

GREEN MICROEMULSIONS: SUSTAINABLE APPROACHES AND EMERGING INDUSTRIAL APPLICATIONS

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ABSTRACT

Green microemulsions are a novel type of microemulsion that have been studied in the recent past with various environmental benefits when compared to the current microemulsions employed in various industries. Such microemulsions are free from petroleum surfactants since they incorporate oils, naturally occurring surfactants, and other suitable environmentally friendly surfactants and cosurfactants. In turn, this changes how things are done by reducing the carbon footprint, reducing toxicity and increasing biodegradability. Green microemulsions are proved to perform efficiently in a variety of areas, such as active ingredients delivery systems, with focused applications within the cosmetic, food, agricultural, and pharmaceutical industries, where they enhance stability, provide effective active ingredients delivery and active ingredients bioavailability. The production of these formulations also addresses the growing demand for environmentally friendly products by providing a way for businesses to respond to customer requirements without compromising on the product's efficacy. This review paper presents the processes involved in the production of green microemulsions, the advantages of using green microemulsions as well as the possible new areas where they can be used.

Keywords: Green microemulsions, Sustainable formulations, Bio-based surfactants, Environmental applications, Eco-friendly technology

1. INTRODUCTION

Microemulsions are a novel and significant achievement in the field of liquid dispersion having the unique properties of being thermodynamically stable and optically clear. They are made mostly of two normally immiscible liquids, which are usually oil and water, in which a special interfacial film made up of surfactants and co-surfactants holds them together. This peculiar structure distinguishes them from ordinary emulsions and other colloidal systems. These systems have several unique benefits in their pharmaceutical and industrial uses. The fact that they can be formed spontaneously would render complex manufacturing processes unnecessary, making them ideal for large scale use. Their intrinsic thermodynamic stability avoids many separation problems associated with the more standard emulsions and suspensions. As for drug development and related applications, microemulsions can be used as drug carriers, especially for the delivery of hydrophobic substances, which usually are difficult to solubilize. Improved bioavailability of therapeutic compounds can be achieved through the enhanced solubilization capacity of microemulsions making them valuable in drug delivery systems. Manufacturing simplicity, stability, and enhancement of drug delivery system .[1], [2], [3] This unique structure sets them apart from traditional emulsions and other colloidal systems. These systems offer several distinct advantages in pharmaceutical and industrial applications. In pharmaceutical applications, microemulsions excel as drug carriers, particularly for hydrophobic drugs that typically present solubility challenges. The enhanced solubilization capacity of microemulsions directly translates to improved bioavailability of therapeutic compounds, making them invaluable in drug delivery systems. The combination of simple manufacturing requirements, stability, and enhanced drug delivery capabilities makes microemulsions an increasingly important tool in modern pharmaceutical formulation and other industrial applications.[3], [4], [5]

Green microemulsions represent a significant advancement in sustainable formulation technology, emerging as a response to growing environmental consciousness and consumer demand for natural products. These innovative systems maintain the beneficial properties of traditional microemulsions while incorporating eco-friendly, biodegradable, and renewable components. Unlike conventional microemulsions that often rely on petroleum-based ingredients, green microemulsions utilize natural oils, bio-based surfactants, and non-toxic co-surfactants derived from renewable resources. This environmentally conscious approach not only reduces the carbon footprint but also addresses concerns about toxicity and environmental persistence.[6], [7] The versatility of green microemulsions has led to their widespread adoption in various industries, from pharmaceuticals and cosmetics to food and agriculture, where they offer sustainable alternatives without compromising performance. Their development marks a crucial step toward more sustainable practices in chemical formulations, aligning with global initiatives to protect the environment while meeting modern consumer preferences for natural and safe products. Green microemulsions, in particular, are being developed as environmentally friendly alternatives to conventional formulations. Green microemulsions are being explored in various

fields, including pesticide formulations, enhanced oil recovery, and biofuel production. In the case of pesticides, water-based microemulsions are being developed as potential alternatives to conventional formulations, offering good insecticidal performance with minimal environmental impact [8], [9], [10], [11]. For enhanced oil recovery, environmentally friendly surfactants Coco Glucoside are being investigated to create Winsor Type-III microemulsions with low interfacial tension[12]. In biofuel applications, sugar-based surfactants are being used to formulate microemulsion biofuels, addressing the high viscosity issues of palm oil while maintaining comparable fuel properties to biodiesel)[13]. In conclusion, green microemulsions offer a promising approach to developing environmentally friendly formulations across various industries. By utilizing biodegradable and less toxic components, these systems can provide effective solutions while minimizing environmental impact. However, challenges remain in optimizing formulations and scaling up production for commercial applications

Table 1: - Environmental and Technical Comparison: Traditional vs. Green Microemulsions

Category	Sub-Category	Traditional Microemulsion	Green Microemulsion
Components	Base Materials	Petroleum-based oils, Synthetic chemicals,	Vegetable oils, Plant-derived components,
Components	Resource Type	Non-renewable resources, High carbon footprint	Renewable resources, Lower carbon footprint
Surfactants	Types	Synthetic Surfactant	Green & Natural Surfactant
Surfactants	Effects	Potential skin irritation, Environmental concerns	Skin-friendly, Environmentally safe
Co-Surfactants	Types	Solvents	Green Solvent & oils
Co-Surfactants	Properties	High VOC content, Potentially toxic	Low VOC content, Non-toxic
Sustainability	Life Cycle	Non-biodegradable, Long-term persistence	Biodegradable, Short environmental lifecycle
Environmental Impact	Ecosystem Effects	Aquatic toxicity, Environmental accumulation	Minimal ecotoxicity, No bioaccumulation
Environmental Impact	Degradation	Difficult to degrade, Affects ecosystem balance	Readily biodegradable, Ecosystem friendly

2. EMERGING INDUSTRIAL APPLICATIONS

2.1 Cosmetic Formulation

Green microemulsions are gaining prominence in the cosmetic industry as sustainable and eco-friendly formulations. These systems align with the growing consumer demand for environmentally conscious and "green" cosmetic products. Microemulsions offer several advantages in cosmetic applications, including improved stability, enhanced delivery of active ingredients, and increased bioavailability of compounds. The use of green microemulsions in cosmetics reflects the industry's shift towards sustainable ingredients and formulations. This trend is driven by increasing environmental awareness and consumer preferences for clean labels and eco-friendly. Green microemulsions typically incorporate naturally derived surfactants, oils, and other components, reducing the reliance on synthetic chemicals and potentially harmful ingredients. Interestingly, the COVID-19 pandemic has further accelerated the demand for sustainable and green cosmetic products, including microemulsion. This shift has led to increased research and development efforts in creating innovative, environmentally friendly formulations that meet consumer expectations for both efficacy and sustainability. The integration of nanotechnology and green chemistry approaches in developing these microemulsions offers promising perspectives for creating sustainable and eco-friendly cosmetic ingredients.[14], [15], [16]

2.2 Food Industry

Green microemulsions are gaining prominence in the food industry due to their unique properties and potential for sustainable applications. These systems combine the benefits of microemulsions with environmentally friendly components, addressing the growing demand for greener food products. Microemulsions are homogeneous, transparent liquids consisting of oil, water, and surfactants, often with cosurfactants. They offer advantages such as significant interfacial area, low interfacial tension, and the ability to solubilize and deliver hydrophobic substances. In the food industry, microemulsions and nano emulsions are becoming increasingly popular due to their stability and optical clarity.

These systems can be used to encapsulate, deliver, and protect food components like oil-soluble Flavors, vitamins, colorants, preservatives, and other bioactive ingredients. Interestingly, the incorporation of essential oils in nano emulsions has shown promise in developing environmentally friendly food packaging materials. By nanoemulsifying essential oil, it is possible to increase their antimicrobial activity while reducing the amount required, addressing concerns about organoleptic acceptance levels. This approach can help extend the shelf-life of food products while improving their quality and safety during storage. In conclusion, green microemulsions offer a sustainable solution for various food applications, from packaging to ingredient delivery. The use of natural emulsifiers, such as phospholipids, saponins, proteins, polysaccharides, and biosurfactants, further enhances the eco-friendly aspect of these systems. As the food industry continues to prioritize sustainability and consumer demands for greener products, the development and application of green microemulsions are likely to expand, contributing to more environmentally responsible food processing and packaging solutions.[17], [18], [19]

2.3 Agrochemical industry

Green microemulsions have emerged as promising potential pesticide carriers, offering numerous advantages over conventional formulations. These environmentally friendly systems are thermodynamically stable, transparent liquids composed of polar and non-polar phases, surfactants, and often co-surfactants. They provide improved solubilization of active ingredients, enhanced bioavailability, and better stability during application, resulting in increased efficacy for pest control. The development of green pesticide microemulsions involves careful selection of components to ensure environmental compatibility.

For instance, a chlorpyrifos microemulsion was successfully formulated using environment-friendly compounds, consisting of chlorpyrifos, ethyl acetate, agricultural emulsifier, natural carboxylate, glycol, ethanol, and water. Similarly, sophorolipid biosurfactants have been utilized to create cost-effective and environmentally friendly nano pesticide systems loaded with lambda-cyhalothrin, demonstrating superior insecticidal efficacy compared to commercial emulsifiable concentrate formulations. (Interestingly, the stability and performance of agrochemical microemulsions depend on various factors, including the nature of the pesticide, surfactant type and concentration, and the match between surfactant and oil phase. However, water quality has been shown to have minimal effect on the cloud point of agrochemical microemulsions.

These findings highlight the importance of optimizing formulation parameters to achieve desired performance characteristics. In conclusion, green microemulsions offer a promising approach to developing sustainable and effective pesticide carriers. Their unique properties, such as high stability, spontaneous formation, and excellent solubilization potential, make them ideal candidates for improving pesticide delivery and reducing environmental impact as research in this field continues to advance, green microemulsions are likely to play an increasingly important role in the development of eco-friendly agricultural solutions.[20], [21], [22], [22], [23], [24]

2.4 Pharmaceutical industry

Green microemulsions have emerged as a promising approach in drug delivery systems, offering numerous advantages over traditional methods. These systems combine the principles of microemulsion technology with environmentally friendly and sustainable practices, resulting in more effective and safer drug delivery vehicles. Microemulsions are excellent candidates for drug delivery due to their improved drug solubilization, long shelf life, and ease of preparation and administration.

They offer high solubilization capacity, transparency, thermodynamic stability, and high diffusion and absorption rates compared to solvent systems without surfactants. The green synthesis of microemulsions further enhances these benefits by utilizing eco-friendly and cost-effective approaches. Interestingly, the combination of green nanotechnology and microemulsions has led to innovative drug delivery systems. For instance, the use of plant extracts as reducing agents in the synthesis of silver nanoparticles has shown promise in developing advanced drug delivery systems.

This approach not only aligns with environmentally friendly practices but also provides a cost-effective and scalable method for nanoparticle production. Similarly, the incorporation of Sargassum cristaefolium fucoidan into nano emulsions has demonstrated improved physicochemical properties, antioxidant capacity, and biocompatibility. In conclusion, green microemulsions represent a significant advancement in drug delivery systems, offering improved efficacy, safety, and sustainability. By combining the benefits of microemulsion technology with environmentally friendly synthesis methods, these systems have the potential to revolutionize drug delivery across various routes of administration, including oral, dermal, and parenteral.

As research in this field continues to evolve, green microemulsions are likely to play an increasingly important role in the development of novel and effective drug delivery strategies.[25], [26], [26], [27], [28].

3. SUMMERY

Green microemulsions show a great potential to be a sustainable chemical formulation due to the possibility of different industrial applications. Use of renewable, biodegradable and less toxic raw materials allows green microemulsions to respond to the ecological challenges of traditional formulations. Such trends can be noticed in cosmetics, pharmaceuticals, agriculture and food industries as their products offer better stability, higher effectiveness and cater the global demand for more environment friendly solutions. Even though there are some difficulties in optimizing and scaling the production, green microemulsions have proved their worth as clean alternatives with great performance. Their further advances and use will contribute to greater applications of sustainability and give businesses the means to decrease negative impacts while being productive.

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