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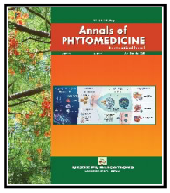

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Nanonutraceuticals and their impact on non-communicable diseases: A review

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Abstract

Noncommunicable diseases (NCDs) represent one of the most critical health concerns worldwide, being responsible for about 68% of all deaths annually, which equates to roughly 38 million people. In India, they contribute to nearly 60% of disease-related morbidity, affecting around 5.87 million individuals. Chronic ailments such as diabetes mellitus, cardiovascular disorders, cancers, endocrine and urogenital diseases, vascular complications, and respiratory illnesses account for the majority of these deaths, causing nearly 41 million fatalities each year, approximately seven out of every ten global deaths. Beyond mortality, NCDs impose severe socio-economic challenges through elevated healthcare costs, diminished productivity, and financial instability, particularly evident during infectious disease outbreaks like COVID-19. In response, the preventive and therapeutic potential of nanonutraceuticals, the bioactive compounds derived from medicinal plants, fruits, vegetables, and grains, incorporated into nanoscale delivery systems, has gained increasing scientific attention. Traditional nutraceuticals often face challenges such as poor water solubility, low chemical stability, and limited bioavailability, which restrict their clinical efficacy. Nanotechnology-based formulations offer a promising solution by enhancing the solubility, stability, absorption, and targeted delivery of these bioactives, thereby maximizing their biological effectiveness and therapeutic outcomes. This review summarizes the emerging importance of nanonutraceuticals in mitigating and managing non-communicable diseases, emphasizing their potential as complementary strategies alongside conventional medical interventions.

1. Introduction

The term “noncommunicable diseases” (NCDs) refers to chronic illnesses that are not primarily caused by infections. These illnesses frequently create long-term health problems and call for ongoing medical care. They are often termed as lifestyle diseases, arising from genetic, environmental, and behavioural factors rather than infection. In India, they account for about 52% of all deaths, primarily due to cardiovascular diseases, diabetes, cancer, and chronic respiratory disorders. Despite government initiatives since the 1980s, the burden remains high due to the limited effectiveness of prevention and management efforts. Strengthening early diagnosis, health promotion, and preventive strategies is crucial. Effective monitoring, integrated care, and public awareness are essential to curb the growing NCD crisis (Sahu *et al.*, 2024). About 17.9 million fatalities annually are attributed to cardiovascular illnesses, making them the leading cause of NCD-related mortality (WHO, 2024). While 4.1 million people die from chronic respiratory diseases and 2.0 million from diabetes, including complications from diabetes related renal disease, cancer claims the lives of almost 9.3 million people annually (Bhattacharyya *et al.*, 2022). NCDs cause nearly 17 million premature deaths each year, defined as deaths occurring before the age of 70. About 86% of these deaths occur in low and middle-income countries, with diabetes, cancer, cardiovascular diseases, and chronic respiratory disorders accounting for over 80% of the total premature NCD mortality (WHO, 2024).

Several behavioural and environmental risk factors, including poor eating habits, sedentary lifestyles, smoking, alcohol misuse, and exposure to air pollutants, cause the onset of NCDs. These habits frequently show up as metabolic abnormalities, such as obesity, dyslipidaemia, hypertension, and hyperglycemia, which raise the risk of cardiovascular illnesses, the primary cause of premature NCD

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death (WHO, 2024).Research strongly emphasizes the urgent need for effective interventions to prevent and mitigate the growing burden of cancer, diabetes, hypertension, and obesity.

In this regard, the potential of nutraceutical substances obtained from food sourcesto enhance health, postpone ageing, and lower the risk of chronic illnesses is becoming more widely acknowle-dged. Recent studies have highlighted the significant therapeutic potential of nutraceuticals in managing a wide range of chronic diseases, including immune dysfunction, obesity, diabetes, osteoporosis, cardiovascular disorders, and cancer. Puri *et al*. (2022) provided a comprehensive review of nutraceuticals' therapeutic roles and formulation challenges, while Dama *et al.* (2024) demonstrated their ability to modulate oxidative stress and inflammation in metabolic disorders. Similarly, Scarpa *et al.* (2024) reported on the antioxidant, antidiabetic, and pro-osteogenic activities of polyphenols in diabetes and osteoporosis. Clinical evidence from Ricottini*et al.* (2024) confirmed improvements in metabolic and lipid parameters among overweight patients receiving nutraceutical combinations. Despite their therapeutic potential, many nutraceuticals exhibit low bioavailability due to chemical instability and reactivity. Some compounds are volatile or sensitive to environmental factors like heat and moisture, leading to degradation during processing or storage. Delivery technologies based on nanotechnology, like nanoparticles and nanocarriers, have been created to overcome these obstacles. These systems enhance stability, minimize nutrient loss, and improve bioavailability. Nanoencapsulation techniques, in particular, provide controlled release and protection of sensitive compounds during formulation (Estevinho, 2020). Such nanocarrier-assisted delivery approaches not only increase the efficacy of nutraceuticals in NCD management but also enable the utilization of compounds that were previously unsuitable for conventional formulations. This review explores the current state of noncommunicable diseases (NCDs) and how nanonutraceuticals are transforming treatment approaches for managing and preventing them.

2. Nanotechnology in nutraceuticals delivery

2.1 Nutraceuticals' impact on human health

According to Fung *et al*. (2018), nutraceuticals are bioactive compounds that have physiological effects beyond simple nourishment and help prevent or treat a number of illnesses. These substances exhibit a variety of health promoting properties, including anti-inflammatory, antidiabetic, cardioprotective, immunomodulatory, and organ protective effects (Dutta *et al.*, 2018). Regular consumption of nutraceutical enriched and functional foods has been reported to play a crucial role in lowering the risk of age-related, degenerative, and chronic conditions such as Parkinson's disease, Alzheimer's disease, osteoporosis, cardiovascular diseases, diabetes, and several types of cancer (Prakash and Kumar, 2011). Functional foods are traditional dietary components that have been improved or enriched by bioactive compounds, thus conferring beneficial physiological effects beyond their mere nutritional value. In distinction to food products in general, nutraceuticals are finite forms of these bioactive compounds in more concentrated, purified or isolated forms marketed specifically for the prevention of targeted diseases, such as capsules, tablets and powders. This difference reflects the increasing significance of bioactives from food in the move towards linkages between nutrition and medicine. Beyond their metabolic benefits, nutraceuticals also influence the gut microbiota, thereby supporting metabolic and neurological health. Modification of the intestinal flora has been linked to protection against metabolic diseases such as type 2 diabetes, obesity, and non-alcoholic fatty liver disease, as well as neurological and developmental conditions like multiple sclerosis (MS), Parkinson's disease (PD), and autism spectrum disorder (ASD). Several nutraceuticals have shown gut-modulatory potential, *i.e.*, polyphenols (from green tea, grapes, and berries), omega-3fatty acids (from flaxseed, fish oil, and walnuts), curcumin (from turmeric), resveratrol (from grapes and red wine), and probiotics and prebiotics (from fermented foods like yogurt, kefir, and dietary fibers such as inulin) (Wang *et al.*, 2022a; Wang *et al.*, 2022b; Cerullo *et al.*, 2025; Kezer *et al.*, 2025; Kumar *et al.*, 2025). Recent evidence further suggests that nutraceuticals may mitigate complications associated with preterm birth, including bronchopulmonary dysplasia, infant eczema, necrotizing enterocolitis, and growth restrictions (Kerry *et al.*, 2022). These bioactives act through multiple mechanisms such as modulating gut microbial diversity, enhancing anti-inflammatory pathways, and maintaining intestinal barrier integrity.

2.2 Principles of nanotechnology

Nanotechnology involves the desigzsn, modification, and application of materials at the nanoscale, typically less than 100 nm, to impart unique physical, chemical, and biological properties. When applied to nutraceutical delivery, nanoscale encapsulation enables targeted release and enhanced absorption of bioactive molecules following oral intake (Manocha *et al.*, 2022). Through the creation of nanonutraceuticals, nanotechnology improves the stability, solubility, and therapeutic efficiency of sensitive compounds (Singh *et al.*, 2022). Nanocarriers provide several advantages such as high encapsulation, slow or sustained release and protection from microbial degradation. Furthermore, they offer to better biological effect and higher therapeutic efficacy. Furthermore, nanomaterials have been developed as the nano-sensor or bionano sensors that are capable of encapsulating biomolecules (*i.e.*, peptides, antibodies and enzymes), which indicate an advanced diagnosis or delivery functions (Singh *et al.*, 2022). Nanostructured vehicles not only effectively improve stability and bioavailability of nutraceuticals, but also facilitate a targeted delivery to certain tissues or cells, especially for the treatment of obesity and related complications like type 2 diabetes, dyslipidemia and cardiovascular disease. These nanocarriers may be employed to enhance the therapeutic efficacy, to decrease the amount of needed doses, and to lower side effects through an accurate delivery of bioactive compounds at the diseased location (Aguilar-Pérez *et al.*, 2023). Molecular diffusion movement from regions of high to low concentrationis central to nanoparticle transport. While fat soluble nanoparticles pass through cell membranes passively, small, non-polar molecules can diffuse easily across them. In contrast, water-soluble molecules need help to cross cell membranes, typically moving through specialized membrane pores, with their ability to pass influenced by factors like particle size and charge. Larger nanoparticles, however; rely on specific transporter proteins that actively carry them across the membrane, even against concentration gradients (Magne *et al.*, 2023).

2.3.Drug delivery using nanoparticles

The delivery of drugs and nutraceuticals has been completely transformed by the development of tailored nanoparticles. Such systems address key challenges associated with conventional

formulations, including low stability, poor solubility, and limited ability to cross biological barriers. These barriers vary widely across tissues and individuals, highlighting the need for adaptable and precision oriented nanocarriers (Smith *et al.*, 2020; Zhao *et al.*, 2022). To address these challenges, precision nanoparticle design applies the principles of personalized medicine, creating drug delivery systems that are customized to an individual's unique physiological and disease characteristics (Chen *et al*., 2021). Although, current research often relies on generalized design frameworks, innovations in lipid-based, polymeric, and inorganic nanoparticle systems continue to advance encapsulation efficiency, biocompatibility, and site-specific targeting (Kumar *et al.*, 2019; Patel *et al.*, 2023). Emerging approaches now focus on 'surface functionalization' for target specificity and biocompatibility (Gorohovs and Dekhtyar, 2025), 'stimuli-responsive behaviour' for drug release kinetics and timing (Wu *et al*, 2023), and biomimetic coatings for immune evasion and biological communication (Abesekara and Chau, 2022) to fine-tune nanoparticle interactions with biological environments, optimizing their performance for specific medical applications (Li *et al.*, 2022). These intelligent nanostructures represent the next generation of personalized drug-delivery platforms, capable of navigating patient specific physiological barriers and optimizing therapeutic outcomes (Chehelgerdi *et al.*, 2023).

2.4 Nanocarriers for nutraceuticals delivery

Encapsulation technology is designed to protect the sensitive bioactive compounds while enabling their controlled release. This is achieved by enclosing the active nutraceutical (the core material) within a protective layer made of lipids, proteins, or polysaccharides (Esfanjani *et al.,* 2018). The resulting micro- or nanocapsules can be engineered as emulsions, biopolymeric matrices, or vesicular systems to achieve desired release characteristics. Liposomes, which are spherical vesicles made up of phospholipid bilayers, are the most efficient lipid-based transporters. Lipid membranes and watery cores can contain hydrophilic and lipophilic substances, respectively. Liposomes exhibit biocompatibility, biodegradability, and enhanced intestinal absorption due to their ability to interact with enterocyte transport pathways and lymphatic systems (Subramanian, 2021). Starch based nanocarriers are capable of delivering nutrients or drugs directly to specific areas of the digestive system. They remain stable in the acidic environment of the stomach and adhere to the intestinal wall, which enhances nutrient absorption (Rostamabadi *et al*., 2019). Similarly, casein micelles (CMs), which are natural particles found in milk, serve as effective carriers for nutrients such as minerals, fats, vitamins, and plant compounds (Semo *et al*., 2007; Rehan *et al*., 2019). Curcumin, which is derived from turmeric powder, has significant therapeutic effects, including anticancer, antidiabetic, anti-inflammatory, nephroprotective, and antiobesity properties (Figure 1). However, due to its poor water solubility and low bioavailability, encapsulating curcumin in nanocarriers can enhance its stability, absorption, and overall effectiveness. The milk protein β-casein can independently form small particles that effectively trap fat-soluble compounds such as curcumin (Figure 2). This encapsulation process improves the solubility and health benefits of these compounds (Rezagholizade-Shirvan *et al.,* 2024).

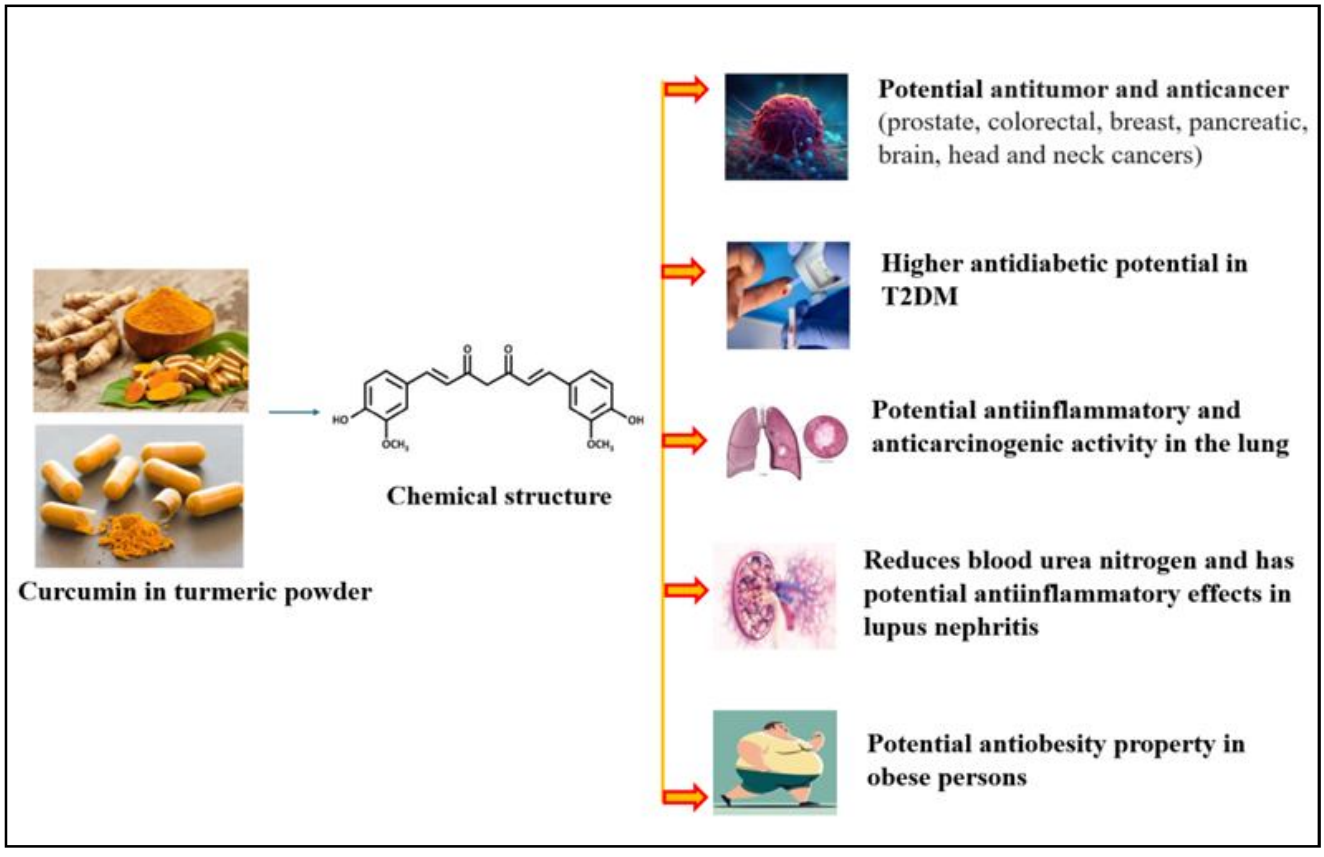

Figure 1: Therapeutic properties of curcumin.(Source: Created by the authors).

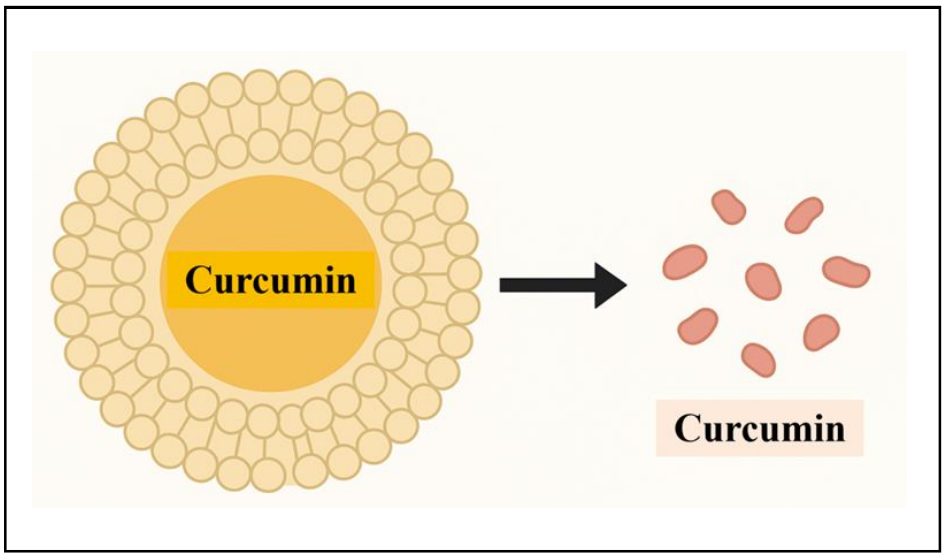

Figure 2: Schematic representation of curcumin encapsulation and delivery using nanocarrier systems. (Source: Created by the author).

Solid lipid nanoparticles (SLNs), which combine the benefits of polymeric nanoparticles with conventional emulsions, are another intriguing concept. Small particle sizes, high loading capacities, enhanced bioavailability, and physical stability are all provided by SLNs. Antioxidant nutraceuticals such as β-carotene, astaxanthin, zeaxanthin, lutein, curcumin, quercetin, and anthocyanins have been effectively encapsulated in them, preventing degradation and boosting their biological activity (Gunawan and Boonkanokwong, 2023). Table 1 summarizes representative nanonutraceutical systems and their therapeutic applications across various health conditions.

Table 1: Nanonutraceuticals and their action to cure various medical conditions

Noncommunicable diseases	Nanonutraceuticals	Nanocarrier type/material	Mechanism or biological effect	References
Diabetes mellitus	Combined extracts of *C. grandis*, *S. auriculata*, and *M. koenigii*	Gelatine nanoparticles (GNPs)	Streptozotocininduced rats and high-fat diet rats showed improved glucose tolerance, suggesting strong antihyperglycemic action.	Wickramasinghe *et al.*, 2024
	Anthocyanin formulation (pelargonidin)	Nanoparticles of poly (lactide-co-glycolic acid) (PLGA)	Participates in the regulation of glucose metabolism	Nunes *et al.*, 2023
	Curcumin and berberine combination	Polymeric nanoparticles	Demonstrated superior antidiabetic potential in experimental type 2 diabetes mellitus (T2DM) models	Ganesan *et al.*, 2017
Gestational diabetes mellitus (GDM)	Resveratrol nanocomplex	Chitosan-ZnO-resveratrol (CS-ZnO-RS) nanoparticles	Lowered blood glucose, reduced inflammation (IL-6, MCP-1), and modulated ER-stress markers (GRP78, p-IRE1α, *etc*.)	Du *et al.*, 2020
Cancer	Curcumin with temozolomide	Magnetic nanoparticles	Induced apoptosis and tumour suppression *via* activation of cell-death pathways	Dilnawaz and Sahoo, 2013
Breast cancer	Thymoquinone formulation	PLGA nanomatrix	Increased apoptosis in MCF-7 cells, downregulated Bcl-2, and upregulated p53 to increase the effectiveness of doxorubicin	El-Far *et al.*, 2018
Lung cancer	*Bauhinia tomentosa* leaf extract	Silver nanoparticles (AgNPs)	Exhibited cytotoxic and anticancer activity toward A-549 lung carcinoma cells	Mukundan *et al.*, 2015

	Curcumin	Krill lipid-based liposomes (marinosomes)	Displayed strong cytotoxicity and anticancer potential against A-549 cells	Ibrahim *et al.*, 2018
Lung cancer and pulmonary fibrosis	Curcumin nanoformulation	CuR-NPs	Demonstrated anticarcinogenic actions and anti-inflammatory	Bhat *et al.*, 2023
Chronic obstructive pulmonary disease (COPD)	Berberine nanodispersion	Liquid crystalline nanoparticles (LCNs)	Decreased bronchoepithelial and macrophage production of reactive oxygen species (ROS)	Paudel *et al.*, 2022a
Respiratory disorders (Asthma, COPD)	Quercetin-3-O-rutinoside and vitamin D	Rutinbased nanoformulation	Exhibited anti-inflammatory, antiallergic, antioxidant and immunomodulatory functions	Paudel *et al.*, 2022b
Obesity	Oleoresin capsicum	Nanoemulsion	Decreased body fat formation through glycerol-3-phosphate dehydrogenase inhibition and AMPK activation	Kim *et al.*, 2014
	Nigella sativa seed oil	Fucoidanbased nanoemulsion	Prevented lipid buildup and steatosis in the hepatic tissue	Oliyaei *et al.*, 2023
	Soybean seed extract	Phytosomalthermogel nanoliposomes	Improved lipid profile, controlled body weight, and less adipose tissue	El-Menshawe *et al.*, 2018
	Caffeine and chlorogenic acid (from green coffee beans)	Solid lipid nanoparticles (SLNs)	Produced antiobesity effects through lipidmetabolic modulation	Uner and Celebi, 2023
	Pterostilbene inclusion complex	Chitosanbased polymeric nanoparticles	Induced sustai nable weight loss with minimal side effects; potential oral antiobesity agent	Heikal *et al.*, 2022
Chronic kidney injury	Quercetin	Quercetin macroparticles (QMPs)	Downregulated pro-fibrogenic and pro-inflammatory cytokines while enhancing antifibrotic responses	Sánchez-Jaramillo *et al.*, 2022
Hepatic cirrhosis	Thymoquinone (black seed oil)	Solid lipid nanoparticles (SLNs)	Reduced hepatic oxidative stress markers and improved liver protection	Al-Gabri *et al.*, 2021
Lupus nephritis	Curcumin	Nanoemulsion	Lowered blood urea nitrogen and exerted anti-inflammatory effects	Young *et al.*, 2015
	Allium jesdianum leaf extract	Silver nanoparticles	Reduced levels of kidney and serum inflammatory cytokines (TNF-α, IFN-γ, IL-12, and IL-6) and urine protein	Sun and Zhang, 2024

3. Noncommunicable diseases and potential benefits of nanonutraceuticals

3.1 Diabetes mellitus

It is a chronic metabolic condition that, over time, can damage vital organs like the kidneys, nerves, eyes, heart, and blood vessels, and is characterised by elevated blood glucose levels. The majority of the 422 million persons with diabetes globally reside in the nations with low- and middle-income. The disease directly accounts for approximately 1.5 million deaths annually, and its prevalence has steadily increased in recent decades, reflecting the growing impact of lifestyle and metabolic disorders. Nutraceuticals derived from foods, plants, and natural sources have gained considerable attention as preventive and therapeutic interventions. In 2024, the World Health Organization reaffirmed its goal to halt the rising prevalence of diabetes by 2025, addressing a major contributor to the global NCD burden. The WHO Global Diabetes Compact, launched in 2021, emphasizes prevention, early diagnosis, and effective treatment, with a focus on equitable access in low- and middle-income countries. This initiative highlights the urgent need for global action to prevent and manage diabetes and obesity, aiming to reduce their impact on public health worldwide. This noncommunicable disease significantly

contributes to premature illness and death among individuals aged 30-70 years (Arokiasamy *et al.*, 2021). The financial impact of diabetes is equally concerning. The International Diabetes Federation (2015) states that 5-20% of total healthcare costs in most countries are related to diabetes. In 2015, it was estimated that the world would spend about USD 673 billion on diabetes and its implications; by 2040, that amount is likely to rise to USD 802 billion (Herman, 2017). These figures underscore the pressing need for cost-effective and sustainable management strategies.

Nanoformulated nutraceuticals have shown promising potential in diabetes management by enhancing the bioavailability, metabolic stability, and targeted delivery of bioactive compounds. Lipid based nanopolyphenols have been reported to increase hepatic glycogen stores while reducing glucose, albumin glycation, total cholesterol, and HbA1C levels. Flavonoids encapsulated in liposomal systems show superior antidiabetic potential compared to their free forms, with liposomal delphinidin chloride exhibiting particularly enhanced efficacy (Rocha *et al.*, 2021).

A wide range of oral nano-delivery systems has been developed for the effective management of T2DM, including polymeric nanoparticles, lipidbased nanosystems, micelles, vesicular systems, inorganic nanocarriers, and nanosuspensions. These advanced delivery platforms offer several advantages over conventional formulations. By bypassing hepatic firstpass metabolism, nanocarriers allow a greater proportion of the active compound to reach systemic circulation. They also enhance cellular uptake by facilitating the transport of bioactive molecules across biological membranes and improve the physicochemical stability of sensitive phytochemicals, protecting them from degradation in the gastrointestinal tract. Furthermore, nanoformulations can control the rate and site of drug release, often through the lymphatic transport pathway, ensuring sustained and targeted delivery. As a result, phytocompounds encapsulated within these nanocarriers demonstrate enhanced antidiabetic efficacy, lower systemic toxicity, and greater therapeutic efficiency even at smaller or less frequent doses (Nie *et al*., 2020). Animal model investigations further confirm the superior therapeutic potential of phytobased nanocarriers. For instance, in streptozotocin (STZ)-induced diabetic rat models, berberine loaded nanoparticles significantly reduced fasting blood glucose levels, prevented excessive body weight gain, and improved pancreatic is let function (Ganesan *et al.*, 2017). Similarly, copper nanoparticles (CuNPs) synthesized using *Dioscorea bulbifera* extract demonstrated both antioxidant and antidiabetic activities in streptozotocin (STZ)-induced diabetic rats, indicating their potential in preventing oxidative-stress-related diabetic complications. Moreover, CuNPs were identified as potent inhibitors of pancreatic α-amylase and intestinal amylase (Marella *et al.*, 2018).

According to Rambaran (2018), nanoquercetin provides both neuroprotective and renoprotective effects in diabetic conditions by reducing oxidative stress and neuroinflammation. This process improves memory and helps mitigate diabetic nephropathy. The mechanism of action for nanoquercetin includes inhibiting acetylcholinesterase, downregulating proinflammatory cytokines, and suppressing NF-κB activation. Together, these actions contribute to the preservation of cognitive function in diabetes. Furthermore, nanoquercetin reduces the expression of intercellular adhesion molecule-1 (ICAM-1) in endothelial tissues, which helps alleviate diabetic nephropathy. Additionally, encapsulating anthocyanins in chitosan nanoparticles has demonstrated beneficial metabolic effects by reversing hyperlipidemic changes in rats that were fed high-fat and alcohol-rich diets. These effects are primarily achieved through the inhibition of lipogenesis, activation of antioxidant enzymes, and suppression of lipid peroxidation. Similarly, in alloxan-induced diabetic mice, loading anthocyaninrich extracts from vaccinium arctostaphylos onto zinc oxide nanoparticles resulted in a significant reduction in fasting blood glucose and low-density lipoprotein (LDL) levels, along with an increase in high-density lipoprotein (HDL) levels (Sapian *et al*., 2022).

3.2 Cancer

Cancer continues to be one of the major global health challenges, with significant variations in incidence and mortality across different regions and age groups. In developed countries, nearly 78% of cancer cases occur in individuals over the age of 55, while this figure is about 58% in developing nations (Deo *et al*., 2022). Recent global estimates show a dramatic increase in both cancer incidence and mortality. It is projected that the number of new cases will rise by 61%, reaching approximately 30.5 million by 2050. Meanwhile, annual cancer-related deaths are expected to increase by nearly 75%, reaching 18.6 million. This surge is largely attributed to population growth and an ageing population (Health Data.org and IHME, 2025). The most commonly diagnosed cancers include breast, lung, colorectal, and prostate cancers, which account for the majority of global cancer morbidity and mortality. The increasing burden of cancer is primarily linked to ageing populations, changes in lifestyle, and environmental factors. This highlights the urgent need for effective strategies that focus on prevention, early diagnosis, and comprehensive treatment (WHO, 2024).

Nanotechnology has revolutionized the therapeutic landscape of cancer nutraceuticals by enhancing drug solubility, absorption, stability, and tumour specific targeting, thereby minimizing systemic toxicity. Nanonutraceuticals enable precision delivery of phytoconstituents such as curcumin, quercetin, and resveratrol, leading to higher intracellular concentrations and improved anticancer responses (Singla *et al.*, 2023). Advances in nanoscale systems, including polymeric nanoparticles, liposomes, nanoemulsions, and lipidbased carriers, have markedly improved the therapeutic efficiency of many plant bioactives. Current studies demonstrate that these nano-formulations not only increase bioavailability but also enable controlled release and tissue specific accumulation. Reduced cytotoxicity to normal cells and potential for personalized therapeutic modulation are among their key advantages. Nevertheless, challenges such as large-scale reproducibility, safety validation, and regulatory standardization continue to impede clinical translation. For nanonutraceuticals to be included in conventional cancer prevention and treatment, these translational gaps must be filled. Figure 3 illustrates the role of nanotechnology in enhancing targeted cancer treatment.

Resveratrol loaded polymeric nanoparticles, for example; caused G1/S cell cycle arrest, mitochondrial depolarisation, DNA fragmentation, and ROS accumulation in prostate cancer (LNCaP) cells, which in turn decreased cancer cell viability (Nassir *et al.*, 2018). Liposomal doxorubicin (Doxil), a clinically approved nanomedicine, exemplifies the advantages of nanocarrier-based drug delivery. In this formulation, doxorubicin is encapsulated within

liposomes, which protect it from rapid degradation and extend its plasma circulation time. The liposomal system enhances tumour accumulation through the enhanced permeability and retention (EPR) effect while minimizing exposure to healthy tissues, thereby significantly reducing cardiotoxicity compared with free doxorubicin (Salama *et al.*, 2020). When added to hydrogels and microspheres, omega-3 polyunsaturated fatty acids (PUFAs), particularly docosahexaenoic acid (DHA), have also demonstrated improved antitumour properties against colon cancer cells. DHA's high degree of unsaturation (six double bonds) makes it highly peroxidizable, thereby augmenting the oxidative cytotoxicity of anthracycline drugs such as doxorubicin, improving their overall anticancer performance (Serini *et al.*, 2022).

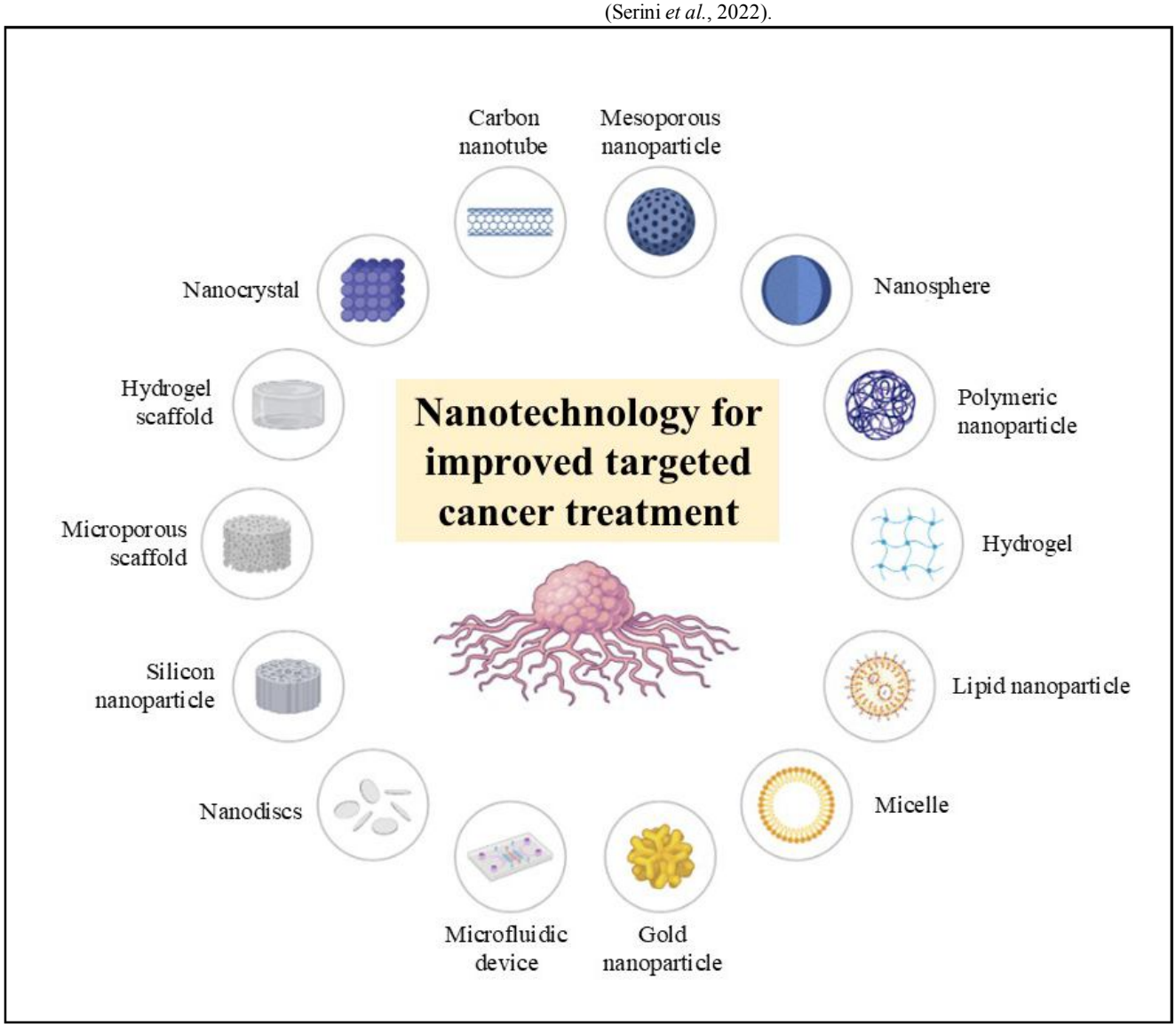

Figure 3: Nanotechnology for improved targeted cancer treatment. (Created with BioRender.com.).

3.3 Cardiovascular diseases

Cardiovascular diseases remain the leading cause of death globally and are a major factor contributing to reduced life expectancy. The WHO (2025) reports that cardiovascular diseases (CVDs), such as heart and blood vessel diseases (cerebrovascular illness, rheumatic heart disease, and coronary heart disease), are the leading cause of death globally, accounting for an estimated 19.8 million deaths annually, representing approximately 32% of all global deaths. Among these, 85% are due to heart attacks and strokes, and onethird occur prematurely in individuals under 70 years of age. Among the main behavioural risk factors that lead to CVDs are poor diet, excessive alcohol consumption, tobacco use, and physical inactivity. Intermediate risk factors like obesity, hypertension, hyperglycemia, and hypercholesterolaemia are frequently brought on by these behaviours. Early detection of these metabolic risk factors in primary healthcare settings can help diminish the likelihood of severe cardiovascular complications like heart failure, myocardial infarction, and stroke (WHO, 2024).

The incorporation of nanotechnology into cardiovascular therapeutics has yielded notable benefits, primarily through improved delivery and efficacy of natural cardioprotective agents. By inhibiting P-glycoprotein (P-gp) expression, bioperine, a black pepper alkaloid

encapsulated in PLA-chitosan/PEG-coated nanoparticles, exhibited enhanced cytotoxic activity against multidrug-resistant breast cancer cells. In addition, this nanoformulation may offer cardiovascular protection through the modulation of oxidative stress (Pillai *et al.*, 2021). Strong cardioprotective effect is demonstrated by lycopene-enriched nanoemulsions, which reduce heart tissue damage and drug-induced cardiotoxicity while lowering inflammatory responses and oxidative stress (Quagliariello *et al.*, 2018). Furthermore, metallic nanocarriers like gold and silver nanoparticles improve the action and transport of phytoconstituents with cardioprotective and anticancer properties. These nanoparticles can increase reactive oxygen species (ROS) production selectively within tumour cells, promoting apoptotic or necrotic death while sparing healthy tissue (Singla *et al.*, 2023).

Curcumin encapsulated in carboxymethyl chitosan nanoparticles was effectively delivered to damaged cardiac tissue in Wistar rats, where it reduced myocardial hypertrophy and apoptosis, indicating a potential role in post-ischemic recovery (Ray *et al.*, 2016). In people with dyslipidaemia, taking nanocurcumin supplements has also been shown to improve triglyceride, total cholesterol, and LDL profiles while raising HDL cholesterol. Furthermore, nanocurcumin has strong anti-inflammatory properties that support general cardiovascular protection by suppressing proinflammatory indicators, including IL-6 and CRP (Ashtary-Larky *et al.*, 2021).

3.4 Obesity

Over the past few decades, obesity, once thought to be a problem exclusive to wealthy societies, has grown to become a significant global public health concern. Childhood overweight and obesity continue to be significant global health issues, according to the WHO (2024) and UNICEF (2023). In 2022, approximately 390 million children and adolescents aged 5 to 19 were classified as overweight, with around 160 million considered obese. Additionally, about 37 million children under the age of five were overweight. These statistics underscore the rising global trend of childhood obesity, especially in low- and middle-income countries, where urbanization and changes in dietary habits have greatly impacted energy balance and physical activity levels. Obesity results from an imbalance between caloric intake and energy expenditure, influenced by various factors such as genetics, environment, and psychosocial conditions. Environmental factors, including sedentary lifestyles, urbanization, and the easy availability of highcalorie foods, have significantly contributed to the increasing prevalence of obesity worldwide (WHO, 2024). In developing countries like India, limited access to nutritious food, insufficient physical activity, and lifestyle changes have heightened the risk of obesity related disorders. Specifically, abdominal obesity has been identified as a major risk factor for cardiovascular diseases within the Indian population (Ahirwar and Mondal, 2019).

Nanotechnology has offered new strategies for managing obesity by improving the delivery and physiological performance of bioactive compounds with lipidmodulating and thermogenic effects. Niosomes loaded with anthocyanins have been demonstrated to improve insulin sensitivity and glucose tolerance by lowering blood levels of insulin, cholesterol, glucose, and leptin, so mitigating metabolic abnormalities linked to obesity (Sapian *et al.*, 2022). Among emerging nanoformulations, pterostilbene nanoparticles have demonstrated remarkable antiobesity effects while remaining biocompatible and nontoxic. Their oral administration effectively lowered serum cholesterol and promoted sustained weight management, positioning them as an innovative and safe therapeutic option for obesity control (Heikal *et al.*, 2022).

A clinical investigation by Salem *et al.* (2023) indicated that consumption of a polyherbal tea blend produced significant reductions in body mass index and improved lipid and glucose profiles. The blend appeared to reduce systemic inflammation by downregulating mRNA expression of genes linked to lipogenesis, like ADD1/SREBP-1C and TNF-α, while upregulating key lipolytic markers, including GLUT-4 as well as P-AMPK, Sirt-1, and PPAR-γ. These molecular responses point to the blend's potential role in managing obesity through simultaneous modulation of lipid metabolism and inflammatory pathways. In animal models, oleoresin capsicum nanoemulsions dramatically decreased body weight and adipose tissue mass in rats that were made obese by a high-fat diet. According to Kim *et al.* (2014), these benefits were ascribed to AMPK activation and glycerol-3-phosphate dehydrogenase inhibition, which led to decreased lipogenesis and improved energy utilisation. Similarly, rats on a high-fat diet showed a 23.5% decrease in body weight increase when quercetin loaded nanoemulsions were given orally, demonstrating their function in controlling adiposity (Pangeni *et al.*, 2017).

Furthermore, the combination of probiotic nanoemulsions with indigenous herbal extracts has been found to improve hepatic markers such as bilirubin, aspartate aminotransferase (AST), and alanine aminotransferase (ALT) while exerting synergistic antiobesity effects (Rathod and Yadav, 2024). When taken as a whole, nanonutraceutical systems offer a versatile strategy for metabolic regulation by effectively increasing the solubility and bioactivity of poorly absorbed antiobesity phytocompounds.

3.5 Chronic respiratory diseases

Chronic respiratory illnesses are conditions that damage the airways and other structures of the lungs over an extended period of time (CRDs). Common CRDs include chronic obstructive pulmonary disease (COPD), occupational lung diseases, pulmonary hypertension, and asthma. The use of tobacco, air pollution, occupational exposure to dust and chemicals, and recurrent lower respiratory infections in children are significant risk factors (WHO, 2024). Although, chronic respiratory diseases cannot be cured, effective management strategies can help alleviate symptoms, enhance lung function, and improve overall quality of life. Conditions such as interstitial lung disease, pulmonary sarcoidosis, and pneumoconiosis (*e.g.,* asbestosis and silicosis) are also categorized under CRDs. Despite overall global declines in age standardized mortality and disability-adjusted life years between 1990 and 2017, the absolute prevalence of CRDs continues to rise, mainly due to environmental and behavioural factors, including tobacco smoking, indoor air pollution from biomass fuel use, occupational dust exposure, ambient air pollution, and low physical activity levels. Among these, smoking remains the predominant risk factor for chronic respiratory morbidity and mortality, particularly among men in all regions (Labaki and Han, 2020).

Persistent airway inflammation and oxidative stress are major causes of chronic respiratory diseases like asthma and chronic obstructive pulmonary disease (COPD). Nanoencapsulated formulations of curcumin and other phytochemicals have demonstrated significant

improvements in pulmonary function and inflammatory control. Clinical data suggest that nanocurcumin supplementation in patients with severe COPD improves respiratory indices such as FEV, FVC, and FEV/FVC ratio, while reducing serum IL-6 levels and systemic inflammation (Zare'I *et al.*, 2024). Experimental studies using berberine-encapsulated solid lipid nanoparticles (SLN) coated with chitosan revealed enhanced therapeutic potential against cigarette smoke induced airway injury in rats. These berloaded nanoparticles outperformed free berberine in terms of their anti-inflammatory activity, significantly lowering inflammatory cytokines such as interleukin-1 (IL-1), IL-6, IL-17, and tumour necrosis factor-alpha (TNF-α), as well as reducing neutrophil and macrophage infiltration in bronchoalveolar lavage fluid (Liu *et al.*, 2022).

Other promising herbal nanosystems include micelles, lipid based liquid crystalline nanoparticles, and nanoemulsions, which serve as advanced carriers for phytochemicals used in asthma management (Yang *et al.*, 2022). Chitosan coated SLN nanoparticles improve berberine's solubility and intestinal absorption, thereby enhancing its anti-inflammatory action in respiratory tissues. Their high bioavailability and mucoadhesive properties make them particularly suited for oral or inhalation based drug delivery in chronic respiratory disorders (Young *et al.*, 2015). Overall, nanonutraceuticals in respiratory therapy offer dual advantages, improved pharmacokinetics and targeted modulation of oxidative and inflammatory pathways, thus representing a promising adjunct to conventional treatment strategies for chronic airway diseases.

3.6 Chronic kidney diseases

Chronic kidney disease (CKD) is a progressive and irreversible loss of kidney function, which reduces the kidneys' ability to eliminate waste and excess fluid from the body. As kidney function declines, harmful levels of electrolytes and toxins can build up, leading to systemic complications. Key risk factors for CKD include diabetes, hypertension, obesity, cardiovascular disease, and smoking (WHO, 2024). Although, CKD cannot be cured, early detection and effective management can help delay its progression and minimize complications. Globally, CKD affects approximately 13-14% of the population, with 5-7 million people needing renal replacement therapy for end-stage disease (Lv and Zhang, 2019).

Progressive nephron loss and deteriorating renal function are hallmarks of chronic kidney disease, which frequently results in end-stage renal failure. Nanonutraceuticals have become protective agents that can reduce inflammation, oxidative stress, and fibrosis linked to renal decline. Strong antioxidant properties of ironoxide nanoparticles (IO-NPs) coupled with glutathione (GSH) preserve normal renal physiology without changing the structure of cortical or medullary tissue. Selenium nanoparticles (SeNPs) have also been shown to counteract cadmium chloride induced nephrotoxicity and neurotoxicity by scavenging free radicals, chelating heavy metals, and regulating apoptosis and cell protective pathways (Upadhyay, 2017).

Clinical findings indicate that oral intake of nano-emulsified curcumin (40 mg/kg/day) significantly ameliorates glomerulonephritis pathology, suggesting therapeutic potential against autoimmune renal inflammation such as lupus nephritis (Young *et al.*, 2015). Likewise, quercetin nanoparticles have demonstrated antifibrotic activity and the ability to attenuate chronic renal failure (Sánchez-Jaramillo *et al.*, 2022). Nanocurcumin supplementation improved vascular and renal outcomes in haemodialysis patients by lowering inflammatory indicators such as hs-CRP and adhesion molecules (ICAM-1, VCAM-1) (Vafadar-Afshar *et al.*, 2020). Further investigations by Futuhi *et al.* (2022) showed that curcumin supplementation in patients with CKD significantly improved metabolic and inflammatory profiles. The study reported notable reductions in serum triglycerides, total cholesterol, and LDL levels, as well as a decrease in systemic inflammatory markers. This indicates curcumin's potential role in alleviating lipid abnormalities and inflammation associated with CKD. Treatment using metalorganic frameworks (MOFs) produced through nanochelating techniques also resulted in decreased urinary albumin, malondialdehyde, and 8-isoprostane, alongside reduced plasma uric acid, blood urea nitrogen, and insulin resistance indices, while improving creatinine clearance, underscoring chromium's renal protective potential (Fakharzadeh *et al.*, 2021).

In rats with streptozotocin-induced hepatorenal impairment, Ebokaiwe *et al.* (2019) showed that *Loranthus micranthus* leaf nanoparticles (LMLNPs) and selenium nanoparticles (SeNPs) have nephroprotective effects. Both SeNPs and LMLNPs have exhibited considerable antioxidant and protective effects in diabetic models. The administration of these nanoparticles significantly reversed oxidative damage, restored antioxidant enzyme activity such as superoxide dismutase, catalase, and glutathione peroxidase, and improved hepatic and renal biomarkers, including ALT, AST, creatinine, and urea. In comparison to untreated diabetic control groups, those receiving both nanoparticles demonstrated pronounced improvements in oxidative balance and organ function, thereby underscoring their potential role in alleviating oxidative damage associated with diabetes. In a separate study, curcuminloaded chitosan nanoparticles protected rabbit kidneys from cypermethrin induced biochemical and histopathological alterations, highlighting the potential of nano-curcumin as a preventive intervention against nephrotoxic insults (Anwar *et al.*, 2020). Collectively, these findings demonstrate that nanonutraceutical systemsby enhancing antioxidant defence, modulating inflammatory cascades, and improving renal cellular resilience offer substantial promise in mitigating CKD progression and associated metabolic disorders.

4. Conclusion

Nanotechnology has revolutionized the field of functional foods and nutraceuticals by improving sustainability, reducing toxicity, and enhancing the bioavailability of active compounds. Nanonutraceuticals have emerged as innovative healthcare supplements capable of precise and targeted delivery of bioactives. These advanced formulations exhibit considerable therapeutic promise in diverse disease conditions. They help to regulate the glucose metabolism in diabetes mellitus, suppress inflammatory responses in renal and pulmonary diseases, reduce cardiotoxic effects, and enhance anticancer efficacy. In light of the escalating global incidence of noncommunicable diseases, nanonutraceuticals offer a forward looking approach for disease prevention and health maintenance. Their integration into dietary and clinical practices underscores their potential as vital components of next generation therapeutic nutrition.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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