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Review Article

From nanotechnology concepts to pioneering patents: Innovations in nanotherapeutic nutrition

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A B S T R A C T

Recent advances in nano-nutrition have opened up new avenues for the treatment and prevention of a variety of health conditions. Emerging approaches focus on improving nutrient delivery, bioavailability, and therapeutic efficacy through novel nano-carrier systems. Leading patients, often facing chronic diseases or unique health challenges, are at the forefront of this advanced approach. Collaborative research and innovative clinical trials are providing invaluable insights into the real-world applications of nano-nutrition, helping to improve treatment modalities and ensure that nutritional therapies are effective, accessible, and sustainable. These innovations address global challenges such as malnutrition, obesity, and chronic diseases. Advances in food processing, sustainable sourcing, and nutrient delivery systems are enhancing access to and increasing the efficiency of essential nutrients. Additionally, digital tools such as artificial intelligence and wearable devices are enabling real-time monitoring of dietary habits, encouraging more informed and healthier food choices. Nanotechnology enables the precise delivery of therapeutic agents directly to diseased cells, reducing side effects and increasing therapeutic effects. Using nanoparticles, liposomes, and nano-polymers, the bioavailability of drugs is enhanced, their solubility is improved, and controlled release is enabled. In oncology, these technologies pave the way for more effective, personalized, and less invasive medical treatments. In addition to therapeutic applications, nanotechnology plays a major role in the development of functional foods and nutritional supplements that offer therapeutic benefits such as reduced inflammation, improved gut health, and prevention of chronic diseases such as diabetes, heart disease, and obesity. It also contributes to ensuring food safety through smart packaging solutions with antimicrobial properties and real-time biomonitoring of food quality. Despite the transformative potential of these developments, challenges related to safety, regulatory frameworks, and long-term effects require careful consideration to ensure the safe integration of nanotechnology into nutrition and healthcare. This review highlights the latest innovations, applications, and future directions of nanotechnology in nutrition and disease prevention, emphasizing its potential to revolutionize global health.

INTRODUCTION

Advances in nanotherapeutic nutrition innovations have ushered in a new era of targeted, efficient, and patient-tailored nutrient delivery systems that overcome the limitations of conventional formulations (Ediriwickrema and Saltzman, 2015). These state of the-art nanocarriers ranging from multifunctional polymeric nanoparticles to cyclodextrin-based scaffolds enhance the bioavailability, solubility, and controlled release of bioactive nutraceuticals,

addressing challenges related to stability and low absorption inherent in traditional nutrient therapies (Payamifar *et al.*, 2025). At the forefront of this revolution, pioneering patents have emerged that detail novel fabrication methods and design architectures for nano systems capable of delivering dietary supplements and therapeutic nutrients with precision and minimal side effects (Chavan *et al.*, 2025).

Innovative strategies, such as the use of exosome-based nano formulations, are also being explored for their potential to facilitate hepatic drug and nutrient delivery, further expanding the scope of nanotherapeutic applications into metabolic and nutritional regulation (Kanojia *et al.*, 2025). In parallel, advancements in nanomaterial synthesis and functionalization have enabled these delivery systems to be engineered for enhanced targeting, controlled kinetics, and improved patient compliance, thereby fostering a platform for personalized nutrition and disease prevention. Collectively, this surge in novel patent filings not only underscores the rapid technological evolution in the field but also paves the way for future developments that integrate multidisciplinary expertise in materials science, medicine, and nutritional research (Yadav *et al.*, 2025).

Nano drug delivery systems offer a transformative approach to overcome many of the limitations found in traditional dosage forms by enhancing bioavailability, improving targeting specificity, and reducing drug toxicity (Lopalco *et al.*, 2024). These systems utilize nanoparticles and nanocarrier-based strategies designed to deliver therapeutic agents precisely to targeted sites, which is particularly beneficial in cancer treatment and colon-targeting applications (Hasan *et al.*, 2025). Consequently, advanced nano formulations not only improve the stability of the carried drugs but also provide controlled release profiles that optimize therapeutic efficacy while mitigating adverse effects (Kondos *et al.*, 2024). Overall, the integration of nanotechnology into drug delivery represents a significant forward leap in treatment modalities, combining innovative design with advanced materials to tailor therapies to individual patient needs (Noreen *et al.*, 2025).

In summary, the integration of nanotechnology with nutrition science is transforming the development of nutraceuticals into a highly precise discipline, as evidenced by cutting-edge research and the advent of transformative pioneer patents that offer innovative solutions for optimized nutrient delivery.

Food and nutrition

Food is essential for life because it contains nutrients that are important for the body's growth, repair, and regulation of its vital functions, and it also provides the necessary energy through calories (James, 2023). Nutrition is the act of eating food in proportion to the body's needs. Good nutrition is essential for health and the maintenance of life (Fieldhouse, 2013). Nutrition is the study of the effects of food and nutrients on the human body, including vitamins, proteins, fats, etc. (Skerrett and Willett, 2010). It is important to eat a variety of foods such as fruits, vegetables, and dairy products for growth and good health. Nutrition helps improve health by understanding the effects of food on the body (Sorensen, 2024). Food science focuses on the manufacture and production of food, while nutrition science focuses on maintaining the health and well-being of individuals (Knorr, 2024).

Nanotechnology

Conventionally, the nanoscale ranges from 1-100 nanometers, where a nanometer is one billionth of a meter. Individual atoms or very small groups of them are not considered nanoparticles, and nanotechnology must involve a group of atoms that are at least one nanometer in size (Peng and Li, 2024). In nutrition research, nanotechnology applications may assist with obtaining accurate spatial information about the location of a nutrient or bioactive food component in a tissue, cell, or cellular component (Adetunji *et al.*, 2024) Nanotechnology is used in many medical fields such as diagnosis, treatment of diseases, regenerative medicine, gene therapy, dentistry, and oncology. It can also improve materials to become stronger, lighter, more reactive, and more efficient in electrical conduction (Ma *et al.*, 2024). Nanoparticle-based therapies help induce cancer cell death and increase neoantigen release, and can also be used to enhance antigen presentation and T-cell activation. Nanoparticles facilitate diagnosis and treatment through non-invasive imaging, helping to select the right patients for treatment and its effectiveness. Among the most widely used nanoparticles are gold, silver, iron, and copper, with gold nanoparticles being used as targeted drug carriers due to their controllable size and surface properties (Taiarol *et al.*, 2020) [Figure 1].

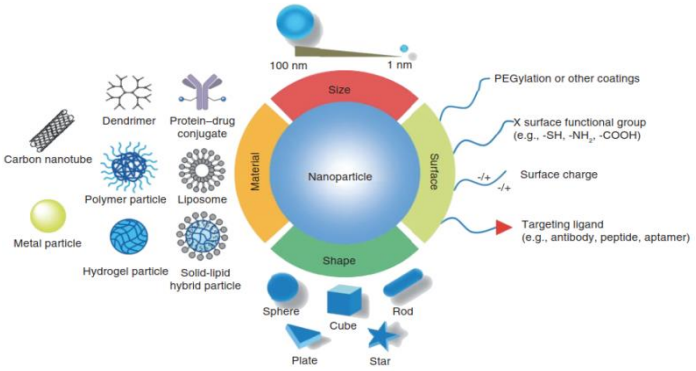

Figure 1: A broad summary of the primary nanoparticle types used in cancer treatment, along with their potential functionalization strategies (Taiarol *et al.*, 2020).

Nano nutrition and therapy

The benefits of nano foods include improved health, improved shelf life, and new flavors. Nanotechnology in food science also contributes to the detection of pathogens using fast and sensitive nanosensors (Darwish *et al.*, 2024) Nanotechnology is used in surgery to produce surgical instruments and suture materials, as well as in imaging, targeted drug therapy, and wound, burn, and scar healing techniques (Sridhar *et al.*, 2024). Nanomaterials act as carriers for vaccine delivery and enhancement of immune responses and are used in the prevention of infectious diseases and immunotherapy of tumors (Tang and Li, 2024). The application of nanotechnology in pharmaceutical research has led to the development of nanomedicines, which are used as nanometer-sized drug delivery systems and provide medical benefits in clinical nutrition (Yang and Santamaria, 2021).

Nanoparticles as carriers of active food components, such as antimicrobials or bioactive chemicals, show a higher ability to interact with microbial cells and increase bioavailability. However, current research is limited to a limited number of studies, and a broader investigation is needed that includes diverse bioactive substances and the interaction of nanoparticles with food components such as proteins and carbohydrates. It is necessary to test their incorporation into real food matrices and evaluate their toxicological safety and biological fate in the body (Altemimi *et al.*, 2024) [Figure 2].

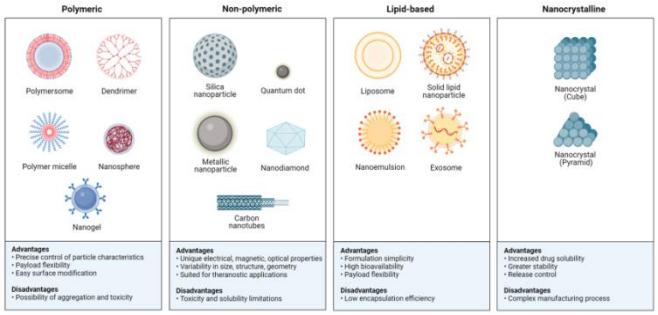

Figure 2: Classification of nanoparticles (Altemimi *et al.*, 2024).

Nanoencapsulation of bioactive nutraceuticals

Recent scientific advances have significantly improved our understanding of how nutritional strategies can enhance health and wellness. according to Nicolescu *et al.*, (2023), extensive research demonstrates the potential of nutrient-rich foods in disease prevention and treatment. however, bioactive compounds present three major challenges: instability in various conditions, limited solubility, and poor bioavailability in the body. To address these limitations, researchers employ encapsulation technology, which protects bioactive compounds within carrier materials. Rashidi (2021) classifies these encapsulated particles into three categories based on size to nanocapsules, microcapsules, and macrocapsules (<0.2, 0.2-5000, and >5000 µm), respectively. Natural encapsulation systems exist in nature, as identified by Kole *et al.*, (2019), include milk casein micelles (<100 nm), mitochondria (500-10,000 nm), and viruses (10-300 nm).

On the other hand, absorption challenges summarized as particle size effects, while, large particles dissolve slowly and tend to clump together, also, both very large and very small particles show reduced nutrient absorption, uneven distribution in the digestive tract impacts absorption efficiency (Saifullah *et al.*, 2019 and Dima *et al.*, 2020). the other challenge is the wall component issues, while, high concentrations can impede degradation, and some materials resist digestive enzymes, also, slower nutrient release affects overall absorption (Perry and Mcclements, 2020).

Benefits of nanoencapsulation, increased surface area for absorption, enhanced bioavailability of food ingredients, which particularly effective for compounds with limited solubility, substances detected at low levels, and ingredients with rapid metabolism (Boostani and Jafari, 2021 and Pateiro *et al.*, 2021). Consequently, Taliyan and Singhvi, (2022) confirmed that bioactive compounds can help prevent and treat various diseases, including cancer and neurological disorders. Nano-encapsulated foods offer superior stability and absorption compared to traditional microcapsules, making them a promising alternative for delivering active nutrients effectively. This enhanced protection and controlled release system represents a significant advancement in nutritional science, offering improved methods for delivering beneficial compounds to the body while overcoming traditional limitations of bioactive ingredients (Altemimi *et al.*, 2024) [Figure 3].

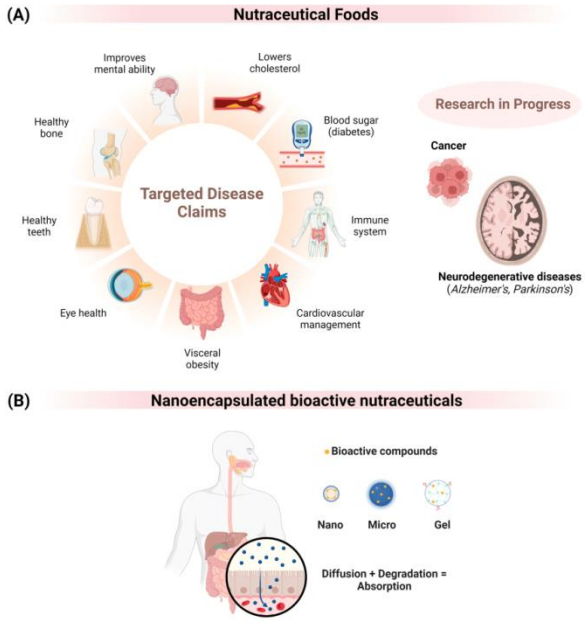

Figure 3: (A) Nutraceutical foods, (B) Nano-encapsulated bioactive nutraceuticals (Altemimi *et al.*, 2024).

Chronic long-term low-intensity inflammation

Inflammation is a response of white blood cells to protect the body from infection or injury. It may become chronic due to failure to clear an irritant, an autoimmune response, or as a result of a chronic, low-intensity irritant (Chopra *et al.*, 2024). Chronic inflammation is a slow, long-term inflammation lasting from months to years, characterized by chronic but low-level production of inflammatory factors. Associated conditions include obesity, depression, chronic pain, and chronic diseases such as high blood pressure, diabetes, liver and kidney disease, and cancer (Tezcan *et al.*, 2024). Chronic inflammation occurs when inflammatory cells persist in the body without danger, such as in rheumatoid arthritis where inflammatory cells attack joint tissue, leading to recurring inflammation and damage to the joints (Jouybari *et al.*, 2024).

To sum up, the relationship between low-grade inflammation (LGI) and brain imaging patterns, demonstrates that LGI may lead to subclinical cognitive decline or neurological diseases through structural neural pathways. The findings revealed stronger associations between LGI and brain atrophy in males or individuals with physical frailty, contributing to the development of diagnosis and treatment while offering a new perspective on early preventive strategies, such as dietary intervention in the absence of clinical symptoms. Bao *et al.* (2024) analyzed 37,699 participants from the UK Biobank to study the effect of low-grade inflammation (LGI) on the brain using the INFLA index (C-reactive protein, white blood cells, platelets, neutrophil-to-lymphocyte ratio). A linear regression model was applied with control for variables (age, sex, lifestyle, chronic diseases), and subgroup analysis was performed. The

results showed an association between LGI and atrophy in brain regions such as the subcortex and the frontal, temporal, parietal, and insular lobes [Figure 4].

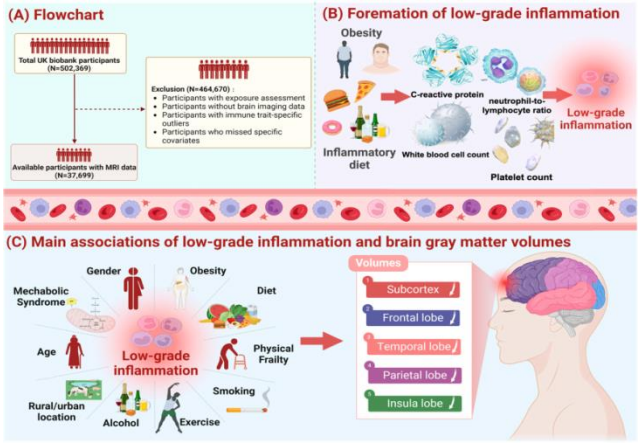

Figure 4: Chronic low-grade inflammation and brain structure in middle-aged and elderly adults (Bao *et al.*, 2024).

Nutrition, diseases and nanotherapy

The benefits of nanofood include health additives, longer shelf life, and the detection of food pathogens using fast and sensitive nano sensors (Darwish *et al.*, 2024). Nanotechnology is used in surgery to produce tools, suture materials, targeted therapy, and wound and burn healing techniques (Sridhar *et al.*, 2024). Nanomaterials act as adjuvants and vaccine delivery vectors to enhance immune responses and are used in infectious disease prevention and tumor immunotherapy (Tang and Li, 2024). The application of nanotechnology in pharmaceutical research has led to the development of nanodrugs, which operate at the nanometer scale and provide medical benefits in clinical nutrition (Yang and Santamaria, 2021). Nanotechnology has brought a revolution in medicine, impacting the treatment of cancer, infectious diseases, and cardiovascular diseases. It improves drug solubility and stability, reduces side effects, and concentrates drugs at target sites. Nano toxins have been developed as vaccines and drugs for treating cancer and bacterial infections (Balaji *et al.*, 2024). Some nanotechnology-based drugs, like Abraxane, which treats breast cancer, lung cancer, and pancreatic cancer, are examples of nanotechnology in medicine. Combining nano nutrition with immunotherapy allows for the efficient delivery of immune agents, reducing toxicity and increasing solubility, stability, and half-lives (Chaurasia *et al.*, 2023).

Nanomaterials used in nano vaccines and drug delivery

Nanomaterials have emerged as a tool to improve the effectiveness of subunit vaccines by loading and modifying antigens due to their unique properties. Nano vaccines enable the absorption of antigens and adjuvants by immune cells, stimulating immunity quickly. They offer multiple delivery routes, good stability, and better protection of antigens from premature degradation, with the ability to target specific cells or tissues. The selection of nanomaterials is crucial in nano vaccine preparation (Tang and Li, 2024). Inorganic nanoparticles are nanocarriers with a solid core to which antigens are conjugated to enhance the immune response. They have a hard structure, stable performance, and controllable synthesis but cannot be made biodegradable. To improve biocompatibility, their physical and chemical properties need modification. Common nanomaterials include gold, carbon, and silicon nanoparticles. Nano vaccines can activate immune cells such as CD4+ and CD8+T cells to kill infected cells (Tang and Li, 2024). [Figure 5].

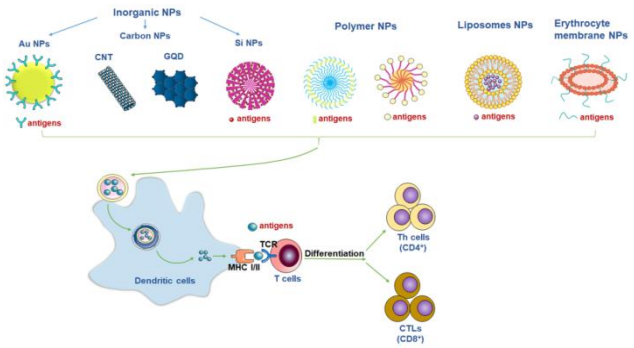

Figure 5: The nanomaterials used as the nano vaccines (Tang and Li, 2024).

Examples of bio-nanomaterials, spherical gold nanoparticles (AuNPs) are among the most widely used gold nanostructures in drug delivery applications. They can be easily synthesized using the reduction of chloroauric acid with sodium citrate. They have broad applications in cancer treatment and drug delivery due to their unique properties such as high X-ray absorption, photosensitization, surface plasmon resonance (SPR), ease of functionalization, and stability. Nanoparticles are small enough to pass through capillaries and undergo efficient cellular uptake, unlike microparticles with a diameter greater than 1 µm, which cannot be administered via intravascular routes (Elumalai *et al.*, 2024). Likewise, carbon nanotubes (CNTs) offer an innovative approach for functionalizing ligands in drug delivery due to their unique properties, such as large surface area and exceptional mechanical and electrical characteristics. They have been used in applications like drug-delivery stents, nerve catheters, and bone implants. Despite their promising applications, CNTs may exhibit toxicity depending on their purity, size, and shape. They can also be used as multifunctional biological transporters and near-infrared agents for selective cancer cell destruction (Sonowal and Gautam, 2024). Similarly, mesoporous silica nanoparticles (MSNs) are widely used in drug delivery due to their favorable chemical properties, thermal stability, and biocompatibility. Their shape, size, and surface functionality can be customized for safe drug transport in circulation. MSNs have gained significant attention as an effective drug delivery carrier due to their large surface area and excellent biocompatibility (Lérida-Viso *et al.*, 2023).

In addition, magnetic iron oxide nanoparticles (MIONPs) have emerged as a promising platform for tumor imaging and targeted drug delivery due to their unique properties. At diameters between 15 and 100 nm, they have proven effective as contrast agents, drug delivery vehicles, and thermal-based therapeutics (Montiel Schneider *et al.*, 2022). Also, polymer nanoparticles include polymers such as polyacrylamide and chitosan, with drug molecules incorporated during or after polymerization. They are key tools for improving bioavailability or targeted drug delivery, mainly used in hydrogels, micelles, and polyplexes.

Encapsulating biologics in these nanoparticles prevents degradation in the gastrointestinal tract, but transport across the intestinal epithelium remains a major challenge for efficient oral delivery (Dristant *et al.*, 2023). Last but not least, liposome-based nanoparticles protect drugs from external degradation and, due to their similarity to biological membranes, facilitate drug delivery to cells. Drugs are placed in the aqueous core of the liposome, shielded by the lipid bilayer, and are released when the bilayer deteriorates. Liposomes can deliver both hydrophilic and hydrophobic drugs. Micelles are easier to prepare but less stable (Reinsalu *et al.*, 2024).

Autoimmune diseases

Autoimmune diseases occur when the immune system responds chronically to self-antigens, attacking the body's cells. Dysfunction in innate and adaptive immunity leads to the loss of immune tolerance. The optimal treatment strategy is to modify the immune system to restore tolerance without affecting responses to other antigens. Nano vaccines that induce immune tolerance align with this principle. Nanomaterials provide a platform for loading and modifying antigens, promoting rapid and durable immunity while protecting antigens from early degradation. Nano vaccines can also be designed to target specific tissues or cells (Tang and Li, 2024).

Insulin resistance: from mechanisms to therapeutic strategies

According to the World Health Organization, the number of people with diabetes increased from 108 million to 463 million between 1980 and 2019, and it is expected to reach 700 million by 2045. Insulin resistance, as a primary cause of metabolic diseases, should be considered a therapeutic target. Ectopic fat accumulation in tissues is more strongly related to insulin resistance than endoplasmic reticulum stress or inflammation. Suppressing fat synthesis in the liver and stimulating fat oxidation in skeletal muscle may reduce insulin resistance and improve sensitivity, potentially preventing or delaying type 2 diabetes (T2DM). Therefore, treatments should follow multidisciplinary strategies targeting these factors (Lee *et al.*, 2022).

Type 2 diabetes mellitus

Diabetes is a chronic, multifactorial disease that is increasingly prevalent worldwide. The number of affected individuals is expected to double in the next decade, putting pressure on healthcare systems, especially in developing countries. Preventing and treating diabetes and its complications have become major health concerns. Nanotechnology has emerged as a promising solution, with scientists increasingly using it to study complications, prevention, and treatment, opening new avenues for detection and therapy. Nanotechnology offers innovative solutions in diabetes management, revolutionizing the delivery of hypoglycemic drugs using nanocarriers such as nanoparticles and liposomes. These carriers provide higher efficiency in controlling blood glucose levels, improve targeted drug delivery, and protect the drugs from degradation. Thus, nanotechnology offers hope for better diabetes control and reduced short- and long-term consequences (Mandal *et al.*, 2023).

Nanocarriers for drug delivery for Type 2 diabetes

Nanotechnology presents innovative approaches to enhancing the delivery of hypoglycemic drugs for Type 2 Diabetes Mellitus (T2DM). By utilizing nanocarriers, drug efficacy, bioavailability, and targeted delivery can be significantly improved, making them a valuable tool in diabetes treatment (Tiwari, 2015). These nanocarrier-based systems enhance drug absorption and stability by protecting medications from degradation in the gastrointestinal tract (Dixit *et al.*, 2023). Additionally, nanocarriers can be engineered to specifically target certain cells or tissues, such as pancreatic beta cells, optimizing drug delivery efficiency (El-Dakroury *et al.*, 2023). Moreover, by directing medications to precise locations, nanocarriers help minimize side effects and enhance patient tolerance (Patel *et al.*, 2017). They also facilitate controlled and sustained drug release, which improves therapeutic stability and reduces the need for frequent dosing (Natarajan *et al.*, 2014).

Beyond drug delivery, nanotechnology plays a crucial role in monitoring glucose and insulin levels, allowing for more precise and non-invasive diabetes management (Arya *et al.*, 2008). Advances in nano-based sensors contribute to the early detection of insulin-related disorders and improved patient care (Shoaib *et al.*, 2023). Wearable nanosensors enable continuous glucose monitoring, reducing reliance on traditional fingerstick testing (Huang *et al.*, 2020). Fluorescent quantum dots that respond to glucose levels provide highly sensitive and accurate blood sugar measurements (Chen *et al.*, 2014). Additionally, nanoparticle-based colorimetric tests offer a rapid and cost-effective glucose measurement solution, particularly beneficial in resource-limited settings (Brasiunas *et al.*, 2021). Electrochemical biosensors at the nanoscale, utilizing materials like graphene and carbon nanotubes, further enhance glucose detection sensitivity (Zhu *et al.*, 2012). The integration of nanotechnology in insulin monitoring and blood sugar detection has transformed diabetes care, enabling precise tracking and empowering individuals to make informed decisions regarding treatment and lifestyle (Mandal *et al.*, 2023) [Figure 6].

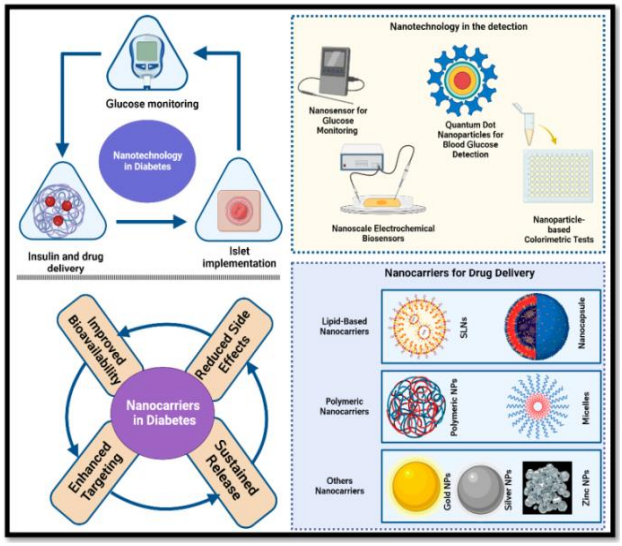

Figure 6: Nanotechnology is used in diabetes detection and treatment (SLNs = Solid Lipid Nanoparticles, NPs = Nanoparticles) (Mandal *et al.*, 2023).

Alzheimer's disease

Alzheimer's disease: Alzheimer's disease is a major neurological challenge due to its increasing prevalence and lack of effective treatments, requiring innovative strategies. Stem cell therapy holds promise as it can help in neuroregeneration and protection against the disease. The article reviews the latest developments in stem cell therapy for Alzheimer's disease, focusing on cell migration, differentiation, and effects on the brain. Despite the promise associated with stem cells, clinical applications face challenges such as ethical, regulatory, and immunological issues. The article also discusses developments in the use of genetic engineering and biomaterials, emphasizing the need for interdisciplinary collaboration to overcome these challenges. The goal is to develop safe and effective treatments for Alzheimer's disease, which represents a new step in the fight against this disease (Pan *et al.*, 2025).

Alzheimer's disease (AD) is a neurodegenerative disorder that causes neuronal loss and cognitive decline (Joe and Ringman, 2019), leading to memory impairment, cognition, and behavioral changes as the disease progresses (Pan *et al.*, 2025) [Figure 7]. Early symptoms may be unnoticeable, which hinders diagnosis and treatment (Tiwari *et al.*, 2019). The disease is a leading cause of disability and death among elderly and poses an economic and emotional burden. Despite extensive research, the underlying cause of the disease is still not fully understood, with specific pathological features of its development (Ouyang *et al.*, 2022).

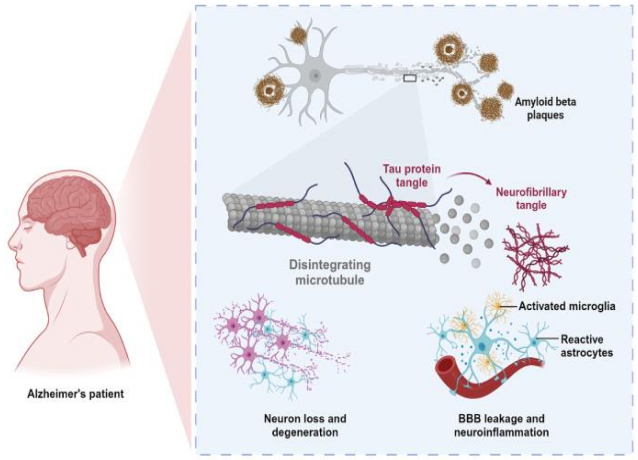

Figure 7: Neurological features of Alzheimer's Disease (Pan *et al.*, 2025).

Advantages over traditional treatment options

Conventional treatments such as cholinesterase inhibitors and NMDA receptor antagonists temporarily improve symptoms without addressing the underlying neurological deterioration in Alzheimer's disease. In contrast, stem cell therapy offers a comprehensive approach by regenerating neurons, reducing inflammation, secreting trophic factors such as BDNF and VEGF, and being able to cross the blood-brain barrier. Additionally, stem cells provide long-term effects by addressing the root causes of neurodegeneration and may also influence the gut microbiota. Overall, stem cell therapy is more comprehensive than conventional treatments (Pan *et al.*, 2025).

Stem cell therapy based on genetic engineering

Gene transfer technology is a major advance in the treatment of neurodegenerative diseases such as Alzheimer's disease (Wu and Yossifon, 2021). An important tool in this field in microRNAs (miRNAs) that regulate genes by binding to target mRNAs, making them potential biomarkers of the disease. Huang *et al.*, (2021) used gene transfer techniques to modify neural stem cells and enhance the expression of the enzyme NEP, which promotes the degradation of beta-amyloid. A nanoparticle containing plasmid RNA and retinoic acid was also designed to stimulate neuronal differentiation and transplant microglia in vivo [Figure 8].

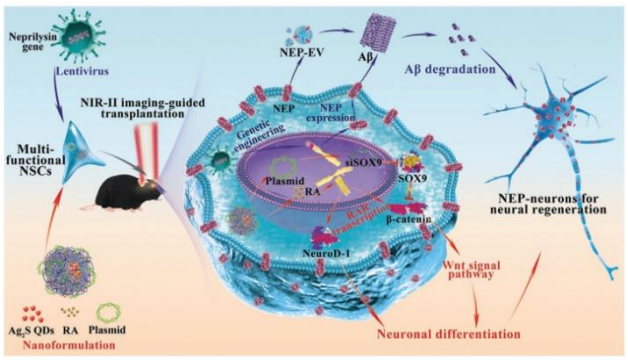

Figure 8: A schematic illustration depicting a multifunctional neural stem cell-based therapy designed for treating Alzheimer's disease (Huang *et al.*, 2021).

Neural stem cells (NSCs) first genetic specific NEP, for a prominent Aβ-degrading proteases, was an engineer to beautify the Aβ evacuation capacity and resistance. NEP expressed in the cellular membrane and released in EVS for continuously a β -fall in the mind, which allows the existence of NSC in the AD micron environment (blue arrow). Then, a multidisciplinary nano PPAR-siSOX9 components implemented NSCs and manual neuronal discrimination performance (pink arrows) in vivo cellular transplantation (black arrow). Ag_2S QDs in nanocomponents can be used on direct NSCs implants. The SOX9 siRNA expression and retinoic acid (RA) has been used to beautify neuronal discrimination of NSC inside the pathological AD microgenation, which is used to beautify NSC's neuronal discrimination in pathological AD microelement, through a continuous regulation of WNT/β-catetin and RA-signaling router. First, the released RA receptor (RAR) can activate the transcript, resulting in the construction of NeuroD1 and β-catenin. A reduction of SOX9 expression can inhibit the degradation of β-catenin in cells, thereby increasing the activation of the Wnt/β-catenin pathway and promoting the differentiation of neural stem cells into neurons (Huang *et al.*, 2021).

Jahangard *et al.*, (2020) examined the ability of over-terms, its role suggested in reducing symptoms in the treatment of Alzheimer's disease, by modifying the mouse bone marrow pluripotent stem cell and HEK-293T cells using recruitment expression vectors, using engineering exosomes to improve spatial learning and cognitive function in the model of Alzheimer's disease. Suggestion promises of miRNA interventions in reducing cognitive deficits. However, the complexity of the disease requires a comprehensive approach to addressing more pathological properties at the same time, and integration of nanomedicine, gene therapy and stem cells

provides an effective solution for Aß resolution and neuronal regeneration. However, challenges remain as the lack of clinical class nerve stem cells and the need to detect alternative sources that induced pluripotent stem cells (iPSCs). The lack of effective interventions against rope - pathology also creates a large difference in existing agents, which requires the development of broader therapeutic approaches that target aβ and rope together (Pan *et al.*, 2025).

Challenges of nano delivery systems in stem cell therapy

The clinical application of stem cell therapies for Alzheimer's disease encounters multiple obstacles, which become even more complex with the integration of nano delivery systems. These challenges span from the manufacturing process to ensuring both safe and efficient delivery, particularly in overcoming the blood-brain barrier and achieving precise, long-lasting therapeutic effects. While stem cell therapies offer significant potential for treating neurodegenerative diseases, the advancement of effective nano delivery strategies is crucial for maximizing their benefits. A key challenge is the blood-brain barrier, which restricts the transport of most therapeutic agents into the brain. Researchers are currently investigating nano delivery systems, such as exosomes, to enhance targeted delivery, though technical and clinical hurdles remain (Pan *et al.*, 2025).

Correspondingly, Biocompatible nanomaterials, especially carbon nanotubes (CNTs), have gained attention in biomedical applications, particularly in skin diseases and wound healing. Due to their superior physical and chemical properties, they have the potential to promote wound healing through antibacterial and antioxidant properties (Sridhar *et al.*, 2024).

Exploring intranasal drug delivery via nanocarriers

Glioblastoma is a type of glioma with a high mortality rate. Traditionally, treatment has involved surgical resection followed by chemotherapy and radiation. Recently, the focus has been on the use of nanocarriers to improve drug delivery to the brain, especially via the nose, offering advantages such as reduced toxicity and the ability to cross the blood-brain barrier. Nanocarriers can be customized to facilitate their passage through the nasal mucosa using techniques such as size modification or coating with adhesive agents. These carriers have high efficacy in delivering drugs to the brain despite challenges such as limited drug loading capacity in nasal drug delivery technologies such as metallic and polymeric nanoparticles, nanogels, and polymeric micelles (Deshmukh *et al.*, 2025) [Figure 9].

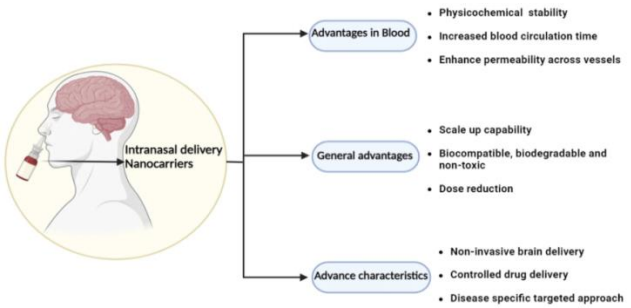

Figure 9: Benefits of drug delivery via intranasal route (Deshmukh *et al.*, 2025).

Cancer definition, types, stages, development

Maintaining a healthy diet is crucial in reducing the risk of chronic diseases, including cancer, and can also influence the effectiveness and toxicity of chemotherapy. Research indicates that dietary modifications and nutritional supplements may play a role in both cancer prevention and treatment. Certain nutrients and food groups, such as proteins, fatty acids, polyphenols, vitamins, minerals, fruits, vegetables, fish, white meat, and whole grains, have been associated with a lower cancer risk. Overall, dietary interventions offer a cost-effective strategy to enhance patient outcomes and quality of life. However, for optimal benefits, these interventions should be personalized to individual patient needs and integrated with other treatments and lifestyle adjustments (Hao *et al.*, 2024).

It is essential to clearly define the role of nutritional intervention in cancer research. In low-income countries, limited socio-economic development often restricts access to adequate food and essential nutrients, particularly fresh fruits and a diverse selection of vegetables. Due to the high prevalence of nutritional deficiencies or even the complete lack of certain nutrients, targeted nutritional supplementation becomes both necessary and practical. In contrast, while high-income countries generally have an adequate food supply, specific segments of the population may still experience nutrient deficiencies. Furthermore, to aid in cancer prevention and slow disease progression, nutritional interventions should begin early and be maintained throughout life. Combination therapy, which integrates anti-cancer foods and supplements, tends to be more effective than monotherapy, provided these interventions are safe and have minimal side effects. Since cancer is a complex, multifactorial disease, it requires long-term strategies rather than short-term supplementation, which alone is unlikely to alter disease progression. Instead, a comprehensive approach, including nutrient-rich diets that mitigate toxicity, is recommended. Maintaining a balanced diet, engaging in regular physical activity, and sustaining a healthy weight are all critical in reducing cancer risk and slowing its advancement (Hao *et al.*, 2024) [Figure 10].

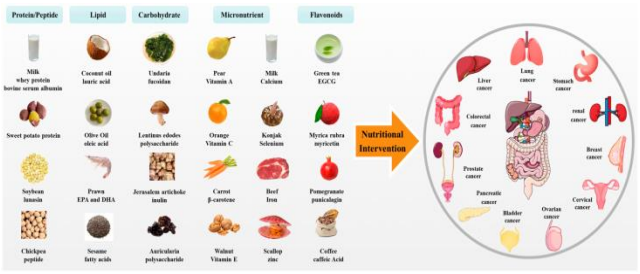

Figure 10: Summary of foods containing macronutrients, micronutrients and polyphenols with anticancer properties (Hao *et al.*, 2024).

The human body consists of trillions of cells that coordinate to form tissues and organs. Cells naturally proliferate to repair damage, then stop dividing. When cell growth control is lost, cancer occurs. This arises from DNA damage caused by factors like genetics, infection, pollution, UV radiation, and unhealthy habits such as smoking and alcohol consumption. DNA damage leads to genetic changes affecting proto-oncogenes, tumor suppressor genes, and

DNA repair genes. Proto-oncogenes regulate normal cell growth, but mutations transform them into cancer-causing genes, allowing uncontrolled cell proliferation. Tumor suppressor genes control cell division; alterations lead to loss of cell division control. DNA repair genes maintain damaged DNA; mutations cause mutations in other genes, resulting in cancer. Cancer types are characterized by specific genetic alterations determining their characteristics. (Sivasubramanian *et al.*, 2025).

Some cancer cells travel from the original tumor to other parts of the body through the blood or lymphatic system, forming new tumors that are different from the original tumor, a process known as metastasis. Metastatic tumors cause significant damage to normal body functions, leading to increased cancer-related mortality. Cancer cells create a microenvironment around themselves, taking over normal cells, molecules, and blood vessels to provide nutrients and oxygen for tumor growth and remove waste products. Although the immune system is designed to defend the body and remove infected or defective cells, cancer cells can outwit it. They hide from the immune system and exploit it to create a favorable environment for their growth and survival. Controlling the growth of cancer cells and reducing symptoms is the primary goal of treatment (Sivasubramanian *et al.*, 2025), the production of cancer cells in the body is based on the introduction of chemicals to the body that lead to repair and damage of DNA. In normal situations, this leads to apoptosis (cell death), but in the case of cancer, the cells with damaged DNA multiply abnormally and finally, cancer cells are produced in a huge number [Figure 11].

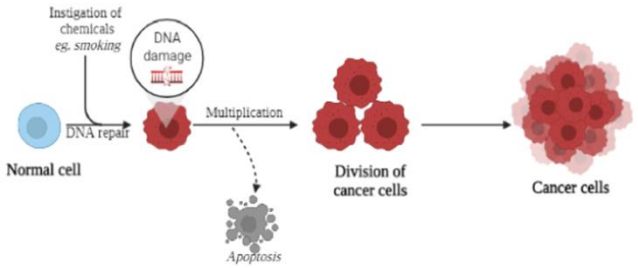

Figure 11: The production of cancer cells in the body (Sivasubramanian *et al.*, 2025).

Cancer development, genetic basis and mechanisms

Cancer studies are known as oncology, and the genes responsible for its development are called oncogenes. The activation of these genes is as a result of genetic changes that include mutation, gene amplification and chromosomal relapse. Gene amplification means that there are several copies of a gene in the cell's genome, which allows some cancer cells to become resistant to medication. Chromosomal relapse, which includes translation and vice versa, consists of malignant tumors, both blood and solids. Cancer cells begin in the form of a single cell or a small group that increases abnormally as a result of changes in oncogenic and tumor limitation genes, which are capable of continuous breeding for the emergence of cell clones. Over time, only the strongest cells survive, and the dysfunctional cells are replaced, leading to the tumor becoming malignant, making treatment more difficult. Cancer gene research has shown that most cancer cells take more than 60 mutations, mutation signatures are unique to each type of cancer. Some genetic mutations in cancer cells are found to be more common than others, especially the mutation of rat sarcoma virus (RAS) signaling of proteins, which is the overgrowth of receptors. Certain mutations can be countered using chemotherapeutic agents that specifically target proteins. For example, Herceptin is used in breast cancer treatment by inhibiting tyrosine kinase receptors, while Gleevec treats chronic myelogenous leukemia by blocking aberrant signaling pathways. Cancer cells can spread to different parts of the body, and once they establish themselves in certain organs, they may undergo metastasis. This process allows them to adapt to new environments and develop resistance to chemotherapy and radiation. As a result, early cancer treatment is advised to prevent these cells from acquiring adaptive mechanisms, making treatment more effective and minimizing complications (Sivasubramanian *et al.*, 2025), metastatic tumor cells detach from the primary tumor, enter the bloodstream, and migrate to nearby tissues and organs, leading to cancer progression at multiple sites [Figure 12].

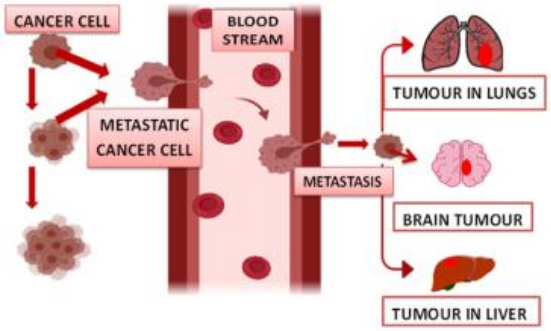

Figure 12: Cancer cells detach from the primary tumor and enter the bloodstream, allowing them to migrate to nearby tissues and organs. This process contributes to the spread of cancer, leading to its development in multiple areas of the body (Sivasubramanian *et al.*, 2025).

Types of cancer and staging

Cancer is a condition marked by the uncontrolled growth of abnormal cells in tissues or organs, with various types affecting individuals differently based on gender. In men, prevalent cancers include those of the throat, esophagus, lung, stomach, intestine, bladder, prostate, testicles, and skin. In women, commonly diagnosed cancers affect the throat, esophagus, lung, breast, stomach, intestine, bladder, uterus, skin, and ovaries. Cancer is categorized into five primary types: carcinomas, which originate in the skin or the lining of organs; sarcomas, which develop in bones, cartilage, and connective tissues; leukemias, which arise in the blood and bone marrow; lymphomas, which affect the immune system; and central nervous system cancers, which begin in the brain or spinal cord (Sivasubramanian *et al.*, 2025) [Figure 13].

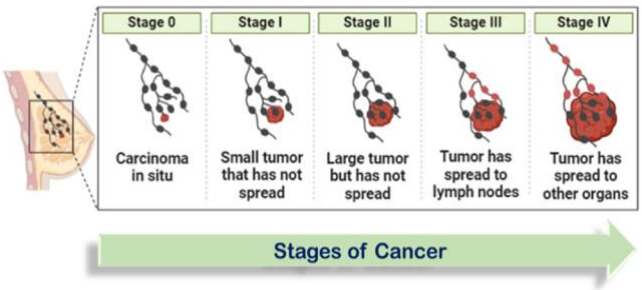

Figure 13: A schematic representing the different stages in the development of breast cancer (Sivasubramanian *et al.*, 2025).

Nanoparticle systems for enhanced cancer therapeutics

Over the past decade, there has been significant progress in utilizing magnetic nanoparticles for cancer detection and treatment, particularly in magnetic resonance imaging and sensing techniques. Extensive research is being conducted on these nanoparticles to enhance drug delivery to specific sites using an external magnetic field. Additionally, efforts are underway to develop personalized cancer treatments that integrate imaging techniques for more effective systemic therapy. A review article explores metal-ion-based compounds combined with organic ligands to create structures of varying dimensions, with an emphasis on their interaction with cancer cells at the primary site. It also discusses key topics such as clonal evolution theory, the role of magnetic nanoparticles in cancer diagnosis and treatment, targeted drug delivery strategies, and metal-organic frameworks for tumor therapy, while offering insights into future advancements in this field (Sivasubramanian *et al.*, 2025). Multifunctional nanoparticles, which can incorporate drugs, polymer coatings, ligands, fluorescent molecules, and other agents, serve purposes in imaging, diagnosis, and targeted drug delivery for cancer treatment. Ideally, functionalized nanoparticles could be optimized for personalized therapies [Figure 14].

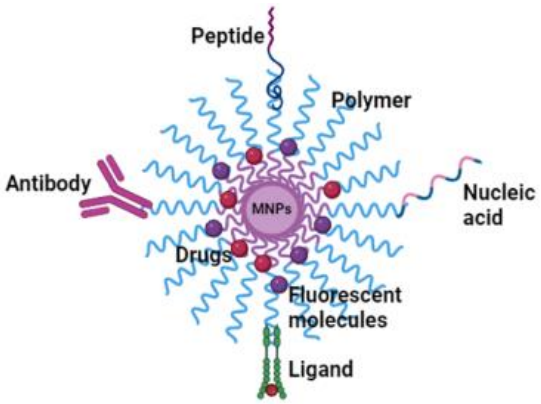

Figure 14: Use of multifunctional drug-conjugated nanoparticles in imaging, diagnostics, and as drug delivery agents for cancer treatment (Sivasubramanian *et al.*, 2025).

Nano drug delivery system for liver cancer therapy based on mitochondria-targeting

Numerous studies have explored nano-based drug delivery systems for liver cancer treatment, highlighting the drawbacks of conventional therapies, such as low effectiveness and significant side effects. These advanced systems are designed to target mitochondria, which possess unique characteristics in hepatoma cells, thereby enhancing cancer treatment efficacy. Although research has yielded promising results, additional work is required before these technologies can be widely adopted in clinical practice. The studies emphasize the vital role of mitochondria in the onset and progression of liver cancer through metabolic and dynamic processes and examine recent developments in nano-based drug delivery. They also discuss the benefits and limitations of these approaches, particularly those involving cationic nanoparticles, metal nanoparticles, and mitochondrial peptide modifications as promising strategies for liver cancer therapy (Chen *et al.*, 2024) [Figure 15].

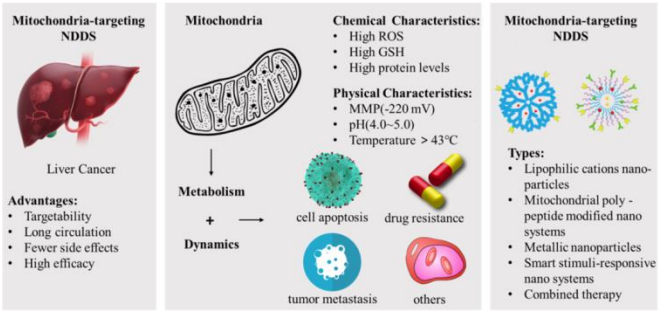

Figure 15: Mitochondrial peptide modification, among others, are effective strategies for treating liver cancer (Chen *et al.*, 2024).

Nano drug delivery systems for breast cancer therapy

Breast cancer remains one of the most prevalent diseases, affecting millions of women worldwide each year. Despite advancements in early detection and treatment, the associated health risks remain high (Obeagu and Obeagu, 2024). Effective cancer treatment plays a crucial role in improving survival rates and enhancing patients' quality of life (Ming *et al.*, 2024). Due to the complexity of breast cancer, innovative treatment approaches, particularly within drug delivery systems, are essential for increasing therapeutic efficacy while minimizing adverse effects (Abolhasani *et al.*, 2024). Advances in scientific research have significantly contributed to medical progress, revolutionizing treatment options and improving patient outcomes (Wang *et al.*, 2024). The success of breast cancer therapy largely depends on optimizing drug delivery systems (Zhang *et al.*, 2022).

Nanotechnology has shown significant potential across various fields due to its transformative capabilities (Dai *et al.*, 2024). Within medical applications, this interdisciplinary field offers promising solutions for enhancing disease management and treatment strategies (Xia *et al.*, 2024). Nanotechnology plays a pivotal role in medical science, particularly in cancer therapy and gene editing, shaping the future of healthcare (Zhao *et al.*, 2024). Various polymer-based structures, including linear chains, branched networks, and cross-linked materials, exhibit unique properties that are valuable in material science (Tang *et al.*, 2024). Some of these polymer-based materials stand out due to their distinctive characteristics. Starch, a versatile biopolymer derived from plant sources and composed mainly of amylose and amylopectin, is particularly attractive for biomedical applications due to its natural abundance, low cost, and biodegradability (Zhang *et al.*, 2024).

Starch's biocompatibility ensures minimal immunogenicity and toxicity, which are key considerations in designing drug delivery systems. Furthermore, its physicochemical properties, such as solubility and gelation behavior, can be modified through various techniques to meet specific medical requirements (Wang *et al.*, 2024). Different starch-based drug delivery systems have been developed, each offering unique advantages. While native starch is beneficial, chemical and physical modifications can enhance its performance (Li *et al.*, 2024). Chemical alterations, including esterification and etherification, improve starch's applicability in drug delivery by modifying its solubility, stability, and bioavailability. Specifically, introducing ester or ether bonds into starch molecules enhances its

compatibility with lipid-based drug carriers (Kaur *et al.*, 2024). This process increases starch's lipophilicity, making it more suitable for lipid-based drug delivery systems (Wang *et al.*, 2020).

Starch-based carriers can also protect drugs from degradation in the gastrointestinal tract, potentially improving bioavailability (Lemos *et al.*, 2021). Given its unique characteristics, starch holds significant potential for biomedical applications. Chemical modifications, such as esterification and etherification, optimize starch for drug delivery by improving drug loading, controlled release, and patient outcomes. Physical modifications like gelatinization and retrogradation further alter starch's structural properties to enhance functionality (Compart *et al.*, 2023). Additionally, the development of starch nanoparticles and nanocomposites has opened new avenues for targeted drug delivery, while starch-based hydrogels offer promising prospects for sustained drug release (Morán *et al.*, 2023).

Several starch-based nanocomposites have been designed to improve drug-loading efficiency, controlled release kinetics, and targeted drug delivery within tumor environments. Hydroxyethyl starch and zein-starch composites, for instance, enhance drug encapsulation and release properties, particularly in combination with nanosheets (Pourmadadi *et al.*, 2024). These starch-based nanocomposites exhibit pH-responsive behavior, ensuring controlled drug release in the acidic tumor microenvironment while minimizing side effects in healthy tissues. Furthermore, incorporating micro- and nanofibers such as collagen and chitosan enhances the mucoadhesive properties and mechanical strength of starch-based drug delivery systems (Borji *et al.*, 2024). These advancements underscore the potential of starch-based nanocarriers as efficient and biocompatible options for targeted cancer therapies. In the context of breast cancer treatment, starch-based drug delivery systems have demonstrated considerable promise by ensuring high drug concentrations at the tumor site while reducing systemic toxicity (Pei *et al.*, 2024).

Moreover, starch-based systems can be integrated with clinical imaging agents for early detection, further enhancing their versatility in cancer management (Pourmadadi *et al.*, 2023). A comprehensive examination of starch-based drug delivery systems highlights their properties, modification techniques, and potential benefits in breast cancer therapy. These systems can be tailored to improve therapeutic outcomes (Mei *et al.*, 2024).

Starch nanoparticles (SNPs), typically ranging from 10 to 100 nm in size, exhibit high surface area, biocompatibility, and biodegradability, making them highly versatile for various applications. SNPs have proven valuable in both biomedical and industrial fields, particularly in drug delivery systems that require controlled release and targeted distribution of therapeutic agents. Their eco-friendly nature further enhances their appeal for advanced applications. A notable development involves nanomedicine targeting fibroblasts within the tumor microenvironment. For example, doxorubicin-loaded hydroxyethyl starch conjugated with peptides has been shown to effectively target cancer-associated fibroblasts while inducing hyperthermia under mild radiation, combining chemotherapy and photothermal therapy to improve treatment outcomes (Gong *et al.*, 2022).

These findings support the potential of nanotherapeutics in addressing breast cancer (Wang *et al.*, 2023). In summary, starch nanoparticles provide a versatile platform in nanomedicine, facilitating the development of targeted therapies for various cancers. Studies highlight their role in enhancing treatment efficacy through novel strategies, addressing challenges such as tumor microenvironment modulation, cancer stem cell targeting, and controlled drug release. Each of these approaches showcases the adaptability and effectiveness of SNPs in advancing cancer treatment while paving the way for future research and clinical applications (Gong *et al.*, 2022) [Figure 16]. The integration of medical technology and targeted drug delivery continues to enhance treatment precision and efficiency, contributing to significant scientific progress (Lei *et al.*, 2024; Zhen *et al.*, 2024). Polymer structures improve therapeutic effectiveness due to their biocompatibility and versatility (Wei *et al.*, 2024). Starch-based nanostructures for breast cancer treatment offer promising strategies to enhance efficacy while minimizing side effects (Pei *et al.*, 2024).

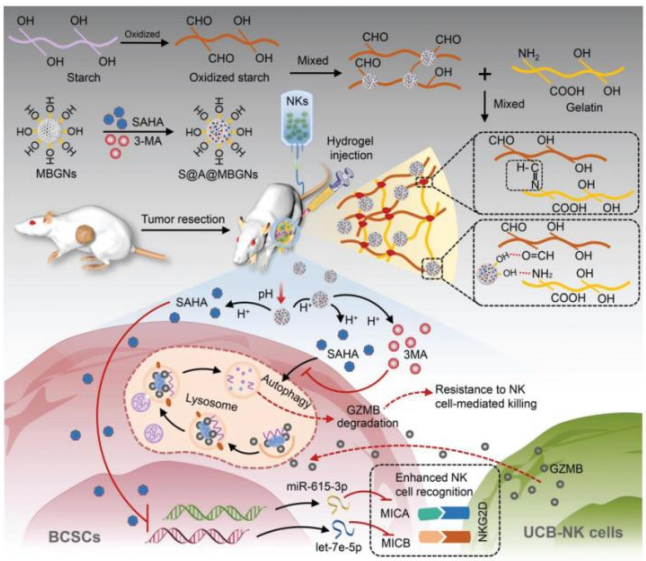

Figure 16: Triple-Negative Breast Cancer combination represents an advanced therapeutic strategy for enhancing cancer treatment outcomes (Gong *et al.*, 2022).

Oral nano-formulations for endocrine therapy

Endometrial cancer is one of the three main malignant tumors of the reproductive system that threaten the life and health of women. The incidence of this disease is increasing worldwide. Most cases of endometrial cancer involve endometrioid adenocarcinoma, the treatment of which is hampered by factors such as its high relapse rate and the need to maintain fertility in young patients. Therefore, oral endocrine therapy has become the most important treatment model. The most important drugs used in oral endocrine therapy are progestins, selective estrogen receptor antagonists, and aromatase inhibitors. However, their clinical use is hampered by their low solubility and limited oral use. The rapid development of nanotechnology allows the combination of these drugs with oral nano-formulations to create a suitable carrier. Such nanocarriers, such as nanospheres, nano-capsules, and micelles, can protect the drug from leakage and increase the site specificity of drug delivery (Cui *et al.*, 2024) [Figure 17].

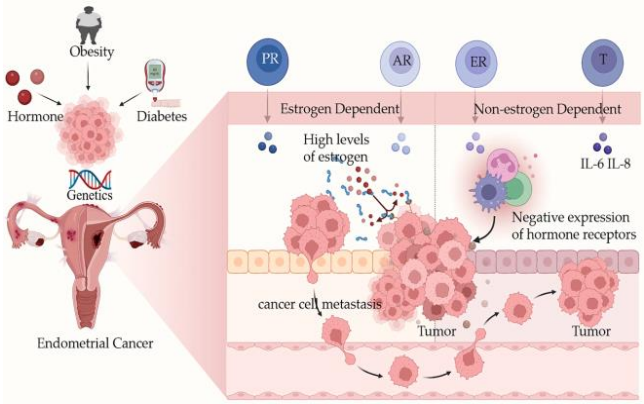

Figure 17: Pathogenesis of endometrioid adenocarcinoma (Cui *et al.*, 2024).

The pathogenesis of endometrioid adenocarcinoma involves multiple molecular alterations affecting cell survival, proliferation, and apoptosis. Key genetic mutations in PTEN, CTNNB1, TP53, KRAS, and PI3K drive tumor development by dysregulating critical signaling pathways. Understanding these molecular mechanisms is crucial for developing targeted therapies, such as PI3K/AKT/mTOR inhibitors or Wnt pathway modulators, which could improve treatment outcomes for patients with endometrial cancer. (Cui *et al.*, 2024) [Figure 18].

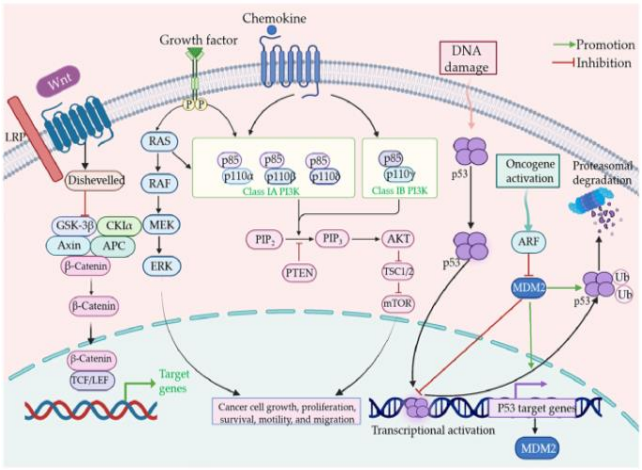

Figure 18: Pathogenetic pathway of endometrioid adenocarcinoma (Cui *et al.*, 2024).

The silent information regulator protein sirtuin 1 (SIRT1), a highly conserved NAD^+-dependent deacetylase belonging to the sirtuin family, is a post-translational regulator that plays a role in modulating inflammation. SIRT1 could be a novel therapeutic target for these diseases, and small molecules or natural products that modulate its function have potential as therapeutic agents. SIRT1 expression in endometrial cancer (EC) was significantly higher than in normal endometrial tissue, and that SIRT1 inhibition significantly inhibited tumor cell growth. Individualized and targeted therapy focusing on specific molecular targets in EC plays an important role in therapeutic outcomes and patient prognosis, representing an important future line of research for EC performance (Cui *et al.*, 2024) [Figure 19].

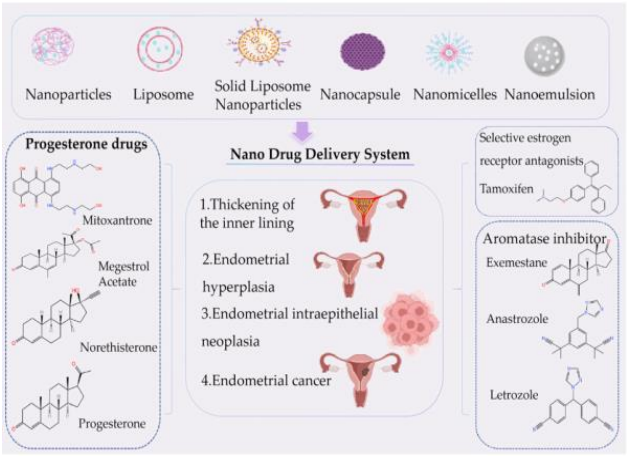

Figure 19: Oral nano-formulations for endometrioid adenocarcinoma (Cui *et al.*, 2024).

Targeted therapy for leukemia based on nanomaterials

Leukemia is a type of blood cancer that originates in the bone marrow and leads to abnormal production of white blood cells (Chennamadhavuni *et al.*, 2021). It is classified into five main types based on cell origin, progression speed, and severity. Acute Lymphoblastic Leukemia (ALL), a rapidly progressing cancer that affects immature lymphocytes, mainly in children. Causes may include genetic mutations and exposure to radiation or chemicals. Symptoms include fatigue, frequent infections, easy bruising, and bone pain. Severity is high without treatment, but survival rates have improved with modern therapies (Chennamadhavuni *et al.*, 2021). Acute Myeloid Leukemia (AML), a fast-growing cancer affecting myeloid cells, occurring in both adults and children. Causes include genetic predisposition, smoking, previous chemotherapy, and chemical exposure. Symptoms include fever, anemia, bleeding, and infections. Severity is high, requiring urgent treatment with chemotherapy or bone marrow transplants (Cortes *et al.*, 1996). Chronic Lymphocytic Leukemia (CLL), a slow-progressing cancer affecting mature lymphocytes, common in older adults. Causes are largely unknown but may include genetic factors and immune system dysfunction. Symptoms often appear gradually, including swollen lymph nodes, fatigue, and weight loss. Severity varies; some cases remain stable for years, while others require treatment (Nabhan and Rosen, 2014). Chronic Myeloid Leukemia (CML), a slow-developing cancer of myeloid cells, linked to the Philadelphia chromosome genetic mutation. Causes are primarily genetic mutations, often without known environmental triggers. Symptoms include fatigue, night sweats, and an enlarged spleen. Severity progresses from a chronic to an acute phase if untreated, but targeted therapies have improved outcomes (Baccarani *et al.*, 2019). Hairy Cell Leukemia (HCL), a rare, slow-growing form of leukemia affecting B lymphocytes. Causes are unclear but may involve genetic mutations and environmental factors. Symptoms include fatigue, recurrent infections, and an enlarged spleen. Severity is generally low, and many patients respond well to treatment, with long remission periods (Mendez-Hernandez *et al.*, 2023). Each leukemia type requires specific diagnostic tests and treatment approaches, including chemotherapy, targeted therapy, immunotherapy, or bone marrow transplants, depending on severity and progression (Hallek and Al-Sawaf, 2021).

The outcome of leukemia depends on various factors, including the type of leukemia, disease progression, patient's age, and overall health condition. Many patients succumb to leukemia due to complications such as severe infections (bacterial, fungal, or viral), nutritional deficiencies, and multi-organ failure. Recent studies suggest that nanoparticles can improve the efficacy-to-toxicity ratio of anti-leukemic drugs. Additionally, nanomaterials are being developed to deliver biomolecules (such as antibodies) that detect and monitor leukemia biomarkers, enabling early diagnosis and personalized treatments (National Institutes of Health, 2021).

Ongoing research continues to explore the complex interplay of genetic, environmental, and immune factors in leukemia development and progression. With advancements in genetic and molecular research, scientists have identified key gene mutations and signaling pathways, paving the way for targeted therapies. This progress marks the beginning of a new era in personalized medicine, offering more effective and tailored treatments for leukemia patients.

A comparative analysis, as shown in [Figure 20], illustrated the difference between normal blood components (RBCs, WBCs, and platelets) and leukemia-affected blood, where abnormal cancer cells rapidly outcompete healthy cells (Saha *et al.*, 2024).

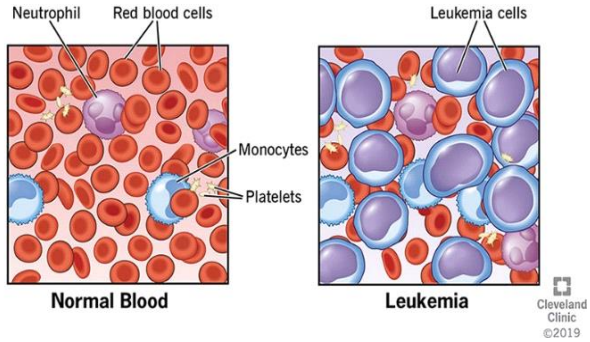

Figure 20: Comparison between normal blood and leukemia (Saha *et al.*, 2024). https://my.clevelandclinic.org/health/diseases/4365-leukemia

Nanomaterials, with their unique properties, are promising agents for targeted leukemia therapy. Recent studies have demonstrated their role in enhancing treatment efficacy by serving as carriers for drug delivery, precisely targeting leukemic cells, minimizing side effects, and maximizing effectiveness. These materials include liposomes, polymers, protein-based materials, cell-derived materials, and inorganic substances. They can deliver anticancer drugs and genes directly to affected cells, modifying gene expression and inducing cancer cell death, with the potential for long-term disease remission. Additionally, nanomaterials are used to improve leukemia cell imaging techniques, such as magnetic resonance imaging (MRI) and fluorescence imaging, providing accurate, high-resolution images that aid in detecting and monitoring affected cells during treatment. With their ability to deliver therapies and enhance imaging, nanomaterials represent a promising innovation for significantly improving leukemia treatment outcomes (Qian *et al.*, 2024) [Figure 21].

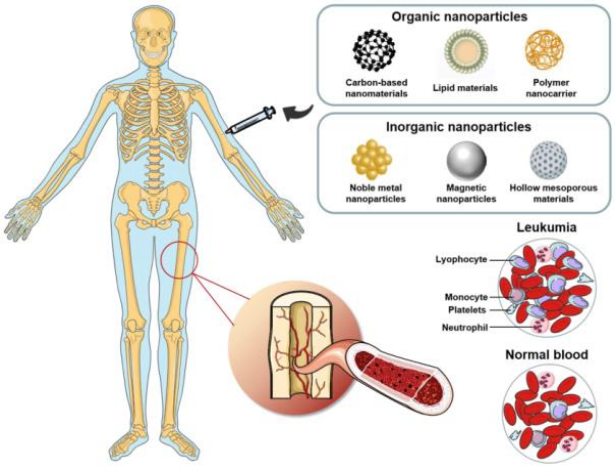

Figure 21: Nanomaterials for the treatment of leukemia (Qian *et al.*, 2024).

Nano-drug delivery systems play a crucial role in improving leukemia treatment by allowing drugs to perform multiple functions, such as combining chemotherapy with targeted or immunotherapeutic agents. These systems provide several benefits, including extended drug circulation, enhanced bioavailability, precise tumor targeting, reduced drug resistance, and fewer side effects. Targeted therapies focus on specific molecular markers within leukemia cells, lowering the risk of resistance and proving more effective when used alongside conventional or other targeted treatments, ultimately enhancing patient outcomes and quality of life. However, challenges remain in physiological environments, such as the formation of "protein coronas" on nanocarriers and their uptake by immune cells, which can reduce effectiveness. While laboratory and animal studies have shown promising results, only a few systems, such as PEGylated and iron oxide nanoparticles, have reached clinical trials. The complexity of their design remains a major barrier to widespread clinical use, but ongoing research in medicine, nanomaterials, and cell biology is key to overcoming these limitations and advancing leukemia therapy (Qian *et al.*, 2024).

Nanocarrier-based drug delivery system for prostate cancer

The prostate is a gland that plays a key role in male reproductive function by producing fluid that supports sperm during ejaculation. It surrounds the urethra, the duct responsible for urine excretion from the body. When the prostate becomes enlarged, it indicates an increase in gland size (Andersson and Wein, 2016). Prostate cancer develops when abnormal cells within the prostate multiply uncontrollably, potentially invading nearby tissues or spreading to distant areas of the body. As part of the male reproductive system, the precise cause of prostate cancer remains uncertain, but certain factors can elevate the risk (Capogrosso *et al.*, 2021). These risk factors include advancing age, with most diagnoses occurring in men over 50, and ethnicity, as black men have a higher incidence of the disease compared to Asian men (Parsons *et al.*, 2020). Prostate cancer is categorized into four main stages, with lower stages indicating limited spread and higher stages, such as stage four, signifying extensive metastasis (Kumar *et al.*, 2024) [Figure 22]. The Tumor, Nodes, and Metastasis (TNM) system is the standard framework for staging prostate

cancer. It assesses the progression of the disease, with the T (tumor) score evaluating the size and extent of the primary tumor, and the N (nodes) score determining whether cancer has spread to nearby lymph nodes (Terrone and Billia, 2018).

Nanoparticle-based drug delivery systems are emerging as a promising approach to improving prostate cancer treatment by addressing the limitations of conventional chemotherapy. One key advancement in this field is the application of nanoparticles to enhance drug delivery directly to prostate cancer cells. These nanoscale carriers offer multiple advantages, such as enhanced drug solubility, prolonged circulation time, and precise targeting of cancerous cells. By encapsulating chemotherapeutic agents, nanoparticles facilitate controlled drug release, thereby reducing systemic toxicity while maintaining therapeutic potency. Additionally, modifying these nanocarriers with targeted ligands allows for their accumulation within the prostate tumor microenvironment, further optimizing treatment effectiveness (Kumar *et al.*, 2024).

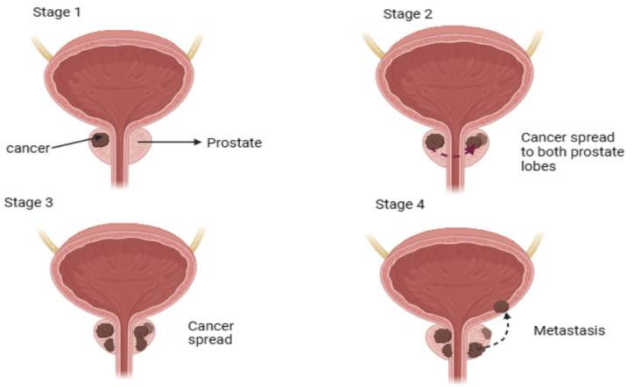

Figure 22: Different stages of prostate cancer (Kumar *et al.*, 2024).

Current role of nanoparticles in the treatment of lung cancer

Lung cancer is the most prevalent cancer in developed nations and remains the leading cause of cancer-related deaths worldwide, accounting for 18.4% of all cancer fatalities (Bray *et al.*, 2018). Around 70% of lung cancer cases are diagnosed at advanced stages, and the five-year survival rate is only 15% (Siegel *et al.*, 2018). Diagnosis typically involves a combination of physical examinations, patient medical history, and imaging techniques such as X-rays, computed tomography (CT), magnetic resonance imaging (MRI), and PET-CT scans, which are considered the standard methods for identifying tumor size and location (Rivera *et al.*, 2013; Hochhegger *et al.*, 2015). Various treatment options are available, including surgery, radiotherapy, radiosurgery, chemotherapy, and immunotherapy. The choice of treatment depends on the cancer stage, the patient's overall health, and the histological classification of the tumor. Surgery is regarded as the most effective option; however, it is not suitable for cases with metastasis or late-stage disease. In such instances, a combination of radiation and chemotherapy has traditionally been the preferred approach, though the incorporation of targeted therapy and immunotherapy has significantly altered treatment strategies (Kozower *et al.*, 2013; Ko *et al.*, 2018).

Nanoparticles (NPs) are artificially engineered particles smaller than 100 nanometers, typically composed of polymers, lipids, or metallic elements such as gold. Due to their distinctive functional characteristics, they are widely utilized in medical applications, particularly for cancer diagnosis and treatment (Horikoshi and Serpone, 2013). By incorporating therapeutic agents within biodegradable carriers, nanoparticles enable localized drug delivery with controlled and prolonged release (Chow and Ho, 2013). Their ability to efficiently enter body tissues and the circulatory system enhances bioavailability, making them promising tools in lung cancer therapy (Baetke *et al.*, 2015). Research on nanoparticle-based treatments aims to develop targeted drug delivery methods that specifically reach tumors. However, further investigation is needed into their in vivo toxicity and biodistribution, as many nanoparticle formulations remain in preclinical stages (Carrasco-Esteban *et al.*, 2021). Before these technologies can be widely adopted in clinical practice, their effectiveness and safety must be confirmed through rigorous clinical trials. The advancements in nanotechnology have helped address challenges associated with traditional therapies, targeted treatments, and immunotherapy, such as drug resistance and systemic toxicity, offering new possibilities for improving lung cancer treatment outcomes (Li *et al.*, 2021) [Figure 23].

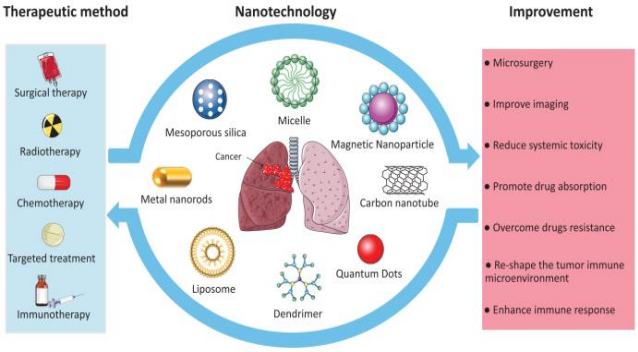

Figure 23: Schematic diagram of nanotechnology improving the treatment of lung cancer (Li *et al.*, 2021).

Food supplementation with nanotherapeutic composites

A well-balanced diet containing essential nutrients, including vitamins and antioxidants, is vital for maintaining the health of both humans and animals. In recent years, there has been a growing emphasis among medical professionals on consuming food products enriched with specific ingredients that can help prevent and manage diseases such as cancer and diabetes. The fortification of food with dietary supplements is feasible when the stability of the active ingredient is maintained until the product's expiration date. Nano-formulations of bioactive compounds, developed using biodegradable nanocarriers such as polymeric matrices, micelles, and liposomes, not only enhance stability but also enable the controlled release of nutrients. These nano-formulations can be incorporated into food and beverages to enrich them with beneficial components. Unlike nutraceuticals available in pharmacies, which can pose health risks if consumed in excessive amounts, supplementing food products with nano-formulated ingredients minimizes the risk of overconsumption. However, all nanoscale materials used in the food industry should undergo careful evaluation to assess their cytotoxicity and potential toxicity, considering factors such as surface reactivity due to their small size. It is essential to adhere to guidelines and regulations established by the European Food Safety Authority (EFSA) to ensure safe usage (Jampilek *et al.*, 2019).

Biocompatible nanomaterials are developed to introduce unique properties in the food industry, including reducing toxicity and enhancing immune responses. By modifying the shape and size of these nanomaterials, their compatibility with functional foods and nutraceuticals is improved. These materials serve various purposes, such as food safety, processing, packaging, and quality control, without exhibiting toxic effects. Additionally, they play a role in detecting toxins and pathogens, improving sensory attributes like color, flavor, and aroma, and facilitating the production of edible films. The systematic reviews examined the biocompatibility of nanomaterials, focusing on their synthesis, advanced applications in food production and processing, safety and quality control measures, and the associated regulatory framework. It also addresses health and safety concerns, potential toxicity, and public perceptions regarding the incorporation of nanomaterials in the food sector (Ranjha *et al.*, 2022) [Figure 24].

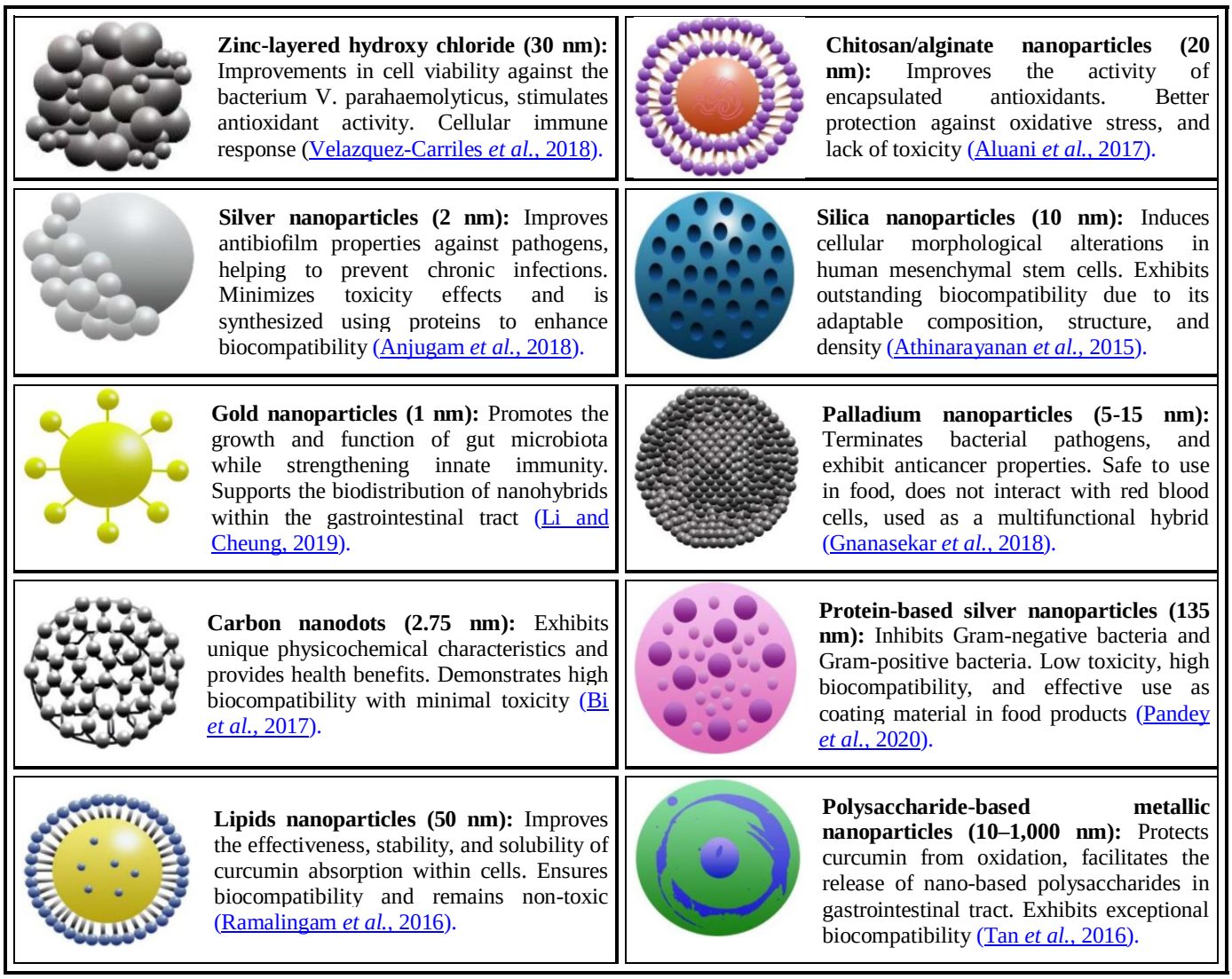

Figure 24: Biocompatibility of nanomaterials by consuming different nanofoods products (Ranjha *et al.*, 2022).

The green synthesis of nanoparticles using metals such as silver, zinc, copper, and iron derived from garlic (*Allium sativum*) and ginger (*Zingiber officinale*) extracts has been investigated. The study involved analyzing phenolic content and antioxidant activity, with HPLC used to separate phenolic and flavonoid components. Findings revealed that copper-ginger nanoparticles exhibited the most potent anticancer effects against various cell lines. Additionally, these nanoparticles were assessed for their antibacterial and antifungal properties against multiple bacterial and fungal strains, showing significant antimicrobial activity when compared to conventional antibiotics. The results highlight that synthesizing nanoparticle using natural extracts is a safer and more efficient method, offering a promising alternative for cancer treatment and antimicrobial applications (El-Refai *et al.*, 2018a; 2018b).

The environmentally friendly synthesis of selenium and zinc nanoparticles utilizing plant extracts such as *Ginkgo biloba* and *Sargassum latifolium* algae has also been explored. These nanoparticles demonstrated their effectiveness in stabilizing corn and soybean oils at varying concentrations of 200, 400, and 800 ppm. They exhibited resistance to thermal degradation and oxidation, helping to preserve the polyunsaturated fatty acid content of the oils. Furthermore, their antioxidant efficiency was comparable to that of synthetic antioxidants like tert-butylhydroquinone (tBHQ). Based on these results, these nanoparticles hold potential as natural antioxidants for extending the shelf life of unsaturated vegetable oils (El-Khateeb *et al.*, 2019; El-Badawy *et al.*, 2020).

Additionally, an eco-friendly approach was employed to synthesize nanoparticles using extracts from rhus and

safflower plants in combination with four metal ions, zinc, copper, silver, and iron. Antioxidant assessments of these extracts and their nanoparticles showed that the safflower extract and its silver nanoparticles (AgNPs) displayed the highest free radical scavenging activity, as determined by the "2,2-diphenyl-1-picrylhydrazyl" (DPPH) and "2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)" ($ABTS^{\bullet+}$) assays. The $DPPH^{\bullet}$ assay results confirmed that all extracts exhibited strong antioxidant properties. Furthermore, both rhus and safflower extracts, along with their nanoparticles, were tested for antimicrobial activity, with the safflower extract and its AgNPs and copper nanoparticles (CuNPs) demonstrating the strongest antibacterial and antifungal effects. This enhanced antimicrobial activity was attributed to the smaller particle size of the metal ions and the clustering of nanoparticles. Conversely, the larger size of zinc and iron nanoparticles reduced their antimicrobial efficacy. Moreover, anticancer evaluations revealed that safflower extract, along with its AgNPs and CuNPs, exhibited significant cytotoxic effects against the Caco-2, HEPG2, and T47D cancer cell lines, with effectiveness increasing at higher extract concentrations (Ibrahim *et al.*, 2019).

Future vision and modern exploratory knowledge in nanotherapeutic nutrition

Nanotechnology is the cornerstone of building a healthier, smarter, and more sustainable future. From targeted nutrition to advanced nano therapies, this technology offers unprecedented potential to improve the quality of life and combat diseases in more efficient and precise ways. It is not only a scientific revolution, but the promise of a healthier and more prosperous future for all. Nanotherapeutics is expected to revolutionize medicine through multifunctional nanoparticles, capable of precisely targeting diseased cells and efficiently treating chronic diseases. These technologies will enable the development of "one drug for multiple diseases" that treats different conditions simultaneously, bringing about a paradigm shift in the management of incurable diseases such as cancer, heart disease, and neurological diseases such as Alzheimer's and Parkinson's, etc. Nanotherapeutics will combine artificial intelligence, big data, and genetic technology to analyze patient data in real-time. Intelligent systems will deliver personalized treatments based on precise genetic analysis and the health status of each individual. In the future, nanotherapeutics will be like "tiny robots" that go to affected areas in the body, delivering drugs or even repairing diseased cells without the need for surgical intervention. Nanotechnology will foster collaboration between scientists, industry, and governments to create a fertile research environment that will contribute to achieving tangible results at the global level. These partnerships will contribute to developing sustainable and effective solutions to health challenges, turning the corner in building a healthier, smarter future. All things considered, the thorough review is an invaluable tool for scientists and medical professionals, promoting a better comprehension of the complexities associated with nanotherapeutic nutrition and directing future efforts toward more advanced detection and therapy.

CONCLUSION

Nanotherapeutics represents a paradigm shift in medicine and nutrition, opening new horizons towards unprecedented precision and efficiency in treating diseases and promoting health. This technology is reshaping healthcare concepts by providing innovative solutions to treat incurable diseases, improve nutrient absorption, and develop functional foods to enhance quality of life. In medicine, nanotherapeutics is leading a revolution in personalized medicine, and targeted and regenerative therapies, paving the way for an era where diseases can be eliminated, rather than merely managed. The integration of nanotechnology with artificial intelligence and genetic engineering enhances the innovation potential, expanding the scope of quality of life and human longevity. In nutrition, nanotechnology offers solutions to improve food quality and the effectiveness of nutritional therapies, contributing to the prevention of chronic diseases and smart nutrition management. However, challenges remain regarding safety, scalability, and accessibility, which require clear regulatory frameworks to ensure responsible use. The future that nanotechnology promises is a healthier and more prosperous world, based on precision therapies and smart nutrition. As innovation continues, we are on the cusp of a new era where healthcare and nutrition become targeted and personalized, steering humanity on a healthier and more sustainable.

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