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A comprehensive review on nutraceuticals: Therapy support and formulation challenges

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Abstract

Nutraceuticals, a blend of “nutrition” and “pharmaceutical,” represent bioactive compounds derived from food sources that provide health benefits beyond basic nutrition. In recent years, they have gained considerable attention due to their potential role in the prevention and management of chronic diseases such as cardiovascular disorders, diabetes, cancer, osteoporosis, and neurodegenerative conditions. Nutraceuticals include a wide range of products such as dietary supplements, functional foods, herbal extracts, probiotics, and fortified nutrients. Their therapeutic actions are attributed to antioxidant, anti-inflammatory, immunomodulatory, and neuroprotective mechanisms that support physiological functions and reduce the risk of disease progression. Growing scientific evidence suggests that nutraceuticals can complement conventional therapies, offering a safe, cost-effective, and preventive approach to healthcare. However, challenges related to standardization, clinical validation, and regulatory frameworks remain significant barriers to their widespread acceptance in modern medicine. Future research focused on clinical efficacy, safety, and molecular mechanisms will further strengthen their role in global healthcare systems.

Keywords: Nutraceuticals, functional foods, dietary supplements, antioxidants, immunomodulation, chronic disease prevention, herbal extracts, probiotics

Introduction

The concept of using food as medicine dates back to Hippocrates, who famously stated, “Let food be thy medicine and medicine be thy food.” The term “nutraceutical” was coined by Dr. Stephen DeFelice in 1989 by combining “nutrition” and “pharmaceutical” [1]. Nutraceuticals lack a universally accepted definition but are generally considered products derived from food sources that provide additional health benefits, including the prevention and treatment of chronic illnesses. The increasing prevalence of lifestyle-related diseases such as diabetes, obesity, cardiovascular disorders, and neurodegenerative conditions has accelerated interest in nutraceuticals as preventive and adjunct therapies [2].

Classification of Nutraceuticals: Nutraceuticals are broadly classified into categories: (i) Nutrients such as vitamins, minerals, amino acids, and fatty acids; (ii) Herbal products including curcumin, ginseng, and green tea polyphenols; (iii) Dietary supplements like probiotics, prebiotics, and antioxidants; (iv) Phytochemicals such as carotenoids, flavonoids, and polyphenols; and (v) Functional foods enriched with health-promoting compounds [3]. They are further divided into traditional nutraceuticals (naturally occurring) and non-traditional nutraceuticals (biotechnology-derived, fortified products) [4].

Mechanisms of Action: Nutraceuticals act through multiple pathways. Polyphenols scavenge free radicals and reduce oxidative stress [5]. Omega-3 fatty acids modulate lipid metabolism and inflammatory mediators [6]. Probiotics balance gut microbiota, enhancing immunity and metabolic health [7]. Bioactive peptides derived from milk and soy proteins exhibit antihypertensive and antioxidant activity [8]. Many nutraceuticals also affect gene regulation and epigenetic mechanisms, a focus of emerging nutrigenomics research [9].

Health Benefits and Applications

- **Cardiovascular health:** Cardiovascular diseases are among the leading causes of mortality worldwide, largely associated with risk factors such as high cholesterol, hypertension, obesity, and oxidative stress. Nutraceuticals play a crucial role in supporting cardiovascular health by improving lipid profiles, reducing inflammation, and enhancing vascular function. Omega-3 fatty acids obtained from fish oil and flaxseed are effective in lowering triglyceride levels and improving endothelial activity. Plant sterols and stanols act by reducing the intestinal absorption of cholesterol, leading to decreased LDL-cholesterol concentrations. Polyphenols present in green tea, grapes, and berries provide antioxidant protection, improve nitric oxide bioavailability, and promote healthy blood pressure regulation. Similarly, dietary fibers such as β -glucan from oats and psyllium husk reduce total and LDL cholesterol, thereby decreasing cardiovascular risk. Other nutraceuticals, including coenzyme Q10 and L-carnitine, support cardiac energy metabolism and have shown benefits in heart failure management. Overall, the integration of nutraceuticals into daily diets, along with lifestyle modifications, can significantly reduce cardiovascular disease risk and improve long-term heart health [6].
- **Diabetes and obesity:** Chromium, dietary fibers, and isoflavones regulate insulin sensitivity and glucose metabolism [10]. Herbal extracts like *Momordica charantia* have anti-diabetic effects [11].
- **Cancer prevention:** Phytochemicals such as curcumin, lycopene, and resveratrol modulate pathways linked to carcinogenesis [12]. However, results from large clinical trials remain mixed [13].
- **Neuroprotection:** Nutraceuticals have gained significant attention for their potential role in neuroprotection, as they offer natural compounds that can protect the brain and nervous system from oxidative stress, inflammation, and age-related degeneration. Several bioactive substances such as omega-3 fatty acids, polyphenols, flavonoids, curcumin, resveratrol, and vitamins (like vitamin E and B-complex) have been shown to enhance neuronal survival, improve synaptic plasticity, and reduce the risk of neurodegenerative disorders including Alzheimer's disease, Parkinson's disease, and dementia. These compounds act through multiple mechanisms such as scavenging free radicals, regulating neurotransmitter function, modulating mitochondrial activity, and inhibiting neuroinflammation. Regular dietary intake of nutraceuticals with neuroprotective potential not only supports cognitive performance but also delays the progression of neurological disorders, making them a promising complementary strategy in brain health management [14].
- **Joint and bone health:** Nutraceuticals play an important role in maintaining joint and bone health by providing essential nutrients and bioactive compounds that support skeletal strength and mobility. Key nutraceuticals such as calcium, vitamin D, magnesium, and phosphorus are vital for bone mineralization and prevention of conditions like osteoporosis and rickets. In addition, nutraceuticals like glucosamine, chondroitin sulfate, collagen peptides, and hyaluronic

acid are widely used for improving joint flexibility, reducing inflammation, and alleviating symptoms of osteoarthritis. Polyphenols and omega-3 fatty acids further contribute by modulating inflammatory pathways and protecting cartilage from degeneration. Regular intake of these nutraceuticals not only enhances bone density and structural integrity but also improves overall joint function, thereby reducing the risk of age-related bone disorders and mobility impairments [15].

- **Immune system:** Nutraceuticals are widely recognized for their role in strengthening the immune system and protecting the body against infections and chronic illnesses. Essential vitamins such as vitamin C, vitamin D, and vitamin E act as powerful antioxidants that enhance the activity of immune cells, support antibody production, and reduce oxidative stress. Minerals like zinc, selenium, and iron are equally important in regulating immune responses and improving resistance to pathogens. In addition, bioactive compounds such as polyphenols, flavonoids, beta-glucans, probiotics, and omega-3 fatty acids help modulate inflammatory pathways, enhance gut microbiota balance, and boost both innate and adaptive immunity. Regular consumption of these nutraceuticals has been linked to improved defense against viral and bacterial infections, reduction in inflammation, and lowered risk of autoimmune and age-related immune decline. Thus, nutraceuticals offer a natural and preventive approach for maintaining immune health and overall well-being. [16].

Formulation and Bioavailability: A major limitation of nutraceutical efficacy is low bioavailability. Curcumin, for instance, is poorly absorbed but its activity can be enhanced by piperine co-administration [17]. Nanotechnology-based delivery systems such as liposomes, nanoparticles, and phytosomes improve solubility, stability, and absorption of poorly bioavailable compounds [18]. Probiotic efficacy depends on strain viability and survival through gastric acidity [19].

Safety, Quality, and Regulation: Though often perceived as safe, nutraceuticals may cause adverse effects at high doses. Fat-soluble vitamins like A and D can be toxic in excess [20]. Herbal products may interact with prescription drugs; for example, St. John's wort induces CYP3A4 and reduces drug effectiveness [21]. Quality issues such as adulteration, contamination, and inconsistent labeling are common [22]. Regulatory frameworks differ globally: in the U.S., nutraceuticals fall under the DSHEA (1994), while in Europe, they are classified as food supplements [23]. Harmonization of global regulations and stringent quality control are urgently needed.

Future Prospects: The future of nutraceuticals lies in their integration with precision nutrition, biotechnology, and personalized healthcare approaches. Advances in nutrigenomics and metabolomics will help identify how individual genetic variations influence responses to bioactive compounds, enabling the development of customized nutraceutical interventions tailored to specific populations. Novel formulation technologies, including nanoparticles, liposomes, and phytosomes, are being explored to overcome bioavailability challenges of poorly

absorbed compounds such as curcumin and resveratrol. Sustainable sourcing and the use of food industry by-products for nutraceutical production will also play a significant role in meeting rising global demand while minimizing environmental impact. Furthermore, increasing consumer awareness and the preference for natural, preventive therapies will continue to drive innovation in the nutraceutical industry. However, to achieve their full potential, nutraceuticals must undergo rigorous clinical trials, standardized quality control, and harmonized global regulations to ensure safety, efficacy, and reliability. In the coming years, nutraceuticals are expected to become an integral component of mainstream healthcare, complementing conventional therapies and contributing to the prevention and management of chronic diseases ^[24].

Conclusion

Nutraceuticals serve as a bridge between nutrition and medicine, offering preventive and therapeutic benefits for lifestyle and chronic diseases. While they hold strong potential in cardiovascular, metabolic, neurodegenerative, and immune-related disorders, limitations in evidence, standardization, and regulation must be addressed. With advancements in biotechnology and stronger regulatory frameworks, nutraceuticals can become integral components of global healthcare strategies.

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