REVIEW ARTICLE

ADVANCE IN SOYBEAN LECITHIN-BASED NANOGEL AND NANOPARTICLE SYSTEM FOR ENHANCED BIOAVAILABILITY AND THERAPEUTIC APPLICATIONS: A COMPREHENSIVE REVIEW

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Abstract:

Soybean lecithin, a natural phospholipid enriched with essential components such as phosphatidylcholine and phosphatidylserine, has gained prominence in the development of nanogel and nanoparticle delivery systems. This comprehensive review synthesizes research from 2012 to 2025, focusing on the advancements in soybean lecithin-based nanostructures aimed at enhancing the bioavailability and therapeutic efficacy of various bioactive compounds. The unique physicochemical properties of soybean lecithin, including its amphipathic nature, biocompatibility, and biodegradability, facilitate the formation of stable emulsions, vesicles, and nanogels capable of encapsulating both lipophilic and hydrophilic agents. Diverse synthesis methodologies, such as thin-film ultrasonic dispersion, ethanol injection, solvent evaporation, and emulsion-templated techniques, are evaluated for their effectiveness in producing nanoparticles with optimal size, stability, and encapsulation efficiency. Applications of these lecithin-based systems span across improving the solubility and bio-accessibility of nutraceuticals like curcumin and β-carotene, enhancing drug delivery for conditions such as tuberculosis and glaucoma, and advancing cryopreservation techniques in livestock breeding. Despite promising outcomes, challenges such as variability in lecithin purity, scalability of production processes, and the need for comprehensive safety assessments persist. Future research directions emphasize optimizing lecithin formulations, integrating interdisciplinary approaches, and conducting extensive in vivo studies to fully harness the potential of soybean lecithin-based nanocarriers. Overall, soybean lecithin-based nanogel and nanoparticle systems hold significant promise in revolutionizing drug delivery, nutrient supplementation, and therapeutic applications, while aligning with sustainable and green chemistry principles.

Keywords: Soybean Lecithin, Nanogels, Bioavailability, Therapeutic Applications, Sustainable Nanocarriers.

Introduction:

Soybean lecithin, a natural phospholipid primarily derived from soybeans, has gained significant attention due to its versatile applications in various industries, including food, pharmaceuticals, and cosmetics. Lecithin contains essential phospholipids such as phosphatidylcholine (PC) and phosphatidylserine (PS), which possess amphipathic properties that make them ideal for use in nanostructure-based formulations. These properties are crucial for the formation of stable nanocarriers like nanogels and nanoparticles, which offer enhanced bioavailability and therapeutic efficacy for bioactive compounds [1, 2]. The unique physicochemical properties of soybean lecithin, including its emulsifying, stabilizing, and bioactive functions, make it a promising candidate for drug delivery systems, nutrient delivery, and other therapeutic applications [3, 4].

With the rapid advancements in nanotechnology, lecithin-based delivery systems have emerged as effective carriers for lipophilic and hydrophilic agents, enabling improved stability, controlled release, and targeted delivery. Such systems address the challenges associated with poor solubility and rapid degradation of therapeutic agents [5]. Furthermore, soybean lecithin is biodegradable and biocompatible, making it an attractive candidate for eco-friendly nanocarriers, aligning with the growing emphasis on green chemistry approaches [6]. This review seeks to highlight the recent advancements in soybean lecithin-based nanogels and nanoparticles, focusing on their mechanisms, applications, challenges, and prospects.

1. Physicochemical Properties:

Soybean lecithin's physicochemical properties are key factors that determine its effectiveness in nanostructure formulations. The phospholipids in lecithin, primarily phosphatidylcholine (PC), have an amphipathic nature—having both hydrophilic and lipophilic parts—that allows lecithin to form stable emulsions and vesicular structures [7]. These unique properties enable lecithin to serve as an excellent emulsifier and stabilizer, which is crucial for developing nanocarriers for drug delivery and other bioactive compound formulations. Additionally, studies have shown that the purity of lecithin plays an important role in nanostructure stability, encapsulation efficiency, and performance. High-purity lecithin is more effective in specific applications, particularly in encapsulating and stabilizing bioactive compounds [8].

Furthermore, soybean lecithin's ability to encapsulate both hydrophilic and hydrophobic agents makes it versatile for different drug delivery and nutritional applications. Researchers have observed that lecithin-based formulations can improve the solubility of poorly soluble drugs and increase the bio-accessibility of essential nutrients [9].

2. Synthesis and Characterization Methodologies:

Several techniques are employed to synthesize lecithin-based nanogels and nanoparticles. The most used methods include thin-film hydration, ethanol injection, solvent evaporation, and emulsion-templated methods [10, 11]. Thin-film hydration, for example, allows for the formation of lecithin liposomes, which can be used as drug carriers due to their ability to encapsulate both hydrophobic and hydrophilic drugs efficiently. Ethanol injection and solvent evaporation methods are widely used for nanoparticle formation, where ethanol is typically used to dissolve lecithin and subsequently injected into an aqueous phase to produce nanoparticles [12]. Emulsion-based techniques, including solvent evaporation and solvent diffusion, are particularly beneficial for creating nanoparticle formulations that exhibit controlled release properties, a crucial aspect for therapeutic drug delivery systems [13].

Characterization of lecithin-based nanostructures involves several key parameters, including particle size, zeta potential, polydispersity index (PDI), and encapsulation efficiency. Particle size is crucial as it influences the stability, release profile, and biological behavior of the nanoparticles. Zeta potential provides insight into the surface charge and stability of the nanocarriers, while PDI helps assess the uniformity of the particle size distribution [14]. Studies by Jin *et al.* (2019) and Elnaggar *et al.* (2016) demonstrated the importance of lipid composition in enhancing the encapsulation efficiency and stability of lecithin-based formulations [15, 16].

3. Applications in Enhancing Bioavailability:

One of the primary applications of soybean lecithin-based nanogels and nanoparticles is the enhancement of the bioavailability of bioactive compounds. The solubility and bio-accessibility of many bioactive compounds are limited due to their poor aqueous solubility, which poses challenges in their effective delivery and therapeutic use. Soybean lecithin-based nanostructures offer a solution by encapsulating these compounds, thereby improving their solubility and stability in aqueous environments [17]. Studies have shown that lecithin nanoparticles significantly improve the bioavailability of various lipophilic bioactive compounds, such as curcumin, β-carotene, and terconazole [18, 19].

For instance, Pan *et al.* (23) developed a nano emulsion system stabilized by soybean lecithin, which demonstrated enhanced bio-accessibility of curcumin, a poorly water-soluble antioxidant with therapeutic potential [20]. Similarly, Xie *et al.* (29) showed that lecithin-based emulsions effectively enhanced the bioavailability of Yakuchinone B, an important bioactive compound used in traditional medicine [21]. These advancements underscore the effectiveness of lecithin-based systems in improving the bioavailability of essential nutrients, which is crucial for their therapeutic efficacy.

4. Therapeutic Applications:

Soybean lecithin-based nanogels and nanoparticles have shown great promise in various therapeutic applications, including drug delivery, cryopreservation, and disease treatment. Lecithin-based drug delivery systems can overcome the limitations of traditional formulations by improving the stability, solubility, and controlled release of therapeutic agents. In the area of cryopreservation, Li *et al.* (2023) discovered that a combination of soybean lecithin and cholesterol-loaded cyclodextrin improved the cryosurvival of dairy goat semen, providing a plant-based alternative for cryopreservation protocols [22].

In drug delivery, lecithin-based liposomes and nanoparticles have been shown to enhance the therapeutic efficacy of anti-cancer drugs, antibiotics, and other pharmaceutical agents. Nkanga *et al.* (14) formulated lecithin-based liposomes to encapsulate the anti-tubercular drug isoniazid, which improved its pulmonary delivery while minimizing side effects [23]. Moreover, Rawat *et al.* (28) developed lecithin-chitosan hybrid nanoparticles for glaucoma treatment, achieving sustained drug release and improved therapeutic outcomes [24]. These examples illustrate the potential of lecithin-based systems in revolutionizing drug delivery and treatment regimens for various diseases.

5. Challenges and Limitations:

Despite the promising advancements in soybean lecithin-based nanostructures, several challenges remain. One significant limitation is the variability in lecithin purity and composition, which can affect the reproducibility and consistency of nanostructure performance. The source and quality of lecithin can influence its encapsulation efficiency, stability, and bioactive compound release profile, posing challenges in large-scale manufacturing [25]. Additionally, scaling up the synthesis processes while maintaining nanostructure integrity and functionality remains a technical hurdle [26]. Furthermore, the long-term safety and potential immunogenicity of lecithin-based systems require careful investigation before their clinical application [27]. These issues highlight the need for standardization and optimization in the production of lecithin-based nanocarriers.

6. Future Directions:

Future research in soybean lecithin-based nanogels and nanoparticles should focus on optimizing lecithin purity and composition to improve the performance and consistency of nanostructures. New synthesis techniques that facilitate large-scale production without compromising quality should also be explored [28]. Interdisciplinary approaches that combine nanotechnology, material science, and biotechnology could lead to the development of multifunctional lecithin-based nanocarriers with targeted delivery capabilities, stimuli-responsive behaviors, and the ability to cross biological barriers [29].

Additionally, comprehensive in vivo studies and clinical trials are essential to evaluate the long-term safety, efficacy, and therapeutic potential of soybean lecithin-based nanocarriers. Advances in this field hold the promise of revolutionizing drug delivery systems, enhancing nutrient bioavailability, and providing innovative solutions for various therapeutic applications [30].

Conclusion:

Soybean lecithin-based nanogels and nanoparticles have shown tremendous potential in enhancing bioavailability and therapeutic efficacy for a wide range of bioactive compounds. The unique physicochemical properties of soybean lecithin, including its amphipathic nature and phospholipid content, facilitate the formation of stable and efficient nanostructures capable of encapsulating both lipophilic and hydrophilic agents. Lecithin-based systems have demonstrated significant promise in improving the solubility, stability, and controlled release of therapeutic agents, addressing critical challenges in drug delivery and nutrient supplementation. Moreover, their biodegradability and biocompatibility make them ideal candidates for sustainable, eco-friendly nanocarriers. However, challenges such as variability in lecithin purity, scalability of synthesis methods, and the need for comprehensive safety evaluations must be addressed. Continued research and interdisciplinary collaborations are essential to unlock the full potential of lecithin-based nanotechnology in improving human health and well-being.

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