Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 3 (2025)

A Comprehensive Review on Recent Developments in Nano-Food Industry and Food Science in Processing and Safety

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Abstract:- Food science is emerging in a fast way with collaboration of nanotechnology. The food market demands technologies, which are essential to keep market leadership in the food processing industry to produce fresh authentic, convenient and flavorful food products and nanotechnology is the answer to it. With the fast technological evaluation, nanotechnology keeps a leadership role and largely contributes to the food industry in different aspects. Nanotechnology is transforming food science by introducing ground-breaking solutions that improve food safety, quality, and sustainability. This study examines the cutting-edge uses of nanotechnology in food systems, with an emphasis on nutrition delivery, packaging innovation, contaminant detection, and agricultural breakthroughs. The application of nano-encapsulation enables the controlled release of bioactive compounds, improving the stability, bioavailability, and targeted delivery of essential nutrients, antioxidants, and probiotics. This advancement is particularly beneficial in fortifying functional foods and beverages without compromising sensory attributes. Additionally, nanostructured emulsions and liposomes have revolutionized fat replacement strategies, enabling healthier formulations with improved texture and stability. This report finishes by outlining possible future uses for nanotechnology, establishing it as a cornerstone of modern food systems. Nanotechnology has prospective revolution in food industry by design of nutrient delivery system to produce nano-formulated agrochemicals, enrich nutritional values and generation of novel products through bioactive encapsulation. It has been used in innovative development of biosensors for detection of pathogens and chemical contaminants. Beyond safety and quality, nano engineered food structures contribute to superior food processing techniques by enhancing emulsification, gelling properties, and controlled moisture retention. These innovations ensure improved texture, flavor retention, and prolonged stability across a range of food products. This new technology also raises a serious concern about toxicological aspects of nanoparticles in food, with emphasis on the risk assessment and safety issues. Also, it reflects the urgent need for regulatory framework capable of managing any risks associated with implementation of nanoparticles in food technology. Different applications of nanoparticles in food industry are explained in brief which makes a path to nanotechnology, am emerging field in food industry.

Keywords: *Food nanotechnology in food processing, nanoencapsulation, nano tubes, nano-emulsions, nano-coatings, nano additives, nano-nutraceuticals, nanoparticles, nano-fertilizers, nanocarriers, toxicity assessment, emerging technology.*

1. Introduction

Nanotechnology is the field deals with the materials of nanoscale, (Samal, 2017). The National Nanotechnology Initiative calls it “nanotechnology” if only, “the research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, creating and using structures, devices and systems that have novel properties and functions because of their small and/or intermediate size and ability to control or manipulate on the atomic scale" (Ozimek et. al, 2010). Nanotechnology is an interdisciplinary field encompassing biology, chemistry, mechanical engineering, and electronics. Its aim is to comprehend, manipulate, and design devices with extraordinary properties at the atomic, molecular, and supramolecular levels (Bumbudsanpharoke, 2015). Nanoparticles and Nano capsules containing several foods are currently available for purchase, though without being required to indicate the presence of these Nano materials on their packaging (Paul and Dewangan, 2016). Nanomaterials are categorized based on their configuration, size, and properties (Khare and Kukkar, 2019).

Modern food systems have issues such as assuring safety, maintaining nutritional quality, and minimising environmental effect. These needs have accelerated innovation, with nanotechnology emerging as a transformational force (Akshaya, 2025). Nanotechnology is emerging as a rapidly growing field with its wide application in science and technology for manufacturing of new materials at nanoscale level is shown in figure 1 (Albrecht et al., 2006; Berekaa, 2015 and Samal, 2017). The unique properties of these nanostructures and nanomaterials including physical, chemical, and biological properties are considerably different from their bulk counterparts alter the understanding of biological and physical occurrence in food systems. Several recent reports and reviews have identified potential applications of nanotechnology for the food sector to improve food safety, to enhance packaging and lead to improved processing and nutrition (Pathakoti et al., 2017).

In recently years, huge advances in nanotechnology open up a new era in industrial technology. Majority of nanoparticles incorporated into products related to several fields (Benn and Westerhoff, 2008; Heinlaan et al., 2008; Li et al., 2008; Wokovich et al., 2009). Recently, innovative nanotechnology has revolutionized the food industry (Sanguansri and Augustin, 2006; Weiss et al., 2006; Chaudhry et al., 2008; Silvestre et al., 2011; Cushen et al., 2012; Rossi et al., 2014; Thangave and Thiruvengadam, 2014). There is progressive improvement in use of nanoparticles in food industry especially on food processing, packaging, storage and development of innovative products. Nanoparticles aimed at enhancing bioavailability of nano-sized nutraceuticals and health supplements, improving taste and flavor, consistency, stability and texture of food products (Chaudhry et al., 2008; Chaudhry et al., 2010; Momin et al., 2013). Due to antimicrobial characteristics of nanoparticles, it can be incorporated into the food packaging materials to increase shelf life and keep it safe for human consumption.

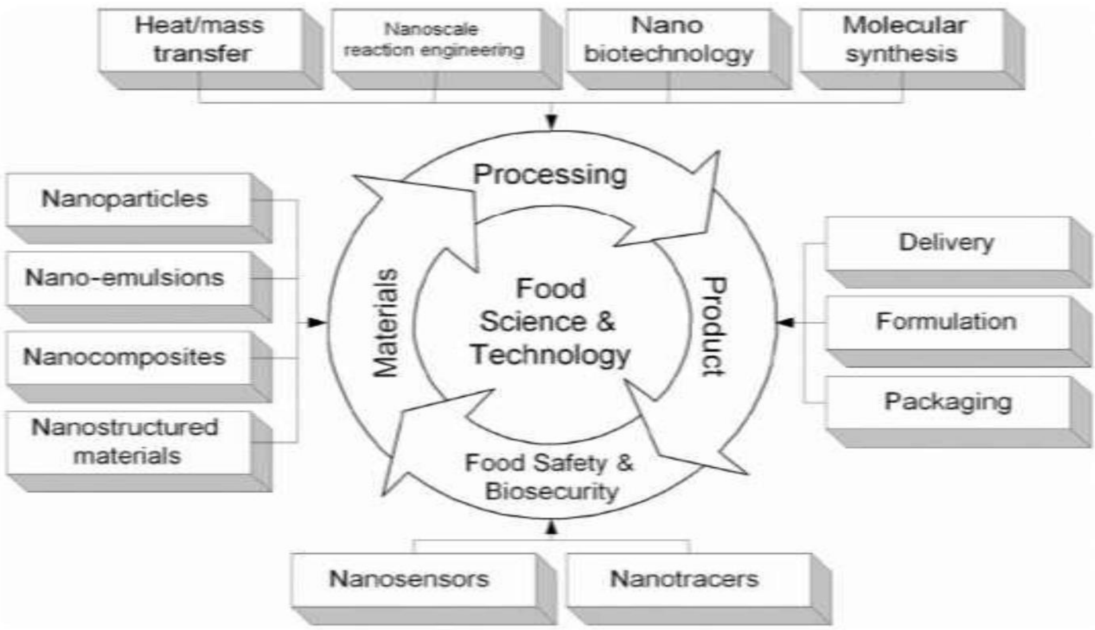

Figure 1: Application matrix of nanotechnology in food science and technology

(Samal, 2017)

Nanoparticles prepared by plant extract mediated synthesis method are being studied for their antioxidant activities, antibacterial properties, in-vitro cytotoxicity applications on human cancer cell lines (i.e. anticancer activity), in photodynamic therapy and in treatment of tumor hyperthermia (Sankar et al., 2013; Reddy et al., 2014). The details of these techniques are presented in figure 2. Nanomaterials produced by any technique are gaining far-reaching attention in food industry and find exclusive applications that facilitate food storability, nutrition enrichment, as well as assured delivery of bioactive and functional components which are discussed in subsequent section (Sahoo et., 2022).

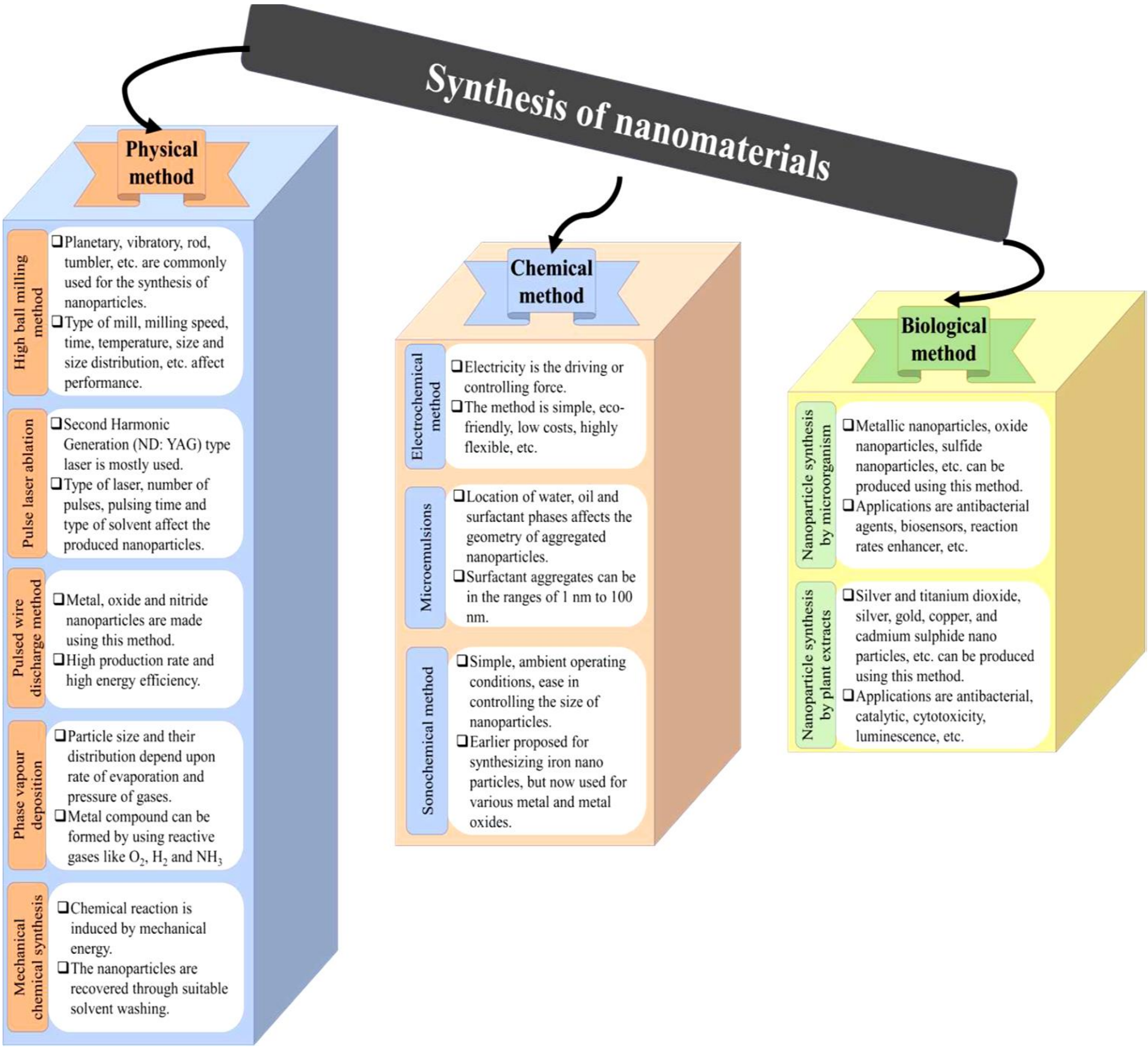

Figure 2: Different Methods for nanomaterial Synthesis (Sahoo et al., 2022)

2.Nanotechnology in Different Aspects of the Food Industry:

2.1 Nanotechnology in food processing:

Nanoparticles are used to improve the food structure through texture modifications and flavor improvements and prolong the shelf life. Dairy products, cereals, bread, and beverages are incorporated with vitamins, probiotics, antioxidants, and minerals to improve nutritional quality and structure (Thathsarani et al., 2023). During food processing, nanoparticles have been applied to improve nutritional quality, flow properties, flavor, color and stability or to increase shelf life. Indeed, nanotechnology might help in development of healthier food with lower fat, sugar and salts to overcome many food-related diseases is shown in figure 3 (Sahoo et a., 2022). Recently, bulk amounts of SiO2 and TiO2 oxides have been permitted as food additives (E551 and E171, respectively) (EFSA, 2000). Recently, bulk amounts of SiO2 and TiO2 oxides have been permitted as food additives (E551 and E171, respectively) (EFSA, 2000). Food processing methods like incorporation nutraceuticals, mineral and vitamin fortification, gelation and viscosifying agents, nutrient delivery and nanoencapsulation of flavors use nanomaterials in their contents (Pradhan et al. 2015).

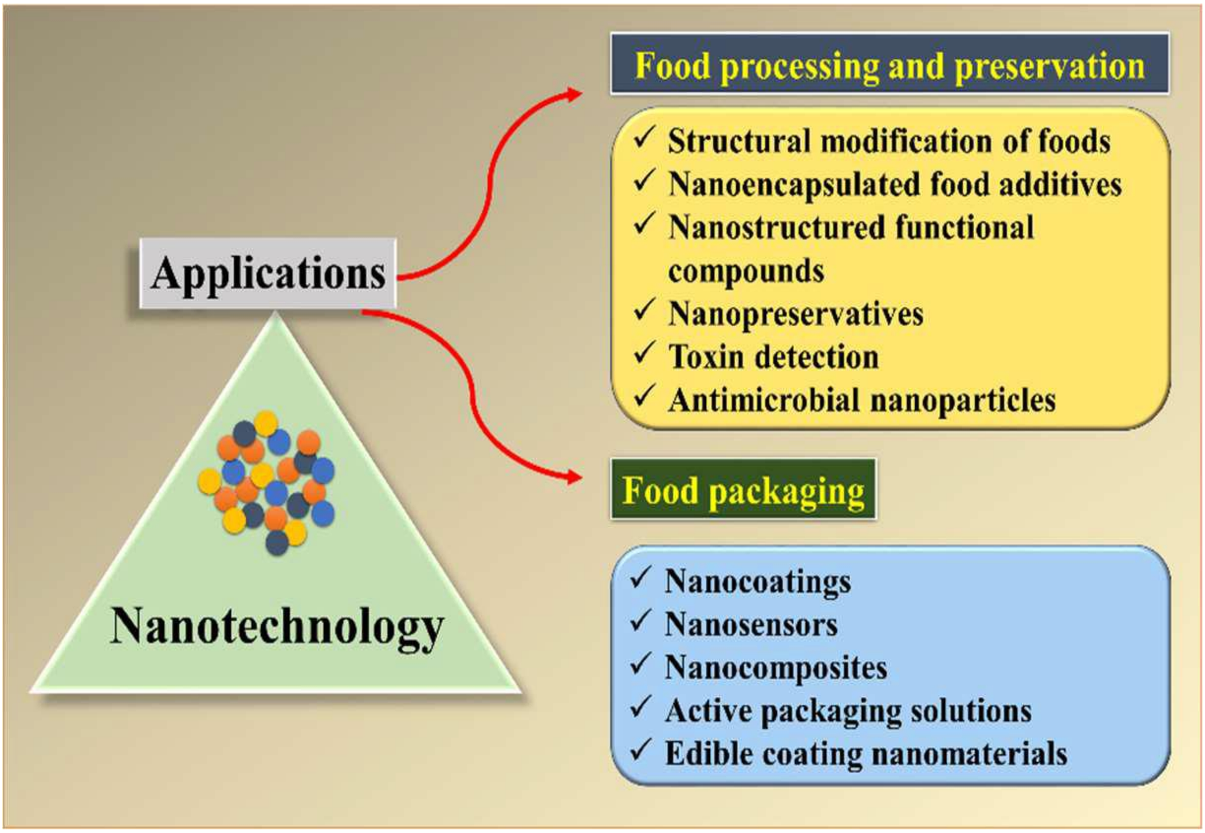

Figure 3: Broad Application areas of nanotechnology in Food Sector

2.2 Nano-sized food additives:

The food industry is starting to use nanotechnology to create ingredients at the nanoscale to enhance food's flavor, texture, and colour (Singh and Bhushan, 2017). Food additives include amorphous silica, TiO2, and SiO2 nanoparticles (McClements, 2016). Nanomaterials can be used as bioactives in functional foods The potential of nanotechnology in functional food, design of nutritional supplements and nutraceuticals containing nanosized ingredients and additives such as; vitamins, antimicrobials, antioxidants, and preservatives are currently available for enhanced taste, absorption and bioavailability (Momin et al., 2013). The nano food additives are capable of developing new flavors and improving the bioavailability of nutrients in food (Chaudhry et al., 2008). Nutraceuticals and nutritional supplements containing nano additives are currently available as vitamins, antimicrobials, and antioxidants (Han et al., 2015). Cho et al. (2010). reported that nano-food additives are used to enhance the vitamins and minerals in some processed foods and to speed the production time for meat processing.

2.3 Nano nutraceuticals:

Nutraceutical compounds such as bioactive proteins are used in functional foods to impart a health benefit to consumers in addition to the nutrition that the food itself offers (Chau et al., 2007; Lamba and Garg, 2018). Some nutraceuticals incorporated in the carriers include lycopene, beta-carotenes and phytosterols are used in healthy foods to prevent the accumulation of cholesterol (Berekaa, 2015). The prospect of the production of nutraceuticals at the nanoscale, which will have increased stability throughout the processing chain, will be of significant interest to food processors trying to maximise nutrient content and hence will ultimately be of benefit to consumers (Cushen et al., 2012). Some nutraceuticals incorporated in the carriers include lycopene, beta-carotenes and phytosterols are used in healthy foods to prevent the accumulation of cholesterol (Mozafari et al., 2006). Recently, nanotechnology has been applied to Omega-3 fatty acids, lycopene, vitamin D2, probiotic bacteria species, and β-carotene as Nano Nutraceuticals (Sohaimy, 2012).

2.4 Nanoencapsulation:

Nano-encapsulation has emerged as a revolutionary technology in food science, significantly enhancing the stability, bioavailability, and controlled release of functional ingredients (Singh et al., 2017). The design of nanostructured assemblies for delivery of food additives recently reviewed (Augustin and Hemar, 2009). During nanoencapsulation the food additive substances are enclosed in nanocomposite polymer e.g. Octenyl succinic anhydride-- polylysine for controlled release (Yu et al., 2009; Sekhon, 2010). Anti-cancer activity of curcumin was enhanced by encapsulation in hydrophobically modified starch (Yu and Huang, 2010). Nanoencapsulation of probiotics to be targeted to specific region in GI tract has been achieved (Vidhyalakshmi et al., 2009). Recently, nanocapsules and nanoemulsions have been used in production of nanopesticide e.g. products containing pristine engineered nanoparticles, such as metals, metal oxides, and nanoclays (Kahand Hofmann, 2014; Kookana et al., 2014). Patented “Nano drop” delivery systems are in the form of encapsulated materials, such as vitamins. It is administered transmucosally, rather than through conventional delivery systems such as pills, liquids, or capsules (Paul and Dewangan 2016).

Doronio et al., (2022) used this nanoencapsulation strategy to enhance the stability and preserve antioxidants extracted from garlic. Wrisany et al., (2022) reported that applying nanoencapsulation to preserve volatile compounds in essential oils is an effective method and can improve water dispensability, chemical stability, volatility, and bioactivity. Moreover, encapsulation can be applied to convert liquid to powders. Encapsulation also enhances the stability of sensitive compounds like probiotics, which are prone to degradation due to heat, oxygen, and stomach acidity (Bouwmeester et al., 2009). By embedding probiotics in protective nanostructures, their survival rate in the gastrointestinal tract improves, ensuring greater efficacy in promoting gut health (Berekaa, 2015). Similarly, nano-encapsulation of omega-3 fatty acids prevents oxidation, maintaining their nutritional value and preventing off-flavors in fortified foods (Zhou et al., 2023). These nanocarriers are increasingly applied in functional food formulations, including vitamin-enriched beverages, probiotic dairy products, antioxidant-infused snacks, and omega-3-fortified spreads (Nurfatihah and Siddiquee, 2019). For instance, nano-encapsulated vitamin D has demonstrated enhanced absorption and stability in milk and plant-based alternatives, addressing widespread deficiencies (Joseph et al., 2024). Similarly, nano-structured coenzyme Q10 has shown improved bioavailability in energy drinks, enhancing its efficacy as a dietary supplement (Prakash et al., 2013).

2.5 Nanoemulsion:

Nanostructured emulsions play a critical role in improving food texture, stability, and sensory properties, contributing to the development of healthier and more palatable products (Kirdar, 2015). Nanoemulsion production for delivery of functional compounds is one of the emerging fields of nanotechnology applied to food industry (Samal, 2017). Unilever has made ice cream healthier without compromising on taste through the application of Nanoemulsions. The objective is to produce ice cream with lower fat content, achieving a fat reduction from the actual 16% to 1%. Nestlé has a patent in water-in-oil emulsions (10–500 nm), aiming at achieving quicker and simpler thawing through the addition of polysorbates and other micelle-forming substances; these are claimed to contribute to a uniform thawing of frozen foods in the microwave (Silva et al. 2012). Nanoemulsions are small droplets with diameters of less than 100 to 500 nm that can be incorporated into functional food and developed in the decontamination of food packaging (Weiss et al., 2006). A significant application of nano-emulsions is in fat reduction strategies, where they enable the creation of low-fat formulations with desirable mouthfeel and texture (Hosseini et al., 2021). Traditional fat reduction approaches often lead to undesirable sensory changes, such as increased hardness or loss of creaminess in dairy products (Naseer et al., 2018). Caseinates are commonly used as an effective emulsion stabilizer for fats. Fathi et al. (2014) discovered that nanoemulsions have the capability to deliver less water-soluble ingredients such as fish oil and lipophilic vitamins. In addition, they reported that proteins, polysaccharides, and phospholipids are widely used to manufacture nanoemulsions. This has been successfully implemented in reduced-fat mayonnaise, yogurts, and cheese formulations, where nano-emulsions maintain creaminess while reducing overall fat content (Kaur et al., 2024). Beyond fat reduction, nano-emulsions improve gelling properties and structural integrity in food products (Ajayi and Olumide, 2022). In bakery applications, nano-emulsified lecithin enhances dough elasticity, improving the volume and softness of bread and pastries (Dasgupta et al., 2015). In the beverage industry, nano-emulsified flavor oils create more homogenous dispersions, preventing phase separation and enhancing flavor release in fruit juices and carbonated drinks (Velez et al., 2017). Additionally, nano-emulsions improve the stability of plant-based milk alternatives by preventing sedimentation of insoluble particles, thereby increasing consumer appeal (Onebunne, 2024). Texture enhancement is another key benefit of nanostructured emulsions, particularly in processed foods like ice cream and sauces, where smoothness and stability are paramount (Biswas et al., 2022). Similarly, nano-sized emulsifiers in salad dressings improve viscosity control, preventing separation and maintaining consistency during storage (Sekhon, 2014). Future research in this area focuses on optimizing emulsion formulations to reduce synthetic emulsifier dependency, using natural stabilizers like plant-derived proteins and polysaccharides (Wesley et al., 2014).

2.6 Nano-Coatings:

Nanotechnology has introduced advanced coating techniques that improve food quality by enhancing moisture retention, crispiness, and color stabilization (Sahoo et al., 2021). Nano-coatings, applied as thin layers at the molecular level, offer superior protective barriers against external factors such as humidity, oxidation, and microbial contamination (Yu et al., 2018). These coatings are particularly valuable in preserving perishable food products and optimizing the structural properties of processed foods (Momin et al., 2020). In the confectionery and snack industries, nano-coatings play a pivotal role in improving crispiness and texture stability Singh et al., 2023). Potato chips, biscuits, and coated nuts benefit from nano-thin protective layers that maintain crunchiness even in humid storage conditions (Grumezescu and Oprea, 2017). Additionally, nano-structured coatings on chocolate products prevent sugar bloom, a common issue caused by fat migration that affects appearance and texture (Aigbogun et al., 2018).

By enhancing structural integrity, these coatings contribute to longer-lasting product quality and consumer satisfaction (Sahani and Sharma, 2021). Nano encapsulation of these pigments within protective coatings improves their stability, ensuring vibrant coloration in processed foods like fruit juices, jams, and plant-based alternatives (Momin et al., 2013). Additionally, nano-coated edible films containing antioxidants prevent enzymatic browning in cut fruits, extending their visual appeal and marketability (Biswas et al., 2022). As food industries strive for enhanced product longevity and sensory quality, the application of nano-coatings and modified food structures is gaining traction (Chaudhry et al., 2008). Future research focuses on developing natural, biodegradable nano-coatings using plant-based polymers and bioactive compounds to align with sustainability trends (Naseer et al., 2018).

2.7 Nano Tubes:

Nanotubes have a 20 nm diameter, and several micrometers in length and were recently applied as a gelling agent for α-Lactoglobulin and to deliver nutrients and flavors (Jebel et al., 2016). Hashim et al., (2018) observed that carbon nanotubes were able to penetrate the tomato seed coat and increase seed germination and growth. In 2011, Tripathi et al., (2011) revealed that chickpeas using water-soluble carbon nanotubes increase in water absorption and retention. Recently, Nanotube fertilizer carriers have been introduced using cochleate structures. Small-scale cochleate structured nanotubes have been applied to improve the delivery of fertilizer, and pesticides for plants (Mastronardi et al., 2015; Thathsarani et al., 2023).

2.8 Nano-Fertilizers: Enhancing Crop Nutrition:

The global population is projected to reach 9 billion by 2050, putting immense pressure on the agricultural sector to produce more food. Climate change, decreasing agricultural productivity, and variable labor forces are further exacerbating the situation. Nanofertilizers, in particular, have shown great potential in increasing crop yields, reducing environmental impact, and promoting sustainable agriculture. These nanofertilizers are designed to release nutrients in a controlled manner, reducing the risk of over-fertilization and environmental pollution. The use of nanoparticles in agriculture raises questions about their toxicity, bioaccumulation, and potential impact on non-target organisms (Ramees, 2025).

2.9 Nano-Fungicides: Revolutionizing Crop Disease Management:

According to Pudake et al., (2019), nanoparticles have emerged as a promising tool for plant disease management. Silver nanoparticles have also been used to control viral diseases, such as sun-hemp rosette virus and bean yellow mosaic virus. Chitosan nanoparticles are another type of nanoparticle that has shown promise in plant disease management. Chitosan is a biodegradable and biocompatible polymer that has antimicrobial properties. Chitosan nanoparticles have been shown to induce viral resistance in plants and control fungal diseases, such as Fusarium crown and root rot in tomato. Carbon nanotubes have been shown to have antifungal properties and can be used to control fungal diseases (Ramees, 2025).

3 Innovative applications of nanotechnology in food science:

3.1 Nutrient delivery mechanisms:

Nanoencapsulation is rethinking nutrient delivery by protecting bioactive chemicals from degradation and increasing their bioavailability. Nawaz et al., (2022) demonstrate how lipid-based nanoparticles, Nano emulsions, and polymeric carriers protect sensitive substances such as omega-3 fatty acids, vitamins, and antioxidants. These technologies have permitted the fortification of functional foods and drinks to meet specific dietary requirements. Nano emulsions are transforming the food business by allowing hydrophobic chemicals to disperse in aqueous environments, enhancing solubility and absorption, (Su et al., 2022). Nonetheless, scalability remains a hurdle, with high production costs discouraging industrial use. Efforts to democratise these advances by simplifying manufacturing processes and decreasing resource intensity are critical for their widespread application, (Meghani and Moraru, 2020).

3.2 Intelligent packaging systems:

Smart packaging incorporates nanoscale features that interact dynamically with food and its surroundings. Nawaz et al., (2022) describe developments in active packaging technologies, such as oxygen scavengers and ethylene absorbers, which reduce spoilage-causing interactions. Intelligent packaging, which includes colour-changing indicators and RFID-enabled Nano sensors, delivers real-time input on food quality, Dera and Teseme, (2020). Thermochromic materials, which are sensitive to temperature changes, warn customers of potential cold-chain logistical breaches, Akshaya, (2025). While these systems increase openness and confidence, their high production costs prevent widespread implementation. Scaling inexpensive alternatives and harmonising standards across markets are crucial for incorporating smart packaging into global supply chains.

4.Types of Nanoparticles in Food Industry:

Nanoparticles are classified into various types on bases of size, morphology, physical and chemical properties. Mainly nanoparticles are divided into two types: Organic and Inorganic particles (Waghmode et al., 2021).

4.1 Inorganic nanoparticles:

In food industry, many inorganic materials such as iron oxide, zinc oxide and silver are commonly observed. These are amorphous or crystalline in nature at ambient temperature which leads to different surface characteristics and nanoparticles size (Preeti et al., 2014).

4.2 Silver Nanoparticles:

Silver (Ag) nanoparticles have wide application in food industry. It is used as antimicrobial agent in foods packaging. It is used in the packaging container which protects the food from damage of food pathogen It also increases the shell life of the food Along with the advantages there are some disadvantages by using silver particles like it causes lymphocyte infiltration, discharge of mucus granules, pigmentation of villi and abnormal mucus composition of the intestine (Waghmode et al., 2013, 2021; Siddhiprada et al., 2014).

4.3 Zinc oxide nanoparticles:

Zinc oxide (ZnO) can be used in supplementation and functional foods as it is found that it is an essential trace element needed to maintain in human body (Wang, 2014).

4.4 Iron oxide nanoparticles:

Iron oxide particles can be used as colouring agent or source of bioavailable iron. It comes in different forms like size, shape which may change its toxicity. It also has ability to produce ROS which leads to damage of cellular components (Waghmode et al., 2021).

4.5 Organic nanoparticles:

Organic nanoparticles are basically made up of lipids, carbohydrates, proteins. The morphology of these substances tends to be liquid, semi-solid or solid at ambient conditions. They are generally spherical in shape and can vary in their behaviour in different areas of human gastrointestinal tract (Preeti et al., 2014).

4.6 Lipid nanoparticles:

The major advantage of using these particles is to increase the bioavailability and functional performance of encapsulated components. Lipid nanoparticles to the major advantage of using these particles is increase the bioavailability and functional performance of encapsulated components (Waghmode et al., 2021).

4.7 Protein nanoparticles:

In recent studies, protein nanoparticles are being developed to form delivery systems to protect, deliver bioactive agents, encapsulate such as flavours, colour, minerals, vitamins and nutrients (Waghmode et al., 2021).

4.8 Carbohydrate nanoparticles:

Carbohydrate nanoparticles are of two types digestible and indigestible. E.g. - starch, cellulose, alginate, pectin and xanthan. These nanoparticles are spherical or non-spherical depending upon the origin. They can be digested in upper gastrointestinal tract. Organic nanoparticles have less toxicity effect so they can be used in food industry. But proper design and suitable analytical tool has to be developed as some undigested lipids, proteins and carbohydrate nanoparticles may prove to be fatal for humans (Myrick et al., 2014).

Characteristics of food nanoparticles:

The physiochemical and structural properties of nanoparticles play important role. These nanoparticles have characteristics features like they have different morphology, composition, electrical charge and dimensions. These features determine the properties of nanoparticles which can be used in food is shown in figure 4 (Waghmode et al., 2021).

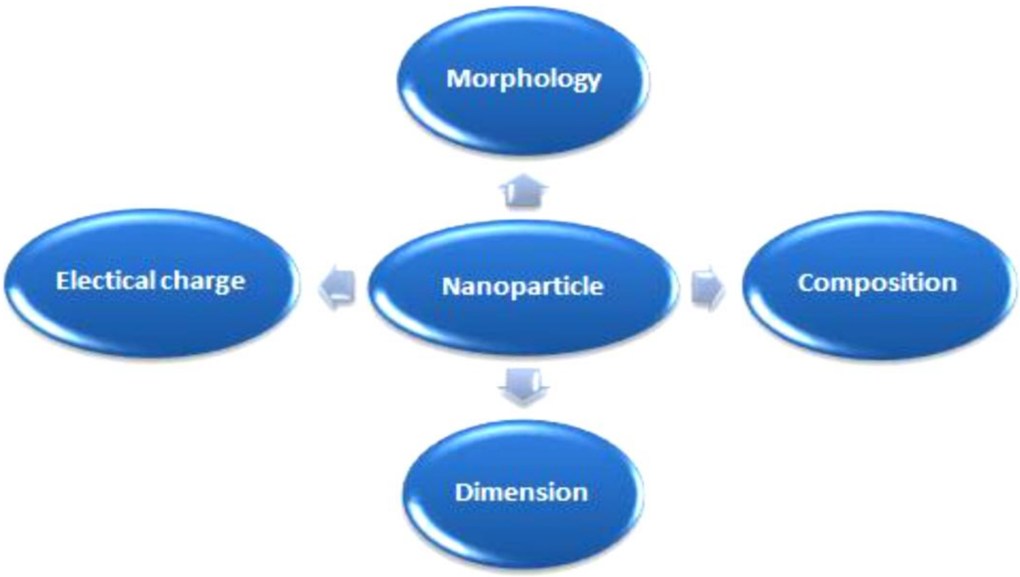

Figure 4: Characteristics of Food Nanoparticles

5 Nanotechnology in Food Safety and Quality Control:

5.1 Nanosensors and nanosieves:

Nanotechnology has been widely researched in the field of food safety and quality control. Food products are an important part of daily life, and prevention of contamination and spoilage of food products is imperative. Contaminated food products can cause several diseases, which necessitate monitoring food products for contaminants (Abdullah and Alwan, 2024). Traditionally, food safety measures include checking the raw material of food products and laboratory examination of the final product (Shafiq et al., 2020). Nanosensors play a pivotal role in modern food safety monitoring, enabling real-time detection of contaminants, spoilage indicators, and environmental conditions that affect food quality (Hosseini et al., 2021). The use of nanoparticles to develop nanosensors for detection of food contaminant and pathogens in food system is another potential use of nanotechnology. Indeed, tailor-made nanosensors for food analysis, flavours or colours, drinking water and clinical diagnostics have been developed (Li and Sheng, 2014). The rapid detection capability of nanosensors enhances food safety by preventing the distribution of contaminated products and minimizing health risks (Olumide, 2024).

Recently, Mihindukulasuriya and Lim (2014) reported the innovative application of nanotechnology in design of smart or intelligent packaging to enhance communication aspect of package. This smart packaging might increase efficiency of information transfer during distribution. The response generated due to changes related with internal or external environmental factor, will be recorded through specific sensor. Detection of bacterial toxins using nanoparticle technology was recently reported (Zhu et al., 2014). A key application of nanosensors is pathogen detection in perishable foods, where microbial contamination poses significant health hazards (Kaur et al., 2024). For instance, nanosensors incorporating gold nanoparticles (AuNPs) or carbon nanotubes (CNTs) can identify bacterial DNA and proteins with high specificity and sensitivity, enabling early intervention before contamination spreads (Ajayi and Olumide, 2022). Such biosensors have been applied in meat, poultry, and dairy industries to detect Salmonella, Listeria, and E. coli, reducing foodborne outbreaks (Dasgupta et al., 2015).

The integration of artificial intelligence (AI) and the Internet of Things (IoT) in nanosensor technology further enhances predictive analytics, improving food quality management and reducing waste (Sahoo et al., 2021). Concerns regarding the safety of nanoparticle exposure and data privacy issues associated with smart tracking systems must be addressed through transparent regulatory frameworks and consumer education initiatives (Nile et al., 2020). Research continues to optimize sensor sensitivity, reduce production costs, and develop biodegradable nanosensor materials to align with sustainability goals (Momin et al., 2013). A concise summary of the recent developments in nanotechnology-based systems and methods for ensuring food safety and quality control is presented, along with case studies of successful applications of nanotechnology in monitoring food quality (Rizvi et al., 2022; Mohammad et al., 2022).

5.2 Nanocarriers for Nutrient Delivery:

Relying on the food and nutrition sciences is critical as it will only be through these developments that we will be able to provide quality and safe food to ensure our health and longevity. Nanocarriers could also be used for targeted delivery in regions of the gastrointestinal tract to enhance the absorption of nutrients (Abdullah and Alwan, 2024). Many types of functional foods and dietary supplements are developed using nanocarrier technology for encapsulating vitamins, minerals, and other nutrients, because of the advantages of nanocarriers (Paolino et al., 2021). Various nanocarriers have been developed for nutrient delivery. The use of liposomes as food nanocarriers in the food industry constitutes the area of most research work and different commercial application. Nanoparticles are generally semi-solid carriers with nano sizes. Lipid and polymer nanoparticles are the two most researched nanoparticles to deliver nutrients.

Biodegradable polymers, such as poly (lactic-co-glycolic acid) (PLGA) and poly (lactic acid) (PLA), are used to prepare nanoparticles to deliver nutrients; however, these polymer nanoparticles are not considered safe because materials are not naturally found in the environment. Many studies have reported using polymer nanoparticles to enhance the bioavailability of nutrients, including using chitosan nanoparticles to deliver vitamins A and E (Gorantla et al. 2021; Plaza-Oliver et al. 2021; Dima et al. 2021). The quality of dairy products is impaired due to high metabolic activity of microorganisms, the high moisture content, the neutral pH, the presence of essential nutrients, that is, proteins and sugars, and the availability of oxygen. There are reports of analytical methods used in the dairy sector in analyses of vitamins (B2, B12, D2/D3), adulteration by the presence of bovine milk in the presence of favourite milk, detection of milk pasteurization and infections in the uterine environment of cows. The inclusion of silver nanoparticles and gold nanoparticles performed by spraying and lyophilization in various dairy products contributed to the enhancement of the antimicrobial activity (Hamid et al., 2025).

6 Technical Limitations in Nano-Food Technology:

The challenging task is to produce safe edible delivery systems using cost-effective processing operations (Dupas and Lahmani, 2007; Sahoo et al., 2022). Higher amounts of such compounds inhaled or absorbed through the skin pose a major threat to human health, particularly in terms of long-term toxicity (He and Hwang, 2016). These nanoparticles could build up in different organs like stomach, small intestine, kidneys, liver and spleen (McClements and Xiao, 2017). Problems like kidney damage, lung damage and hepatic injury could occur due to single oral intake of ZnO nanoparticles (Esmaeillou et al., 2013). The application of titanium oxide and its downstream disposal can have adverse effect on human health as well as environment (Yang et al., 2014). There exist many challenges in the path of nanotechnology's ability to develop innovative food related products and processes (He and Hwang, 2016). The main issue is creating edible delivery systems with efficient formulation for human consumption while ensuring safety and utilizing cost-effective processing methods. At the nanoscale materials behave differently, and our understanding of their analysis is still limited (Akter, et al., 2018). A comprehensive understanding of the toxicities and nanoscale functions of nanoparticles will improve safety standards and practical applications (Ray, et al., 2017). It is essential to investigate the impacts of nanoparticles, potential risks, toxicological issues, and environmental challenges (Zhang, et al., 2016). Synthesis of nanoparticles by different chemical methods has negative outcomes and produces harmful non-ecofriendly by-products resulting in severe environmental pollution (Singhal et al., 2011). In addition to public awareness, risk assessment programmes, regulatory policies and biosafety concerns must be taken care of while processing of nanotechnology-based food products, its packaging and subsequent consumption (Bajpai et al., 2018; Yu et al., 2012). Furthermore, prior to commercial application of nanoparticles, in vitro and in vivo research concerning the nanoparticle interactions with living matters are required (Das et al., 2011).

In the United States, the FDA regulates food nanotechnology through existing food safety laws, requiring manufacturers to demonstrate the safety of nanomaterials before commercialization (Kalpana et al., 2013). Although there is no separate regulatory framework for nanotechnology, the FDA assesses engineered nanomaterials on a case-by case basis under the Generally Recognized as Safe (GRAS) designation (Nurfatihah and Siddiquee, 2019). The European Union (EU) has implemented more stringent regulations under the EFSA, requiring mandatory risk assessments for nanomaterials used in food and food contact materials (Prakash et al., 2013). The Novel Food Regulation (EU 2015/2283) mandates that food products containing engineered nanomaterials undergo pre-market authorization and labeling to ensure transparency for consumers (Joseph et al., 2024). China's National Food Safety Standard (GB 2760-2014) includes provisions for assessing nanoparticle safety in food additives, while India's Food Safety and Standards Authority (FSSAI) has issued draft guidelines on risk assessment for nanotechnology in food (Chukwunweike et al., 2024). As nanotechnology continues to evolve, regulatory agencies will need to adapt policies to address emerging risks while promoting innovation in the food industry (Kaur et al., 2024). For promoting these novel materials to assure the Food and Drug Administration (FDA) and consumers about the safe use of nano additives, formulated guidance standards are necessary for deciding if a foodstuff contains nano-sized additives. Pharmacology-based studies would help to take an approach toward the safe use of nanotechnology, including encapsulation of flavors, bioactive peptides, lipids, etc. Many of these studies have been conducted at lower levels of exposure to the target tissues. (Lugani et al., 2021; Anilakumar, 2021; Salama et al., 2022; Guleria et al., 2023 and Jiya & Balogu, 2023).

7. Emerging trends and collaborative opportunities:

Nanotechnology is set to transform the future of food systems as it converges with other disruptive technologies (Akshaya, 2025). Integration with artificial intelligence and blockchain can improve data analytics and traceability, hence increasing supply chain efficiency. Furthermore, advances in green nanotechnology, which uses renewable resources to create eco-friendly nanomaterials, provide opportunities to address environmental challenges. Policy frameworks and public-private collaborations play critical roles in transforming laboratory ideas into scalable commercial applications. This cooperation can increase cost and accessibility while assuring equal benefits across varied markets. Additionally, nano-coatings provide barrier properties that prevent moisture loss, oxidation, and spoilage, thereby improving food stability and reducing waste (Samanta et al., 2024).

Various Nano systems are still in their early of development as potent nanocomponents. Beyond preservation, nanotechnology is being utilized to enhance the sensory attributes of food products. Nano-sized flavor carriers, for instance, allow for controlled flavor release, improving taste perception while reducing the need for excessive flavoring agents (Joseph et al., 2024). Similarly, nano-structured food additives help in achieving desirable texture modifications without altering the nutritional composition of food (Kirdar, 2015). Effective regulations and laws tailored to address safety concerns are essential for nanotechnology to dominate the food processing industry. Forecasts suggest that by 2050, nanotechnology will emerge as a cutting-edge technology with exponential growth potential. Its ability to find collaborative solutions at both micro and macro levels is set to revolutionize industrial and societal challenges (Fadahunsi, 2025). Despite its potential, nanotechnology in food science faces regulatory and consumer perception challenges (Chukwunweike et al., 2024). Regulatory bodies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) have established guidelines for the safe application of nanotechnology in food, emphasizing the need for rigorous risk assessments and transparency in labelling (Kalita and Baruah, 2019). However, consumer acceptance remains a hurdle, as public concerns about potential health risks associated with nanoparticles persist (Hosseini et al., 2021) is shown in figure 5. Addressing these concerns requires comprehensive risk assessments, public education, and clear regulatory frameworks to ensure consumer confidence in nanotechnology-enhanced food products (Naseer et al., 2018). For instance, chitosan-based nano-coatings have been successfully applied to extend the shelf life of strawberries, preventing fungal growth and maintaining firmness for longer durations (Alfei et al., 2020). Oxygen scavengers based on nanotechnology further enhance shelf life by preventing oxidation, a primary cause of food degradation (Ayala and Chavez, 2021). Traditional oxygen absorbers often rely on iron-based compounds, which can be bulky and less efficient in controlled environments (Kirdar, 2015). Additionally, protein-based nanocarriers, derived from whey or soy proteins, have shown significant potential in delivering hydrophobic nutrients with improved solubility and absorption rates (Kaur et al., 2024). Several real-world applications highlight the effectiveness of nanotechnology in shelf-life extension. In the dairy industry, nano-packaging solutions have been implemented to extend the freshness of milk and cheese by reducing microbial contamination and oxidation (Rodrigues et al., 2017). Ongoing research aims to develop biodegradable nanomaterials that align with environmental goals while ensuring food safety compliance (Sahoo et al., 2021). Looking ahead, the integration of nanotechnology with emerging fields such as synthetic biology, AI, and precision nutrition holds great promise for the future of food science (Ranjha et al., 2022).

Current worldwide scientific trends regarding nanotechnologies in dairy product quality are presented (Hamid et al., 2025). Data available indicate nanotechnology is an increasing research field related to food and dairy in its broadest concept (Saadi et al., 2022). The actual state of this research shows that still there is a lot to explore and more scientific efforts should be made to assess eventual risks associated with nanotechnology and nanotoxicology. (Anilakumar, 2021; Lugani et al., 2021; Hoque et al., 2021; Salama & Bhattacharya, 2022 and Al-Bedrani et al., 2023). The formulation of dairy products presents interesting challenges, which could be partially solved by using current knowledge in nano-sciences. For instance, physical interactions in conventional yoghurt are greatly limited by the presence of a 3D structure built from the gelation of proteins. This gelation could be tunable at a molecular scale to control the final properties of the product, improving interaction with gut biology or suppressing the settling of fruits (Lugani et al., 2021; Salama et al., 2022). EPS coated whey protein isolate nanoparticles are also synthesized using EPS with an α carbohydrate and β-peel emulsion property that depends on EPS incorporation. Thus, WPI nanoparticles stabilized with EPS might offer potential as food emulsifiers or edible food coatings (Chaturvedi & Dave, 2020; Nile et al., 2020 and Lugani et al.,2021).

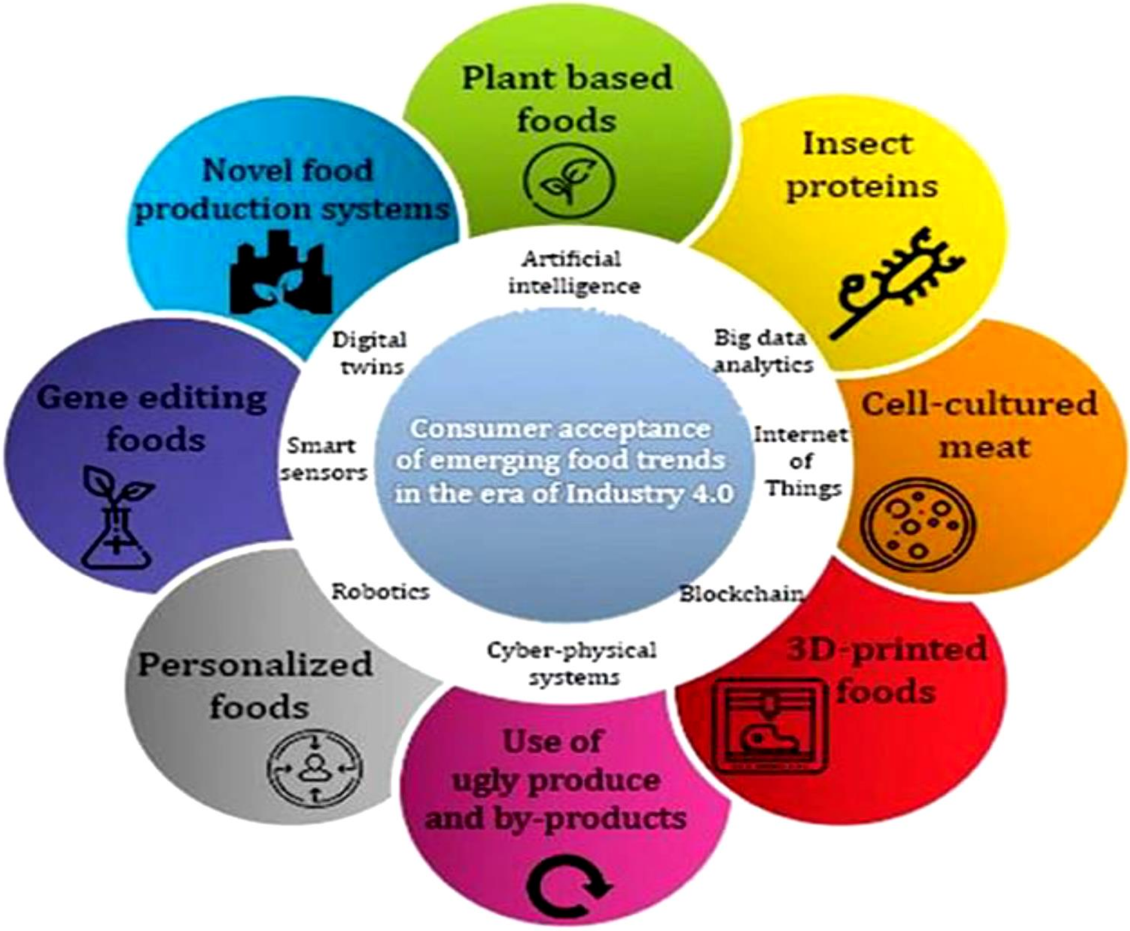

Figure 5: Consumer Acceptance of emerging food trends in the era of industry 4.0

(Gupta et al., 2024)

Recent distribution, advancements and in nanosciences and nanotechnologies have allowed the development of many new materials and devices with applications in food science (Rambaran and Schirhagl, 2022). The dairy products market increasingly demands products with higher added value since functional ingredients beneficial to health are being searched (Rizvi, et al., 2022). Regulators also support such innovations to promote the advances for the consumers as long as products are correctly labelled and correct legislation is applied (Verma and Pandey, 2021). Encapsulation offers many opportunities for the food industry, which in particular can be advantageously used in coffee creamer powders, in the production of cheese flavors, and in micellar casein characteristics, among other products (Lugani et al., 2021; Anilakumar, 2021; Sahoo et al., 2021; Naskar et al., 2022 and Salama et al., 2022)

8. Conclusion:

Nanotechnology represents a new frontier in food research, providing unprecedented opportunity to solve difficult issues of safety, quality, and sustainability. Nanotechnology in the food industry provides numerous benefits that enhance food quality, safety, and shelf life. It marks a significant advancement in food processing, safety, and packaging. By improving the taste, texture, and availability of food additives, this innovative technology offers creative options. For instance, nanoparticles like titanium dioxide and amorphous silica are already enhancing the flavour, colour, and texture of food products. However, realising its full potential would need collaborative efforts to overcome obstacles in safety validation, regulatory harmonisation, and consumer education. his advancement will positively affect the shelf-life, quality, safety, and security of foods, which will ultimately benefit both the producers and consumers. Despite these advantages, there are concerns about using nanotechnology in the food industry. The possibility of nanoparticles migrating from packaging into food raises health and safety issues due to their potential accumulation in organs when consumed or inhaled. Therefore, thorough risk assessments and strict regulations are necessary to address these challenges. Extensive research is still required to understand the long-term effects of nanoparticles on human health as well as their toxicity. One major challenge facing nanotechnology in the culinary field is the technical limitations in producing affordable edible delivery devices that are both effective and safe.

However, precautionary principles should be applied and more research is needed, especially on the migration behaviours of Nanomaterials in food and their potential impacts on health/safety, as well as the environment. Addressing environmental impacts from nanoparticle synthesis is crucial for eco-friendly applications, especially concerning toxic byproducts from chemical processes. The future outlook for nanotechnology in the food industry appears promising with continuous breakthroughs expected to enhance food quality, safety, and functionality. Successful commercialization of nanotechnology-based food products hinges on robust regulatory frameworks and safety standards to mitigate potential risks. Integrating nanotechnology into food science is set to drive innovation towards creating functional foods that meet consumer demands for sustainability, quality, and safety. Potential risks, toxicological issues, and environmental considerations must all be addressed. The concerned rules and regulations are only to be laid to overcome various prevailing safety challenges after which, it would rule the entire food industrial domain.

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