert et al., 2019).

Lee et al (examined oil-in-water emulsions that were insonated with polymer-coated amphiphilic gold nanoparticles (GNP) (Lee et al., 2019). The investigations showed that cavitation has to occur as a result of the application of acoustic fields to generate Pickering emulsions utilizing sterically stabilized particles. Since cavitation was not produced in the presence of weak acoustic fields, there was no particle adsorption. The dense coating of gold nanoparticles, which is close to the tight-packing limit, allowed for high surface coverage in the study.

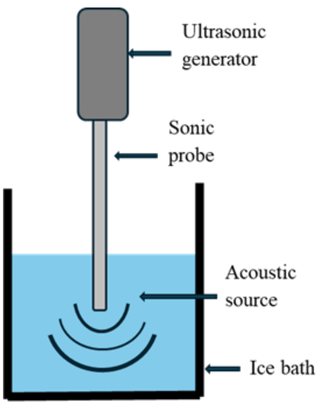

Fig. 4. Schematic representation of Ultrasonicator

High-pressure homogenization: It involves high-pressure pumps (ranging from 3 to 500 MPa) and specified nozzles for carrying out the emulsification process continuously. It is the most widely used continuous emulsifying method in industry and advised to do a pre-emulsification phase to produce an initial coarse emulsion to produce a fine emulsion at the homogenizer's outlet later on (Albert et al., 2019). In the pre-emulsification step, which produces a coarse emulsion is forced through the high-pressure homogenizer's small slits to change the primary emulsion into a finer emulsion, through the techniques using cavitation, turbulence, and shear forces (Pandita et al., 2024).

Nanoparticles often significantly increase abrasion in a service period, especially when high pressure is applied, which is not suitable for a commercial operation. However, the issue was resolved by using a mixing stream right behind the mixing and homogenizing valve (SHM-valve) i.e. an operation without passing the nano-particles through the high-pressure area (pump and orifice) (Köhler et al., 2010). Hence, the risk of damage caused by highly abrasive particles to the high-pressure homogenizer can be solved by adding particles just after the nozzle with the mixing stream (Albert et al., 2019).

To refine coarse emulsions, the high-pressure homogenizer and the microfluidizer are frequently employed. The geometry of the two processes is different, yet they work similarly. Usually, multiple runs through the homogenizer or microfluidizer are required to produce a nano-emulsion (Gauthier & Capron 2021).

Rotor-stator homogenization: Generally regarded as a relatively low-efficiency homogenization technique, several Pickering emulsions are obtained using rotor-stator mixers such as the Ultra-Turrax (Gauthier & Capron 2021). The rotor-stator homogenizer is one of the most popular devices for mixing and emulsifying highly viscous liquids, it consists of a perforated stator screen closure with one or more rows of rotor blades mounted on an impeller shaft (Pang et al., 2021).

Effective emulsification can be obtained when the liquids are drawn axially towards the rotor-stator head as the rotor rotates, accelerated tangentially, and then released radially through the slots in the stator screen (Mortensen et al., 2017). High amounts of hydraulic cutting are produced, rapid homogenization is encouraged, and tiny droplets are produced within the Pickering emulsions when the difference speed between the rotor and stator is nearly equal to the tolerance (De Carvalho-Guimarães et al., 2022). In the case of Pickering emulsions, the emulsification times range from 30 seconds to a few minutes, and the rotation rates are primarily between 5,000 and 30,000 rpm with a velocity of 5 to 20 m/s (Albert et al., 2019).

Microfluidic technology: A micrometer-sized channel with a specific geometry in which fluids circulate makes up a microfluidic device (Albert et al., 2019). The continuous phase flows vertically, while the dispersed phase in parallel and when these two phases intersect, there is formation of spherical droplets by the dispersed phase takes place in the continuous phase (Yao et al., 2018). With this "bottom-up" method of emulsification, even with low fluid volumes, excellent multiple emulsions with total control over the quantity and movement of encapsulated inner droplets can be created (Engl et al., 2008).

The resulting emulsions from microfluidic technology are far more stable than those produced with conventional homogenizers and have several benefits, including simple preparation and accurate droplet control. A thick layer forms around the droplets to stabilize the emulsion since microfluidic technology is a gentle and promising technique that does not destroy the stabilizer's agglomerates due to its low shear pressure application (Chen et al., 2020). This process divides the emulsion into two streams, which collide to reduce droplet size. Several microfluidic devices with various types of junctions to date have been designed for the generation of Pickering emulsion droplets including T-junction, cross-junction and Y-junction (Pandita et al., 2024).

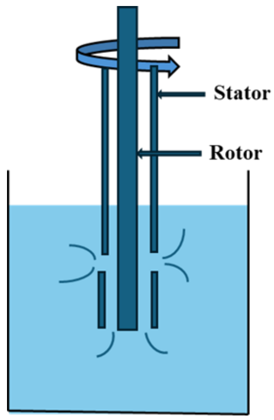

Fig. 5. Schematic representation of rotor-stator homogenizer

A sharp edge is made available by the T-junction microchannel device to create micro-droplets from biomaterial solutions. The scattered phase is introduced from the perpendicular channel in the T-junction design, whereas the continuous phase flows in the main channel. When the pressure gradient and the shear forces applied by the continuous phase combine, the scattered phase's tip elongates into the main channel until it fragments into a droplet

(Jamalabadi et al*.,* 2017). Two opposing streams of the continuous phase focus the dispersed phase flow in a cross-junction configuration, and droplets form when the dispersed phase jet becomes too thin to endure inside the continuous phase. The balance between the interfacial tension and shear forces determines how the droplets are generated in a Y-junction shape (Pandita et al*.*, 2024).

Membrane emulsification: It involves the formulation of PEs by precisely controlling the shearing conditions and injection rate through microporous membranes (Manga et al., 2012). Direct membrane emulsification (DME) and Premix membrane emulsification (PEM) are two methods of membrane emulsification (ME) that primarily create emulsion droplets by forcing a pure dispersed phase or a pre-mix emulsion into a continuous phase through a microporous membrane (Piacentini et al*.*, 2014).

The phase parameters like density and viscosity of the dispersed and continuous phase, interfacial tension, and the membrane parameters including geometry and distance, pore size, porosity, and surface wettability have a major impact on membrane emulsification process along with various process parameters like shear stress, temperature and transmembrane pressure (Pandita et al*.*, 2024).

To boost productivity, several methods have been developed, such as rotating/vibrating membrane emulsification, stirred-cell membrane emulsification, and cross-flow membrane emulsification (Holdich et al*.*, 2020). Although it is an eco-friendly process that uses low energy to create an emulsion with the same particle size, maintaining particle size consistency and homogeneity, this approach takes more time, results in low yields, and works best with low-viscosity systems (Yuan et al., 2009).

9.2 Low Energy Methods

Phase inversion is an alternative PE production option that optimizes components for concentrated PEs with thin droplets and minimal energy consumption, even when viscous oils are used. There is little study on low-energy Pickering nano-emulsions, including steam condensation or spontaneous emulsification.

Spontaneous emulsification (Ouzo effect): Here stabilization of emulsion brought by employing stabilizing particles by constant stirring of aqueous phase which involves mixing water-insoluble oil with a water-soluble co-solvent. Co-solvents which are soluble in water destabilize the oil, leading to nanodrop production via nanoprecipitation. Stabilizing particles sustain these droplets, resulting in an oil-in-water emulsion following co-solvent evaporation. Oil content can be raised via solvent shifts (Song & Kovscek, 2019).

Komaika et al., examined the potential use of a low-energy technique (spontaneous emulsification) with a natural surfactant (sunflower phospholipids) to create oil-in-water emulsions (Komaiko et al., 2015). The emulsions were unstable to gravitational separation because the droplets created by spontaneous emulsification were comparatively large (d > 10 µm). At low SOR (surfactant-to-oil ratio) values of 0.1 and 0.5, phospholipid-based emulsions exhibited lower particle sizes than those prepared using synthetic surfactants (Tween 80). At a higher SOR (1.0), however, this trend reversed, indicating that low-energy methods could be employed with natural surfactants for applications that do not require tiny droplets. For purposes where tiny droplets are not necessary, natural emulsifiers can be added to spontaneous emulsified emulsions.

Low-energy techniques, however, might only work with particular oils and emulsifiers and frequently call for large quantities of surfactants, making them unsuitable for different food applications (McClements & Rao, 2011).

Vapor condensation: Water-in-oil Pickering emulsions can be obtained through water-vapor condensation on the oil surface. At an appropriate temperature and humidity nanodroplets of water are formed by condensation on oil surfaces by utilizing the unique properties of water (Gauthier & Capron, 2021). Kang et al studied that even at very low nanoparticle loadings (approximately 0.2 % silica by weight), Pickering nanoemulsions can be produced with droplet diameters below 500 nm in a single-step process by condensing water vapor on a subcooled oil infused with nanoparticles that spread on water (Kang et al., 2018). Highly monodisperse nanoemulsions can be created by adjusting variables including nanoparticle size, concentration, and condensation duration.

Condensation-based emulsion production is a quick, scalable, and energy-efficient method that

Table 1. Advantages and disadvantages of Pickering emulsion

Method	Advantages	Disadvantages
Ultrasonication	"Green" technology with low environmental impact, enhances uniform particle distribution and easy to clean	Droplet size depends on time, frequency, and amplitude and may cause some degradation of sensitive components
High-Pressure Homogenization	Widely used in industry, capable of producing fine emulsions continuously and suitable for large-scale production	Requires pre-emulsification step, high pressure may lead to a rise in temperature, high cost, and difficulty in clean
Rotor-Stator Homogenization	Effective for emulsifying viscous liquids, simple and widely available in labs and industries, fast process	Considered as lower-efficiency method, not be suitable for producing very fine emulsions and high shear rate
Microfluidic Technology	Precise control over droplet size, produces highly stable emulsions-Eco-friendly and energy-efficient	Limited to small-volume applications, more complex setup and design
Membrane Emulsification	Eco-friendly, low energy consumption and provides consistent droplet sizes	Time-consuming, has Low yield in some cases, and works best for low-viscosity systems
Spontaneous Emulsification	Simple and eco-friendly, low energy consumption and works well with natural surfactants	larger droplet sizes may be produced, requires specific oils and emulsifiers and may need large amounts of surfactant
Vapor Condensation	Quick, scalable, and energy-efficient, produces highly monodisperse emulsions, low energy input required	Limited to specific systems (e.g., water-in-oil emulsions) and requires careful control of temperature and humidity

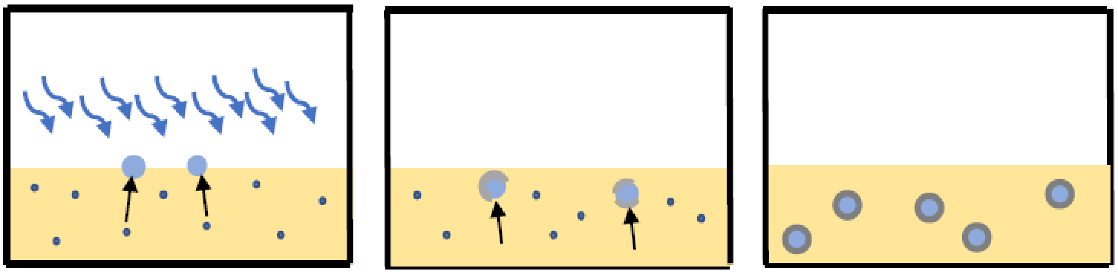

Fig. 6. Formation of Water-in-oil emulsion by Vapor condensation

may be modified for a broad range of emulsion-based applications. Initially, silica is blended with oil and the combination is thereafter kept at 2 °C with steady humidity in a thermostatic chamber. The air in the chamber is kept below its dew point by regulation. Water droplets are formed by condensation on the oil. The pictorial representation of the process is shown in the below Fig. 6.

10. POTENTIAL APPLICATIONS IN THE FOOD INDUSTRY

Low-Fat Products: Animal fats and vegetable hydrogenated oils are widely used in foods such as cream, ice cream, and butter and products are loved by consumers because these fats and oils have delicate and dense taste. Animal fats are expensive and have a high carbon footprint. Whereas The trans fatty acids formed during the hydrogenation process of vegetable hydrogenated oils have negative effects on the cardiovascular system when ingested by the human body (Tian et al., 2024a). Chronic excess intake of trans and saturated fats is the major cause of cardiovascular disease, type 2 diabetes, obesity, ischemic stroke, and hike in low-density lipoprotein cholesterol (De Souza et al., 2015). Since chronic illnesses account for almost 80% of all deaths globally, the World Health Organization notes their prevalence as a significant obstacle to sustainable development.

The food industry is encountering that its tricky to find healthier alternatives that don't alter the final products' physical and sensory qualities due to the obligation to remove partly hydrogenated oils (PHOs) from food items (Wang et al., 2016). Hence Scientists and manufacturers are actively searching for fat substitutes that do not affect the organoleptic properties of food and are acceptable to consumers.

It is feasible to reduce the fat content by using food-grade multiple w/o/w Pickering emulsions as an internal water phase can partially replace the oil phase. Lipid oxidation can be effectively reduced and the oil digestion process can be delayed by the microstructure of solid particles at the oil-water interface (Klojdová & Stathopoulos, 2022). Ex: Cream in the preparation of frozen yogurt and ice cream can be replaced by Pickering emulsions stabilized by ethyl cellulose (Zhang et al., 2023). Butter (20%) was replaced by Pickering emulsion enriched with cinnamon essential oil (EO) in cakes resulting in reduced calories and longer shelf life by prevent yeasts and molds growth without changing the colour and texture (Feng et al., 2020).

Encapsulation and Controlled Release: Pickering emulsions have gained a lot of interest for this purpose because of their high loading capacities, good stability characteristics, and tunable properties (Cui et al., 2021). These properties make them a promising tool for improving active substance delivery as they function as excellent carriers for active ingredients that are sensitive to environmental conditions (Tian et al., 2024b).

Pickering emulsions generally have good stability and are more efficient on bacteria and biofilms as they have good encapsulation efficiency for antibacterial and antibiofilm components. (Gauthier & Capron, 2021). High internal phase Pickering emulsions (HIPPE) can deliver bioactive components, protecting them against light exposure and heat treatment due to their structural and functional properties. Serve as drug delivery carriers without any negative side effects (Ji & Luo, 2023).

Using gel-like Pickering emulsions stabilized by pea protein isolate (PPI), a lipophilic bioactive β-carotene release in the colon may be delivered sustainably (Cheon et al., 2023). Stability and loss of encapsulated curcumin was investigated in starch granule (quinoa starch) stabilized Pickering emulsions by Marefati et al where results indicated that heat-treated emulsions (HT) retained more curcumin even when exposed to simulated environmental and physiological conditions in-vitro digestion (Marefati et al., 2017).

The Pickering emulsification technique has become a viable strategy for safeguarding active compounds from evaporation and oxidation, helping to solve the stability problems associated with bioactive compounds (Pandita et al., 2024). Thus, as an active carrier for the delivery of bioactive compounds, Pickering emulsions have a promising future.

3-D Food Printing Technology and Porous Design: 3D printing technology is based on computer-aided design, which allows small quantities of customized goods to be manufactured at comparatively low costs by stacking printing inks layer by layer using a numerical control system and software (Berman, 2012).

It is an innovative food manufacturing process that has multiple benefits, such as low waste, time savings, high precision, and high efficiency (Tian et al., 2024b). Personalized nutritional profiles are developed along with complex edible-shaped products by 3D printing technology. 3D food products which are having good appeal and can be made healthy with Pickering emulsion formulated by natural ingredients making them nutritionally superior.

The kind and concentration of emulsifiers, the emulsion's pH and temperature, the mixing speed and duration, and other emulsion parameters can all be changed to create porous materials with a variety of pore sizes and shapes (Ji & Luo, 2023). Ex: Plant protein-based edible Pickering emulsions (PEs) and high internal phase PEs (HIPPEs) for 3D printing and delivering flavouring substances were investigated by (Feng et al., 2022) opening possibilities for food-grade particle usage in Pickering emulsion and its potential application in 3D printing with enhanced flavour retention.

Wan et al worked on protein-polysaccharide complexes created by structuring rice proteins (RPs) and carboxymethyl cellulose (CMC) using synergistic interactions as stabilizers for high internal phase Pickering emulsions (HIPPEs) for fabricating food-grade three-dimensional printing. The complexes were fabricated by a simple pH-cycle method, which displayed outstanding colloidal stability during heat treatment and long-term storage (Wan et al., 2021).

Formulation of Plant-Based Food Products: Researchers in the food industry are constantly motivated to create plant-based products due to customers' demand for vegan food products. For example, plant-based mayonnaise was created using Pickering emulsions stabilized by gum nanoparticles (Sharkawy & Rodrigues, 2024). Similarly in a study when the chickpea protein content is 5%, and the oil phase is 69%, or when the oil phase is 65% with a homogenization pressure of 40 Bar, the emulsion demonstrates an optimal appearance and rheological characteristics that are fairly similar to those of commercial mayonnaise products (Bi et al., 2024). Polysaccharide(rice flour)-based Pickering emulsions/foams were used in the preparation of gluten-free rice bread without additives to retain the gas produced by fermentation and to promote the swelling ability of the batter/bread (Yano et al., 2017).

Pickering emulsion was produced using soybean isolate (SPI) which was heated and crosslinked with transglutaminase (TG) enzyme. The plant-based ice cream which was stabilized using Pickering emulsion prepared by using these modified soy protein particles had better stability against creaming, required the lowest temperature for ice crystal formation, and had better freeze-thaw stability (Hei et al., 2024).

Food Preservation and Packaging: Active packaging film can be developed having antioxidant or antibacterial properties by incorporation of substances having such properties, through encapsulation by Pickering emulsions (Gauthier & Capron, 2021). Surfactant-free Pickering emulsion has been regarded as an active carrier to load oil-soluble active agents for the preparation of active edible films to keep food quality and safety.

A study reveals that there was delayed decay of strawberries when coated with -konjac glucomannan composite films stabilized by Pickering emulsion than plastic wrap (Zhao et al., 2024). Hemmatkhah et al were successful in preparing WPI (whey protein isolate) and inulin a-stabilized Pickering emulsion microcapsules which had increased encapsulation efficiency for cumin seed essential oil using the ultrasonication method. Hamburgers' shelf life was extended when packed with these fabricated active papers as encapsulated CSEO (Cumin seed essential oil) exhibited good antioxidant and antimicrobial activities without changes in sensorial attributes. with controlled release of the active substance by Pickering emulsion (Hemmatkhah et al., 2020).

Dihydromyricetin was loaded into Dialdehyde cellulose nanocrystals (DCNC) and these were used as stabilizers for Pickering emulsion. Later incorporated into the gelatin matrix to fabricate gelatin-based active edible films. The films had strong UV barrier ability, high transparency, good water resistance, favourable mechanical properties, effective antioxidant activity, and stability during storage (Xu et al., 2021).

Modification of Lipid Digestion: Pickering emulsions can be designed to control the digestion and absorption of lipids in the gastrointestinal tract, thereby increasing satiety and reducing appetite, which may be an effective strategy to tackle obesity. Polysaccharide-based particles as stabilizers for Pickering emulsions have gained lot of attention as they are able to regulate lipid absorption and digestion. For this, starch particles, chitosan, cellulose nanocrystals, and chitin nanocrystals have all been often employed (Cui et al., 2021).

In an in-vitro lipid digestion study by Tzoumaki et al, there was significant and permanent adsorption of the chitin nanocrystals at the o/w contact. Pickering emulsion stopped lipase and bile salts from widely dislodging the solid particles, and the nanocrystals formed a network in the bulk (continuous) phase that slowed down the kinetics of lipid digestion and caused delayed lipid digestion (Tzoumaki et al., 2013).

Nanochitin-supported Pickering emulsions were obtained and their characteristics were noted as they passed through a human GIT model. The adsorbed nanochitin layer hindered the ability of lipase to reach the lipid phase, which reduced the area of lipids accessible to the lipase; and, the cationic nanochitin bound to anionic bile acids, fatty acids, or lipase and resulting in lipid digestion which is helpful for developing high-satiety foods but the nutritional adverse effect was reduces vitamin bioaccessibility (Zhou et al., 2020).

As Catalyst: Pickering emulsions are particle-stabilized surfactant-free dispersions whose droplets have a large specific surface area, and can be used as interface catalytic reactors that can greatly improve catalytic efficiency as they have the potential to trap the enzymes into the liquid phase with the particles at the water-oil interface as the solid barrier which protects enzymes from the organic medium.

Table 2. various applications of Pickering emulsions in food industry

Application Area	Details	References
Low-fat Products	Pickering emulsions can replace animal fats and hydrogenated vegetable oils in products like cream, ice cream, and butter, reducing calories and improving shelf life without affecting texture, flavor, or color. Microstructure reduces lipid oxidation.	Tian et al., 2024a; Klojdová & Stathopoulos, 2022; Feng et al., 2020; Zhang et al., 2023
Encapsulation and Controlled Release	Used for efficient delivery of active ingredients (e.g., antibacterial agents, bioactive compounds), protecting them from environmental factors. Examples: β-carotene delivery, curcumin stability, and biofilm control.	Cui et al., 2021; Gauthier & Capron, 2021; Cheon et al., 2023; Marefati et al., 2017
3-D Food Printing Technology and Porous Design	Enables the creation of customized, nutritionally superior food with Pickering emulsions stabilized by natural ingredients. The process allows for flavor retention, better textural properties, and enhanced sensory attributes.	Feng et al., 2022; Wan et al., 2021; Ji & Luo, 2023
Formulation of Plant-based Food Products	Used to create plant-based products such as mayonnaise, ice cream, and gluten-free bread, retaining desired rheological properties while meeting vegan requirements.	Sharkawy & Rodrigues, 2024; Bi et al., 2024; Hei et al., 2024
Food Preservation and Packaging	Used for developing active packaging with antioxidant or antimicrobial properties, extending the shelf life of foods like strawberries, hamburgers, and essential oil encapsulation.	Gauthier & Capron, 2021; Hemmatkhah et al., 2020; Zhao et al., 2024
Modification of Lipid Digestion	Regulates lipid digestion and absorption to promote satiety and reduce appetite, potentially combating obesity. Various stabilizers like chitosan, starch, and cellulose nanocrystals are employed.	Cui et al., 2021; Tzoumaki et al., 2013; Zhou et al., 2020
As Catalyst	Pickering emulsions can be used as catalytic reactors, enhancing catalytic efficiency, promoting selective catalysis, and enabling enzyme protection in the organic medium.	Ni et al., 2022; Xi et al., 2021
Prevent Lipid Oxidation	Extend shelf life and improve oxidative stability by creating thicker oil-water interfaces that protect lipid peroxides, reducing oxidation risk.	Tian et al., 2024a; Kaderides et al., 2021
Wastewater Treatment	Pickering emulsion liquid membranes (PELMs), supported by nanoparticles (e.g., magnetic), are used to treat wastewater, offering high stability, ease of de-emulsification, and effective extraction efficiency.	Hussein et al., 2019; Lin et al., 2016
Detergents	Biodegradable Pickering particles in detergents offer superior stain removal while being environmentally friendly, reducing the negative impact of conventional surfactant-based detergents.	Zhang et al., 2023
Bioimaging/Biosensing	Graphene quantum dots as stabilizers in Pickering emulsions can enable bioimaging, drug delivery, and biosensing applications due to their high surface area and luminescent properties.	Wu & Ma, 2016

Excellent recovery of solid catalyst, vast interfacial area to boost reaction kinetics, selectively catalysing action, spontaneous separation of key products based on the ‘phase transfer’ process, and prohibiting pointless secondary reactions are major properties due to which Pickering interfacial catalysis (PIC), Pickering-assisted catalysis (PAC) and Pickering interfacial biocatalysis (PIB) have drawn great interest for research in field of Catalysis technology (Ni et al., 2022).

Xi et al employed phosphorylated zein nanoparticles (ZCPOPs) mounted in gold nanoparticles (Au NCs) to stabilize the Pickering emulsion system for the biphasic cascade catalysis process in oil-in-water (o/w). With unpredictable catalytic activity and horseradish peroxidase-like characteristics, the combination of chemo- and bio-catalysis increased the catalytic yield by more than two times when compared to solitary metal catalysis (Xi et al., 2021).

Pickering emulsions have unmatched qualities that lead to their bright application prospects in food catalysis, even though there has been few research conducted on their usage as biomimetic interfacial catalytic reactors in the current food sector (Tian et al., 2024b).

Prevent Lipid Oxidation: Food lipid oxidation can be caused by irradiation, active oxygen species, transition metal ions, enzymes, etc., and can result in potentially harmful components that reduce the nutritional and sensory value of fatty foods (Kaderides et al., 2021). Pickering emulsion stabilizers can extend the shelf life of food items, improve their lipid oxidative stability, and raise their market appeal. The oil-water interface layer of plant-based protein Pickering emulsions is much thicker than that of surfactant emulsions. It can better prevent lipid peroxides in oil droplets from contacting transition metal ions in the phase to delay oxidation (Tian et al., 2024a).

Wastewater Treatment: The need for cutting-edge and environmentally friendly wastewater treatment technologies has increased due to growing global concerns about pollution and water scarcity. Pickering emulsions have become a viable wastewater treatment option because of their stability, adjustable characteristics, and capacity to treat a variety of contaminants. A new ELM trend called the Pickering emulsion liquid membrane (PELM) has been developed. PELM supported by nanoparticles may provide two advantages, especially if the nanoparticles are magnetic i.e. increased stability of the emulsion droplet under a variety of experimental conditions and ease of de-emulsification after extraction operations (Hussein et al., 2019).

A study was conducted for removing 4-methoxypheno from wastewater using Oleic acid-coated magnetized nano-Fe3O4 particles as Pickering particles for stabilizing W/O/W Pickering emulsion liquid membrane (PELM) system. It reported that there was over 86% of extraction efficiency and the idea can also be applied to non-magnetic nanoparticles, where centrifugation can be used to demulsify the particles and oil phase, making it simple to collect and reuse them. This would lessen the environmental impact and cut down on material consumption and costs (Lin et al., 2016).

Detergents: Companies that manufacture and prepare food inevitably generate a lot of oil and grease, and the key component in conventional detergents is surfactant. Extended usage of these detergents can have negative environmental effects. Therefore, detergents made from solid-particle (biodegradable Pickering particles) offer superior stain removal as well as being ecologically sound (Zhang et al., 2023).

Bioimaging/Biosensing: Highly luminescent graphene quantum dots can be employed as stabilizers to produce Pickering emulsions and particles with controlled nanostructures and high luminescence, which would be useful for bioimaging, drug delivery, and optoelectronic devices. Colloidosome shells are usually composed of hundreds or thousands of nanoparticles. They have smooth surfaces with large surface areas, which facilitates the grafting of functional groups or makes possible other applications needing large surface areas, such as biosensing or bioimaging (Wu & Ma, 2016).

11. ADVANTAGES OF PICKERING EMULSION

Pickering emulsions offer the following numerous special benefits:

- Pickering emulsions find their applications in various industries like coatings, paints, adhesives, rubber, sealants, drug release systems, etc due to their properties like high stability, low viscosity and transparent nature along with their ability to reduce surfactant (Gauthier & Capron, 2021).
- They afford higher stability, less toxicity, and stimuli-responsiveness compared to surfactants’ stabilized emulsions. Many low-molecular-weight surfactants have various kinds of biological adverse effects,

the commonly described of which include peripheral neurotoxicity, acute hypersensitivity reactions, and membrane-damaging effects. In contrast, Pickering nanoparticles are removed by splenic and liver macrophages during systemic circulation (Wu & Ma, 2016).

- It uses biodegradable compounds making it completely safe for usage in the food sector. Even by-products can thus be used efficiently, increasing the environmental friendliness of emulsion technology (Klojdová & Stathopoulos, 2022).
- Additionally, many essential oils (EOs), which are functional components, are conveyed by it, serving as fantastic carrier of bioactive compounds. Addition of these compounds into the coating or packaging film composition greatly extends the food products' shelf life that is packaged (Pandita et al., 2024).
- Even though its preparation is easy and simple, and emulsion system is not prone to Ostwald ripening, coalescence, and demulsification resulting in superior emulsion stability (Yang et al., 2017).
- The emulsion system's desired physical and chemical characteristics, including controlled release, stimulus-response, and durability, can be attained by modifying the particle characteristics and the preparation process, making it suitable for both simple and complex formulations (Rayees et al., 2024).
- Pickering emulsions can create unique food textures by altering the water-to-oil ratio and using various solid particles. This gives food designers a new tool to make products with rich textures and excellent sensory properties (Cheng et al., 2024).

12. REGULATORY CONSIDERATIONS

Advanced methods, such as microfluidic devices, are being explored for the efficient production of Pickering emulsions, necessitating updated regulations to accommodate these technologies (Klojdová & Stathopoulos, 2022).

In the food industry, PEs must comply with food-grade standards, using particles like proteins and polysaccharides that are Generally Recognized as Safe (GRAS) (Cassani & Gómez-Zavaglia, 2024).

Compared to their conventional counterparts, nanoform substances exhibit distinct chemical and physical properties, mostly because of their increased reactivity, larger surface area, and smaller particle size. New stabilizers such as bacterial cellulose nanofibrils, cellulose microfibers, and nanocellulose should be evaluated for safety by the European Food Safety Authority (EFSA) on a case-by-case basis (De Farias et al., 2025)

13. CHALLENGES

Although the development of a steric interfacial barrier can stop coalescence, the comparatively large emulsion droplet size may be encountered and leading to creaming or sedimentation, resulting in appearance defects in food products stabilized by Pickering emulsion (Berton-Carabin & Schroën, 2015).

In laboratory testing, certain studies have shown that Pickering emulsions are highly stable in storage and effective at releasing chemicals in a regulated manner when used in packaging materials. But, merely a small number of research, have examined its uses in commercial food products. Hence it is still necessary to carefully examine the structure of various potential Pickering emulsion components and how they interact with various film matrices for commercial usage (Niro et al., 2021).

Sourcing and using food-grade particles (such as starches, proteins, or silica) can be challenging, as not all materials are approved for use in food products by regulatory bodies. Due to a lack of experimental efforts and a lack of theoretical support, the benefits provided by this class of emulsions are not yet completely utilized or commercially available (Xiao et al., 2016).

When using natural-based particles for Pickering emulsions, they should possess desirable sensory and physicochemical properties or else modification of particles increases the cost of production. Large-scale, dependable production must be achieved through economical and dependable processing methods. They need to be able to break down in the human digestive system and efficiently release any nutrients (Yan et al., 2020).

14. CONCLUSION

Pickering emulsions use solid particles as emulsifiers to stabilize the emulsion where they adsorb irreversibly at the oil-water interface, reducing the interfacial tension and increasing desorption energy. Particles must often be driven to the interfaces using a lot of external energy to create a stable emulsion. Rotor-stator homogenization, high-pressure homogenization, and ultrasonic emulsification are widely used methods for preparing Pickering emulsions. Their superior stability, and biodegradability, make them ideal for applications in low-fat products, encapsulation, 3D food printing, plant-based formulations, and food preservation. These emulsions not only enhance the sensory and nutritional qualities of food but also offer solutions for healthier alternatives by reducing trans fat and saturated fat contents and active carriers of bioactive compounds. They represent a transformative advancement in food science and technology, offering creative and sustainable solutions to address long-standing challenges within the food industry. They find the potential application in personalized nutrition, functional foods, Biosensing, ecofriendly detergents and even wastewater treatment.

To fully realize the potential of Pickering emulsions in commercial food applications, a systematic and cost-effective approach is required. Moreover, safety concerns, including toxicity and allergenicity of new particles, must be thoroughly addressed through clinical and in-vivo studies to ensure their safe use in food products. There is a growing demand for emulsions that offer low viscosity, high transparency, low toxicity, and extended shelf life, which can be effectively achieved by Pickering emulsions that are devoid of surfactants making them environmentally sustainable. Pickering emulsions have become a significant area of study in colloidal and emulsion science, with enormous potential for the application of novel biological particles as stabilizers. With continued innovation and development, Pickering emulsions are set to become a key component in creating sustainable, functional, and high-quality food products. The future applications appear promising, with the technology anticipated to expand into various sectors of the food industry.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS DISCLAIMER

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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