

**HARNESSING THE POTENTIAL OF MULTIPLE EMULSIONS: A COMPREHENSIVE
REVIEW OF MANUFACTURING METHODS AND APPLICATIONS*****Harshal Patil and Jyotsna Waghmare**Department of Oils, Oleochemicals and Surfactant Technology Institute of Chemical Technology (ICT), Nathalal Parikh
Marg, Matunga (E), Mumbai-400019, Maharashtra. India.***Corresponding Author: Harshal Patil**Department of Oils, Oleochemicals and Surfactant Technology Institute of Chemical Technology (ICT), Nathalal Parikh Marg,
Matunga (E), Mumbai-400019, Maharashtra. India.

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ABSTRACT

Multiple emulsions are advanced colloidal delivery systems with hierarchical structures droplets in droplets in concentric phases providing considerable benefits over traditional emulsions. This extensive review examines the underlying science, formulation approaches, and growing applications of these multiphase systems. Water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O) systems allow for simultaneous encapsulation of incompatible constituents, sheltering of delicate actives, controlled release features, and improved stability profiles. The review analyses production methods such as two-step and one-step emulsification, membrane emulsification, microfluidic strategies, phase inversion techniques, and ultrasonication, reviewing their respective strengths and weaknesses. Emerging technological innovation in interface engineering, such as progress in amphiphilic particle stabilizers, responsive polymers, and accuracy manufacturing processes, has resolved long-standing stability issues, widening viable applications in several industries. The review emphasizes the innovative applications of multiple emulsions in cosmetics pharmaceuticals, agriculture, and food science. Though tremendous strides have been made, problems persist with large-scale manufacture, stability over long periods, and regulatory approval. As formulation methods and stabilization approaches become more sophisticated, multiple emulsions are set to play an ever more crucial role in creating next-generation products that address today's needs for increased functionality, sustainability, and multifunctionality.

KEYWORDS: - Multiple emulsions, controlled release, cosmetic applications, pharmaceutical delivery systems, interface engineering.

1. INTRODUCTION

Multiple emulsions are intricate colloidal systems formed by droplets within droplets in concentric phases. Such "emulsions of emulsions" have a three-phase structure with the innermost phase being surrounded by an intermediate liquid barrier separating it from the continuous phase, producing a structural complexity beyond single emulsions. The idea of multiple emulsions has existed since the early 20th century, but real progress in formulation methods and stabilization strategies only came in recent decades, making them go from theoretical curiosities to viable delivery systems.^{[1],[2]}

The two most prevalent forms are water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O) emulsions. In W/O/W systems, water droplets are trapped within oil droplets, which are dispersed in an external aqueous phase. In O/W/O systems, oil droplets are trapped within water droplets, which are dispersed in an external oil phase. This structural variation leads to enormous flexibility in formulation design and application

opportunities. This architectural sophistication enables encapsulation of compounds with opposing solubility profiles simultaneously, which means multiple emulsions are able to surpass several limitations of traditional emulsions.^[3] Their unique structure is not only environmentally stress-protected and targeted and sequential release promotion-suitable but also makes them excellent encapsulants for hydrophilic and hydrophobic active ingredients at the same time. This is why multiple emulsions are very valuable in numerous industries, including cosmetics, pharmaceuticals, and food science. One of the primary advantages of multiple emulsions is that they can provide controlled and sustained release of entrapped substances through their structured form, which acts as a diffusion barrier.^[4] By careful selection of the properties and composition of inner and outer phases and the emulsifiers, the release kinetic of active ingredients can be tailored to meet specific requirements. For example, in cosmetic products, W/O/W emulsions can be designed to release moisturizing actives over an extended period of time,

giving sustained hydration and improved skin barrier function. Similarly, in pharmaceuticals, multiple emulsions could modulate drug release profiles, ideally reducing dosing frequency and improving compliance in patients.^{[5],[6],[7],[8],[9]}

The multi-compartmental nature of the multiple emulsions also offers unique opportunities for enhancing stability and bioavailability of labile drugs. Labile constituents are shielded against degradative environments in the external surroundings, while the internal phase can be optimally designed to maintain their integrity. Furthermore, the organized structure of the phases can be utilized to bypass delivery drawbacks associated with compounds of low solubility, stability, or permeability characteristics. Despite stabilizing functional benefits, multiple emulsions present rigorous stabilization challenges since they are inherently thermodynamically unstable and encompass complex interfacial processes. The two stabilizing interfaces produce opposed tension systems that require sophisticated stabilization methods beyond those needed for single emulsions. Long-term stability requires fine tuning of formulation parameters, including the choice of emulsifiers, phase viscosities, and processing conditions. Their complex character makes them inherently susceptible to the destabilizing processes such as coalescence, flocculation, and phase separation that can undermine efficacy and storage stability. Conventional methods of stabilizing multiple emulsions involve employing a blend of hydrophilic and hydrophobic surfactants by two-step emulsification. Nevertheless, this conventional method has a tendency to yield systems that are less stable and with restricted droplet sizes, which can restrict their prospective applications. Current endeavours have focused on designing newer stabilization methods to surmount such limitations and extend the utilization of multiple emulsions. One of the encouraging techniques is the use of interfacial complex films prepared from macromolecules such as gelatine, bovine serum albumin, and polyvinyl alcohol.^{[3],[10],[11],[12],[13]}

These macromolecules are able to adsorb at the interface and create a strong mechanical barrier that inhibits droplet coalescence and increases emulsion stability. Analogously, application of biopolymers like gum or synthetic diblock copolymers as exclusive stabilizers has proven highly promising in forming more stable multiple emulsion systems. Pickering emulsions, stabilized by particles instead of traditional molecular emulsifiers, are another novel method of improving the stability of multiple emulsions. Particle-stabilized systems have the advantage of strong adsorption of particles at the interface, exhibiting good resistance to coalescence and phase separation. Application of stimuli-responsive particles as Pickering stabilizers has also broadened the functionality of such systems, allowing for triggered release of entrapped compounds based on certain environmental stimulate.^[5]

The latest breakthroughs in interface engineering, such as developments in amphiphilic particle stabilizers, responsive polymers, and precision manufacturing methods, have now started overcoming these long-standing constraints. Methods like control of osmotic pressure between the aqueous phases, biopolymeric emulsifier-based systems, and creating multilayer emulsions with selective mixtures of proteins and polysaccharides have made high stability and effectiveness a reality. Furthermore, advancements in emulsification technology such as high-pressure homogenization and microfluidics have boosted the stability and reproducibility of multiple emulsions. Preparation of intelligent multiple emulsions that can be triggered by external stimuli is particularly an exciting aspect of this science. They can be designed to release their cargo on activation by specific stimuli including pH, temperature, light, or enzymatic action, ensuring that the control of active ingredient release is maintained with respect to time and site. This is achieved by incorporation of stimuli-sensitive polymers, lipids, or particles within the emulsion matrix to generate responsive systems against changes in their environment. In the cosmetics industry, emulsions are used extensively due to their ability to improve the sensory properties, activity, and stability of the product. They are also used extensively in moisturizers, anti-aging products, sunscreens, and shampoos and conditioners, where they provide better delivery of active ingredients and a luxurious feel. Besides, the growing trend of multifunctional and green cosmetic products has initiated research on green multiple emulsions design using natural and biodegradable ingredients in pharmaceutical fields, multiple emulsions have unique characteristics for drug delivery, including improved bioavailability of poorly soluble drugs, controlled release of active ingredients, and targeted delivery to targeted organs or tissues. They also allow for a versatile system for the concurrent co-delivery of two or more therapeutic drugs, enabling synergistic combination therapy. The compatibility of both hydrophilic and hydrophobic drugs in being encapsulated under one formulation places multiple emulsions in especially high demand when it comes to tackling intricate therapy problems. The food industry has also welcomed multiple emulsions for their potential in producing low-fat products without sacrificing flavors and texture, encapsulating Flavors, and nutrients, and creating functional foods with improved nutritional qualities. By substituting a proportion of the oil phase with water droplets in W/O/W emulsions, products with lowered caloric values but good sensory properties can be obtained.^{[9],[14],[15],[16],[17],[18],[19],[20],[21]}

This review discusses the underlying science, formulation approaches, and new applications of these multiphase systems, looking at how recent advances in technology are turning multiple emulsions from abstract curiosities into useful delivery vehicles in pharmaceutical, nutritional, cosmetic, and agricultural

applications. Although tremendous progress has been made in the last few years, there is still much room for innovation in this area, especially in creating more stable

and useful multiple emulsion systems for commercial use.

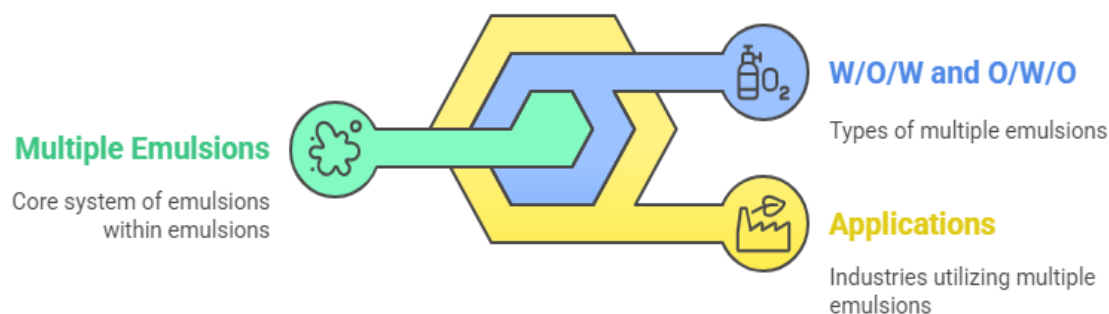


Figure 1: Hierarchy of Multiple Emulsion.

2. TYPES OF MULTIPLE EMULSIONS

Multi-emulsions are complex systems in which droplets of one phase hold smaller droplets of another phase. These hierarchical structures can be broadly classified into two types.

2.1 Water-in-Oil-in-Water (W/O/W): The outermost emulsion is water droplets in an internal oil phase

dispersed in an external water phase. Such systems find applications in the controlled release of water-soluble materials in pharmaceuticals, cosmetics, and food.^{[9],[13]}

2.2 Oil-in-Water-in-Oil (O/W/O): In this system, oil droplets are emulsified in water, which is itself dispersed in an external phase of oil. Such systems are suitable for the encapsulation of oil-soluble substances.^{[10],[12],[13]}

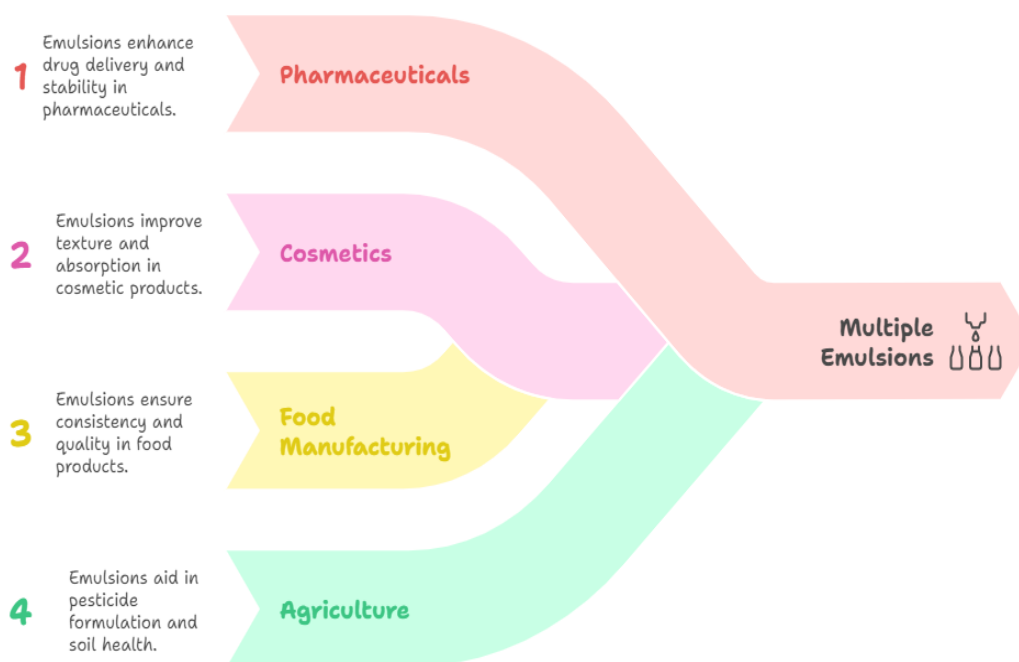
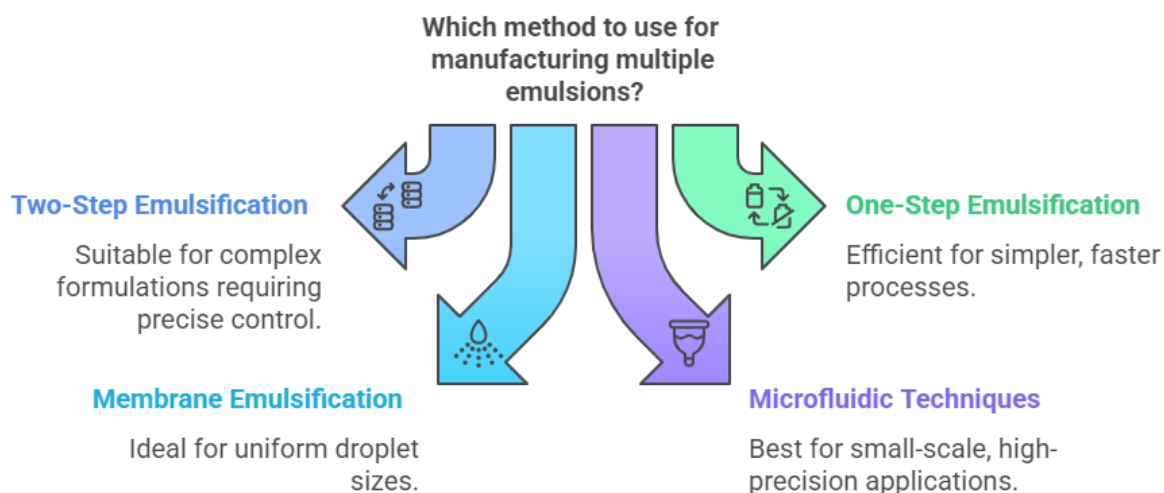


Figure 2: Application of Multiple emulsion.

Table 1: Advantage & Disadvantage of Multiple emulsion. ^{[4],[4],[7],[10],[17],[19],[22],[23]}

Sr.no	Advantages	Disadvantages
1	Enhanced protection of sensitive active ingredients	Thermodynamically unstable systems
2	Controlled/sustained release of encapsulated compounds	Complex manufacturing processes
3	Ability to deliver incompatible ingredients simultaneously	Higher production costs compared to simple emulsions
4	Reduced total oil content while maintaining sensory properties	Limited shelf life without proper stabilization
5	Masking of unpleasant tastes and Odors	Difficult scale-up from laboratory to industrial production
6	Improved bioavailability of certain drugs	Sensitive to temperature, pH, and mechanical stress
7	Compartmentalization of reactive components	Requires careful selection of emulsifier systems
8	Enhanced permeation across biological membranes	Higher viscosity can limit certain applications
9	Environmental protection for sensitive compounds	Potential for leakage of internal phase contents
10	Targeted delivery capabilities	Specialized equipment and expertise required

3. Multiple Emulsion Manufacturing Methods

**Figure 3: Manufacturing method.**

3.1 Two-Step Emulsification for Multiple Emulsions

Two-step emulsification is the most common technique for the preparation of multiple emulsions in laboratories and industry. The procedure starts with the creation of a primary emulsion, either water-in-oil (W/O) or oil-in-water (O/W), through the use of a high-shear mixing tool like a homogenizer or high-shear mixer in combination with the right lipophilic emulsifiers. This initial emulsion is next dispersed carefully in an outer phase under less strenuous mixing conditions to form the final multiple emulsion (O/W/O or W/O/W). The efficiency of this process relies mainly on balancing the mixing energies - during the second step, one needs much lower shear forces in order to avoid rupture of the initial emulsion structure. The general equipment combinations are rotor-

stator homogenizers in the first step and magnetic stirrers or low-speed impellers in the second. Its popularity is due to its relative simplicity and flexibility towards the use of available manufacturing facilities, although it does pose difficulty in reproducibly generating stable multiple emulsions with evenly distributed droplets. Consideration of formulation is especially important since the emulsifier system needs to be carefully formulated with varying HLB (Hydrophilic-Lipophilic Balance) values for each interface. Low-HLB emulsifiers are usually used to stabilize the main W/O interface, whereas high-HLB emulsifiers are used at the secondary O/W interface. Other stability aids like viscosity modifiers, biopolymers, or other structural stabilizers are

also added to avoid coalescence of the internal droplets and phase separation on storage.^{[17],[24],[25],[26]}

3.2 One-Step Emulsification for Multiple Emulsions

One-step emulsification is an even more direct method for preparing multiple emulsions in that both primary and secondary emulsions are produced at once under a single processing operation. Unlike two-step techniques, no intermediate step is present, possibly offering the advantages of shorter processing times and lower emulsion structural stresses. The method is based on well-designed surfactant systems capable of spontaneously generating multiple emulsions when the phases are combined under certain conditions. The correct hydrophilic-lipophilic balance is crucial, generally involving specific polymeric emulsifiers or combinations of surfactants capable of stabilizing several interfaces in parallel. Equipment for one-stage emulsification frequently involves transformed homogenizers with special mixer chambers that allow the generation of controlled patterns of turbulence. Input of energy is carefully controlled so that the formation of the sophisticated internal structures results without excessive phase separation or coalescence. Pulsatile or oscillating mixing regimes with some advanced devices preferentially establish hierarchical droplet structures. The main benefit of one-step processes is the lower mechanical stress on the fragile multiple emulsion system, usually leading to increased stability and more homogenous droplet size distribution. Yet, the formulation effort is much larger, with extensive pre-formulation work being needed to find the ideal surfactant system and processing conditions for a given application. The technique is most beneficial for the inclusion of sensitive bioactive molecules that may be destroyed during prolonged or high-energy processing operations.^{[27],[28],[29],[30],[31]}

3.3 Membrane Emulsification for Multiple Emulsions

Membrane emulsification is a milder, more controlled method of multiple emulsion production than traditional mechanical techniques. Membrane emulsification is a process where the dispersed phase is forced through a microporous membrane into the continuous phase under moderate pressure conditions. The formation of droplets takes place at the pores of the membrane, and the droplet size is mainly controlled by the pore diameter, membrane surface characteristics, and cross-flow conditions of the continuous phase.

For multiple emulsions, membrane emulsification is usually carried out in two successive steps. Initially, a primary emulsion (e.g., W/O) is prepared by the normal procedure or a first membrane process. The primary emulsion is then passed through a second membrane into an external aqueous phase to produce the final W/O/W multiple emulsion. The major benefit is the exact control over the diameter of the secondary droplets, which can be precisely controlled by choosing proper membrane specifications. Different types of membranes can be

used, such as ceramic, glass, metal-coated, and polymeric membranes of pore size in the range of submicron to a few microns. Shirasu Porous Glass membranes have become quite popular because they have a uniform distribution of pore size. The operation can be designed in several modes: direct membrane emulsification, premix membrane emulsification, or cross-flow designs where the continuous phase passes tangentially over the surface of the membrane. The main advantages of membrane emulsification are drastically reduced energy input, lower mechanical stress on emulsion ingredients, outstanding uniformity of droplet size, and improved protection of sensitive ingredients. Nevertheless, the method has restrictions in throughput potential relative to high-shear technologies, which results in difficulty scaling up for industry. Membrane fouling also takes place upon prolonged operation, especially with difficult-to-formulate mixtures such as proteins or other surface-active ingredients.^{[32],[33],[34],[35]}

3.4 Microfluidic Techniques for Multiple Emulsions

Microfluidic strategies are the frontiers of simultaneous emulsion manufacturing with unparalleled handling of droplet size, internal structure, and composition. The methods employ micron-scale microchannels precisely engineered between tens and a few hundred micrometers to handle fluid flow at the micron scale where viscosities trump inertial effects. The most prevalent microfluidic structures for the production of multiple emulsions are T-junctions, flow-focusing devices, and co-flow systems. In these structures, immiscible fluids enter through independent inlets and converge at well-designed junction points where controlled breakup leads to emulsion droplets formation. For multiple emulsions, these devices are placed in series or with nested geometries to enable hierarchical structures. For instance, a W/O emulsion created at the first junction carries downstream to a second junction where it's trapped in another water phase to create a W/O/W emulsion. The remarkable accuracy of microfluidic methods is due to the capability to control fluids in a highly precise laminar flow regime. This makes it possible to generate monodisperse droplets with size fluctuations frequently less than 3%, significantly better than traditional techniques. In addition, sophisticated designs allow the generation of intricate internal structures like multiple cores, asymmetric distributions, or compartmentalized domains within individual droplets. In spite of these benefits, microfluidic methods are severely challenged in production scale-up. The low throughput nature of single-channel devices has led to the creation of parallelized systems with multiple production units, although it is still challenging to maintain uniform flow conditions in all channels. Microfluidic fabrication also usually involves the use of specialized materials and microfabrication methods, which make production more expensive than traditional methods. These constraints now limit microfluidic multiple emulsion manufacturing mainly to high-value pharmaceutical, specialty cosmetic, and research

applications where droplet uniformity and structural accuracy justify the increased production expense.^{[36],[37],[38]}

3.5 Phase Inversion Methods for Multiple Emulsions

Phase inversion techniques apply thermodynamic and compositional transitions to spontaneously generate multiple emulsions instead of using mechanical energy input alone. These methods take advantage of the natural instability of emulsion systems at specific compositions or temperatures to cause structural reorganization into higher-order architectures. The most general method is the phase inversion temperature (PIT) technique, which takes advantage of the thermally dependent solubility behavior of non-ionic surfactants. In response to variations in temperature, these surfactants exhibit a change in hydrophilic-lipophilic balance that precipitates an emulsion phase inversion at a relatively fast rate. By slowly heating or cooling around this phase inversion temperature, it is possible to create multiple emulsions spontaneously. For instance, a W/O emulsion can go through a bicontinuous state before reconfiguring into an W/O/W multiple emulsion structure. Likewise, the phase inversion composition (PIC) technique produces similar results by gradually varying the system composition by the targeted addition of components. This is often done by adding water to an oil-surfactant combination or vice versa at regulated rates, moving through a phase inversion zone where several emulsion structures emerge. The catastrophic phase inversion method is another variation, in which the ratio of phases abruptly is changed beyond a critical value, initiating spontaneous multiple emulsion formation. Such methods are highly energy efficient, with many involving little or no mechanical agitation compared to traditional methods. The resulting multiple emulsions are often highly stable because of the more natural surfactant arrangement at interfaces. Nevertheless, phase inversion processes are formulation-dependent and sensitive to process conditions, demanding much development work per new system. Their usefulness is also confined to specific classes of surfactant systems which can undergo the required phase changes, so they are less flexible than

mechanical procedures but possibly more powerful for suitable formulations.^{[16],[39],[40],[22],[41]}

3.6 Ultrasonication for Multiple Emulsions

Ultrasonication is a high-energy method of multiple emulsion preparation that involves acoustic cavitation to produce high levels of local mixing and disruptive forces. Ultrasonic waves, generally in the range 20-40 kHz, are used to produce the areas of alternating compression and rarefaction within the liquid medium. The major process of ultrasonication is the generation and violent collapse of cavitation bubbles (microbubbles) in the liquid phases. During their collapse, the bubbles create localized high-temperature zones (about 5000 K) and high-pressure zones (up to 1000 atm), as well as intense shock waves and liquid jets. The strong forces disintegrate droplets into submicron sizes with the additional effect of improving the adsorption of surfactants at fresh interfaces. In case of multiple emulsions, ultrasonication is most often employed in a controlled two-stage process. The initial emulsion (W/O or O/W) is first prepared using moderate ultrasonic intensity and treatment time. The primary emulsion is subsequently dispersed into the outer phase with milder ultrasonication parameters to produce the resultant multiple emulsion structure. Accurate regulation of the ultrasonic power, treatment time, and temperature is essential, as excessive energy input leads to destruction of the primary emulsion droplets and destabilization of the whole system.

Contemporary ultrasonication systems for emulsification are probe-type sonicators for lab-scale production and flow-through ultrasonic reactors for continuous industrial operation. The method has benefits of creating extremely fine droplets with small size distributions and increased stability. Some drawbacks are the possibility of thermal effects on temperature-sensitive ingredients, the problem of scaling up without uniform energy distribution, and the necessity to optimize under careful conditions to avoid too much disruption of the primary emulsion system during the second step of emulsification.^{[42],[43],[44],[45]}

Table 2: Key Differences Between Multiple and Traditional Emulsions.

Feature	Traditional Emulsions	Multiple Emulsions
Structure	Simple two-phase systems (O/W or W/O).	Complex systems with three phases (e.g., W/O/W or O/W/O).
Applications	Widely used in food, cosmetics, and pharmaceuticals for basic formulations.	Specialized applications in controlled drug delivery, targeted therapy, and encapsulation.
Release Mechanism	Immediate release of active ingredients.	Sustained or controlled release due to the presence of multiple phases.
Stability	Less stable compared to multiple emulsions, requiring additional stabilizers.	More stable due to the presence of two types of surfactants and multiple phases.
Formulation Complexity	Relatively simple to formulate.	More complex, requiring precise control of surfactant ratios and phase compositions.

4. APPLICATIONS OF MULTIPLE EMULSIONS

4.1 Cosmetics and Personal Care

Multiple emulsions have transformed the cosmetic market with unprecedented cosmetic formulation flexibility and performance benefits compared to traditional products. These advanced systems have become a key resource for cosmetic formulators intent on creating products with upgraded efficacy, superior sensory profiles, and new functional features. Multiple emulsion systems' intricate architecture especially water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O) systems opens up exceptional possibilities for the resolution of various cosmetic issues while delivering an outstanding consumer experience. One of the primary benefits of multiple emulsions in cosmetics is their enhanced capability for enhanced active ingredient delivery. Their compartmentalized structure allows for simultaneous entrapment of both hydrophilic and hydrophobic actives in a single formulation, avoiding solubility limitations facing traditional systems.^{[7],[19],[23],[46]} The two-phase encapsulation prevents sensitive ingredients from being degraded by environmental factors such as oxygen, light, and incompatibility with other formulation ingredients. For instance, water-unstable vitamin C can be effectively stabilized in the innermost water phase of an aqueous-phase inner/oil-phase middle/water-phase outer emulsion and shielded until application. Similarly, oxidation-sensitive retinoids and other molecules may be saved from premature degradation and thus retain their potency along the product's shelf life. The programmed release mode of poly-emulsions is yet another significant advantage for cosmetics. Through deliberate design of interfacial structure and phase proportions, formulators can design systems that deliver active ingredients on specified stimuli upon application. This is temporal control of delivery, permitting sequential delivery of complementary actives to maximize synergy and improve total product performance. For instance, a facial serum in the form of a multiple emulsion could release moisturizing ingredients when applied initially, followed by delayed release of anti-aging ingredients as the product interacts with the natural environment of the skin. Multiple emulsions have also found to be most useful in moisturizing products, where they provide enhanced hydration properties over standard offerings. The water-dense inner phase of W/O/W emulsions can act as a reservoir for water that can be released progressively into the skin for long-term hydration effects. Furthermore, the multifaceted nature forms a multi-layer film at the surface of the skin that efficiently impedes trans-epidermal water loss while possessing a pleasant, non-greasy texture. This blend of instant and long-term moisturization meets a central consumer need for products that provide both immediate and long-term benefits.^{[20],[22],[24]} In sun protection, multiple emulsions have facilitated important advances in formulation aesthetics and performance. Conventional sunscreens tend to struggle with the balance between high SPF protection and cosmetic beauty. Systems of multiple

emulsions enable strategic partitioning of UV filters between the aqueous and oil phases, maximizing their protective potential and preserving excellent sensory characteristics. Compartmental structure also enables easy incorporation of antioxidants and soothing compounds in addition to UV filters to form integrated photoprotection systems that take into account a variety of effects of sun damage the unique sensory properties of multiple emulsions have rendered them very highly valued in high-end cosmetic products. Their special rheological characteristics produce transformational textures that reform during application, providing new sensory profiles that heighten consumer satisfaction.^{[5],[47]} For example, multiple emulsions can be designed to have a luxurious, rich texture in the package that changes into a light, refreshing sensation upon application to the skin. This "break and release" effect gives an impression of effectiveness and opulence to which consumers respond very strongly. In addition to their functional effects, several emulsions also cater to the trend toward sustainability and "clean" cosmetic ingredients.

By packaging active ingredients more effectively, these systems tend to be able to function at lower functional ingredient concentrations for the same level of performance. This lowering of ingredient load can reduce the environmental impact of formulations without compromising or even improving product performance.^{[46],[48],[49]} In addition, the sophisticated stabilization processes used in multiple emulsions occasionally permit reducing or even avoiding synthetic stabilizers, as preferred by consumers with a desire for more natural product formulations. While their many benefits, the effective use of multiple emulsions in commercial cosmetics necessitates close attention to stability issues and manufacturing intricacies. The intrinsic thermodynamic instability of these systems demands advanced stabilization techniques and stringent process control. Nevertheless, recent developments in emulsification technologies and new stabilizing agents have greatly enhanced the practical feasibility of multiple emulsions in commercial cosmetic uses, broadening their potential in a wide range of product categories.^{[50],[51],[7],[19],[46],[52]}

4.2. Pharmaceuticals

Multiple emulsions have become drug delivery systems with significant strength in the pharmaceutical domain, providing promising advantages for confronting many therapeutic hurdles. These composite systems, both water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O) emulsions, provide novel remedies for controlled drug delivery, enhancing bioavailability, targeting, and preservation of reactive active pharmaceutical components. The capacity for controlled delivery by multiple emulsions stands among their greatest pharmaceutical uses. The multi-compartmental system forms sequential diffusional barriers that control drug release kinetics to provide sustained or pulsatile delivery profiles that are not possible with traditional

formulations. Pharmaceutical scientists can engineer systems that sustain therapeutic drug levels over prolonged periods by controlling the properties of individual phases and interfaces. This regulated release process is especially beneficial for drugs with small therapeutic windows or those needing site-specific delivery to achieve maximal efficacy with minimal systemic side effects. Several emulsions are very effective in improving the bioavailability of problematic drug molecules. For less water-soluble compounds, which represent a large majority of new chemical entities in pharmaceutical development pipelines, O/W/O systems can offer lipophilic microenvironments with enhanced solubilization and aqueous biological fluid compatibility. W/O/W emulsions, in contrast, can promote the absorption of hydrophilic macromolecules by shielding them from enzymatic degradation and allowing them to traverse biological barriers. This versatility makes multiple emulsions particularly valuable in addressing the delivery challenge of both small molecule drugs and biologics.^{[2],[53],[54]} Multiple emulsions' compartmentalized structure offers unmatched protection for fragile therapeutic agents. Proteins, peptides, vaccines, and nucleic acids that are prone to degradation by environmental factors can be shielded in the innermost phase, maintaining their structural integrity and biological activity. The protective role of enhancing shelf life and therapeutic effect, overcoming core issues in formulating biopharmaceuticals. Furthermore, multiple emulsions can facilitate alleviation of chemical incompatibility among multiple active ingredients through separating them to different phases such that combination therapy otherwise pharmaceutically incompatible becomes possible.^{[5],[8],[53]}

In the area of site-specific drug delivery, multiple emulsions offer advanced approaches toward site-specific activity. Through the incorporation of targeting ligands on the interface of the outermost phase or stimuli-sensitive interfaces, these systems can be made to selectively target their payload to certain tissues, cells, or subcellular compartments. pH-sensitive multiple emulsions, for instance, can be stable at physiological pH but release the contents in the tumor or inflammatory tissues' acidic pH. Similarly, enzyme-activated systems may react to certain biochemical markers of disease states, offering controlled spatial and temporal drug delivery. Multiple emulsions have also shown much promise in the delivery of vaccines, where they may serve not only as carriers for antigens but also as adjuvants. Such systems mimic the multi-compartmental architecture of pathogens, likely increasing immune detection and response. The capacity for antigen and immunostimulatory molecule co-delivery while shielding them from degradation has demonstrated high potential to enhance vaccine stability and efficacy, especially for subunit and nucleic acid vaccines that are not intrinsically immunogenic. Taste-masking is another useful pharmaceutical utility, especially for pediatric and

geriatric formulations where palatability directly affects compliance. By encapsulating bitter or unpleasantly flavored drugs inside the inner phase of a multiple emulsion, contact with taste receptors is avoided, enhancing patient acceptability without sacrificing therapeutic effect. Though the potential is great, bringing multiple emulsion technology from the lab to the market as commercial drugs is hampered by several problems, such as manufacturing complexity on a large scale, long-term stability issues, and regulatory concerns. Yet, technological advances in emulsification techniques, new stabilizers, and better characterization tools are increasingly overcoming these disadvantages, increasing the practical uses of multiple emulsions in various therapeutic applications and dosage forms. With advancements in research by pharmaceutical scientists, multiple emulsions are likely to be increasingly significant elements of the next generation of drug delivery systems.^{[55],[56],[57],[58]}

4.3. Agriculture

Multiple emulsions have been revolutionary delivery systems in agriculture that provide advanced solutions to age-old problems in plant protection, nutrient delivery, and environmentally friendly cultivation practices. The hierarchical systems involving droplets of droplets exhibit special benefits for agricultural products that cannot be obtained through traditional delivery systems. For crop protection, multiple emulsions have made pesticide delivery revolutionized by making controlled release of active ingredients possible. The compartmentalized nature enables pesticides to diffuse slowly through several phases, prolonging their longevity in the field but at effective levels. The mechanism of prolonged release reduces the frequency of application, lessening labour and minimizing environmental exposure. For example, W/O/W emulsions have the ability to entrap water-soluble insecticides within the internal aqueous phase, preventing them from undergoing rapid degradation in the environment and providing continuous release over an extended period. Multiple emulsions' protective role is particularly advantageous in protecting delicate agrochemicals from environmental stresses. Biopesticides, biologicals such as beneficial microbes and plant growth-promoting rhizobacteria exhibit poor stability of field because these are vulnerable to UV radiation, heat, and dehydration. In encapsulation, these bioactive compounds can be incorporated within the innermost layer of the multiplicity emulsion, whereby it is enhanced quite significantly as for shelf life of these materials while their performance field is optimized. Multiple emulsions proved of great use while reducing the environment impact of the agrochemicals. Their structured nature minimizes leaching and runoff of active compounds, decreasing water pollution and off-target impacts. This targeted delivery method is in line with precision agriculture guidelines, minimizing ecosystem disturbance while ensuring that inputs find their target locations. Some formulations are composed of pH-

sensitive or biodegradable compounds that respond to specific environmental stimuli and release the active compounds only when conditions favor their optimal efficiency. In fertilizers, double emulsions open up new opportunities for nutrient delivery and utilization efficiency. By encapsulating macronutrients and micronutrients in distinct compartments, these systems can synchronize release with plant nutrient uptake rhythms to reduce losses through leaching and volatilization. This enhanced nutrient use efficiency solves one of the most important sustainability issues in current agriculture, having the potential to decrease fertilizer application without decreasing or even enhancing crop yields. The flexibility of multi-emulsions allows for synergistic agricultural inputs that are otherwise incompatible to be delivered jointly. Antagonistic action fertilizers and pesticides can be separated into separate phases of the emulsion to be used in single-application treatments for multiple purposes. This functional integration not only streamlines field operations but can also increase overall effectiveness through complementary mechanisms of action.^{[49],[59]} Seed treatment is another potential use, where emulsions may be used to form protective films that contain fungicides, insecticides, growth regulators, and nutrients in one product. Release of these components in a layered fashion aids germination and seedling development and protects against pest and disease during this susceptible stage of growth. Although they have immense potential, the use of various emulsion technologies in agriculture is confronted with some challenges, such as manufacturing scale-up, economics, and regulatory issues. Nonetheless, current advancements in green chemistry strategies, such as the formation of multiple emulsions stabilized by biodegradable surfactants and natural polymers, are meeting the sustainability requirements and broadening their applications in agriculture. With agriculture increasingly moving towards more sustainable and efficient farming practices, the use of multiple emulsions as advanced delivery systems provides nuanced delivery platforms that both maximize agronomic performance and minimize environmental impact, making them important components in next-generation agricultural technology development.^{[60],[61]}

4.4. Food & Flavors

Multiple emulsions have become novel food technology systems with unprecedented benefits that benefit both technical issues and changing consumer expectations. Hierarchical multiple emulsion systems, with their conventional water-in-oil-in-water (W/O/W) or oil-in-water-in-oil (O/W/O) forms, are excellent flexible tools for food scientists to design healthier, more stable, and functionally improved food items. The highest food science application of multiple emulsions has been creating low-fat products without sacrificing sensory characteristics.^{[14],[33],[47],[62],[63]} By substituting some of the oil phase with water droplets in W/O/W emulsions, product formulators can develop products having significantly reduced fat content but keeping creamy

textures and mouthfeel traits of full-fat counterparts. It has been well implemented in foods across many product categories, such as salad dressing, spreads, sauces, and dairy foods, so that it becomes possible to reduce calories but not consumer acceptance. The encapsulation properties of multiple emulsions offer great prospects for safeguarding delicate food ingredients. Bioactive compounds like vitamins, antioxidants, and probiotics commonly vulnerable to breakdown upon processing, storage, or digestion can be protected in the innermost phase, enhancing their stability and bioavailability for example, water-soluble vitamins present in the internal aqueous phase of W/O/W emulsions are better retained during thermal processing and shelf life, thereby addressing one of the most serious problems confronting fortified food formulation. Flavors delivery is another useful application of multiple emulsions to foods. By selective partitioning of flavor compounds into different phases, formulators can create controlled release profiles which maximize the taste perception. This compartmentalization enables sequential release of flavor ingredients to create more sophisticated and dynamic flavor profiles. Additionally, multiple emulsions are able to mask off-flavors inherent with some functional ingredients, such as polyphenol-evoked bittering or mineral fortification-induced metallic aftertastes, to increase palatability of nutritionally enhanced foods. The structured character of multiple emulsions offers distinct potential for modulating the fate and bioavailability during digestion of nutrients. By creating interfaces with targeted properties, formulators can control the way that emulsions interact with digestive enzymes and the release and absorption of encapsulated nutrients in the gastrointestinal tract. This technique has been promising in increasing the bioavailability of lipophilic nutrients such as carotenoids and fat-soluble vitamins, meeting a major challenge in food formulation for nutritional foods. Salt reduction schemes have also been advantageously impacted by multiple emulsion technology. By generating discontinuous salt distribution in food matrices through W/O/W systems, the developers are able to increase salt perception at decreased total sodium content. This localized concentration effect activates taste receptors more effectively, enabling sodium reductions of as much as 25% without sacrificing flavor profiles meeting public health needs for reduced sodium intake.^{[56],[64],[65],[66],[67],[68]} Multiple emulsions have shown utility in texture modification and stability improvement of complex food systems. Their distinctive rheological characteristics can be used to develop new textural properties or to stabilize difficult-to-formulate systems that are susceptible to phase separation. This application has been of specific utility in plant-derived alternatives to dairy and meat foods, where replicating genuine textures and mouthfeel is still a major technical problem. Although they hold significant potential, large-scale deployment of multiple emulsions in commodity foods is hampered by issues of long-term stability, industrial-scale cost-effective production, and regulatory issues. Nonetheless, innovation in emulsification

technologies, natural stabilizers, and process enhancement is increasingly overcoming these constraints. As food producers look for more creative solutions to healthier, more sustainable, and more differentiated foods, multiple emulsions provide high-tech solutions that reconcile nutritional advantage with the sensory attributes that create consumer acceptability.^{[47],[63],[69],[64],[56]}

5. CONCLUSION

Multiple emulsions are now a cutting-edge technology in many industries with sophisticated delivery systems and new advantages over conventional emulsions. Its complex hierarchical structure either water-in-oil-in-water (W/O/W) or oil-in-water-in-oil (O/W/O) enables the simultaneous encapsulation of incompatible compounds, protection of unstable compounds, control of release, and stabilization of active compounds. In cosmetics, multiple emulsions have revolutionized product formulas with better moisturization, enriched sensory properties, and better delivery of active compounds. The pharmaceutical industry has also applied these systems for drug delivery in controlled forms, bioavailability enhancement, and stabilization of vulnerable therapeutic agents. In agriculture, multiple emulsions offer sustainable solutions for low-environmental-impact delivery of pesticides and fertilizers. These systems have been applied by the food industry to generate low-fat products without compromising sensory properties and improving nutrient bioavailability. Though they hold tremendous promise, challenges have to be overcome to boost the level of production, ensure long-term stability, and address regulatory issues. Advances in emulsification technology presently available, e.g., microfluidics, membrane emulsification, and novel stabilizers, are ever more addressing these limitations, thereby further enhancing the potential applications in practice of multiple emulsions. With ongoing advancement in the development of formulation techniques and stabilization procedures, multiple emulsions stand to become even more important in the development of the next generation products in industries. Their versatility and range of functions position them for the strategic resolution of contemporary issues in product development and meeting evolving market and consumer needs for higher functionality, sustainability, and multifunctionality.

6. REFERENCE

1. A. Y. Khan, S. Talegaonkar, Z. Iqbal, F. J. Ahmed, and R. K. Khar, "Multiple emulsions: an overview," *Curr. Drug Deliv.*, Oct. 2006; 3(4): 429–443. doi: 10.2174/156720106778559056.
2. M. Serdaroglu, A. Kara, and B. Öztürk, "MULTIPLE EMULSIONS AND THEIR APPLICATIONS IN FOOD," 2013; 2.
3. Anisha Agrawal* and Sunisha Kulkarni, Shyam Bihari Sharma, "Recent advancements and applications of multiple emulsions," *Int. J. Adv. Pharm.*, 2015; 6(4): 94–103, doi: 10.7439/ijap.
4. R. Kumar, M. S. Kumar, and N. Mahadevan, "Multiple Emulsions: A Review".
5. M. V. Swamy, S. Metta, A. A. Kumar, C. J. Mohan Reddy, G. Dharani, and K. Ramya, "Formulation and Characterization of a multiple Emulsion containing Vitamin - C," *Res. J. Pharm. Dos. Forms Technol.*, Mar. 2023; 1–6, doi: 10.52711/0975-4377.2023.00001.
6. Nitin Singh, "Technology, Recent Advancement, and Application of Multiple Emulsions: An Overview," *ASIAN J. Pharm.*, 15(03), doi: 10.22377/ajp.v15i3.4143.
7. S. Rathod, K. Shinde, N. Shinde, and N. Aloorkar, "Cosmeceuticals and Nanotechnology in Beauty Care Products," *Res. J. Top. Cosmet. Sci.*, Dec. 2021; 93–101, doi: 10.52711/2321-5844.2021.00013.
8. S. Nakhare and S. P. Vyas, "Preparation and characterization of multiple emulsion based systems for controlled diclofenac sodium release," *J. Microencapsul.*, Jan. 1996; 13(3): 281–292, doi: 10.3109/02652049609026016.
9. N. Sharma, R. Devi, S. Singh, A. Garg, R. Khathuriya, and I. Singhvi, "AN OVERVIEW ON MULTIPLE EMULSIONS".
10. A. Yaqoob Khan, S. Talegaonkar, Z. Iqbal, F. Jalees Ahmed, and R. Krishan Khar, "Multiple Emulsions: An Overview," *Curr. Drug Deliv.*, Oct. 2006; 3(4): 429–443, doi: 10.2174/156720106778559056.
11. G. S. Dhadde, H. S. Mali, I. D. Raut, and M. M. Nitalikar, "An Overview on Multiple Emulsions," *Asian J. Pharm. Technol.*, May 2021; 156–162, doi: 10.52711/2231-5713.2021.00026.
12. N. K. Verma and J. N. Mishra, "Multiple emulsions and its stabilization: A review".
13. N. K. Verma, S. P. Srivastava, and S. Kumar, "MULTIPLE EMULSIONS AND ITS APPLICATIONS A REVIEW," 2019.
14. Y.-H. Cho, E. K. Bae, T.-S. Shin, S.-W. Choi, K.-H. Choi, and J. Park, "Development of W/O/W Multiple Emulsion Formulation Containing".
15. H. Ghasemi, S. Darjani, H. Mazloomi, and S. Mozaffari, "Preparation of stable multiple emulsions using food-grade emulsifiers: evaluating the effects of emulsifier concentration, W/O phase ratio, and emulsification process," *SN Appl. Sci.*, Dec. 2020; 2(12): 2002. doi: 10.1007/s42452-020-03879-5.
16. N. Singh, N. Garud, R. Joshi, and W. Akram, "Technology, Recent Advancement, and Application of Multiple Emulsions: An Overview".
17. G. Muschiolik and E. Dickinson, "Double Emulsions Relevant to Food Systems: Preparation, Stability, and Applications," *Compr. Rev. Food Sci. Food Saf.*, May 2017; 16(3): 532–555, doi: 10.1111/1541-4337.12261.
18. "10.Sagar-Savale-Uday-Mali-Patil-Prafulla."
19. T. Mahmood and N. Akhtar, "Stability of a Cosmetic Multiple Emulsion Loaded with Green

- Tea Extract,” *Sci. World J.*, Jan. 2013; 1: 153695, doi: 10.1155/2013/153695.
20. S. Chintala, “EXPLORING THE VERSATILITY OF MULTIPLE EMULSIONS: A COMPREHENSIVE REVIEW OF PREPARATION TECHNIQUES, EVALUATION METHODS, AND DIVERSE APPLICATIONS,” 2021; 08(04).
 21. P. Sb, “An overview of Preparation, Evaluation and Applications of Multiple Emulsions”.
 22. R. L. Deshmukh, “MULTIPLE EMULSION: STRATAGIC AND TECHNOLOGY,” 2014; 2(2).
 23. Y. Sakai, “Application of emulsion technology to cosmetics,” *Int. J. Cosmet. Sci.*, Apr. 2005; 27(2): 133–133, doi: 10.1111/j.1467-2494.2005.00260_1.x.
 24. N. Garti, “Double emulsions — scope, limitations and new achievements,” *Colloids Surf. Physicochem. Eng. Asp.*, May 1997; 123–124, pp. 233–246, doi: 10.1016/S0927-7757(96)03809-5.
 25. N. Garti and C. Bisperink, “Double emulsions: Progress and applications,” *Curr. Opin. Colloid Interface Sci.*, Dec. 1998; 3(6): 657–667, doi: 10.1016/S1359-0294(98)80096-4.
 26. S. Kim, K. Kim, and S. Q. Choi, “Controllable one-step double emulsion formation via phase inversion,” *Soft Matter*, 2018; 14(7): 1094–1099, doi: 10.1039/C7SM02134H.
 27. L. Hong, G. Sun, J. Cai, and T. Ngai, “One-Step Formation of W/O/W Multiple Emulsions Stabilized by Single Amphiphilic Block Copolymers,” *Langmuir*, Feb. 2012; 28(5): 2332–2336, doi: 10.1021/la205108w.
 28. J. M. Morais, O. D. H. Santos, J. R. L. Nunes, C. F. Zanatta, and P. A. Rocha-Filho, “W/O/W Multiple Emulsions Obtained by One-Step Emulsification Method and Evaluation of the Involved Variables,” *J. Dispers. Sci. Technol.*, Jan. 2008; 29(1): 63–69, doi: 10.1080/01932690701688391.
 29. S. Saffarionpour, “One-step preparation of double emulsions stabilized with amphiphilic and stimuli-responsive block copolymers and nanoparticles for nutraceuticals and drug delivery,” *JCIS Open*, Oct. 2021; 3: 100020, doi: 10.1016/j.jciso.2021.100020.
 30. L. Hong, G. Sun, J. Cai, and T. Ngai, “One-Step Formation of W/O/W Multiple Emulsions Stabilized by Single Amphiphilic Block Copolymers,” *Langmuir*, Feb. 2012; 28(5): 2332–2336, doi: 10.1021/la205108w.
 31. “2011_angewchem_kim.”
 32. W. Liu, X.-L. Yang, and W. S. Winston Ho, “Preparation of Uniform-Sized Multiple Emulsions and Micro/Nano Particulates for Drug Delivery by Membrane Emulsification,” *J. Pharm. Sci.*, Jan. 2011; 100(1): 75–93, doi: 10.1002/jps.22272.
 33. C. Charcosset, “Preparation of emulsions and particles by membrane emulsification for the food processing industry,” *J. Food Eng.*, Jun. 2009; 92(3): 241–249, doi: 10.1016/j.jfoodeng.2008.11.017.
 34. S. M. Joscelyne and G. Trägårdh, “Membrane emulsification — a literature review,” *J. Membr. Sci.*, Apr. 2000; 169(1): 107–117, doi: 10.1016/S0376-7388(99)00334-8.
 35. S. Vandergraaf, C. Schroen, and R. Boom, “Preparation of double emulsions by membrane emulsification? a review,” *J. Membr. Sci.*, Apr. 2005; 251: 1–2, pp. 7–15, doi: 10.1016/j.memsci.2004.12.013.
 36. G. Vladislavljević, R. Al Nuamani, and S. Nabavi, “Microfluidic Production of Multiple Emulsions,” *Micromachines*, Mar. 2017; 8(3): 75, doi: 10.3390/mi8030075.
 37. C. Choi, J. Kim, J. Nam, S. Kang, S. Jeong, and C. Lee, “Microfluidic Design of Complex Emulsions,” *ChemPhysChem*, Jan. 2014; 15(1): 21–29, doi: 10.1002/cphc.201300821.
 38. A. Sattari, P. Hanafizadeh, and M. M. Keshtiban, “Microfluidic preparation of double emulsions using a high aspect ratio double co-flow device,” *Colloids Surf. Physicochem. Eng. Asp.*, Nov. 2021; 628: 127297, doi: 10.1016/j.colsurfa.2021.127297.
 39. A. Kumar, S. Li, C.-M. Cheng, and D. Lee, “Recent Developments in Phase Inversion Emulsification,” *Ind. Eng. Chem. Res.*, Sep. 2015; 54(34): 8375–8396, doi: 10.1021/acs.iecr.5b01122.
 40. A. Perazzo, V. Preziosi, and S. Guido, “Phase inversion emulsification: Current understanding and applications,” *Adv. Colloid Interface Sci.*, Aug. 2015; 222: 581–599, doi: 10.1016/j.cis.2015.01.001.
 41. X. Wang, X. Lu, L. Wen, and Z. Yin, “Incomplete phase inversion W/O/W emulsion and formation mechanism from an interfacial perspective,” *J. Dispers. Sci. Technol.*, Jan. 2018; 39(1): 122–129, doi: 10.1080/01932691.2017.1300909.
 42. “2020_Khadem_Ultrasound_Hal.”
 43. M. Ganguly, D. Debraj, N. Mazumder, J. Carpenter, S. Manickam, and A. B. Pandit, “Impact of Ultrasonication on the Oxidative Stability of Oil-in-Water Nanoemulsions: Investigations into Kinetics and Strategies to Control Lipid Oxidation,” *Ind. Eng. Chem. Res.*, Jun. 2024; 63(23): 10212–10225, doi: 10.1021/acs.iecr.4c00506.
 44. C.-Y. Lin and L.-W. Chen, “Emulsification characteristics of three- and two-phase emulsions prepared by the ultrasonic emulsification method,” *Fuel Process. Technol.*, Apr. 2006; 87(4): 309–317, doi: 10.1016/j.fuproc.2005.08.014.
 45. A. Taha *et al.*, “Ultrasonic emulsification: An overview on the preparation of different emulsifiers-stabilized emulsions,” *Trends Food Sci. Technol.*, Nov. 2020; 105: 363–377, doi: 10.1016/j.tifs.2020.09.024.
 46. “9. Multiple emulsions in cosmetics,” in *Industrial Applications I*, De Gruyter, 2017; 193–212. doi: 10.1515/9783110555257-010.
 47. L. Bai, S. Huan, O. J. Rojas, and D. J. McClements, “Recent Innovations in Emulsion Science and Technology for Food Applications,” *J. Agric. Food Chem.*, Aug. 2021; 69(32): 8944–8963, doi: 10.1021/acs.jafc.1c01877.

48. T. F. Tadros, "Future developments in cosmetic formulations," *Int. J. Cosmet. Sci.*, Jun. 1992; 14(3): 93–111, doi: 10.1111/j.1467-2494.1992.tb00045.x.
49. T. Tadros, "Agrochemical Formulations," in *Encyclopedia of Colloid and Interface Science*, T. Tadros, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2013; 3–80. doi: 10.1007/978-3-642-20665-8_7.
50. "8. Formulation of multiple emulsions in cosmetics," in *Formulations*, De Gruyter, 2016; 179–192. doi: 10.1515/9783110452389-009.
51. T. Yanaki, "Preparation of O/W/O type multiple emulsions and its application to cosmetics," in *Studies in Surface Science and Catalysis*, vol. 132, Elsevier, 2001; 1009–1014. doi: 10.1016/S0167-2991(01)82255-2.
52. M. E. Carlotti, M. Gallarate, S. Sapino, E. Ugazio, and S. Morel, "W/O/W Multiple Emulsions for Dermatological and Cosmetic Use, Obtained with Ethylene Oxide Free Emulsifiers," *J. Dispers. Sci. Technol.*, Mar. 2005; 26(2): 183–192, doi: 10.1081/DIS-200045584.
53. A. K. Jena, A. K. Nayak, A. De, D. Mitra, and A. Samanta, "Development of lamivudine containing multiple emulsions stabilized by gum odina," *Future J. Pharm. Sci.*, Jun. 2018; 4(1): 71–79. doi: 10.1016/j.fjps.2017.10.002.
54. "41.Naman-Kumar-Dr.-Chinu-Sharma-Hitesh-Thakur."
55. J. Wang, A. Shi, D. Agyei, and Q. Wang, "Formulation of water-in-oil-in-water (W/O/W) emulsions containing trans-resveratrol," *RSC Adv.*, 2017; 7(57): 35917–35927, doi: 10.1039/C7RA05945K.
56. S. Ghosh, "Formulation and Charecterisation of Multiple Emulsions With Various Additives".
57. R. P. Sonwane and S. R. Gawande, "Formulation and Evaluation of Multiple Emulsion of Vancomycin HCl," 10(6).
58. J. Jiao and D. J. Burgess, "Rheology and stability of water-in-oil-in-water multiple emulsions containing Span 83 and Tween 80," *AAPS PharmSci*, Mar. 2003; 5(1): 62–73, doi: 10.1208/ps050107.
59. I. Klotjdová and C. Stathopoulos, "The Potential Application of Pickering Multiple Emulsions in Food".
60. K. Sangwan *et al.*, "Development and characterization of W/O/W double emulsion of watermelon rind powder," *LWT*, Jun. 2023; 182: 114848, doi: 10.1016/j.lwt.2023.114848.
61. N. Akhtar *et al.*, "Formulation and characterization of a multiple emulsion containing 1% L-ascorbic acid," *Bull. Chem. Soc. Ethiop.*, Mar. 2010; 24(1). doi: 10.4314/bcse.v24i1.52955.
62. M. Ben Jemaa, H. Falleh, and R. Ksouri, "Encapsulation of Natural Bioactive Compounds: Nanoemulsion Formulation to Enhance Essential Oils Activities," in *Microencapsulation - Processes, Technologies and Industrial Applications*, F. Salaün, Ed., Intech Open, 2019. doi: 10.5772/intechopen.84183.
63. V. M. Balcão, C. A. Glasser, M. V. Chaud, and M. M. D. C. Vila, "Water-in-Oil-in-Water Nanoencapsulation Systems," in *Microencapsulation and Microspheres for Food Applications*, Elsevier, 2015; 95–129. doi: 10.1016/B978-0-12-800350-3.00008-X.
64. G. Øye, S. Simon, T. Rustad, and K. Paso, "Trends in food emulsion technology: Pickering, nano-, and double emulsions," *Curr. Opin. Food Sci.*, Apr. 2023; 50: 101003, doi: 10.1016/j.cofs.2023.101003.
65. C. Tan and D. J. McClements, "Application of Advanced Emulsion Technology in the Food Industry: A Review and Critical Evaluation," *Foods Basel Switz.*, Apr. 2021; 10(4): 812, doi: 10.3390/foods10040812.
66. G. Muschiolik, "Multiple emulsions for food use," *Curr. Opin. Colloid Interface Sci.*, Oct. 2007; 12(4–5): 213–220, doi: 10.1016/j.cocis.2007.07.006.
67. L. Mao, Y. H. Roos, C. G. Biliaderis, and S. Miao, "Food emulsions as delivery systems for flavor compounds: A review," *Crit. Rev. Food Sci. Nutr.*, Jun. 2013; 57(15): 3173–3187, Oct. 2017, doi: 10.1080/10408398.2015.1098586.
68. F. Jiménez-Colmenero, "Potential applications of multiple emulsions in the development of healthy and functional foods," *Food Res. Int.*, Jun. 2013; 52(1): 64–74, doi: 10.1016/j.foodres.2013.02.040.
69. [69] U. Cizauskaite and J. Bernatoniene, "Innovative Natural Ingredients-Based Multiple Emulsions: The Effect on Human Skin Moisture, Sebum Content, Pore Size and Pigmentation," *Mol. Basel Switz.*, Jun. 2018; 23(6): 1428, doi: 10.3390/molecules23061428.