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Nanoparticles In Human Nutrition: Enhancing Nutrient Delivery And Bioavailability For Improved Health Outcomes

Evangelina O. Ohaeri1, Chukwu Rita Mmesoma2, Joseph E. Inya3

1Department of Science Laboratory Technology, Federal University of Technology, Owerri, Imo state. Email: evangelina.ohaeri@futo.edu.ng.

2Department of Science Laboratory Technology, Federal University of Technology Owerri, Imo State. Email: ritammesoms@gmail.com

3Department of Science Laboratory Technology, Federal University of Technology Owerri, Imo state. Email: inyajoegwu@gmail.com.

Abstract: *Nanomaterials are particles whose dimensions read between 1-100 billionths (1-100 x 10^{-9} nm). Nanotechnology has the potential to greatly improve the bioavailability and efficiency of food-based bioactive substances when used for human nutrition. There are many ways in which nanoparticles (NPs) can be used to enhance nutrient absorption and guarantee the safety of food. One of the ways is the encapsulating of vitamins, minerals, and antioxidants inside nanoparticles and the techniques involved in improving food materials with nanoparticles include nanoencapsulation strategies which involve the fabrication of nanofibres, nanocomposites, and nanoemulsions. The possibility of nutrition-based nanotechnology in terms of cost and the nutritional absorption can be investigated in order to enhance biofortification. Despite encouraging development and improvement of food through nanotechnology, there are still many unanswered questions about regulation and safety that need more studies. Consequently, nanotechnology's promise has the ability to usher in new uses and substantial improvements in the food industry, which would be good for people's diets.*

Keywords: Nanotechnology, Nanoparticles, Food, Biofortification, Bioavailability.

1. Introduction to nanotechnology and nanoparticles in nutrition

It would be difficult to find a modern human endeavour that does not make use of nanotechnology in some way. Electronics (Vinodhini & Mahalakshmi, 2014), automobile engineering (Pradeep & Monika, 2020), building (Rao *et al*., 2015), healthcare, pharmaceuticals (Malik *et al*., 2023), environmental protection, and the food industry (Ndlovu *et al.*, 2020; Arshad *et al.*, 2021) are just a few of the many scientific and commercial fields that have been found using highly complex nanomaterials. Nanotechnology is seemly a game-changing innovation that has influenced and shaped many human pursuits, including agriculture, food production, and medicine, with a focus on human nutrition (Singh *et al.,* 2017). According to Collins' definition, "nano" is "so small that only a powerful electron microscope can see it." According to Singh *et al.*, (2017), the prefix "nano" indicates a "one billionth" or "10^{-9}" of anything, or one component in one billion. Nanoscience and nanotechnology may be useful for all other scientific fields, including those that deal with food and nutrition, agriculture, electronics, medicine, and materials science. These fields concentrate on the use and study of extremely small items.

Engineering, manipulating materials and devices at the nanoscale level (usually 1–100 nanometres) is the domain of nanotechnology, a subfield of applied science (Al-Harbi & Abd-Elrahman, 2024). Researchers have focused a lot of emphasis on nanoscale materials because of the innovativeness of nanotechnology of the 21st century. Nanoscale manipulation of atomic and molecular groups is the focus of a new multidisciplinary field of study (Singh *et al.,* 2017). A simple definition of nanotechnology would be the scientific study of materials whose characteristics are very sensitive to scales on the nanometre scale.

It is possible to alter food properties by influencing individual atoms and molecules through the use of nanotechnology. Nanoparticles describe these very small food particles, which are less than 100 nm in size. When compared to the width of a human hair, which is about 100,000 nm, the size of nanoparticles becomes more apparent (Joudeh and Linke, 2022). The particles' chemical and biological activities, as well as their interactions, are greatly enhanced by their increased surface area, which is a result of their diminutive size. In 1959, during an American Physical Society conference at the California Institute of Technology, Richard Feynman first proposed the idea of nanotechnology (nanometre, 10^{-9}) (Joudeh and Linke, 2022). The capacity to construct materials at the micro scale was presented by Professor Norio Taniguchi only fifteen years later, called nanotechnology. Soon after, a plethora of academic institutions began to focus on nanotechnology, with several presenting competing definitions.

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The whole point of nanotechnology is to create materials with unusual characteristics and uses, such improved barrier qualities brought about by the very tiny size of the components (Ranjini *et al*., 2024). The IUPAC defined a nanoparticle as "a particle of any shape with dimensions in the 1×10^{-9} and 1×10^{-7} m range" in its 2012 recommended language for physiologically relevant polymers (Ranjini *et al*., 2024). An earlier version of this definition was provided by IUPAC in 1997 (Hassan, 2015). The three external dimensions of an object must be on the nanoscale for it to be considered a nanoparticle, as defined by the International Standards Organisation (ISO) technical specification. The object must also have axes that are not significantly different from one another, with a typical significant difference being a factor of at least three (Ranjini *et al*., 2024). Typically, nanoparticles have a size between one and one hundred nanometres, making them a thousand to one hundred thousand times smaller than the breadth of a human hair. Smaller than bulk materials, nanoparticles have unusual characteristics such increased chemical reactivity, strength, and optical behaviours (Joudeh and Linke, 2022). Because of the small nature, nanoparticles are a game-changer when it comes to solving nutritional problems, particularly in the areas of vitamin and mineral fortification, nutrient stability and bioavailability, food safety, and targeted nutrient delivery (Ndlovu *et al.,* 2020; Arshad *et al.,* 2021).

Modern advances in our knowledge of nanoscale food materials and how they react during processing have allowed for the creation of new foods that boast enhanced nutrient composition and bioavailability, enhanced organoleptic qualities and functionalities, and longer shelf life (Shang, *et al*., 2019). The use of nanotechnology has the potential to enhance human health in many ways, including the delivery and gradual release of bioactive compounds in functional foods and nutraceuticals, the purification of water, the encapsulation of small molecules, the elimination of odours, the development of novel food packaging, the enhancement of traceability, and the monitoring of foods as they are transported and stored.

Detecting pollutants, producing nutritious food free of contamination for customers, and improving food qualities are all ways nanotechnology is being used in the food industry (Mohammad *et al.*, 2022). The use of nanotechnology-based sensors in food processing has the potential to enhance food safety and quality by reducing the likelihood of contamination. Nutrient supplements, nano-emulsions, nano-laminates, and nano-additives all make use of nanotechnology to improve the nutritional value, texture, colour, and flavour of food. In order to ensure the safety of food while it is being processed, handled, or transported, nanotechnology is mostly used (Mohammad *et al.*, 2022). The food industry is in dire need of new, cutting-edge ways to extend the shelf life of perishable goods, prevent their contamination, and ensure that customers may eat them without worry, and nanotechnology is a key component in this effort.

2. Potential Benefits of Nanoparticles in Addressing Nutritional Challenges

An emerging area called nano-nutrition involves the use of nanoparticles in human nutrition. Food safety and quality are both improved by the use of nanoparticles. It directly contributes to increase nutrient delivery, bioavailability, and stability (Altemimi *et al*., 2024). Problems with nutritional breakdown, inadequate absorption, or digestive instability are the primary targets of these applications.

A. Improving the safety of food and also enhancing the preservation of food: The use of nanoparticles guarantees the security of food and it is receiving numerous attentions all over the world (Ansari, 2023). To make sure that foods are safe to eat, nanoparticles are used as antibacterial agents (Ansari, 2023). The development of methods to assist in food preservation is another area that nanoparticles contribute to. Additionally, nanoparticles may be used in food packaging to identify any signs of contamination or deterioration, guaranteeing that food is safe to eat (Ansari, 2023). As an example, there is hope that silver nanoparticles may inhibit the development of dangerous bacteria in food goods, which would lower the likelihood of contamination and food poisoning. To extend the shelf life of food and decrease the need for chemical preservatives, silver nanoparticles have been used in packaging and have tremendously contributed to the preservation of foodstuffs away for microbes (Han *et al*., 2018).

B. Enhanced Bioavailability of Nutrients: Nutrients, particularly those with low solubility may have much bioavailability and absorption rate when modified with nanoparticles (Arshad, *et al.,* 2021). Nutrients may be delivered to specific parts of the body without being affected by heat, light, or oxygen. This has been achieved through nanoencapsulation technology. Absorption of curcumin, fat-soluble vitamins A, D, E, and K, and other nutraceuticals, lipid nanoparticles may increase their solubility and stabilize them. Micronutrients like zinc and iron may be indigestible in their natural state but polymeric nanoparticles have helped in transportation of these minerals more efficiently in the body system. For examples, one of turmeric's antioxidants, curcumin, is poorly absorbed and very poorly soluble in water. It has the potential to be even more healthful when administered using nanoparticle-based systems (such nanoemulsions) because of the enormous improvement in bioavailability. Another example where nanoparticle compositions enhance absorption and efficiency in the body is coenzyme Q10 (CoQ10), a vital antioxidant (Zhang & McClements, 2016; Arshad, *et al.,* 2021).

C. The stability of nutrients is improved with the use of nanoparticles: The use of nanoparticles prevents the breakdown of nutrients that are particularly delicate. Some foods deteriorate during the manufacturing, processing, and even storage processes.

Using nanoparticles to prevent this and extend their shelf life is a great idea. Encapsulating nutrients in nanoparticles preserves them from oxidation, makes them more stable, and increases their shelf life; this is especially true for vitamins and omega-3 fatty acids, which are susceptible to oxidation (Altemimi *et al*., 2024).

D. Targeted Delivery of Nutrients: Reduced risk of nutrient loss during digestion and maximal effectiveness of that nutrient may be achieved by the tailored distribution of certain nanoparticles to specific tissues or organs. When dealing with people who have trouble absorbing certain nutrients because of disease or starvation, this is a lifesaver. People with vitamin shortages may benefit from the effective release and absorption of folic acid and iron, for instance, by having these nutrients nanoencapsulated (Shang *et al.,* 2019).

E. Nanoparticles ensure the enrichment and the fortification of foods: The development of nanotechnology and nanoparticles has made it possible to fortify food with additional nutrients, such as higher concentrations of vitamins and minerals. Foods' nutritional value is unaffected by this technological development; rather, it enhances their flavour, texture, look, and quality. As an example, food items fortified with nano-sized iron particles do not suffer from the usual sensory problems, including changes in colour and taste, which are linked with traditional iron fortification methods. A good diet rich in calcium is essential for strong bones, and nano-calcium may be easily added to drinks and other foods without changing their flavour or texture. More effective and novel approaches to preventing worldwide nutritional deficits are emerging as nanotechnology develops.

2. Types of nanoparticles used in human nutrition

Importantly, nanoparticles are classified into inorganic, organic and Hybrid and Composite Nanoparticles (Ealia & Saravanakumar, 2019). The different types of nanoparticles used in human nutrition are discussed under the following headings:

A) Inorganic Nanoparticles: Joudeh and Linke, (2022) reported that nanoparticles composing of inorganic substances, such as metals or metal oxides, are known as inorganic nanoparticles. Their size generally falls between one and one hundred nanometres. Two methods exist for creating inorganic nanoparticles: the top-down method involves slicing huge pieces of material into smaller ones, while the bottom-up method involves incorporating individual atoms and molecules into larger nanostructures. Elements such as zinc, gold, silver, titanium, and silica make up inorganic nanoparticles (Joudeh and Linke, 2022). Because of their diminutive size and large surface area, these inorganic nanoparticles display exceptional characteristics. For example, materials such as gold, silver, platinum, and others make up metal nanoparticles. Metallic oxide nanoparticles may be made of either iron oxide (Fe_3O_4), zinc oxide (ZnO), or titanium dioxide (TiO_2). Materials such as alumina (Al_2O_3) or silica (SiO_2) are used to make ceramic nanoparticles. Also, Thomas *et al.,* (2015) also asserted that carbonates, carbides, phosphates, and oxides of metals and metalloids, such as titanium and calcium also form parts of inorganic nanoparticles.

B) Organic Nanoparticles: Materials with lipid, protein, or carbohydrate bases make up organic nanoparticles (Ealia & Saravanakumar, 2019). These organic nanoparticles are mostly used to make antioxidants, vitamins, and minerals more absorbable and stable. Some examples are: i). lipid-based nanoparticles include lipophilic nutrients such as vitamins A, D, E, K, and omega-3 fatty acids which are used to enhance bioavailability, stability, and controlled release. Furthermore, nanostructured lipid carriers (NLCs) and solid lipid nanoparticles (SLNs) are lipid-based nanoparticles (Khan *et al.*, 2019). ii). Encapsulating vitamins and minerals are functional protein-based nanoparticles which prevent nutrients from being broken down in the digestive system. Nutrient stability is improved and bioactive substances are delivered with their support. Casein, whey protein, and soy protein nanoparticles are a few good examples (Shang *et al.,* 2019) and iii). Hydrophilic substances, such vitamins and minerals, which can be controlled by using carbohydrate-based nanoparticles. They improve the bioavailability of some chemicals that are poorly absorbed and also aid in the transport of certain nutrients (Kumar & Lai, 2014). Starch, dextran, and alginate nanoparticles are a few examples.

C) Hybrid and Composite Nanoparticles: These are examples of cutting-edge nanomaterials that have been used to increase the bioavailability of nutrients and bioactive substances by enhancing their transport, absorption, and processing (Winter *et al.,* 2020). The use of nanoparticles in this context is to improve human health by combining materials and chemicals to increase their functionalities. Composite nanoparticles are tiny components that interact with materials at their interfaces. Bioactive substances, including vitamins and minerals, are essential to human health, and these nanoparticles may improve their transport and stability (Winter *et al.,* 2020). One research found that encapsulating vitamin B12 in protein-lipid composite nanoparticles increased its bioavailability and absorption in the gut. Because of the difficulties associated with encapsulation and stability, this is of paramount importance for hydrophilic nutraceuticals. There is evidence that composite nanoparticles (CNPs) may increase nutrients' bioavailability, make bioactive molecules more stable, and provide regulated nutrient delivery. These particles are created by nanoscale, mixing of two or more ingredients, which typically includes both organic and inorganic substances.

In another development, hybrid nanoparticles mix several materials, including polymers and metal nanoparticles, to form structures. Folic acid and vitamin A, for example, may have their solubility and stability improved by these substances added to it, allowing the body to absorb them more easily. In human nutrition, composite and hybrid nanoparticles provide new ways to enhance nutrient delivery to specific targets and increase bioavailability (Winter *et al.,* 2020).

3. Mechanisms of Nanoparticles Functionality

A nanoparticle uses their nature and size to penetrate food substances and manipulate the functionality by enhancing the bioavailability of the mineral contents through:

A). Biological Interactions with Nanoparticles: The microscopic size of nanoparticles makes it to have the features to engage with biological systems in peculiar ways. For example, cellular responses may be stimulated by their ability to enter cells and bind to proteins. Physical and chemical characteristics of nanoparticles are discussed based on dimensions, form, surface charges, and chemical makeup and have been reported seen to have significant role in determining how nanoparticles interact with biological systems (Rawat *et al.,* 2018). A larger surface area of the substance receiving the nanoparticles allows smaller nanoparticles to interact with biomolecules and these molecules include nucleic acids, proteins, and lipids more effectively, leading to a greater reactivity. For example, attachment to protein creates "protein corona." The absorption, distribution, and clearance of the nanoparticles to the cells may be affected by this dynamic layer's ability to change their biological identity. Protein corona makes up nanoparticle-cell interactions complexes and, by extension, leads to cellular response modifications. Endocytosis and membrane penetration are two pathways that nanoparticles might use to get into cells (Behzadi *et al.,* 2017). The type of cell engaged and the characteristics of the nanoparticle determines the precise route. Nanoparticles may elicit distinct responses from immune and epithelial cells. For instance, membrane composition and receptor expression accept nanoparticles in different ways. The transport of nanoparticles to certain organs or tissues may also be achieved through genetic engineering (Behzadi *et al.,* 2017). Nanoparticles may have their surface chemistry adjusted for better interaction with certain cell types or biological barriers, allowing for more precise targeting. The way they interact with immune cells may change the way cytokines are made and how the immune system is activated or suppressed (Mazumdar *et al.,* 2021). In order to incorporate nanoparticle in foods that are healthy for humans, it is essential to understand the interactions properly (Mazumdar *et al.,* 2021).

B). Targeted Delivery and Controlled Release of Nutrients: This is another mechanism through which nanoparticles are incorporated in food and also how they help the food consumed by humans utilize the nutrient. For example, nanoparticles may be channeled to pass the blood-brain barrier to deliver drugs to the brain (Hersh *et al.,* 2021). In plants, nanoparticles can also pierce leaves and translocate to supply nutrients to roots and other tissues (Djanaguiraman *et al.,* 2024). Unarguably, the release rate of nutrients from food samples may be regulated by the composition and shape of nanoparticles. The polymeric nanoparticles and micelles through this mechanism create a delay in the sustenance of the release of contained nutrients. Most times nanoparticles can be coated to shield nutrients from degradation during digestion and allow for regulated release of the nutrients, enhancing nutrients' bioavailability. For example, nutrients may be protected from stomach and intestinal conditions and delivered to the site of absorption by use of nanocarriers. When compared to traditional supplements, this results in a greater utilization of nutrients.

4. **Techniques for Nanoparticles Synthesis**

There are two main approaches to creating nanoparticles, which are particles with a size between one and one hundred nanometers, and these are known as nanoparticle synthesis (Shafey, 2020).

A. Top-Down Approach

Abid *et al.,* (2022) stated that the top-down approach of nanoparticle preparation involves hydrolyzing big particles into smaller partices. The adoption of improved breakdown methods such as grinding, milling, laser, and lithography is deleterious (Abid *et al.,* 2022). Harish *et al.,* (2022) state that nanoparticles of carbon, iron oxide, cobalt (III) oxide, and dichalcogenides are produce using this method. Some of the top-down approaches of synthesizing nanoparticles include:

i. Ball Milling: This is one of the physical methods of preparing nanomaterial. Here, a revolving ball mill is used to reduce large materials to nanoparticles. To reduce large materials to tiny particles, it employs kinetic energy. This technique involves mechanically shrinking materials by means of collisions between hard balls housed in a spinning cylindrical chamber and the material (Abid *et al.,* 2022).

b. Laser Ablation: Irradiating a substance with a laser is done by ejecting and condensing particles into nanoparticles. Substances are vapourized using a focused burst of high-energy laser light to make nanoparticles. It is possible to synthesize ceramic and metallic nanoparticles by following the same procedure in either a vacuum or a liquid medium. Laser ablation is also a useful tool for creating

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oxide nanoparticles, gold nanoparticles, and silver nanoparticles. The top-down method produces high-quality nanoparticles that can be tailored to a wide range of uses, and it also allows for precise control over their size and structure (Isyaka *et al.*, 2024).

B. Bottom-up Approach

The procedures include a variety of reduction and sedimentation techniques, including spin coating, green synthesis, biological synthesis, and sol-gel synthesis. Nanoparticles of bismuth, titanium dioxide, and gold are produced using this method (Abid *et al.*, 2022). Assembling nanoparticles from basic components is the bottom-up method, and it is a long process. Nanoparticles may be gradually built up from more basic elements using this method. This method is not only cost-effective but also quite safe for both people and the environment. Methods that are part of the Bottom-Up Approach include:

a. Sol-Gel Process: The procedure begins with a liquid solution going through a series of chemical reactions and hydrolysis to create a gel. The gel may then be dried and treated to get nanoparticles. Particle size and composition may be precisely controlled using the sol-gel method. Silica and titanium dioxide are oxide nanoparticles that make extensive use of it (Bokov *et al.*, 2021).

b. Chemical Vapour Deposition (CVD): According to Manikam *et al*., (2011), it involves the reduction of metal ions in a solution using chemical reagents such as sodium borohydride or sodium hydroxide to form nanoparticles. Nanoparticles are solidified on a substrate when gaseous precursors undergo a reaction and then condense. The size and shape can be manipulated by changing environmental factors like temperature and pressure. Nanowires, carbon nanotubes, and semiconductor nanoparticles are often made.

C. Hydrothermal methods: In this process, water is heated to very high temperatures and pressures in order to create nanoparticles (Ndlwana *et al*., 2021). Nanoparticles are formed by chemical processes that take place in a water-based solution under conditions of high pressure and temperature. The crystalline nature and size of the nanoparticles is controlled by high pressure. Producing very pure oxide and sulphide nanoparticles is the goal of this technique (Ndlwana *et al*., 2021).

5. Methods used in assessing the sizes, Shapes and Surface Particles of Nanoparticles

Determination and assessment of sizes, shapes and surface of particles of nanoparticles can be done through the following techniques:

✓ **Scanning Electron Microscopy (SEM):** This makes it possible to generate incredibly detailed images of the size and form of nanoparticles. SEM can be used in conjunction with Energy Dispersive X-ray Spectroscopy (EDS) to study elements. Scanning electron microscopy can be used to learn about the form and surface morphology of nanoparticles. By interacting with the surface of a nanoparticle and then emitting secondary electrons, the scanning electron microscope (SEM) produces a high-resolution image of its surface (Ghasempour-Mouziraji *et al.*, 2024).

✓ **Transmission Electron Microscopy (TEM):** Offers atomic-level resolution, enabling a comprehensive examination of the size and shape of nanoparticles. By passing an electron beam through an extremely thin layer of nanoparticles and then detecting the reflected electrons, transmission electron microscopy (TEM) produces an image. Transmission electron microscopy (TEM) can identify particles as small as 0.1 nm, claimed by Tang & Yang (2017).

✓ **Dynamic Light Scattering (DLS):** It is effectively used to determine sizes ranging from 1 nm to many micrometers. This method uses light scattering from suspended particles to ascertain particle size. Nanoparticle hydrodynamic size distribution in colloidal suspension may be measured (Ghasempour-Mouziraji *et al.*, 2024).

✓ **Raman Spectroscopy:** In addition to revealing the nanoparticles' molecular vibrations, this technique reveals their chemical make-up and crystallinity.

✓ **X-ray Diffraction (XRD):** Ascertains the size of particles and their crystal structure. To comprehend the characteristics of materials, it is essential. The X-ray diffraction pattern, when it interacts with the nanoparticle crystal lattice, is measured by XRD (Ghasempour-Mouziraji *et al.*, 2024).

6. Applications of Nanoparticles in Foods

A). Nanoparticle-enriched functional foods

Functional meals may help lower illness risks by using dietary bioactives that have beneficial physiological effects (Biswas *et al.*, 2022). Novel foods that have been engineered to include compounds or living microbes with the potential to improve or prevent illness are known as functional foods. They are safe and adequate to accomplish their intended goal. Nutrients, fibre, phytochemicals, and other compounds, as well as probiotics, may be included as additional ingredients (Biswas *et al.,* 2022). Foods that include bioactive chemicals that may improve health or decrease illness risk are considered functional foods. These foods also have additional nutritional value. In order to get these advantages, these foods might be in one of four forms: whole, fortified, enriched, or enhanced.

I. Conventional Foods: Some examples of food that are naturally rich in nutrients include:

✓ Fruits such as apples, berries, and oranges. It helps to reduce chronic illnesses like cancer and heart disease.

✓ Vegetables such as carrots, broccoli, and spinach are good antioxidants.

✓ Whole grains include oats, barley, and brown rice. The high fibre content of whole grains aids digestion and reduces cholesterol risk.

✓ Seeds and nuts are good sources of healthful fats, fibres, and phytochemicals including lignans. Phytochemicals may be found in almonds, chia seeds, walnuts, and flaxseeds. One plant-based omega-3 fatty acid that has been associated to better heart health is alpha-linolenic acid (ALA), which is found in walnuts (McClement & Xiao, 2012).

II. Modified Foods: Fortified or improved foods are those that have had certain beneficial chemicals added to them. For those who do not have enough nutrients from their typical diet, fortified foods like iodine-enriched salt or calcium-fortified orange juice may fill in the gaps. According to Heaney *et al.,* (2013), foods that are fortified with calcium aid in the prevention of osteoporosis and the maintenance of healthy bones. Some fortified food materials been consumed nowadays include: dairy products fortified, yoghurt enriched with probiotics and fruit juices that have been fortified with calcium are orange juices.

III. Omega-3 Fatty Acid: Foods high in omega-3 fatty acids include walnuts, salmon, eggs, and shellfish. They are essential for heart health and also have anti-inflammatory qualities that lower the risk of cardiovascular illnesses. Supplemented Eggs are also other important source oof omega-3-fatty acids commonly used today (Biswas *et al.,* 2022).

IV. Fermented Foods: Foods strong in pre- and probiotics include kefir, kimchi, sauerkraut, and yogurt. The digestive tract is kept healthy by beneficial bacteria. Probiotics may improve digestion and strengthen the immune system, according to research. By promoting a balanced gut flora, certain strains of Lactobacillus species present in yoghurt can reduce the incidence of gastrointestinal issues (Bansal *et al*., 2020). Consuming a variety of these foods is linked to improved overall health and a lower chance of getting long-term conditions like diabetes and heart disease (Wang *et al*., 2020; Biswas *et al.,* 2022).

7. Roles of Nanoparticles in Enhancing the Nutritional Profile of Functional Foods

I. Improved Bioavailability: Nanoparticles may enhance the solubility and absorption of functional meals. The nutrients in food may be more easily absorbed by the body's digestive system if they are encapsulated in small nanoparticles. Nanoparticles can be designed to provide a steady supply of essential nutrients throughout time by regulating or maintaining the release of nutrients. This makes it possible for functional meals to more effectively supply nutrients to the body's necessary areas.

II. Functional Ingredient Enhancement: In functional food enhancement using nanoparticles, it has been observed that nanoparticles can completely remove the unpleasant flavours or odours of some bioactive ingredients and also improve the palatability of functional meals while maintaining their nutritional value. They are frequently used to enhance texture, which raises nutritional value and consumer satisfaction in functional foods. Nanoparticles not only improve the delivery of nutrients but also increase the overall utility of meals. They may improve stability, alter sensory qualities, and even eradicate bacteria, all of which are beneficial to your health and ensure that food is safe to consume.

III. Protection of Sensitive Nutrients: Nutrients like omega-3 fatty acids, probiotics, or certain vitamins can be shielded from environmental aggressors such as heat, light, and oxygen by using nanoparticle encapsulation (Bansal *et al.,* 2020). These fragile nutrients are encapsulated using a variety of methods, including as nanoemulsions, nanoliposomes, and nano-capsules. Because functional foods are more stable and have a longer shelf life, they can retain their nutritious content until they are consumed. One of the most crucial elements of using nanomaterials is this. Food is protected against bacterial and environmental attacks by nanoparticles due to their size and composition.

8. Fortification and Enrichment Strategies of functional foods

I) Mass Fortification: This method is used in common meals to supplement vitamins and minerals that the normal person requires. Both the Food and Agricultural Organization (FAO) and the World Health Organization (WHO) concur that mass fortification is required when a sizable population is or may become micronutrient deficient. Iodizing salt is another popular procedure to prevent iodine shortage, while fortifying wheat with iron and folic acid to combat anemia is another common example (Pawandeep *et al.*, 2019).

II) Targeted Fortification: By strengthening food vehicles, the objective is to increase micronutrient consumption for a particular population without influencing others. This type of fortification is particularly helpful when mass fortification is not enough to meet the specific micronutrient needs of a target group. Products that are fortified are made to satisfy the dietary needs of specific populations, such children and expectant mothers. Products that employ this method include refugee food, emergency/school meals, and fortified supplemental food (Pawandeep *et al.*, 2019). One can include micronutrient powders in baby's meals to ensure they are getting enough nutrients.

III) Point-of-Use Fortification: "Point-of-use" or "home" fortification is another technique for fortifying food. The term "point-of-use" refers to the process of adding lipid-based or powdered fortifiers to food right before consumption. This approach is most frequently utilized in homes, classrooms, and institutions when cooking on-site. This technique uses powdered fortifiers, which are little sachets of vitamin and mineral powders that can be sprinkled over food wherever it is consumed (Pawandeep *et al.*, 2019).

IV) Biofortification: By indirect nutrient addition, this fortification method enhances the nutritious value of crops. Conventional plant breeding, current biotechnology, which introduces specific genes into crops to increase their nutritional content, and agronomic methods, which employ fertilizers rich in specific nutrients like zinc, can all achieve this goal. Biofortification may be used to improve the nutritional value of crops grown for human consumption in regions where people may be lacking in specific nutrients. In recent years, crops have been biofortified with proteins, iron, zinc, and carotenoids (Wang *et al.*, 2020).

The following are examples of biofortified food products are currently been consumed:

A. Salt with added iodine: Goitre, intellectual disability, and thyroid issues are all symptoms of an iodine deficit. In order to combat iodine deficient illnesses on a worldwide scale, the World Health Organization (WHO) has advocated for universal salt iodization (Pawandeep *et al.*, 2019).

B. Wheat Flour with Additives: This flour is fortified with iron and folic acid to lessen the risk of anaemia and neural tube abnormalities. Fortified wheat flour contains additional nutrients such as niacin, thiamine, folic acid, and iron. There has been a significant decrease in the prevalence of neural tube abnormalities in infants in countries where folic acid fortification of wheat flour is required (Pawandeep *et al.*, 2019).

C. Milk with Added Vitamin D and Calcium: This kind of milk is fortified and adults may develop osteoporosis when there is lack of calcium and Vitamin D. On the other hand, children can get rickets from a lack of vitamin D. Fortifying milk helps the body absorb more calcium, which is good for bone development. Many communities have shown improvements in bone health and a decrease in rickets due to fortified milk.

D. Fortified Rice: This kind of rice is enhanced with substances such as iron, zinc, folic acid, vitamin B12, and vitamin A. Fortifying rice becomes more important in areas where micronutrient deficits are prevalent and rice is the main crop. It aids in treating anaemia and vitamin A insufficiency. Countries such as India have shown substantial reductions in anaemia in pilot areas after using fortified rice in their programs (Peña-Rosas *et al.*, 2019).

E. Cereals with added nutrients: Nano-iron is a component of fortified cereals. Because it is a staple morning dish in many countries, iron-fortified cereal is a popular choice. Iron is essential for warding off iron-deficiency anaemia, a common condition that disproportionately affects young people and women. Efficaciously addressing iron deficiency may be achieved by incorporating nano-iron into cereal, which can raise haemoglobin levels and improve general health (Peña-Rosas *et al.*, 2019).

9. Toxicity of nanoparticles in human nutrition

I. Oxidative Stress and Inflammation: Damage to lipids, proteins, and DNA, as well as long-term inflammatory responses in the gastrointestinal tract and other organs, can occur as a consequence of oxidative stress caused by nanoparticles, which in turn can induce the production of reactive oxygen species (ROS) (Bahadar *et al.*, 2016). Zinc oxide (ZnO) nanoparticles, for example, are a common supplement addition that may cause inflammation and liver damage due to oxidative stress.

II. Genotoxicity and DNA Damage: There is a concern that nanoparticles may play a role in cancer formation due to research showing that they may damage DNA and create mutations. The genotoxic potential of some nanoparticles has been shown; especially those derived from metals like silicon dioxide (SiO_2) and silver (Ag). Direct or indirect interactions with DNA, such as the production of reactive oxygen species (ROS), may lead to strand breakage and chromosomal disruption. Concerns over the long-term impacts, such as the risk of cancer, have been raised due to the genotoxic effects of TiO_2 nanoparticles, which have been shown in both laboratory and living organism studies (Jovanovic *et al.*, 2015; Khan *et al.*, 2018).

III. Microbiome Disruption: Nanoparticles have the potential to change the gut microbiome's makeup and function. All aspects of health, from metabolism to immune function, are influenced by the gut microbiota. Digestive health, metabolic rate, and general well-being may all be impacted by disturbances in the gut flora (Malmo *et al.*, 2013). The makeup of gut microbes can be changed by nanoparticles like TiO_2, which might cause dysbiosis. When a malfunctioning variety of organisms replaces the usual gut flora, it may induce disease states; this condition is known as dysbiosis. Metabolic illnesses and inflammatory bowel diseases are among the many diseases linked to dysbiosis (Malmo *et al.*, 2013).

IV. Accumulation in Organs: Certain nanoparticle buildup in critical organs, such as the liver and kidneys, may result in long-term toxicity and ultimately system failure. Absorption is generally inhibited for particles larger than 100 nanometers. The miniscule size of nanoparticles, however, may allow them to slip through the intestinal barrier, enter the bloodstream, and accumulate in organs such as the liver, spleen, and kidneys. According to Heringa *et al.*, (2016), titanium dioxide (TiO_2) nanoparticles, which are frequently employed as food additives (E171), have the potential to accumulate in organs and cause long-term damage to the liver and kidneys.

10. Current Research Gaps Future Prospects on Nanoparticle-nutrient Interaction

1. Comprehensive Studies on Nanoparticle Behavior in Complex Food Matrices: Future research is necessary to fully comprehend the functions of nanoparticles in foods like beverages and how they interact with other dietary ingredients including proteins, fats, carbohydrates, etc. The stability and bioavailability of the nanoparticles with certain food ingredients should be examined in order to account for these interactions.

II. Long-Term Toxicity and Safety Studies: Because of bioaccumulation, potential toxicity, and prolonged exposure, little is known about the long-term effects of nanoparticles on health, despite their potential to improve nutrition delivery. More studies on the long-term safety of nanoparticles, particularly in human populations, are required before authorities approve them and they can be utilized extensively. The resolution of this problem can be greatly aided by long-term toxicological studies including both humans and animals. Future studies should include concentrate on genotoxicity, chronic exposure, potential bioaccumulation, and impacts on organ systems. This field is also necessary to determine the ADI values for nanoparticles in food products (Jovanovic *et al.*, 2015; Khan *et al.*, 2018).

III. Personalized Nutrition and Nanotechnology: It is advisable to tailor efforts in identifying unique genetic makeup, metabolic rate, and health condition of an individual before giving food fortified with nanoparticles. It is the hallmarks of the new discipline of personalized nutrition. The use of nanoparticles in customized nutrition may enable more precise nutrient delivery to meet particular needs. Researchers must determine how to customize nanoparticle delivery systems based on an individual's age, gender, genetic composition, and health. Depending on the needs of each individual, nanoparticles may be designed to address specific nutritional deficiencies or increase the bioavailability of particular nutrients. Although there are still many unanswered problems, research on the interplay between nutrients and nanoparticles holds great promise for the future of human nutrition. By addressing these gaps, researchers can contribute to the long-term sustainability, effectiveness, and safety of nanotechnology in food and nutrition.

11. Integration of Nanotechnology with Other Nutritional Technologies

A. Nanotechnology in Nutrigenomics: How dietary factors interact with genes to impact health outcomes is the subject of nutrigenomics and should be harnessed. By enhancing the transport and efficacy of bioactive chemicals, nanotechnology has the potential to revolutionize this industry. It was found that bioactive nutrients, such vitamins and polyphenols, may be encapsulated in nanoparticles like liposomes and nanostructured lipid carriers, which improves their solubility and absorption. One bioactive chemical that has low bioavailability is curcumin; nevertheless, its therapeutic efficiency and absorption are greatly enhanced when it is encapsulated in nanoparticles (Aggarwal & Harikumar, (2009).

It has also been applied in targeted therapies in genetic illnesses affected by nutrition which is now possible exploit to nanotechnology, which allows for the delivery of therapeutic genes or RNA molecules to particular organs (Zhang *et al.*, 2016). Metabolic pathways may be successfully altered by delivering small interfering RNAs (siRNAs) to genes associated with obesity using lipid-based nanoparticles (Zhang *et al.*, 2016).

B. Nanotechnology in Microbiome Research: Metabolism, immunological function, and general health are all profoundly impacted by the gut microbiota. Microbiome dynamics may be studied and manipulated with the use of nanotechnology. For example, probiotics may be encased in nanoparticles to increase their effectiveness and prolong their transit through the intestines. In inflammatory bowel disease (IBD) and other similar disorders, improved delivery methods may improve microbiota modification and treatment results (Bansal *et al*., 2022).

According to Altammar, (2023), nanoparticles have the intrinsic ability to be used for in vivo imaging of microbiota dynamics, which might provide light on the interactions and populations of microbes. For a better understanding, the interplay between the microbiome and the host, researchers may utilize magnetic nanoparticles to tag populations of certain bacteria, which can then be tracked in real time.

Nanotechnology has revolutionized nutrition delivery systems by integrating nutrigenomics data with microbiome profiles (Altammar, 2023). To maximize health advantages, nutrient-rich nanoparticles are tailored to design an individual's gut microbiota makeup For instance, nanotechnology has other applications in food production, such as the creation of functional meals that influence the composition of the gut microbiota and provide targeted nutrients (Zhang *et al.,* 2020). Optimal health may be influenced by nanoformulated meals. These foods can stimulate the development of good bacteria while preventing the spread of harmful strains in the body

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