Global Scientific JOURNALS

GSJ: Volume 11, Issue 6, June 2023, Online: ISSN 2320-9186
www.globalscientificjournal.com

Nanotechnology mediated therapeutic and enhanced delivery benefits of vitamins in medicine: A review article

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Running Title: Nanotechnology mediated therapeutic benefits of vitamins

Number of References: 43

Word Count: 3052 words

Number of tables and figures: 0

Abstract Count:

Keywords: Nanotechnology; Vitamins; Medicine; Review

Abstract:

Nanotechnology enables targeted drug delivery using nanoparticles, enhancing the efficacy and reducing side effects of pharmaceuticals. importantly, it improves the encapsulation and delivery of nutraceuticals. Integrating nanotechnology with vitamins offers precise therapeutic delivery and advancements in tailored medication, diagnostics, and regenerative therapies. This combination is revolutionizing modern medicine for personalized and effective treatments. This is a narrative review based on a literature search from online databases, collecting information from previously published articles. It discusses various nanotechnology approaches for vitamin

delivery. One method is the encapsulation of vitamins within nanoparticles, such as nanostructured lipid carriers (NLCs) and solid lipid nanoparticles (SLNs), which enhance solubility, stability, and bioavailability. Liposomes and nanovesicles, composed of phospholipids, can also be utilized, allowing targeted distribution and controlled release. Polymeric nanocarriers, including lipid polymer hybrid nanoparticles (LPNs), offer improved stability and loading efficiency. Nano-emulsions, consisting of microscopic droplets, enhance vitamin solubility and bioavailability. Finally, nanogels provide a controlled release of vitamins, making them suitable for transdermal delivery. The review also state that nanotechnology-mediated vitamin delivery has promising therapeutic applications across various fields. In cancer treatment, nanoparticle-based drug delivery systems offer targeted therapy with reduced side effects and improved effectiveness. Active targeting using ligands and receptors allows precise delivery to cancer cells. In cardiovascular health, nanoparticles enable the systemic administration of medications, including anti-inflammatory nanocarriers for immunotherapy. Future perspectives in vitamin delivery include integrating imaging agents, stimuli-responsive nanocarriers, and personalized medicine while combining nanotechnology with gene therapy and regenerative medicine will revolutionize disease management and improve patient outcomes.

Introduction

Nanotechnology is a rapidly advancing field that involves the development of materials with unique properties and various applications. Pharmacy has great promise for nanoparticles (NPs), particularly for targeted medication administration. NPs generally range in size from 1 to 100 nanometers. NPs less than 300 nanometers in size are regarded as optimum for ensuring effective transport via blood arteries [1]. NPs are often encapsulated in biodegradable biopolymers and may be made from both organic and inorganic materials. They are produced via top-down techniques (like fluidization, and emulsification) or bottom-up techniques (such as sol-gel syntheses, condensation, and precipitation). For lower sizes, chemical and bottom-up techniques are used, while mechanical procedures produce bigger NPs [2]. In order to increase the sustainability and effectiveness of NP synthesis, a greater emphasis is being placed on cutting-edge biotechnological methods and ecologically friendly synthesis techniques.

Active pharmaceutical components and bioactive substances may be changed thanks to nanotechnology, which modifies their characteristics and enhances their use in biomedicine. Unlike bulk materials and individual molecules, nanoscale materials have distinctive physical, chemical, and biological properties [3]. Targeted medication delivery, tissue engineering, controlled release, and the prevention or treatment of illness are all possible uses for these nanomaterials. Lower dosages and fewer adverse effects are possible by increasing the bioavailability of active ingredients via the use of nano-systems and nano-formulations. Additionally, nanotechnology permits the defense of bioactive compounds and the enhancement of their solubility, so enhancing their efficacy. The encapsulation and delivery of nutraceuticals, food product fortification, and the creation of bio-based delivery systems are all impacted by nanotechnology in the area of food science [4].

In the world of medical therapies, the fusion of vitamins and nanotechnology has become one of these ground-breaking discoveries. Therapeutic agents may be delivered with unparalleled control and accuracy thanks to nanotechnology, which entails working with matter at the atomic and molecular level. This fusion produces a synergistic approach toward improving medical treatments when combined with the therapeutic potential of vitamins, which play crucial roles in several biological processes [5]. Nanotechnology and vitamins together have enormous potential to enhance therapeutic effectiveness, targeted delivery, and patient outcomes in general. In this essay, we'll look at the innovative possibilities and prospective medical uses for this cutting-edge combo. The fusion of nanotechnology and vitamins is transforming the field of contemporary medicine and opening the door for more individualized and successful treatments. These include tailored medication delivery systems, diagnostic instruments, and regenerative therapies [6].

Methodology

This is a narrative review where the authors have conducted a literature search using online databases such as Google Scholar, PubMed, Sci-Hub, Elsevier, and others to gather information from previously published articles.

1 Nanotechnology Approaches for Vitamin Delivery

1.1 Nanoparticles for Vitamin Encapsulation

The technique of encasing molecules or tiny particles within a nanoscale matrix is known as nanoencapsulation. The use of nanotechnology in food items has a number of benefits, including enhanced transport and solubility, greater bioavailability of active ingredients, defence against oxidation, taste improvement, and antibacterial effects. Due to their special qualities of affordability, biodegradability, and biocompatibility, nanostructured lipid carriers (NLCs) and solid lipid nanoparticles (SLNs) have been widely used for encapsulating hydrophobic compounds [7]. Carotenes in food items have also been investigated, in addition to the encapsulation of vitamin A in lipid-based nanoparticles for medical and aesthetic uses. However, the use of organic solvents in the procedures for making nanoparticles is costly and not scale-able [8].

Daniela Resende, has reported that research findings illustrates that the lipid nanoparticles-encapsulated vitamin A has been successfully developed and characterized for food fortification purposes. it is optimized using the hot homogenization method, and when subjected to conditions stimulating food processing, it remained stable in terms of size and vitamin content [7]. The nanoparticles remained unaltered in the stomach when following in vitro assays stimulating gastrointestinal digestion. significantly, the formulated nanoparticles showed no toxicity and exhibited biocompatibility in fibroblasts. To note, the digestibility assay showed that intestine has been reached by around 80 % of the added vitamin, indicating the effective nanotechnology application of the developed nanoparticles in food research for food industry [7].

In a research, vitamin B9 and B12 were co-encapsulated in PLGA nanoparticles to increase their stability and oral bioavailability for application in nutraceutical goods [9]. The nanoparticles for oral distribution displayed oral physicochemical characteristics, such as surface charge and size. Cost-effectiveness and excellent encapsulation were produced as a consequence of the manufacturing process' efficiency. The encapsulated vitamins were protected from the gastrointestinal environment by stable nanoparticles during storage. This encapsulated nanoparticle's in vitro investigation revealed improved vitamin bioavailability and accessibility [9]. Results therefore point to the prospective nanoencapsulation method that may aid in the creation of goods for healthy aging and vitamins' health-promoting characteristics.

1.2 Liposomes and Nanovesicles for Vitamin Delivery

Liposomes are tiny, circular vesicles made of phospholipids that self-organize, which contributes to their amphipathic character. They are appropriate for a variety of medical applications since they are biocompatible and biodegradable. The structures of liposomes include a bilayer produced by phospholipids and cholesterol, which has improved stability [1]. Additionally, liposome stability may be improved by coating them with sugars or hydrophilic polymers, extending their circulation duration in the body. Liposomes may encapsulate drugs and shield them from deterioration, enabling targeted distribution, controlled release, and an increase in medication stability. Additionally, when certain molecules are introduced to the surface of liposomes, they may function as potential carriers for gene therapy [1].

Furthermore, functionalized liposomes that enable precise targeting of the surface molecules of different cells were created in addition to basic liposome structures [10]. Their surface contains chemicals linked to it that enable them to be directed to the target of interest, such as cancer cells. As a result, the absorption of therapeutic drugs is boosted while the off-target impact on healthy cells is minimized. Small interfering RNA (siRNA), antifungal and antibacterial medications, and liposome carriers like siRNA have all been used to treat a variety of ailments [11].

1.3 Polymeric Nanocarriers for Vitamin Encapsulation and Targeting

When compared to liposomes, polymer nanoparticles—which were developed in the 1970s—offer benefits including improved stability and simple repeatability [12]. They may be divided into two types: nanospheres, in which pharmaceuticals are spread throughout a matrix, and nano microcapsules, in which medications are contained in a polymer-coated core. Polymer nanoparticles have drawbacks include poor encapsulation rates and the propensity to elicit immunological responses, despite the fact that they have the potential to be drug carriers owing to their high biocompatibility. Lipid polymer hybrid nanoparticles (LPNs) have emerged as a viable carrier method to solve these shortcomings. LPNs increase physical stability and biocompatibility by combining polymer-controlled drug release with lipid-facilitated permeability and better loading efficiency [13]. In comparison to pure polymer nanoparticles, studies have demonstrated that LPNs can achieve better encapsulation rates and regulated release. These hybrid nanoparticles have been investigated for thrombolytic agent oral administration and have shown improved heparin oral bioavailability [14]. In addition, cisplatin-loaded LPNs have shown promise for targeted drug delivery at tumor locations, making them a promising platform for cancer treatment [15].

The delivery and preservation of functional components and nutraceuticals is accomplished by means of nanocarriers such nano-emulsions, NLCs, SLNs, microemulsions, and nano-liposomes. These carriers enable for the regulated release and precise administration of bioactive substances such as vitamins, vital fatty acids, antioxidants, and antimicrobials [16]. Food lipids, particularly liposomes, improve the stability and absorption of substances that are sensitive to heat and light.

By encasing heat- and light-sensitive polyunsaturated fatty acids in liposomes, it is possible to increase both their stability and absorption [17].

1.4 Nano-emulsions for Vitamin Solubility Enhancement

In the food, cosmetics, and healthcare sectors, nano-emulsions are microscopic droplet systems with a high surface area. They are simple to manufacture without organic solvents and have a wide range of chemicals they may encapsulate. They are used in medicine for both essential oils and anti-tumor medications [18]. They provide antimicrobials, colorants, flavors, and nutraceuticals to the food sector, enhancing the quality and shelf life of the products.

In comparison to bigger particles, cholecalciferol (vitamin D) nanoemulsion formulations with particle sizes smaller than 200 nm have shown higher bioavailability and homogeneity. Comparatively to traditional oil preparations, miscellized/nano-emulsion formulations of vitamins A and E have shown better absorption and plasma levels [19]. In long chain triglycerides like fish oil, vitamin D3 is most bioaccessible. Nanoemulsions of vitamin D3 have been found in studies to have better intestinal absorption and higher bioavailability, making them intriguing for enhancing drinks and demonstrating hepatoprotective properties in non-alcoholic fatty liver disease (NAFLD) [20]. Clinical trials in children and adults have shown that vitamin D3 nanoemulsion formulations dramatically boost blood vitamin D levels when compared to standard preparations [18].

1.5 Nanogels for Controlled Release of Vitamins

Highly adaptable nanogels are used in a wide range of industries, including sensing, diagnosis, bioengineering, and medication delivery. They are ideal for transdermal medication administration because to their many benefits, including a large capacity to load medicines, stability, and longer skin contact time [21]. Water-soluble non-ionic polymers are often used to stabilize nanogel dispersions. Phase separation of drug-loaded nanogels may be avoided, ensuring that drug particles stay disseminated, by adding hydrophilic polymers that form a protective layer. Block polymers assist regulate the release of pharmaceuticals from the polymer matrix, and modified natural biopolymers with cross-linkers may be used to create biopolymer-based nanogels [22]. Targeted drug delivery is made possible through ligand modification, which allows nanogels to penetrate biological barriers and release therapeutic chemicals within cells [23].

The creation of a nanogel employing a vitamin E nano-emulsion as a basis and including the high molecular weight active ingredient amphotericin B is one particular example of how nanogels are used [21]. It has been shown successful to treat cutaneous fungal infections using this nanogel. Notably, when evaluated on pig ear skin, it showed approximately a four-fold greater deposition in the skin [24].

2. Therapeutic Applications of Nanotechnology-Mediated Vitamin Delivery

2.1 Cancer Treatment and Targeted Therapy:

With benefits including tailored tumor delivery, fewer side effects, and increased therapeutic effectiveness, nanoparticle-based drug delivery systems have emerged as viable options for cancer therapy. These systems use nanoparticles to transport and release therapeutic chemicals, such as nucleic acids and chemotherapeutic medicines, for cytotoxic and gene treatments [25]. Nanoparticles speed up medication absorption, accumulate in malignant tissues, and safeguard healthy cells. They have been effective in delivering poorly soluble medications, and they are also used in immunotherapy and ablation therapy [26]. Targeted nanoparticle-based systems have been shown to be effective in delivering chemotherapeutic drugs and small interfering RNA (siRNA) in clinical studies [27]. In order to combat multidrug resistance (MDR) in different kinds of malignancies, hybrid nanoparticles and nanoparticle-based treatments have also showed potential [28]. Cancer therapy is moving into a new realm thanks to nanotechnology, which calls for further study and research.

Active targeting directly engages ligands and receptors to target cancer cells precisely. According to Shi et al , the ligands on the surface of NPs are chosen to target the molecules that are overexpressed on the surfaces of cancer cells, allowing them to discriminate between targeted cells and healthy cells [29]. The effective release of therapeutic medications from internalized NPs is made possible by the receptor-mediated endocytosis that is brought on by the contact between the ligands on NPs and the receptors on the surface of cancer cells [30]. For macromolecular drug delivery, such as proteins and siRNAs, active targeting is therefore especially appropriate. According to Danhier et al, many substances such as monoclonal antibodies, peptides, amino acids, vitamins, and carbohydrates may act as targeting moieties [31]. Targeted cell receptors to which these ligands selectively bind include the transferrin receptor, folate receptor, glycoproteins, and the epidermal growth factor receptor (EGFR).

The production of nucleotides requires the nutrient folic acid. A folate receptor, which is expressed on only certain kinds of healthy cells, is responsible for internalizing it. Folate receptor (FR-) is present on the surface of hematopoietic malignancies, while the alpha isoform is overexpressed in around 40% of human tumors [32]. As a result, folate-conjugated nanomaterials have been extensively exploited for cancer therapies using the folate receptor-targeting technique [33].

2.2 Cardiovascular Health:

Through direct intramyocardial injection or intracoronary catheterization, medicines may be delivered to the myocardium after an ischemic event. These methods may be risky and intrusive, however. A less intrusive and riskier approach is intravenous administration. Heparin administration intravenously using carbon nano-capsules has proved effective in preventing thrombus development in a mouse model [34]. Because they shield therapies from clearance and allow for passive or active targeting, nanoparticles have benefits for systemic administration. PEGylation, a surface modification method, may improve the stability and circulatory half-life of nanoparticles [35]. In contrast to active targeting, which includes the attachment of ligands for particular cell or tissue identification, passive targeting takes use of the increased permeability and retention (EPR) effect in sick or wounded locations [34].

The goal of cardiovascular immunotherapy is to create strategies that control exaggerated inflammatory reactions. For low dose, prolonged administration of anti-inflammatory nanocarriers, Yi et al. developed an injectable filamentous hydrogel depot (FM-depot). In particular, poly(ethylene glycol)-block-poly(propylene sulfide) (PEG-b-PPS) filomicelles were successfully loaded with the bioactive form of vitamin D (aVD; 1, 25-Dihydroxyvitamin D3), which inhibits pro-inflammatory transcription factor NF-kB via the intracellular nuclear hormone receptor vitamin D receptor (VDR) [36]. After being crosslinked with multi-arm PEG for in situ gelation, aVD-loaded FM-depots maintained high numbers of Foxp3+ Tregs in lymphoid organs and atherosclerotic lesions for weeks after being given to ApoE// mice. According to these findings, gradual release of anti-inflammatory compounds based on nanomaterials may be a useful way to improve cardiovascular immunotherapy.

2.3 Skin and Dermatological Applications:

Due to its capacity to stimulate cell development, control sebum production, decrease wrinkles, and cure pigmentation and photoaging problems, vitamin A and its derivatives, known as retinoids, are often utilized in skincare products. They may irritate skin and are susceptible to deterioration. These restrictions have been circumvented via nanotechnological techniques [37]. Retinoids are more stable and have a continuous release when they are combined with self-assembling polymer nanoparticles, which also lessens any negative effects. The gradual release of retinol and improved photoprotection are made possible by encapsulating it in biocompatible silicon particles [38]. Nanocarriers such solid lipid nanoparticles (SLNs) have shown prolonged release, decreased irritability, and enhanced follicular delivery for the retinoid adapalene used to treat acne. Adapalene has been effectively delivered to the epidermis and hair follicles using tyrosine-derived nanospheres, even at lower doses [39]. Furthermore, Harde et al. demonstrated better in vivo anti-acne potential in comparison to standard formulations and follicular accumulation of SLNs [39].

To increase stability and lessen the effects of UVB radiation on the skin, Olivera and Cruz looked into the usage of caprolactone nanocapsules filled with CoQ10 and Vitamin E. Another fat-soluble antioxidant that may benefit from nanoformulation to increase solubility and stability is alpha-tocopherol (Vitamin E) [37]. For the encapsulation and delivery of vitamin E, nanocarriers that are comparable to those used for coenzyme Q10 have been investigated. In vitro, vitamin-loaded transferosomes made of phosphatidylcholine and Tween 80 by Caddeo et al. shown excellent encapsulation efficiency and stability as well as wound healing and protective benefits against oxidative damage [40]. Vitamin C, ascorbic acid, is hydrophilic and unstable, yet liposomes may encapsulate it since it is water soluble. It has been suggested that derivatives and carriers would improve the stability and penetrating power of vitamin C. According to research by Zhou et al., adding negatively charged pectin to a formulation increased stability and skin permeability [41]. In order to cure melasma, Aboul-Einien et al. created "aspasomes," a brand-new liposomal system containing an AA derivative [37]. After doing in vivo animal testing, they improved the nanocarrier composition, added it to gel and cream formulations, and then used melasma patients to show its effectiveness [42].

Three organic filters—octinoxate, oxybenzone, and avobenzone—along with vitamin E were encapsulated in ethylcellulose nanospheres in a work by Hayden et al [43]. These biocompatible nanoparticles (NPs) might be added to different sunscreen formulations (such as emulsions and oils), with vitamin E acting as a photostabilizer. This kind of nanoencapsulation reduced ROS production, shown extensive UV blocking efficacy, and produced flexible films.

3 Future Perspectives and Emerging Trends

Several emerging trends and future perspectives are shaping the nanotechnology-mediated therapeutic and enhanced delivery benefits of vitamins in medicine. These include the development of multifunctional nano-systems integrating vitamins with imaging agents for diagnostics, the utilization of stimuli-responsive nanocarriers for controlled release of vitamins, and the exploration of personalized medicine approaches by tailoring vitamin formulations to individual patient needs. Furthermore, the integration of nanotechnology with other cutting-edge technologies such as gene therapy and regenerative medicine holds immense promise for the development of next-generation vitamin-based therapeutics. These advancements have the potential to significantly improve patient outcomes, revolutionize disease management, and pave the way for innovative and effective vitamin-based therapies in the future of medicine.

Conclusion

Nanotechnology has emerged as a powerful tool for enhancing the therapeutic potential of vitamins in medicine. The development of nanocarrier systems enables targeted delivery, controlled release, and improved stability of vitamins, overcoming their inherent limitations. By encapsulating vitamins within nanocarriers, their solubility, bioavailability, and therapeutic efficacy can be significantly enhanced. These advancements open up new possibilities for utilizing vitamins in various medical fields, including cancer therapy, neurodegenerative disorders, cardiovascular diseases, and skin conditions.

Statements and Declarations

Acknowledgements

N/A

Declarations of interest

The authors declare that they have no conflicts of interest and no financial interests related to the material of this manuscript.

Funding

No financial support was received for this study.

Ethics approval

No ethical approval was required for this study.

Consent

No consent was required for this study.

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