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Nutraceuticals: A futuristic approach in the field of biotechnology and nanotechnology

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In recent years, the significance of nutraceuticals has grown considerably due to their perceived safety, health benefits, and role as an alternative to conventional medicine. Nutraceuticals encompass a range of products derived from foods that have medicinal value. This includes food supplements, herbal products, and prebiotics, which provide additional health benefits beyond the basic nutrition obtained from a diet. One major advantage of nutraceuticals is their ability to provide therapeutic effects without the side effects typically associated with traditional medications. Nutraceuticals play a crucial role in enhancing an individual's health, preventing chronic diseases, slowing the ageing process, and supporting the overall structure and physiology of the body. They are referred to as substances that provide medical well-being by preventing diseases. Hence, nutraceuticals fall under the category of broad-spectrum biological therapies used to encourage general health and avoid chronic diseases. Modern technological advances, particularly in biotechnology and nanotechnology, have revolutionised nutraceutical development through enhanced bioavailability, targeted delivery systems, and improved stability of bioactive compounds. This article aims to enhance our understanding of nutraceuticals as a health-supporting alternative to modern medicine. The review also discusses the application and current market demand for these nutraceuticals, including fish oil preparations, prebiotics, and probiotics. Additionally, this comprehensive review examines the integration of biotechnological approaches, including genetic engineering, bioprocessing, and nanotechnology applications, in the production and delivery of nutraceuticals. By exploring the unique properties and benefits of nutraceuticals, along with emerging technological innovations, we can appreciate the value of incorporating them into our lifestyles as a means of promoting overall wellness and advancing personalised healthcare solutions.

Keywords: Biological therapy, Microorganisms, Nutraceuticals, Pharmaceuticals

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Introduction

The term "nutraceutical" is a blend of "nutrition" and "pharmaceutical," referring to food or food-based products that provide medical benefits beyond basic nutrition[1]. Dr Stephen De Felice, who talked first about innovation in the field of medicine, coined the term 'Nutraceuticals' in 1989[2]. The ancient physician Hippocrates, famously referred to as the father of medicine, has already quoted, "Let thy food be thy medicine and the medicine be thy food"[3]. Nutraceuticals are a diverse and rapidly expanding field in the realm of health and wellness. They have gained popularity due to the growing interest in preventive healthcare and the desire for natural alternatives to pharmaceutical drugs.

Nutraceuticals can be inclusive of a wide variety of products, including dietary supplements, fortified foods, herbal extracts, functional foods, and beverages. These products are formulated with bioactive compounds derived from natural sources, including vitamins, minerals, bio macromolecules' monomers like amino acids, fatty acids, and others like phytochemicals, prebiotics, antioxidants,

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probiotics, and herbal extracts, which contribute to their overall well-being[4]. They are often consumed as part of a regular diet or taken in the form of capsules, tablets, powders, or liquids. The primary target of nutraceuticals is to enhance well-being, support specific bodily functions, and prevent or manage certain diseases. They can provide a vast array of health benefits, including immune system support, encourage cardiovascular health, cognitive enhancement, digestive health improvement, weight management, joint health support, and skin health enhancement, among others[5]. One of the key advantages of nutraceuticals is their perceived safety compared to traditional pharmaceutical medications.

Many nutraceutical products are derived from natural sources and are generally considered safe for utilisation. However, it is necessarily notable that regulatory oversight and quality control can vary across different countries and regions, so it's crucial to choose reputable brands and consult with healthcare professionals when considering the use of nutraceuticals in your lifestyle[6]. Scientific research is extremely important for the progress and validation of nutraceuticals. Extensive studies are conducted to conclude the efficacy, validity, and potential interactions of such products[7]. Clinical trials and research papers contribute to our understanding of the benefits and limitations of various nutraceutical compounds, helping to guide their appropriate use. Research and development continue to expand as scientists explore the potential health benefits of various natural compounds. However, incorporating nutraceuticals into food products poses certain challenges. To ensure the protection and preservation of these sensitive compounds, a well-designed delivery system is required. Various microencapsulation technologies have been developed to stabilise nutraceuticals within food matrices, allowing them to exert their desired health impact. Notably, the use of nano-biotechnology has enhanced the stability of nutraceuticals, particularly lipophilic ones that are highly susceptible to degradation[8]. Food safety is already an important aspect, and adding its values in pharmaceuticals requires further quality checks and assurance for safety[9].

Overall, the increasing popularity of nutraceuticals is driven by their potential health benefits and the desire for safer alternatives to conventional medications. The progress of efficient delivery systems, which include nano-biotechnology, is notably maximising the stability and efficacy of nutraceutical compounds.

Methodology

This systematic literature search, carried out using the Scopus database, is essential for identifying, locating, and analysing peer-reviewed literature related to nutraceuticals in this extensive review. This search has documented approximately a 15-year period to cover the recent developments and emerging kinetics in the field. The different search strategy comprises relevant keywords, words that include but are not limited to, "nutraceuticals", "functional foods", "biotechnology", "nanotechnology", "bioactive compounds", "therapeutic applications", "prebiotics", "probiotics", "dietary supplements", and terms that include microorganisms to optimise search results using Boolean operators AND and OR. Additional search terms, such as "pharmaceutical alternatives" and "health benefits," have also been used to achieve broader topical coverage. All publications retrieved from the search were filtered to include only English-language articles that were research papers, review articles, or conference proceedings from reputable, peer-reviewed journals. The inclusion criteria were designed for studies examining the therapeutic potential, biotechnological applications, nanotechnological innovations, and market trends of nutraceuticals. The exclusion criteria eliminated duplicate publications, non-peer-reviewed sources, and those that did not meet adequate methodological standards. The literature collected was systematically compiled and analysed to identify key trends, technological advancements, regulatory improvements, and future prospects for nutraceutical research in the specified decade, driven by the integration of biotechnology and nanotechnology methods in nutraceutical development and delivery systems.

Market of nutraceuticals

Nutraceuticals refer to products that combine both nutritional and medicinal benefits. They provide physiological benefits and prevention against chronic diseases. Nutraceuticals can be taken into consideration to promote health, decelerate the ageing process, prevent diseases, elevate life expectancy, and stabilise the body's physiology[10,11]. These products have drawn considerable attention due to their potential to provide nutrition, quality security, and therapeutic benefits. Recent studies have proved their worth in tackling complications[12]. Nutraceuticals can be divided into three key terms depending on their natural source and chemical grouping: nutrients, herbal extracts, and dietary additives, including dietary fibre. Among these, the most booming sectors of the industry are dietary additives production (which is 19.5%/year) and natural/herbal production (which is 11.6%/year)[13].

The nutraceutical market is currently experiencing significant progress, primarily in the regions of the USA, India, and Europe[14]. However, there are several key issues that have not been well-established yet, for example, the bioavailability, metabolism, dose, and response, and the harmfulness of the bioactive compounds present in food or nutraceuticals themselves. In the nutraceutical industry, various categories of polyphenols, including anthocyanins, pro-anthocyanidins, flavanones, resveratrol, and ellagic acid, are commonly used. To get the crux of the biological effects of polyphenol-containing nutraceuticals, it is crucial to establish their bioavailability, metabolic processing, and tissue distribution in humans[15].

The success or failure of the nutraceutical industry depends on factors such as explosive growth, research advancements, standardisation, marketing practices, quality assurance, and regulations. In India, traditional Indian Ayurvedic Medicines (IAM) are a common form of functional foods and other nutraceuticals, marketed under the category of various brand names[16]. India has a rich variety of medicinal plants, plantations of fruit varieties, and cereal varieties, which enjoy a significant local market with limited overseas competition[17]. However, it is quite notable that Ayurvedic and nutraceutical health production in India lacks strict pharmaceutical regulations[18]. Similarly, in China, large populations, especially in rural and remote areas, rely heavily on herbal remedies and naturally available bio resources for treating common ailments and preventive care[16]. The global nutraceutical market has become one of the greatest money-minting markets, with the potential for rapid growth[19]. In a country like Canada, nutraceutical has the potential to reach $50 billion US. Japan stands as the second huge market for nutraceutical production worldwide, and has a stable growth rate of 9.6% per year (average)[16,20,21].

Nutraceuticals, botanicals, and herbal cures, including new functional foods, are necessary due to their affirmation as modern and new forms of natural substances with potential benefits[22]. However, the rapid expansion in this field raises concerns about an imbalance between increasing claims and products, the requirement for regulatory policies to assure safety and standards, and the necessity for efficient composition checks, including plant extracts and detection of adulteration for improved efficacy. It is noteworthy that the change in consumer preferences is not mentioned as a negative factor, indicating continued interest in these products[22]. While scientific data availability is improving, the validation of nutraceuticals remains a central aspect. The long-standing use of these plants as food provides some assurance of safety. Functional foods offer an opportunity to utilise plants in modern forms to maintain human health.

The nutraceutical industry is still taking its baby steps and is expected to contribute a major portion to the GDP of a nation soon. One of the types of nutraceuticals, which is a dietary supplement, its market in India is estimated to progress with a growth rate of 16% by 2026[10,23]. Fig. 1 shows the history, current and future trends of market size growth for nutraceuticals.

In the face of rising chronic lifestyle diseases, nutraceuticals have become essential for maintaining human health and preventing diseases. India, in particular, has seen significant affirmation about nutraceuticals as an advantageous choice for the well-being of an individual. Over the past 5 years, the Indian market for nutraceuticals has grown to $3 billion USD[24]. The implementation of the Food Safety and Standards Act (FSSA) has brought more defined regulatory terms to the nutraceutical industry, creating

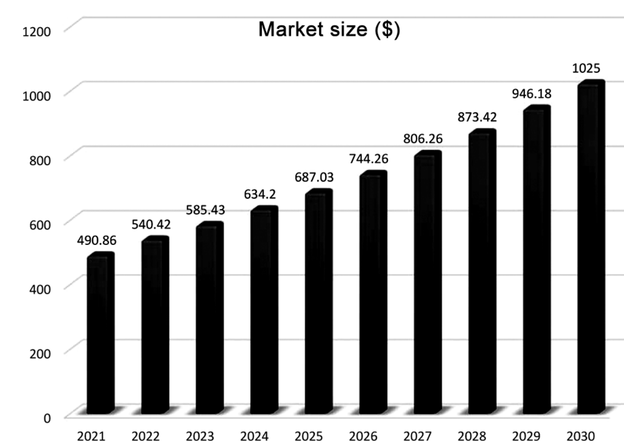

Fig. 1 — Expected market size growth (2021-2030). (Source: Precedence Research).

a regulated and disciplined space for manufacturers. FSSAI oversees various stages of nutraceutical production, which encompass manufacturing, packaging, and labeling[25]. Moreover, FSSAI imposes limitations on nutraceutical advertisements[25]. The Food Safety and Standards Authority of India (FSSAI) makes sure the nutraceutical control in India aligns with overseas values[26].

Categories of nutraceuticals

Nutraceuticals are generally categorised in several groups depending on their composition and intended well-being. Here are a few of the common categories belonging to nutraceuticals[27].

Dietary supplements

This category includes vitamins, minerals, amino acids, herbal extracts, and other bioactive compounds formulated into capsules, tablets, powders, or liquids. Dietary supplements are taken orally to supplement the diet and provide additional nutrients that may be lacking in regular food intake. It is the broadest field of nutraceuticals containing carbohydrates, proteins, vitamins and other biomolecules in their simplest form for easy absorption[28]. The global dietary supplements market represents the largest segment within the nutraceutical industry, driven by increasing health consciousness and preventive healthcare approaches. These supplements offer targeted therapeutic benefits, including immune system enhancement, cardiovascular support, and cognitive function improvement, while maintaining superior safety profiles compared to conventional pharmaceuticals[29]. According to research, carbohydrates, along with a balanced amount of protein, are a boon for gut microbiota; hence, dietary bioactive supplements can be held accountable for a promising future in the field of human health[10].

Functional foods

These are regular food products fortified or enhanced with bioactive ingredients to supply health benefits apart from basic nutrition[30]. Examples include fortified cereals, energy bars, probiotic yoghurts, omega-3 enriched foods, and beverages containing added antioxidants or herbal extracts[31]. Functional food resembles conventional food but possesses a much higher amount of nutrients than conventional food. They are supposed to be consumed as normal food, but give much more nutrition to the body. They contain bioactive compounds like sulphoraphane, beta carotene, lycopene and many more[32]. The global functional foods market has experienced substantial growth due to increasing consumer awareness about preventive healthcare and the therapeutic potential of bioactive compounds. Recent advances in food processing technologies have enabled the development of innovative functional products, including omega-3-enriched dairy products and antioxidant-fortified beverages, which maintain palatability while delivering enhanced nutritional benefits[33].

Herbal and botanical extracts

Nutraceuticals derived from herbs and botanicals have a long history of traditional use for their medicinal properties. Herbal extracts such as ginseng, Echinacea, turmeric, and green tea extract are commonly used in various formulations for their potential health benefits. They provide medicinal benefits due to the presence of many bioactive compounds[34]. For example, garlic (*Allium sativum*), whose properties were undiscovered for a long period of time in spite of having Ayurvedic importance for a long time, has been proven to have anti-cancerous, anti-inflammatory and also anti-viral properties[35]. Some edible flowers also provide a wide array of anti-bacterial, anti-inflammatory, and anti-fungal values[10]. These herbs can be utilised as food as well as for medicinal purposes. Various herbs used for multiple purposes are listed in Table 1.

Probiotics and Prebiotics

Nutraceutical's subcategory, probiotics, refers to living microorganisms that establish health benefits if consumed in an appropriate quantity. They are usually present in fermented foods like yoghurt and kefir. Prebiotics are non-digestible fibres that trigger the progression of beneficial gut bacteria[44]. Probiotics are beneficial bacteria that are commonly found in the gut and help maintain a healthy digestive system[45]. Nutraceuticals belonging to this category include products like yoghurt, fermented foods, and supplements containing specific strains of probiotics or prebiotic fibres. They maintain the homeostasis of these bacteria in the gut, maintaining a good gut microbiome and preventing serious gastrointestinal diseases[46].

Omega-3 fatty acids

These fatty acids, including eicosapentaenoic acid and docosahexaenoic acid, are some of the necessary

Table 1 — Classification of herbs and botanical extracts used as nutraceuticals

Potent vittles	Extraction	Treatment	References
Peruvian medicinal herbs	Achiote (*Bixa orellana*)	diarrhea, vomiting, dermatitis, throat infections, conjunctivitis	36,37
	Sacha inchi (*Plukenetia volubilis linneo*)	Cancer, hormonal balance, blood pressure regulation, cardiovascular diseases	
	Maca (*Lepidium meyenii*)	Anemia, chronic fatigue syndrome, depression, boosting fertility	
	Coca (*Erythroxylum coca*)	Suppress thirst and hunger, blood oxidation, improves cognitive function	
Fruits and vegetables	Green peas (*Pisum sativum*)	Prevent clotting of blood, appendicitis	38,39
	Cabbage (*Brassica oleracea*)	Peptic ulcer, duodenal ulcer, cancer	
	Oranges (*Citrus sinensis*)	Cancers, lowers cholesterol, enhance memory	
	Lemons (*Citrus limon*)	Kills roundworms, dissolve gallstones	
Flavors	Peppermint (*Mentha piperita*)	Irritable bowel syndrome, gastric emptying disorders, tuberculosis	40,41
	Green tea (*Camellia sinensis*)	Weight loss, diabetes, bad cholesterol, heart disease, depression	
	Ginger (*Zingiber officinale*)	Nausea, muscular pain, osteoarthritis, chronic indigestion, cancer	
	Vanilla (*Vanilla planifolia*)	Skin disorders, toothache, coughing, burns, increased libido	
Ayurveda herbs	Amla (*Phyllanthus emblica)*	Asthma, skin disorders, constipation, fever, purification of blood	42,43
	Aloe vera (*Aloe barbadensis miller*)	Inflammation, burns, wounds, cardiovascular health improvement	
	Turmeric (*Curcuma longa*)	Heart disease, cancer, Alzheimer, arthritis, depression	
	Hibiscus (*Hibiscus rosa sinensis*)	Hypertension, anti-bacterial, chemo preventive	

fats that have a notable role in brain health, heart health, and inflammation. They are usually found in fatty fish like salmon, sardines and are also available as fish oil or algae-based supplements[47].

Antioxidants

Antioxidants refer to substances that provide aid to protect cells from destruction due to free radicals, unstable molecules resulting in oxidative stress contributing to the well-being of the individual. Common antioxidants can be listed as vitamins C and E, beta-carotene, selenium, and polyphenols present in fruits, vegetables, and certain herbs[48]. Free radicals are typically required in the body at very low concentrations. Still, a drastic increase in their concentration can result in numerous side effects, including damage to macromolecules and cellular impairment. Therefore, nutraceuticals with defined amounts of antioxidants are a promising approach to reduce oxidative stress. However, a lot of research is still required to uncover more benefits of antioxidants' nutraceuticals[49].

Nutritional enzymes

These are enzymes that help in the breakdown and assimilation of nutrients in the body. They can aid in digestion, enhance nutrient availability, and support overall metabolic processes. A modification in the enzyme accelerates the functioning of the protein. Peptides derived from food behave as Angiotensin 1-converting enzyme inhibitory peptides and reduce blood pressure levels notably. They also show significant ability to prevent lipid oxidation in food[50,51].

Sports and Performance enhancers

These nutraceuticals are targeted towards athletes and individuals looking to enhance their physical performance. They may include products like protein powders, creatinine supplements, branched-chain amino acids (BCAAs), and energy-boosting formulas[52]. Organic fat burners are quite commonly used supplements by sportsmen and bodybuilders. Since the use of supplements often requires extensive research before consumption, nutraceuticals are likely to remain in the limelight due to their proven benefits[53].

Nutritional supplements for special populations

This category includes nutraceuticals designed specifically for certain populations, such as prenatal vitamins for pregnant women, supplements for children, or formulations for older adults with specific nutrient needs. Antioxidant-rich nutraceuticals are beneficial for anti-ageing. Green tea polyphenols also confer anti-inflammatory and anti-cancer characteristics[54].

There are several other nutraceutical categories, including plant sterols and stanols for cholesterol management, glucosamine and chondroitin for joint health, melatonin for sleep support, and more. Nutraceuticals are consumed in the forms of tablets, gels, capsules, and powder. For example, Spirulina is manufactured in the form of powder from spirulina flakes[55]. The form of nutraceuticals is summarised in Fig. 2.

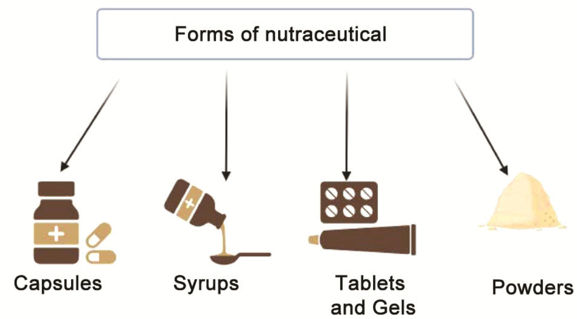

Fig. 2 — Commonly Available Forms of Nutraceuticals.

Some nutraceutical components offer potential protection from oxidative stress, inflammation, and notable development of chronic diseases. They have also shown promise in promoting cardiovascular health, boosting the immune system, and even contributing to healthy ageing. There are certain selected bioactive elements that are chosen to further discuss their chemical and biological properties in Table 2. The stereo structures of compounds mention in Table 2 has been presented in Fig. 3.

Table 2 — Sources and uses

S. No	Nutraceutical bioactive components and it's molecular formula	Sources	Properties/Uses
1	Folic Acid 441.4g/mol	Dark leafy greens, asparagus, broccoli, detox foods, citrus fruits, beans, peas, lentils, avocadoes	stoppage of fetal abnormalities, Alzheimer's disease, numerous types of cancer such as colon and rectum, macrocytosis of RBCs.
2	Curcumin 388.38g/mol	Turmeric (*Curcumalonga),* curry powder, Mango Ginger.	Anti-inflammatory, anti-arthritis properties**,** anti-depressant effects, prevent age-linked deteriorating diseases like Alzheimer's disease, heart related disorders, anti-allergy**.**
3	Limonene 136.23g/mol	Commercial-ly obtained from citrus fruits through two primary methods: steam distillation or centrifugal separation.	Reduces inflammation, cell cycle arrest, has gastric acid neutralising effect, high dose causes renal cancer.
4	Ascorbic Acid 176.12g/mol	Citrus fruit, tropical fruit, peppers, cruciferous vegetables	Prevents rashes, muscle feebleness, joint-pain, fatigue, or tooth loss, antioxidant properties
5	Phenolics 92g/mol	fresh fruits, vegetables, teas, red wine, coffee, curcumin	Antioxidants, healthy aging, antioxidants, anti-inflammatory, anti-carcinogenic characteristics and have capacity to regulate some key cellular enzyme functions.
6	α-Tocopherol 430.7g/mol	Nuts, vegetable oils, green leafy vegetables, soya bean, canola, corn	Antioxidants, prevents the action of protein kinase C thereby averting cell proliferation, diversity in smooth muscle cells, platelets and monocytes, prevents coronary heart disease, cancer, age related muscular degeneration (AMD) and cataracts.
7	Vanillin 152.15g/mol	seed pods of *Vanilla planifolia*	Antioxidant, antimicrobial, anti-mutagenic and anti-inflammatory properties.
8	Diosgenin 414.62g/mol	*Dioscoreavillosa* (wild Yam), seeds of fenugreek	Anti-cancer activity, antimicrobial activity, antithrombotic activity, anti- diabetic activity, Cardio-protective activity, anti-inflammatory activity.
9	Omega-3fatty Acid 909.4g/mol	liver of cod fish (*Gadidae*),	Prevents diseases like arthritis, cancer (lymphoma, prostate, lung and skin), anti-inflammatory agent.
10	Flavonols 224.4g/mol	Blueberries, Parsley(*Petroselinum crispum*), onions, black, green tea	provides protection against osteoporosis, certain forms of cancer, and scavenge highly reactive species, antioxidant potential' antimicrobial activity.

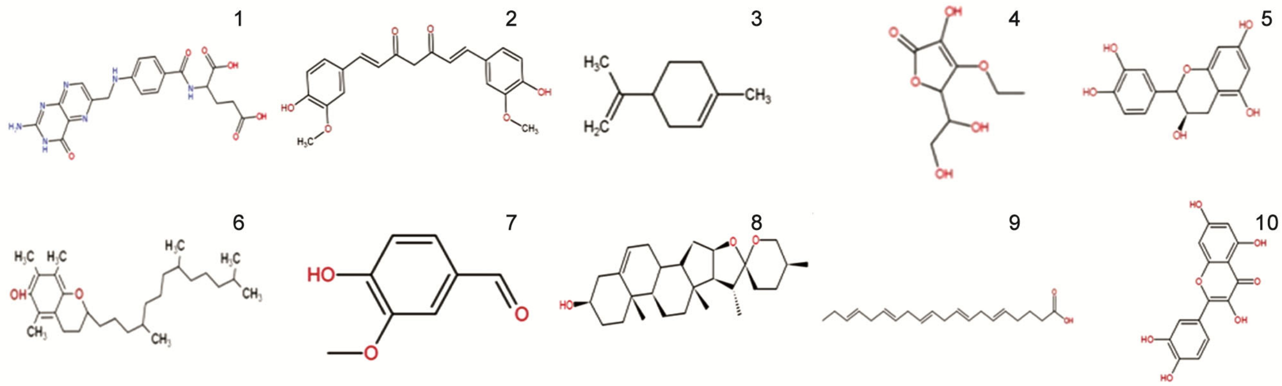

Fig. 3 — Types of stereo-structure of some nutraceutical bioactive compounds. 1. Folic Acid 2. Curcumin 3. Limonene 4. Ascorbic Acid 5. Phenolics 6. α-Tocopherol 7. Vanillin 8. Diosgenin 9. Omega-3 fatty acid 10. Flavonols

It's necessary to note that this categorisation is not mutually exclusive, and many nutraceutical products may contain a combination of ingredients from different categories to target specific health concerns. Additionally, the efficiency and safety of nutraceuticals can vary, so it's advisable to consult with healthcare professionals and rely on scientific evidence when choosing and using nutraceutical products. Categories of nutraceuticals can be summarised as shown in Fig. 4.

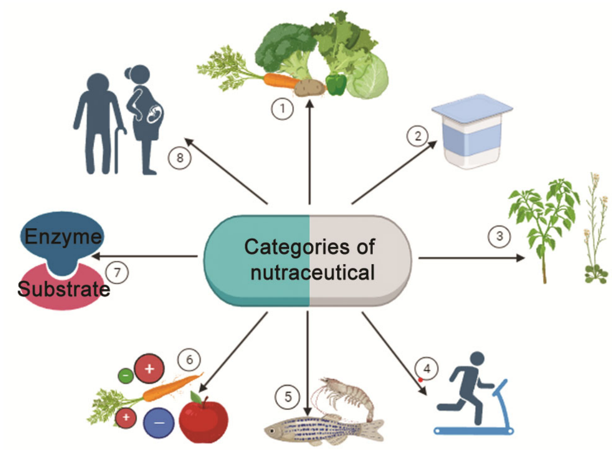

Fig. 4 — Categories of nutraceuticals. 1) Dietary supplements, 2) Probiotics and prebiotics, 3) Herbal and botanical extracts, 4) Sports and performance enhancers, 5) omega rich fatty acids, 6) Antioxidants, 7) Nutritional enzymes, 8) Nutraceuticals for special population including pregnant women and elderly.

Use of biotechnology in nutraceuticals

Biotechnology has its branches extended in the progress and production of nutraceuticals, offering a range of applications that contribute to their efficacy and quality. Some of the key uses of biotechnology in nutraceuticals are[56,57].

Fermentation

Fermentation is a biotechnological process widely used in the production of nutraceuticals. Microorganisms like bacteria, yeast, and fungi are employed to ferment raw materials and produce various functional ingredients. For example, probiotics, which are beneficial live bacteria, are often produced through fermentation and incorporated into nutraceutical products to support digestive health. Biotechnology is undoubtedly important for the progression of functional foods, which are fortified with bioactive ingredients to provide additional health benefits. Fermentation is also a boon for food waste management industries[58]. Genetic engineering and fermentation techniques can be used to introduce or enhance specific functional traits in food crops, enabling the production of value-added ingredients such as prebiotics, omega-3 fatty acids, and plant sterols. For example, the bioactive composition of spirulina can be enhanced through fermenting with *Lactobacillus plantarum*[59].

Genetic engineering

Also called as genetic modification, it refers to the manipulation of an organism's genetic material to introduce or modify specific traits. Biotechnology allows for the genetic modification of plants and microorganisms used in nutraceutical production. This can enhance their nutritional profile, increase the production of desired compounds, or improve their functional properties. For instance, genetically modified crops can be engineered to produce higher levels of certain nutrients or bioactive compounds[60]. The cutting-edge innovations in the CRISPR-Cas9 genome editing have really brought nutraceutical crop development into a different world altogether, offering specific and targeted changes without the traditional ethical issues that transgenics usually have. This pinpointed genome editing technology was extensively employed to biofortify major cereal crops-rice, wheat, barley, and maise-along with vegetable crops such as potato and tomato. The CRISPR modifications have effectively increased levels of several quantitative parameters, such as protein content, gamma-aminobutyric acid (GABA), oleic acid, and anthocyanin, while removing undesirable components like phytic acid and gluten content[61].

Bioprocessing and extraction

Bioprocessing uses biological agents or processes in producing, purifying, and modifying nutraceutical ingredients. Enzymes derived from microorganisms are utilised to catalyse specific reactions, such as converting raw materials into bioactive compounds or improving the extraction efficiency of nutraceutical ingredients. Bioprocessing techniques optimise the production process, increase yields, and enhance the quality of nutraceutical products. Biotechnology offers effective techniques for the process of extraction, purification, and concentration of nutraceutical substances. Techniques, including enzyme-assisted extraction, fermentation, and bioprocessing, allow the drawing out of bioactive compounds from plant sources or microorganisms. These processes can enhance the yield, purity, and stability of nutraceutical ingredients[62]. Contemporary bioprocessing strategies have evolved to integrate upstream and downstream processing methodologies, where upstream processes directly influence downstream efficiency and overall production costs. Enzyme-assisted extraction represents a paradigm shift from conventional extraction methods, utilising specific hydrolytic enzymes including cellulases, hemicellulases, pectinases, amylases, proteases, and lipases to disrupt cell walls and facilitate bioactive compound release[63].

Bioactive compound production and delivery

Biotechnology enables the production of specific bioactive compounds used in nutraceuticals. Through biotechnological methods like cell culture and microbial fermentation, valuable compounds, including polyphenols and plant extracts, can be produced in large quantities, overcoming limitations associated with sourcing them from traditional agricultural practices. Fermentation-based bioprocessing has emerged as a critical technology for enhancing bioactive compound bioavailability and functionality. Polyphenol-rich fermented systems utilise specialised polyphenol-associated enzymes, including tannases, esterases, phenolic acid decarboxylases, and glycosidases secreted by microorganisms such as Lactobacillus, Bacillus, and Monascus species to convert complex polyphenolic compounds into smaller, more bioavailable molecules[64]. Biotechnology can contribute to improving the bioavailability and delivery of nutraceutical compounds. Techniques such as Nanoencapsulation and liposomes can shield bioactive compounds from degradation, elevate their absorption, and facilitate targeted delivery to specific tissues or cells[65].

Cultivation of nutraceutical ingredients

Biotechnology techniques such as tissue culture, cell culture, and genetic engineering can be used to cultivate specific plant species or cells that produce high-quality nutraceutical ingredients. This allows for controlled and optimised production of bioactive compounds, ensuring consistent potency and purity. Biotechnology enables the production of functional ingredients with specific health-promoting properties. For example, probiotics, which are beneficial bacteria that support gut health, can be produced through fermentation processes using genetically modified strains encapsulated for a better delivery system[66]. Similarly, enzymes plus bioactive peptides, along with specific health benefits, can be produced using biotechnological methods[67].

Enhancement of nutrient profiles

Biotechnology can be employed to enhance the nutrient profiles of nutraceutical ingredients. Through techniques like genetic engineering, scientists can modify the genetic makeup of plants or microorganisms to increase the production of desired nutrients or bioactive compounds. This enables the development of fortified nutraceutical ingredients with higher levels of vitamins, minerals, antioxidants, or other beneficial compounds[68]. Antioxidant enhancement strategies focus on manipulating carotenoid and flavonoid biosynthetic pathways to maximise health-promoting compounds. Tomato varieties engineered for enhanced lycopene production through CRISPR-mediated knockout of the STAYGREEN gene, a negative regulator of

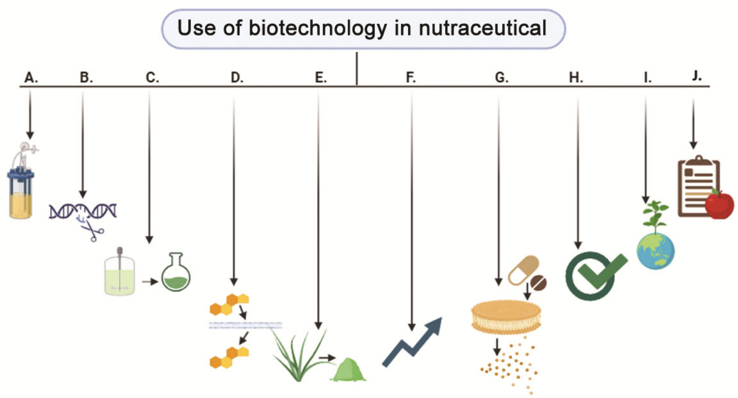

Fig. 5 — Use of Biotechnology in Nutraceutical: (A) Fermentation, (B) Genetic Engineering, (C) Bio processing and Extraction (bioactive compounds are extracted using fermentation technology), (D) Bioactive compounds' production and delivery, (E) Cultivation of nutraceuticals ingredients (production of spirulina powder), (F) Enhancement of nutrient profile, (G) Improved bioavailability and absorption (nutraceutical absorption across membrane), (H) Quality control and standardisation, (I) Sustainable production, (J) Nutrigenomics and personalised nutrition

carotenoid biosynthesis, demonstrated significantly elevated lycopene levels with enhanced antioxidant properties for cardiovascular and cancer protection[69].

Improved bioavailability and absorption

Biotechnology can enhance the bioavailability and absorption of nutraceutical ingredients. For reference, the usage of biotechnology in encapsulation techniques can develop the stability in addition to the solubility of bioactive compounds, facilitating their effective delivery and absorption in the body[70].

Quality control and standardisation

Biotechnological tools such as DNA-based techniques and molecular markers can be utilised for quality control and standardisation of nutraceutical products. These methods allow for the identification and verification of specific ingredients, ensuring product authenticity and consistency[71].

Sustainable production

Biotechnology offers more sustainable production methods for nutraceuticals. For instance, using fermentation processes to produce nutraceutical ingredients can be more environmentally friendly compared to traditional extraction methods. Additionally, biotechnology enables the consumption of renewable resources and reduces the reliance on scarce or endangered plant species[72].

Nutrigenomics and personalised nutrition

Biotechnology and the field of nutrigenomics intersect to provide insights into how individual genetic variations influence the response to nutraceuticals. This knowledge can lead to personalised nutrition recommendations and the development of targeted nutraceutical interventions based on an individual's genetic profile[73].

Overall, biotechnology has a notable importance in the advancement, manufacturing, and customisation of nutraceuticals. It offers innovative methodologies to boost the nutrient profiles, bioavailability, and worth of nutraceutical ingredients while promoting sustainable production practices[56]. Continued advancements in biotechnology are expected to drive further innovation in the nutraceutical industry and contribute to personalised approaches to nutrition and health (Fig. 5).

Use of nanotechnology in nutraceuticals

Nanotechnology has favoured a revolution in multiple industries, including food, pharmaceuticals, cosmetics, and nutraceuticals. Researchers have utilised nanotechnology to address specific challenges in these fields, motivated by the collective demand for healthy food products and enhanced drug delivery systems[74]. The extraordinary features of nanomaterials, resulting from their smaller size and higher surface-to-volume ratio, have enabled their widespread application in the food and nutraceutical segments. Nanomaterial-based carrier systems have shown tremendous potential in incorporating natural products, overcoming their limitations, and preserving their therapeutic effects. In particular, nanotechnology has significantly advanced biomedical science by improving the delivery of nutraceuticals through nanomaterial-based carriers, leveraging the improved permeability and retaining effect in tumours and addressing issues like poor solubility and short half-lives[74].

While the usage of nanoscale particles for targeted drug delivery has been extensively studied, the usage of nanotechniques in the food industry is relatively recent. Natural or nanoparticulate systems based on synthetic polymer, including biomolecules like proteins, lipids, carbohydrates, and other nutraceuticals, hold promise in the industry of food. The extraordinary budding nanotechnology lies in fabricating and combining nanoscale methods and serving platforms to create valuable tools in medical and nutritional sciences at the measure of approximately 1-100 nm. The availability of tools and techniques for studying and intervening at the nanoscale has garnered significant attention in recent years[75].

Nanotechnology has opened up new perspectives across scientific and, more specifically, technological fields. In nanoresearch, herbal drugs, extracts and nutraceuticals have become rapidly growing areas of interest. Various new botanical preparations and nutraceuticals, such as polymeric nanoparticles, nanoencapsulation, nanoemulsions, transferosomes, and ethosomes, have been developed with the help of bioactive compounds obtained from botanical extracts and food materials. These advancements offer remarkable advantages over conventional formulations, including enhanced solubility, bioavailability, consistency, persistent delivery, enhanced tissue distribution, safety from toxicity, improved pharmacological activity, and shield from degradation[76]. The dimension and surface chemistry of nanoparticles has an important role in their direct uptake, which is particularly important for poorly absorbed components. However, it is essential to carefully investigate probable side effects associated with the nanoparticle carriers[77]. Understanding the chemical assembly and characteristics of different nutraceuticals is vital in addressing these challenges.

Nanotechnology plays a significant part in nutraceutical delivery systems of nanoparticles, highlighting its scope in the field[78]. Additionally, nanomaterials are developed for quite sensitive biosensors with the ability to sense pathogens, allergens, and contaminants that alter the eminence and safety of food. By manipulating dimensions of matter to the nanoscale, the stability and solubility of nutrients can be enhanced notably, enabling effective and regulated delivery through nanotransporters. Nanotechnology facilitates specific regulation of properties and functioning at the molecular level, allowing the development of effective encapsulation and delivery systems[79]. Nano formulations elevate the absorption and bioavailability of nutrients and additives in the body. The important use of nanotechnology in the food industry focuses on designing and emerging functional food with amended bioavailability, thermal stability, organoleptic attributes, and biological presentation. However, incorporating these nutraceuticals into foods can be challenging due to their reduced solubility, undesirable flavours, chemical instability, or little bioavailability[80]. Bioactive compound encapsulation in nanoparticle-based delivery systems often overcomes these limitations. When the dimension of the particles comprising them declines, encapsulation can raise the bioavailability of bioactive agents, allowing for more rapid digestion. Nanoparticles are designed to thrive in a particular location of the gut and discharge their load at predetermined locations, by getting the most out of their potential well-being. Nutraceutical-loaded nanoparticles may be manipulated using lipid formulations, specialised equipment, biopolymer nanoparticles, and various other procedures, with their classification centred on the main mechanism or component used for fabrication[81].

Nanotechnology has its applications extended in some segments of the food sector, comprising food refining, packaging, observing, functional food manufacturing, and the development of personalised foods tailored to individual dietary needs. It also enables the creation of stronger flavourings, colourings, and additives with nutritional values while reducing the cost of food supplements and extending the age of food goods. Nanotechnology has the ability to transform the food industry by evolving smart packaging systems that elevate product shelf life. Such systems could repair small damages, respond to environmental changes, and even alert customers if the food is adulterated. Nanotechnology offers measures such as changing the permeation behaviour of foils, improving obstruction properties, developing antimicrobial surfaces, detecting microbiological and biological, along with chemical changes[76]. Additionally, nanotechnology can be used to develop analytical methods for detecting trace quantities of chemical contaminants, viruses, and bacteria in the food processing system, thereby enhancing food safety. However, it is crucial to establish regulatory rules capable of effectively handling any risks associated with nanotechnologically manipulated food and the usage of nanotechnologies in the food industry[82].

In the context of nutraceuticals, nanotechnology has been explored for several applications, inclusive of enhancing bioavailability, improving nutrient delivery systems, and developing novel functional ingredients. Nanotechnology has emerged as a scope for nutraceuticals, offering several potential applications and benefits. Here are some ways in which nanotechnology is being utilised in nutraceuticals[1,83,84].

Nanoemulsions and Nanoparticles

Nanoemulsions are a group of tremendously minute droplets that are morphologically transparent or translucent and have a bluish colouration. They are commonly present in the range of 50 to 200 nm, but are definitely quite reduced than the range (from 1 to 100 mm) for traditional emulsions. Nanoscale delivery systems, including nanoemulsions and nanoparticles, can increase solubility, stability, and presence of less soluble nutraceutical constituents. These transport systems can encapsulate vitamins, antioxidants, and other bioactive compounds, protecting them from destruction and facilitating their absorption in the body[85]. Solid lipid nanoparticles (SLNs) represent a revolutionary advancement in nutraceutical encapsulation technology, offering superior advantages over traditional delivery systems, including liposomes, emulsions, and polymer nanoparticles. SLNs utilise biocompatible lipid matrices that undergo enzymatic degradation into natural components found in the human body, making them ideal carriers for both hydrophilic and hydrophobic nutraceuticals. Advanced formulation optimisation has achieved remarkable encapsulation efficiencies: curcumin-loaded SLNs demonstrate 84.52-99.80% encapsulation efficiency with 12.89% loading capacity, utilising optimised lipid-to-surfactant ratios (2:1.25) and closed-loop high-pressure homogenisation at 300 bar pressure for three cycles[86].

Nanoencapsulation

Nutraceuticals can be encapsulated within nanosized structures to protect them from environmental factors, control their release, and improve their stability during storage and digestion. This encapsulation helps preserve the bioactivity of the compounds and ensures their efficient delivery to the intended site of action. Nanoencapsulation techniques have an advantage in encapsulation of vitamins, plant extracts, and other bioactive compounds, allowing for regulated release and target-specific delivery[87]. The stimuli-responsive nanoencapsulation includes pH-dependent systems that are particularly efficient at delivering cargo through the gastrointestinal tract, as well as poly(acrylic acid)-based nanoparticles that controlled the release of doxorubicin at three different pH values (1.2, 5.3, and 7.4) where those formulations with higher cross-linker content and more alkaline environments released the drug. Multistimuli responsive systems are those that combine two or three stimuli responsiveness, such as the redox/pH dual responsive polypeptide micelles (mPEG-SS-PNLG), which exhibit a relatively low release of drug under physiological conditions (pH 7.4) and a dramatic increase in the release of the drug under acidic conditions (pH 5.0) and elevated redox potential status[88].

Nanostructured lipid carriers

Nanotechnology enables the development of nanostructured carriers such as liposomes, lipid nanoparticles in the form of a solid. These carriers can enhance the delivery of nutraceutical ingredients, shield them from degradation, and improve the uptake and efficacy in the body[89].

Nutrient fortification

Nanotechnology is used to fortify food and beverages with essential nutrients. Nanoencapsulation techniques can be employed to incorporate vitamins, minerals, antioxidants, and other nutraceutical ingredients into food matrices. This enhances their dispersion, stability, and bioavailability, allowing for the improvement of functional foods with improved nutritional profiles. Mineral nanofortification has achieved remarkable success in addressing global micronutrient deficiencies, particularly for iron, zinc, and calcium supplementation. Iron nanoparticles represent a paradigm shift from conventional fortification approaches, overcoming the dual challenge of maintaining bioavailability while preventing organoleptic changes in food vehicles. Nanosized iron compounds produce minimal sensory alterations compared to water-soluble iron complexes like ferrous sulfate and ferrous chloride, while achieving superior absorption rates through increased surface area and improved solubility in gastric acids. Clinical studies demonstrate that reducing iron pyrophosphate particle size from 8 to 4 μm increases adult iron absorption rates by 2-4 fold, highlighting the critical role of particle size optimization[90].

Enhanced bioavailability

Many bioactive compounds in nutraceuticals have poor solubility or stability, which can limit their absorption and effectiveness in the body. Nanotechnology allows for the creation of nanoemulsions, nanoparticles, and other nanoscale delivery systems that can encapsulate these compounds, improving their solubility, stability, and bioavailability. By reducing particle size and increasing surface area, nanotechnology enhances the absorption and cellular uptake of nutraceutical ingredients. For instance, the curcumin problem of lower bioavailability can be solved through nanotechnology[91].

Controlled release systems

Nanotechnology enables the advancement of controlled release systems for nutraceuticals. Nanostructured carriers, inclusive of liposomes and nanostructured lipid carriers, can encapsulate nutraceutical ingredients and provide controlled release profiles. This allows for sustained and targeted delivery, ensuring a more prolonged and efficient discharge of bioactive compounds in the body. Nanotechnology enables target-specific delivery of nutraceuticals in the body. Functionalised nanoparticles are designed to selectively accumulate in certain tissues or cells, allowing for localised delivery of bioactive compounds. The target-specific approach raises the therapeutic worth of nutraceuticals while reducing potential side effects[92,93].

Improved stability and shelf life

Nutraceutical products can be susceptible to degradation and loss of potency during storage. Nanotechnology offers methods to improve the stability and shelf life of these goods. Nanoencapsulation, along with nanocoating techniques, can protect nutraceutical ingredients from environmental aspects, such as light, temperature, and oxidation, preserving their quality and efficacy over a longer period[94].

Sensor technologies

Nanosensors and nano-based diagnostic tools are being developed to detect and monitor various

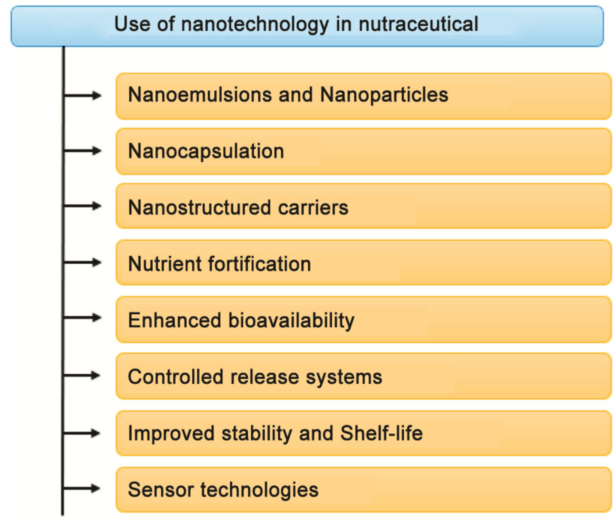

Fig. 6 — Applications of Nanotechnology in Nutraceuticals: Key Areas of Impact.

biomarkers and nutrient levels in the body. These technologies can provide real-time feedback on nutritional status and enable personalised nutraceutical interventions[79].

It is quite notable that the use of nanotechnology in nutraceuticals is an undeniably rapidly evolving field, and ongoing research is being conducted to explore its potential benefits, safety, and regulatory considerations and potential environmental impacts[95]. However, the application of nanotechnology holds promise in improving the effectiveness, stability, and targeted delivery of nutraceutical ingredients, opening up new avenues for enhanced health benefits. The uses of nanotechnology in nutraceuticals have been summarised in Fig. 6.

Conclusion and future outlook

Nutrients present in foods, comprising fruits and vegetables, have been extensively studied and prove to provide noteworthy health benefits. Such nutrients are recognised to protect against various disorders such as osteoporosis, lung-related diseases, cardiovascular diseases, myocardial ischemia, and Alzheimer's disease. As a result of these well-documented health benefits, it is recommended to regularly include nutraceuticals in the diet to reduce risk factors associated with these conditions. The mechanisms by which nutraceuticals exert their effects include a diverse range of biological processes. These include the stimulation of antioxidant battlements, modulation of signal transduction pathways, regulation of gene expression associated with cell survival, promotion of cell propagation and differentiation, and safeguarding mitochondrial integrity.

Currently, there is a need for more research to fully understand the optimal dosage, outcomes, and safety profiles associated with various nutraceuticals. Efforts are being made to address these gaps in knowledge. However, it is important to note that our existing food sources have limitations in providing sufficient nutrients to meet human nutritional needs. Investigations have revealed this deficiency in the nutritional value of our food pantries. Consequently, there is a growing emphasis on developing nutritional products that fulfil desired requirements. This includes the manipulation and modification of pathways of metabolism in crops and medicinal plants to overproduce nutrients such as vitamins and various nutrients extracted from plants, including flavonoids and alkaloids. These advancements have achieved significant progress in the production of nutrient-rich crops.

Nanotechnology has also contributed to eradicating the limitation of poor solubility, undesirable flavours, and chemical instability by the process of encapsulating bioactive compounds and using delivery systems based on nanotechnology. Nutraceutical-loaded nanoparticles can be introduced to the gut, and based on the predetermined target site, they will act more effectively. This advancement of a predetermined and effective encapsulated delivery system adds to the efficient working of nutraceuticals. Nanotechnology not only opened up the scope for nutraceuticals' delivery systems but also developed more applications in the arena of food and nutrition.

Nutraceutical is a vast and expanding field, gaining increasing attention due to their diverse and profound functions. There are still numerous untapped resources in nature that hold potential for the discovery of constituents capable of treating life-threatening diseases such as HIV/AIDS and avian flu. The growing nutraceutical industry is poised to make a significant impact on a global scale. Recent advances in the field include areas such as microbiome diversity, the impact of climate change on nutrient content, seafood, fresh fruits, and the role of vitamin D. However, further research and surveillance are needed to fully explore these areas for the betterment of society through natural means.

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Conflict of interest statement

The authors declare no conflict of interest among themselves.

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