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THE ROLE OF NANOTECHNOLOGY IN FUNCTIONAL FOODS: BRIDGING MICROBIOLOGY AND MATERIAL SCIENCE FOR ENHANCED NUTRITION

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ABSTRACT

The functional foods, that provide a range of health benefits in addition to nutrition, are becoming a recognized concept in the global market, as there are more people concerned about the connection between foods and health. It is in this review that the potential power of nanotechnology in the progression of functional foods is discussed as involving the interface between microbiology and material science. On the scale of 1-100 nm, nanotechnology can be used to give materials new and desirable physicochemical characteristics that are used in new applications throughout the food chain. It also greatly enhances the sensitivity bioavailability and targeted delivery of bioactive compounds which can be vitamins, minerals and antioxidants by protecting the active product against degradation, enhancing its solubility and absorption in the gastrointestinal tract. In addition to this, the nano-enabled systems provide effective shield around the probiotics to deter triggering of their adverse reactions towards the harsh environments in the stomach region, hence enhancing their survivability and effective delivery to the gut where they can be used to metabolize the microbiota effectively. The role of material science in progress with this is in the design and manufacturing of advanced nanoconstructed nanocarriers comprised of food-grade biopolymeric materials (e.g., proteins, lipids, polysaccharides) that are able to control the release as well as be stimuli responsive through the active agent. At the same time, nanosensors, a product of the material science are transforming the quality and safety of foods within the foods sector by real-time monitoring of freshness, spoilage,

pathogens, and nutrient values. Although these are enormous advantages, there remain major problems as it pertains to whether the engineered nanoparticles can be toxic and bio accumulative in the human body and within the food chain. There are also challenges in the form of regulatory landscape which is changing and the higher consumer acceptance which is needed. Future prospects are highlighted towards further interdisciplinary studies especially in synthetic biology, 3D food printing and multi-omics strategies to open up a new era of personalized nutrition as well as sustainable food systems. The combination will bring high specificity, efficiency, and safety in the applications of functional foods to solve nutritional and health issues around the world.

1. Introduction
Defining Functional Foods and their Evolving Importance

The term functional food is loosely defined as those food substances which provide an additional health benefit beyond current nutritional expectations, mainly due to the addition of certain functional substances giving physical or biological benefits (Doyon and Labrecque, 2008). Within the US, an actual definition of a functional food does not exist and the regulation process depends on how the manufacturers choose to market the products. This is usually through the application of the structure-function claims like advising the population that Calcium helps build strong bones and Vitamin D helps to contribute to the building of bones which are not subjected to heavy regulatory risks of the Food and Drug Administration (FDA) unless they are too misleading or the claims are to treat, cure, or even prevent disease (Hasler, 2000).

These food may be divided into two large groups: foods that have beneficial components naturally, and foods to which functional ingredients are added or processed (Süfer, 2025). Examples of naturally made functional foods include tomatoes which contain lycopene linked to prevention of prostate cancer, oats and barley which contain a chemical known as beta glucan and is known to reduce total cholesterol and LDL cholesterol (Tarabella et al., 2019).

The popularity of functional foods has seen an exponential increase on a global level with consumers increasingly becoming more aware of the complex relationships between what they eat and what their long-term health would be (Tsoupras et al., 2023). This drive to the concept of accurate nutrition can be seen as anticipating health progress rather than dietary sufficiency. This is a strong motivator of innovation within the food sector requiring greater scientific and technological capabilities of delivering medicinally proven functionalities. Such a dynamic environment opens a critical avenue for interdisciplinary research and development, particularly involving nanotechnology, microbiology, and material science, to meet these sophisticated consumer needs.

Emergence of Nanotechnology in Food Science

The operation of nanotechnology is at the atomic, molecular or supramolecular level which is below a hundred nanometers.6 At this sub-millimetre level, materials have a different set of physicochemical properties with highly increased surface-to-volume ratio, a change in colour, improvement in solubility, strength, modified diffusivity and reactivity which is significantly different to their macroscale counterpart (Singh et al., 2017).

Although the application of nanotechnology in numerous industries has been prevalent, novel food systems stand out as a speeding spot of the use of nanotechnology. The technology provides a feasible approach towards transforming the food supply chain, including early production, processing, packaging, storing and distribution of food

(Jagtiani, 2022). Important nanostructured products and procedures used in this field are nanofood, nanotubes, nanocomposites, nanopackaging, nanocapsules, nanosensors, liposomes, nanoemulsions and polymeric nanoparticles.6 Specific projects are known to be designed in order to produce key advances in solubilizing food and food additives, lengthening shelf life, improving the access to active chemicals in foods, targeted nutritional supplementation and fortification, and accurate food ingredient release in the human body (Kalpana et al., 2013).

The all-encompassing character of influence that nanotechnology can provide as a means of supplying food industry with solutions that range as far as ingredient enhancement all the way to intelligent packaging makes nanotechnology a potentially radical shift in the food industry. It points to a future that breaks down food products and food related systems form being passive to being active, dynamic and responsive. Because of the possibility to design smart delivery of nutrients and nanosensors delivery, intelligent food and food packaging materials are likely to be the new frontier, which would be able to actively analyze a given situation and release healing compounds as needed, or modulate foods and its packaging as the environment around the food evolves (Rossi et al., 2014). Such technology may give rise to very specific and customized eating interventions that ultimately may work very effectively using this kind of smart food paradigm, but also requires strong ethical and regulatory dimensions regarding these future advanced opportunities.

The Interdisciplinary Convergence: Nanotechnology, Microbiology, and Material Science

The complexities of modern food systems that relate to both safety and quality assurance as well as nutrition maximization and sustainability require an incisively interdisciplinary approach (Schmidt, 2008).

Food science and nanotechnology, microbiology, and material science thus converge and create the synergistic and powerful multidisciplinary area of study (Bainbridge and Roco, 2016).

Within this tethered setting, nanotechnology has created the molecular instruments and foundations, e.g., nanocarriers and nanosensors, that allows handling at a scale never before possible (Khanday, 2015). Material science brings the necessary skills of pattern design and manufacture of these very precise nanostructures using a broad range of biomaterials, such as polymers, lipids, proteins and so on (Coh, 2011). At the same time, microbiology provides an in-depth insight into favorable microbial interactions, e.g., probiotic activities and fermentation in vitro, as well as single out the biological targets of the human body, especially the intestinal microbiota, to intervene effectively (Porter and Youtie 2009). Such second tier integration of specialised knowledge and methods produces synergistic effects and what results, is innovation that could not be achieved by single disciplinary approaches (Jamali et al., 2018). This synergistic approach implies that the future of functional foods is holistic design of food composition as an approach that integrates food components, microbial interactions and mode of delivery to create a synergistic effect in the desired food health contribution to global food security and sustainability.

Scope and Objectives of the Review

The review is systematic in describing the existing knowledge of functional foods, their categories and their health benefits. It goes on to discuss the revolutionary effect nanotechnology will have on nutrient addition, microbe usage in food industry. One of the equally important sections dwells upon the critical role of the material science in the creation of highly-developed nanocarriers and sensors. Besides, the paper critically analyses the challenges, safety concerns, and

constantly changing regulations that surround nano-enabled functional foods. Lastly, it provides some future outlooks with the emerging technologies and important interdisciplinary lines of research work that are required to be done in this field.

2. Functional Foods: Foundations and Microbiological Contributions

Definition, Classification, and Health Benefits of Functional Foods

Functional foods may be broadly defined as foods that put more than just basic nourishment, such as specific ingredients, which provide extra physiological or even biological effects. In the US, no definition exists, so what is advertised to be such functional food relates to the way manufacturers market it, generally using what is called structure-function claims (Doyon and Labrecque, 2008). The claims, like, Calcium builds strong bones or Vitamin D helps to contribute to bone health are not highly regulated, and that provides a peculiar marketplace dynamic as long as these statements are not misleading or make disease claims. It puts the onus on the consumer to countercheck the credible effect on the product thus pointing out to a possible loophole where scientific progress in functional foods especially those that can be developed using nanotechnology maybe ahead of the guidelines stipulated on safety of a product and its working towards the target population (Dable et al., 2020). This scenario highlights the need to address the changing world of regulatory science to keep in tune with innovation, to provide more clarity and use of science-based guidelines possibly with possibly increased oversight of functional food claims to protect the health of the population, satisfy the population and customers to provide the claimed value (Martirosyan and Ekblad, 2022).

The functional foods may be classified into foods that contain functional components such as those that occur naturally and processed foods in which functional ingredients are added or enriched (Arvanitoyannis and Van, 2005). Examples of naturally occurring functional foods are tomatoes with deduced risk of prostate cancer due to the lycopene content, and oats and barley with a lower level of cholesterol due to the presence of beta-glucan substance. The partially processed foods are also foods with increased or added functional ingredients e.g. omega-3 enriched egg, vitamin D fortified orange juice, or fiber-reinforced bread or cereals. The positive health effects of functional foods are broad in terms of the extent of their coverage and are significant including a decreased risk of many chronic illnesses like cancer, heart diseases, osteoporosis, inflammation and type II diabetes (Roberfroid, 2000). The increased awareness of these advantages is associated with the current world tendency to pay much attention to global health initiatives, such as the UN Sustainable Development Goals, urging accuracy in nutrition and calling to combine nutritive and healing qualities in food habits (Roberfroid, 2000).

Table 1: Categories and Examples of Functional Foods with Their Bioactive Components and Health Benefits.

Category	Food Examples	Bioactive Component(s)	Health Benefit(s)	Relevant Source IDs
Naturally Occurring Functional Foods	Tomato	Lycopene	Decreased prostate cancer risk	[1]
	Oats, Barley	Beta-glucan	Reduced total cholesterol and	[2]

			LDL	
	Cranberries	Tannins	Lower oxidative stress and inflammation	[2]
	Tea	Catechins, Polyphenols	Antioxidant effect, reduced cancer and coronary heart disease incidence	[2]
	Citrus	Flavones	Antioxidant effect, widely distributed	[2]
	Flax, Rye	Lignans	Antioxidant effect, widely distributed	[2]
Processed Foods with Enhanced/Added Functional Components	Omega-3 enriched eggs	Omega-3 fatty acids (EPA, DHA, ALA)	Reduced risk of fatal coronary heart disease, supports healthy brain function	[1]
	Orange juice with added vitamin D	Vitamin D	Helps contribute to bone health	[1]
	Breads, Cereals with added fiber	Dietary Fiber (soluble/insoluble)	Improved bowel regularity, reduced cholesterol	[1]
	Yogurt with added probiotics	Probiotics (Lactobacillus, Bifidobacterium)	Improved gastrointestinal health	[2]

Traditional Role of Microorganisms (e.g., Probiotics, Fermentation) in Functional Food Development

Many functional foods are developed through the use of microorganisms, and most often this is accomplished through the fermentation process. They add their benefits to the body in two ways: directly as the result of the ingestion of live useful microorganisms (probiotic activity), or indirectly due to the ingestion of microbial metabolites produced during fermentation (biogenic activity) (Toma and Pokrotnieks 2006). Probiotics are characterized as live microorganisms which provide a health benefit to the host when those live microorganisms are administered in an adequate amount. The most widely used probiotic are bacteria, e.g., Many species of Lactobacillus and Bifidobacterium are routinely added into dairy products such as yogurt to promote gastrointestinal wellbeing. Probiotics must exhibit tolerability to deleterious gastric conditions and bile concentrations and must be proliferative and have the capacity to colonize the gastrointestinal tract (Mitsuoka, 2014).

An old technology called fermentation harnesses the power of functional organisms to change the chemical makeup of raw materials to produce a myriad of effects (Gobbetti et al., 2010). These are:

Increased availability of nutrients: The microorganisms reduce the complexity of compounds to simple compounds that are easily absorbed into the body. As an example, in tempe, Rhizopus oligosporus enhances the presence of folic acid, niacin, and riboflavin whereas non-pathogenic Klebsiella

pneumoniae and Citrobacter freundii manufacture vitamin B12 (Sun et al., 2022).

- **Sensory Quality Enrichment:** Sensory quality, including flavors, aromas, and texture are due to the action of microorganisms, which adds to the overall sensory appeal.

- **Antimicrobial and Bio-preservative Effects and Better Food Safety:** A large number of species of the Lactic Acid Bacteria (LAB) found in fermented vegetable products and milk products produce antimicrobial products, in the form of bacteriocins, and nisin. The compounds prevent the multiplication of spoilage and pathogenic microorganisms such as Listeria monocytogenes, Staphylococcus aureus, thereby increasing the shelf life and food safety (Ashaolu, 2019).

- **Removal Of Harmful Elements:** Microorganisms are capable of splitting up the toxic constituents or anti-nutritive agents that are generally present in raw materials, resulting into safer and nutritious food. Examples of these are the decontamination of cyanogenic glycosides in cassava by Leuconostoc, Lactobacillus and Streptococcus and the removal of indigestible oligosaccharides in tempe by Rhizopus oligosporus (Cui et al., 2024).

- **Biosynthesis of Bioactive Compounds:** The ability of functional microorganisms to produce a variety of health-enhancing compounds such as antioxidants, antimicrobial agents, peptides with potential immunomodulatory or antihypertensive effects, enzymes, etc., imposes the realisation that microbial metabolism is a complex bio-factory capable of producing or unlocking health-enhancing properties in food. This approach recognizes microorganisms as potent, natural resources towards functional food design and, therefore, this future research may take advantage of their potentials of being a kind of bio-factory by generating specific health promoting molecules precisely or food matrices designed to deliver optimal, health-promoting nutrients or prevent diseases (Sun et al., 2022).

3. Nanotechnology's Transformative Impact on Functional Foods

Fundamentals of Nanomaterials in Food Systems

The core definition of nanotechnology lies in the fact that nanomaterials can be controlled on a nano level (referred to as between 1 nanometer to 100 nanometers6) endowing the material with new properties that are very different when compared to those at the macroscale. Seven unique properties are known to exist in nanomaterials; these can be summed up as having a very large surface area to volume ratio, new solubility characteristics, increased strength, altered reactivity, and other properties (Behera et al., 2019).

Nanoparticle-based materials are increasingly needed in food in part because many of them are perceived to be non-toxic and they display stability in many processing conditions such as high temperatures and pressures (Assadpour et al., 2020). In the food industry, the applications are mainly of two categories; food nanostructured ingredients and food nanosensing.6 Nanostructured ingredients have abundant applications including food additives and smart nutrient carriers, anti-caking and antimicrobial agents (Di, 2019). The applications seek to improve the taste, texture and consistency of food products and greatly increases the shelflife of food products by inhibiting microbial infestation. Examples of nanomaterials are nanofood, nanotubes, nanocomposites, nanopackaging, nanocapsules, nanosensors, liposomes, nanoemulsions and polymeric nanoparticles, which consequently have respective functions in food system (Castillo, 2022).

That is, the main premise of nanotechnology is that nanoscale materials present themselves according to their high surface-to-volume ratio and the resultant inherent properties of the material. The ability has been utilized to

their advantage in order to aid in the enhancement of the bioavailability of nutraceutical compounds besides benefiting them in the process of enhancing nutrient absorption. Nevertheless, in the same literature there is also clear documentation that in fact there are many negative or hazardous impacts on health, which are associated with the toxicity and danger of consuming nanoparticles in food, and there is a mention of the fact that toxicity of nanoparticle-based delivery systems can still be a subject of major concern. This poses a by-the-book paradox; the nano scale which endows the product with an increased functionality and bioavailability subjects it to new toxicological issues that were not an issue to the macro counterpart (Karak, 2019).

This vital commentary highlights the importance of a strict balance between functional gains of nanotechnology with a broad basis of safety evaluation that makes specific provisions in consideration of these toxicological manifestations of nanotechnology, which varies with size. This means that a macro-scale material may not be considered safe when it is on a nanoscale, and the ripples in its nature have to be considered through a paradigm change in the evaluation of food additives and ingredients with regard to their safety (Subramanian and Rajkishore, 2019).

Table 2: Key Nanomaterial Types and Their Applications in Functional Food Systems.

Nanomaterial Type	Description/Composition	Key Applications in Functional Foods
Nanoparticles (General)	Materials 1-100 nm, high surface area, unique physicochemical properties	Enhanced nutrient delivery, improved taste/texture/consistency, antimicrobial agents, food additives, food processing aids
Nanoemulsions	Lipid-based dispersions of nanoscale droplets	Increased solubility of lipophilic compounds, improved stability, enhanced bioavailability, controlled release of active agents, probiotic protection
Nanocapsules/Liposomes	Spherical shells (lipid/polymer) encapsulating a core material	Protection of bioactive compounds from degradation, targeted delivery, controlled release, probiotic protection
Polymeric Nanoparticles	Polymer matrix encapsulating bioactive compounds	Encapsulation of bioactive compounds (e.g., flavonoids, vitamins), protection and transport to target functions, enhanced bioavailability, probiotic protection
Nanosensors	Various materials (e.g., gold, silver, carbon nanotubes, metal oxides) with nanoscale dimensions, integrated with recognition elements	Real-time quality/safety monitoring, pathogen detection, contaminant detection, nutrient/vitamin monitoring, freshness indicators, smart packaging

Enhancing Nutrient Bioavailability and Targeted Delivery

Nanotechnology is a revolutionary way of making bioactive compounds in human nutrition far more bioavailable and effective. This overcomes directly some of the known shortcomings of most nutraceuticals i.e., poor aqueous solubility of a lot of nutraceuticals, complex chemical stabilities, and low rates of absorption after their incorporation into the body (Wang, 2024).

The main approach is nanoencapsulation (nano-encaps; Nanks 2012), in which vitamins, minerals, antioxidants, essential oils, and phytochemicals are encapsulated in nanoparticles (NPs), nanocapsules or nanoemulsions (Bhushani et al., 2017). This covering gives the food a thick protective layer, without which vulnerable bioactive food components will be degraded by logistic alteration like changes in pH, photodegradation, thermal, oxidative stress, and enzyme reactions during food processing, storage, and through the gastrointestinal (GI) tract (Gorantla et al., 2022).

Nanoparticle technology makes the micronutrients that are difficult to dissolve such as curcumin to increase water solubility using limited excipients.9 Nano-sized powders especially the nanocochleate structures and nanoemulsions enhance better dispersing and absorption. The increased surface- to-volume mass of the NPs makes it capable of greater interaction with human cells and enhances absorption throughout the GI (Yu et al., 2023).

Targeted delivery is another key factor. It is also possible to design site-specific targeting, and release of nutrients by nanocarriers, so that they are available when and in the ratio needed. Such accuracy of delivery can avoid biological barriers and minimize the possible side effects of non-targeted release (Acosta, 2019). As demonstrated, protein-lipid composite NPs increase the rate of uptake of vitamin B12 and zein NPs increase the bioavailability of folic acid when taken orally by protecting the mucus lining of the jejunum.18 Consistently, the literature has found that NPs can significantly increase the intake of essential micronutrients including vitamin B12, vitamin A, folic acid, and iron (Arshad et al., 2021).

The functions that nanotechnology brings to the process of food fortification including increased bioavailability, specificity, and preservation of the substance represent a complete change of paradigm with regard to the past approach to food fortification. It is not just about the presence of a nutrient anymore, but more about how to promote the best level of absorption, stability, and use of the nutrient by the body, possibly at certain time or place (Gleeson et al., 2016).

Table 3: Mechanisms of Nanotechnology-Enhanced Nutrient Bioavailability and Probiotic Viability.

Mechanism	Impact on Nutrients/Probiotics	Examples/Relevant Bioactives
Encapsulation & Protection	Prevents degradation from oxidation, hydrolysis, enzymes, heat, pH; Shields sensitive compounds during processing, storage, and GI transit.	Vitamins (A, D, B12, Folic acid), Iron, Curcumin, Antioxidants, Essential oils, Coenzyme Q10, Phytochemicals, Probiotics (Lactobacillus, Bifidobacterium)
Improved Solubility & Dispersibility	Increases water solubility of hydrophobic compounds; Enhances dispersibility in food matrices.	Curcumin, Antioxidants, Vitamins, Minerals
Targeted Delivery & Absorption	Directs delivery to specific physiological sites (e.g., intestine);	Vitamin B12, Folic acid, Iron, Probiotics

	Facilitates crossing of biological barriers; Reduces effects of anti-nutrients; Enhances interaction with human cells for better uptake.	
Controlled Release	Ensures availability at a target time and specific rate; Prevents premature degradation.	Active ingredients, Bioactive compounds, Probiotics
Protection from Harsh Environments (for probiotics)	Maximizes viable probiotic cell counts; Extends shelf life of sensitive components in acidic stomach, bile, oxygen, heat, moisture.	Probiotics (Lactobacillus, Bifidobacterium)

Advancing Probiotic Viability and Gut Microbiota Modulation

Their promotion of gastrointestinal health is dependent on probiotics, the healthy live organisms that are present in foods that have been fermented, such as yogurt. Their therapeutic potential, however, is commonly impaired by their extreme sensitivity to adverse environmental conditions, such as gaseous oxygen, heat, the acidic ph and bile salts that are found in the gastrointestinal tract, which hence results in low viability and efficacy of these cells (Bauer et al., 2023).

Nanotechnology poses powerful protective measures towards probiotics in the form of nanoencapsulation and nanoemulsions. These high-tech delivery systems protect probiotics microorganisms against unfavorable conditions (heat, moisture, pH, oxygen) and, therefore, ensure their increased survival rates and prolonged shelf life when being stored and transported (Lin et al., 2021). It has been researched that bacteria have an increased survival rate in simulated GI conditions with the aid of multiple nano-enabled systems, including gum Arabic and alginate microcapsules, magnesium oxide (MgO) nanoparticles, and advanced triple-layered systems (Pires et al., 2024).

In addition to protection, nanoparticles may be prepared to provide tight control and delivery of the probiotics in particular places within the gastrointestinal track, usually the intestinal lumen. This will provide the best colonization and increase the number of the viable cells at the target. This slow release action also prevents early degradation and augments the general efficacy and bio availably of the probiotics by helping it to cross the intestinal barrier (Terpou et al., 2019).

Although there is undoubted improvement in the delivery of probiotics with nanotechnology, it must be noted that there is an intricate interplay between the gut microbiota and nanotechnology. E.g., nanomaterials like titanium dioxide (TiO2), silver (Ag), and zinc (Zn)-based nanomaterials have shown to exhibit antimicrobial properties and have the possibility to cause GM dysbiosis. The studies conducted on the impact of Ag NPs and TiO2 NPs on GM diversity and composition present inconsistent results, some of which denote hazardous effects and others do not represent significant changes (Fentie et al., 2024). On the other hand, certain nanomaterials have demonstrated favorable outcomes in GM, as in the case of selenium NPs, which has exhibited beneficial effects, such as the rise of beneficial bacteria, Lactobacillus, and Faecalibacterium, and thus it might be of potential beneficial modulation. This provides an attractive dualism, such that nanotechnology can be used to ensure protection and efficient delivery of weak probiotics with the result of survival and action at a target site in the gut and thus

serves to directly facilitate the mission of functional foods to improve gut health. But parts of the nano-delivery system may at the same time interfere with the balance of the indigeneous gut microbiome of hosts. It shows why the safety appraisal should be made; The encapsulation of the probiotic has to have efficacy, indeed, but it is also necessary that whatever effects might be produced by the nanocarrier material on its own on the complicated gut ecosystem should thoroughly be examined. This also highlights the necessity of considering intelligent design of nano-materials such as being synonymous to designing towards being beneficial to the gut microbiome or the need to only choose materials which have been established as being not to cause problems or even beneficial to the gut microbiome so that the overall functional food product- puts a net health benefit on the scale (Azad et al., 2018).

4. Material Science in Designing Nano-Enabled Functional Foods

Development of Advanced Nanocarriers

The design and creation of advanced nanostructures to be used as high efficiency delivery vehicles of functional food components is based on material science. This science allows the accurate design of carriers that guard, fix, and deliver bioactive substances effectively around the intricate food substance and biological frameworks (Aguilar et al., 2023).

Polymers, lipids, proteins (in general referred to as biopolymers) are widely used as food-grade encapsulant materials because of their nutritional value, non-toxicity, biodegradability, and because they have the uncanny ability to self-organize into various nanoformations.9 Proteins, being one of the most versatile types of biomaterials, are utilized due to their capacity to form particles of gel size (macro to nanoscale) (McClements et al., 2020). They are able to entrap both lipophilic and hydrophilic substances and load a lot, and do not show any substantial dispersion limit in water. Whey products, which are of bovine milk origin, have been revealed to as having high efficiency on drug encapsulation and cellular uptake, therefore, indicating its controlled future in carrying different bioactive agents. Nanocarriers of polysaccharides, such as natural polymers, chitosan, alginate and beta-glucan, are commonly used (Rajeev et al., 2024). An example of a layer that has been effective is chitosan that has proved to enhance greatly the stability and bioaccessibility of protein-based nanoparticles and their therapeutically important active substances (e.g. curcumin and caffeine) in response to gastrointestinal digestion. The lipid based formulations encompassing liposomes, solid lipid nanoparticles (SLNs), and nanoemulsions form a crucial aspect of enhancing the solubility and stability of sensitive, normally hydrophobic bioactive substances (Younis et al., 2025).

Another major functionality is controlled release, which is attained by designing nanostructures to react in response to particular environmental triggers, including temperature or pH changes, ionic strength or enzyme-induced conditions in the gastrointestinal tract. By so doing, it guarantees targeted delivery of the active agents ensuring that premature degradation of the active agents is avoided and that the active agents perform optimally as therapeutic agents. A wide range of fabrication methodologies is utilized, such as thermally-induced, acid-induced, ionic, enzymatic, combinations with other biopolymers, associative/segregative separation, physical self-assembly of interactive polymers, water-in-oil heterogeneous gelation, sophisticated microfabrication (micromolding, photolithography, microfluidic preparation), scalable approaches (spray-drying, electrospinning/electrospray) (Yin et al., 2018). Interest in controlled release in reacting to environmental stimuli is an

indication that the field is no longer limited to passive encapsulation, but is becoming active, intelligent communication with a biological system. Emergence of bioresponsive components and material with controlled property vindicates the fact that material scientists are imitating in greater context biological processes and programming nanocarriers to sense and react to the physiological condition that will maximize their delivery and actions in the body. This level of futuristic smart material design will also lead to the future where functional foods are no longer the delivery vehicles of nutrients but they control their own destiny in the body. Such degree of precision engineering has a conceptual capability to greatly increase the therapeutic outcomes of bioactive substances, diminish degradation to a minimal and limit possible side effects which ultimately leads to increased targeting and successful dietary intervention. It highlights the need to have a profound interdisciplinary appreciation of not only the material properties but also on how the material will be interacting with the complex biological environments (Mishra et al., 2018).

Nanosensors for Real-time Quality, Safety, and Nutrient Monitoring

Nanosensors utilizing the properties of the nano materials are transforming the food quality and safety certification practice by virtue of their sensitivity, selectivity, and portability over the traditional methods. They play a critical role to facilitate food integrity all along the food supply chain that is between production and consumption (Awlqadr et al., 2025).

This means that nanosensors can be used in different applications involving freshness indicators and spoilage devices where nanosensors can detect certain volatile organic compounds (VOCs) and pH variations that could signal that food has gone stale in real time (Singh, 2020). Biosensors developed to detect degradation indicators like hypoxanthine, ammonia and trimethylamine in meat product, portable electronic noses which conduct analysis of complex odor patterns are a few. These sensors are able to be easily incorporated or incorporated in intelligent packaging materials and supply real-time information steady about the standing of the food, the temperature, the humidity and also the gas content (Kumar et al., 2017).

Nanosensors can be very powerful in the identification of pathogens, food contaminants, and allergens in terms of rapidity and sensitivity of detecting foodborne pathogens (e.g., Escherichia coli, Salmonella, Listeria monocytogenes), diverse toxins (e.g., aflatoxin B1, bacterial toxins, mycotoxins), pesticide residues, heavy metals, food allergens, among others (Mobeen et al., 2025). Nanosensors would also have the potential to be used in monitoring nutrient and vitamin levels. They are able to identify and quantify the biodegradable food components such as vitamins, and antioxidants (Kakimova et al., 2023). Electrochemical nanosensor platforms have emerged to provide accurate and selective quantification of vitamin C in very complex matrices such as lemon juice (Beegum and Das 2022). Moreover, new nanosensors to monitor on a real-time/non-destructive basis iron uptake and speciation (i.e. Fe(II) and Fe(III)) in whole live plants also have been developed with evident potential usage to best crop nutrition and even possibly to being applied directly to food safety testing in future.

Table 4: Applications of Nanosensors in Functional Food Quality and Safety Monitoring.

Application Area	Target Analytes/Indicators	Sensor Type/Mechanism	Benefits
Freshness & Spoilage Monitoring	Volatile Organic Compounds (VOCs), pH changes, Hypoxanthine, Ammonia, Trimethylamine, Microbial growth	Electronic Noses (e-noses), Electrochemical biosensors, Optical sensors	Real-time detection, Early spoilage warning, Reduced food waste, Enhanced shelf life, Portable and low-cost
Pathogen, Contaminant & Allergen Detection	Foodborne pathogens (*E. coli*, *Salmonella*, *Listeria monocytogenes*), Aflatoxin B1, Bacterial toxins, Mycotoxins, Pesticides, Heavy metals, Allergens	Nanozyme-based biosensors, Electrochemical sensors, Optical sensors (e.g., surface plasmon resonance), Immunochromatography (NPs-based)	High sensitivity and selectivity, Rapid detection (minutes vs. days), Multiplexing capability, Enhanced food safety protocols
Nutrient & Vitamin Content Monitoring	Vitamin C, Iron (Fe(II), Fe(III)), Antioxidants	Electrochemical nanosensors (e.g., His-pHEG/Nafion-modified SPCE), Near-infrared (NIR) fluorescent nanosensors (e.g., SWNTs-based)	Precise and selective quantification, Non-destructive monitoring, Real-time tracking of nutrient dynamics, Optimization of fortification strategies

5. Challenges, Safety Considerations, and Regulatory Landscape

Potential Toxicity and Bioaccumulation of Engineered Nanoparticles

Although nanotechnology has a huge potential in its use in food systems, there exist serious health implications to the toxic and long-term implications of consumed manufactured NPs (NPs).

This is because of the unique physicochemical characteristics of NPs and especially their high reactivity and surface area which can have adverse biological effects. Production of reactive oxygen species (ROS) mediating oxidative stress and thereby causing cellular damage, DNA damage, protein denaturation, inflammation and apoptosis is considered to be among the key mechanisms of toxicity. 6 NPs have the ability to interact directly with the biological macromolecules or release toxic metal ions (Uddin et al., 2020).

Since they are small in size, NPs can easily penetrate such biological barriers as the gastrointestinal wall, blood-brain, placental barrier, and blood-testis barrier. Whether the consequence is that they accumulate in other organs and tissues, including the liver, kidneys, lungs, spleen, brain, and the

reproductive organs and cause organ dysfunction and systemic toxicity or not will depend on how strongly the compound is bound to the various proteins in the body (Deng et al., 2017). By way of example, titanium dioxide nanoparticles (nano-TiO2) have been demonstrated to accumulate in cortisol - producing organs (mainly the ovaries and the testes) of mammals, altering fertility and hormonal distribution and leading to pathophysiological reproductive processes (Prajitha et al., 2019).

The presence of engineered nanomaterials may move up the food chain to higher trophic levels (e.g., animals, human beings) via the lower ones (e.g., plants, microorganisms). Although there is some initial evidence that the quantities transferred may be quite small, and should not be magnified heavily up the food chain in some cases by a significant degree with collection in higher-level organisms, there is a concern in the area of bioaccumulation and biomagnification, particularly with metallic NPs such as copper nanoparticles, that top predators and humans can be affected (Hou et al., 2013). An example is nanoplastics, that are thought to pass through the cellular membranes and end up in different organs such as the brain, where they may disrupt the processes of bone cells. It is seen that the impacts of the nanomaterials at the bottom of the chain have an impact that is transmitted up to the human body (Bathi et al., 2022).

There is a big gap in knowledge regarding the long-term impacts of ingested nanoparticles and little evidence exists as to whether there are chronic exposures that may cause small changes in intestinal immune system, protein expression, or microbes. In vitro assays tend to over-predict toxicity in vivo and there is also the ethical aspect of not conducting large scale in vivo studies using humans. Research gaps include the unavailability of long-term in vivo studies and hardly any studies have been done on the effects of organic engineered nanoparticles. Such is the case that the functional benefits that comprise the use of nanotechnology should have a scrupulous consideration against putative safety studies that explicitly consider these size-specific toxicological profiles. It is suggesting that a material that is considered safe at the macro-scale is not necessarily safe at the nanoscale and this means a paradigm shift is required in the method that food additives and ingredients are assessed in regard to safety (Srivastava et al., 2015).

Regulatory Frameworks

Regulation Nanotechnology in the food industry Regulation of nanotechnology in food is a politically, socially and scientifically complicated and developing area, and agencies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) are attempting to put in place suitable regulation (Chau et al., 2007). The current statutory authority ensure that the FDA regulates products that use nanotechnology by addressing them on a product-by-product basis based on a science-based approach. Technical tests are product-specific and it takes into account the impact of nanomaterials in the specific biological and mechanical environment of the specific product and intended application. With regards to products that require premarket review (e.g., food additives, new drugs), nanomaterials are considered by inserting them into established processes, where applicants must provide information on safety and efficacy. In cases where there is no mandatory premarket review requirement (e.g. most dietary supplements, cosmetics, and whole foods), the FDA urges manufacturers to pre-consult with the agency prior to being placed on the market and on post-market surveillance as the key (He et al., 2019).

In Europe, food products that contain nanomaterials can only appear on the market when they have been tested with regard to safety by EFSA. The Scientific Committee of

EFSA gives scientific guidance on evaluating requests regarding engineered nanomaterials on several components of the food chain with regard to hazards to human health and animal health and, more and more, on environmental hazards (Coles and Frewer, 2013). Detailed information about physicochemical characteristics and toxicological characteristics is sought. Even conventional materials that have a fraction of a small particle or nanoscale property must be evaluated in a nano-specific risk assessment scenario as is the case with EFSA which implies that 250nm is the cut-off distance to absorption by the gastrointestinal tract (Cushen et al., 2012).

Consumer Acceptance and Ethical Concerns

The public acceptance is very important element that may lead to success of the market introduction of nano-enabled functional foods. Such issues associated with these new technologies are applicable to consumer confidence and the readiness towards the adoption of new products. Consumers are increasingly conscious of regulatory demands of food safety, authenticity, and nutritional integrity and becoming more active in knowing of the long term impacts of consuming food commodities (Younis et al., 2025).

Ethical concerns also come into play, especially when it comes to the possible health outcomes and environmental effects that cannot be truly known due to the specific qualities of nanomaterials (Otchere et al., 2023). The fact that NPs might find their way around biological barriers and end up accumulating in organs or that they might cause gut microbiota dysbiosis brings concerns of long-term safety that studies have not sufficiently researched yet. Open communication concerning the potential benefits and risks with strong science based studies on toxicology and clear regulatory policies is most important in enhancing confidence in this field and ensuring that there is responsible innovation (Siimes et al., 2022).

6. Future Perspectives and Emerging Trends

Interdisciplinary Research Directions

The fact that there would be an increased and enhanced convergence of nanotechnology, microbiology, and material science is inherently connected to the future of functional foods. This multi trans-disciplinary process is necessary in solving present multidimensional problems on the globe like food security, safety, nutrition, and sustainability.

• **Synthetic Biology and Microorganisms:** Synthetic biology is set to disrupt the food production process with the design and transformation of organisms to host greater capacity, minimal pollution and low energy use. This covers high-quality proteins, lipids and vitamins synthesis at high rates by microorganisms, as well as the application of microbial genomes to perform specific tasks to produce food materials and food functionality supplements. New advances in precision fermentation and enzymatic hydrolysis will allow the extraction of useful compounds of bioactivity in byproducts,

• **Food Printing:** A third application within the food sector is the field of 3D food printing. Material science through the development of 3D food printing can potentially open up unmatched potential in terms of customization and bespoke food, especially in functional foods. The 3D printing technology would have a potential in specialized diet requirements, including military rations, kids, and soft food that is easy to chew by elderly people. Beyond personalization, 3D printing could increase efficiencies, minimize wastage of raw materials, and bring down environmental footprints in food processing

• **Multi-omics Strategies:** A combination of advanced analytical tools,

including single-particle ICP-MS and nanoflow chromatography, and a multi-omics technology, such as metabolomics, proteomics, and transcriptomics, will advance the insight into food composition, microbial dynamics, and how they interact with the host. The multi-omics strategies will allow one to grasp how diet and the gut microbiome interact with its host cell-by-cell, which is key to designing next-generation nutraceuticals and personalized diet

Personalized Nutrition

Nanotechnology, when coupled with microbiology, aided by material science, promises, reaching real-life personalized nutrition. With the use of big data and artificial intelligence, dietary regimes can be personalized using the individual genetic profile, which will yield the best outcomes. The delivery systems provided by nanotechnology featuring a better bioavailability and selective physiological targeting will play an important role in delivering customized nutritional supplements and the functional food components to requirement in the context of available delivery of the conventional formulations due to the restrictions. It is also important to know how the gut microbiota contributes towards metabolic processes of bioactive nutrients and compounds as these processes help in understanding biological individual differences to the effects of bioactivity. This will enable the production of functional foods that should best interact with an individuals highly specific microbiome and result in even more precise and effective nutritional interventions.

Sustainable Food Systems

Innovations on the borders of nanotechnology, microbiology, and material sciences are also essential in the construction of more sustainable food systems.4 Nanotechnology can better endow foods with vitamins and minerals to increase their bioavailability and stability and benefit the nutritional deficiencies and hidden hunger in the world. The use of material science makes it possible to create smart finds of packaging that help prevent shelf life expiration, minimize food waste caused by microbial infection, and enhance energy conservation. With precise fermentation, microorganisms can be used to manufacture high quality protein and micronutrients with low environmental impact and transform renewable raw materials into desirable food ingredients. Nanosensors also help in minimizing food wastage and guaranteeing the food security by allowing monitoring of food quality in real-time with detection of contaminants. This is all part of a coordinated effort to sustainably feed an increasing global population without destroying ecosystems and the natural resources that people need, all with the UN Sustainable Development Goals in mind.

7. CONCLUSIONS

The introduction of nanotechnology into the setting of the functional foods is another revolutionary marvel, and it will go further than merely providing mere nutrients to accelerate health benefits, to facilitate accurate, improved, and specific health benefits. Consumers are increasingly interested in functional foods that have been known to help in reducing chronic diseases and enhancing a better feeling health-wise. The increase in complexities in the field of scientific and technological solutions is due to this growing demand which is being discovered at the interdisciplinary nexus of nanotechnology, microbiology and material science.

Robotic Food By manipulating matter on the nanoscale, nanotechnology provides the means to orchestrate food feature in a way that is unmatched. This brings great potential to the bioavailability and stability of nutrients as well as in delivery to specific sites of the body. As an example, nanoencapsulation helps preserve sensitive bioactive components, providing the safety against geographical

factors and a subsequent optimal absorption and effectiveness in the human body. Moreover, nanotechnology can offer revolutionary solutions to supporting probiotics viability, protecting sensitive microorganisms against other more adverse conditions in the human gastrointestinal tract and get them to be released in a desirable location in the intestine. Nevertheless, the two-facet issue of nanomaterials that they could favor preferable microorganisms but also, at the same time, alter the gut microbiome significantly highlights the immense importance of an all-inclusive safety evaluation based on the whole biological framework.

The presence of material science in this development as a source of knowledge and methodology is more than crucial towards the development of design and fabrication of the advanced nanocarriers based on food registered biomaterials such as proteins, lipids, and polysaccharides. These synthetic constructs provide accuracy in the encapsulation and the control release functionality and they are in many cases smart enough to react to physiological signals. The material science is simultaneously working on the development of highly sensitive nanosensors that are able to simultaneously check on the real-time analysis of quality and freshness, sickness and content of nutrients in food in the supply chain. With such a proactive monitoring of food this will not only help limit waste, but also boost consumer faith, and resource allocation will be in its best possible manner.

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