

Various facets of nanotechnology in food processing (Review)

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Abstract. With increased global food productivity and diversity in food consuming tradition, competitive consumers are often conscious about the safety, hygiene and quality of food. Therefore, the most critical challenge for food scientists and technologists is to develop various strategies with which to increase the percentage of food quality with health benefits and nutraceutical values. The conventional method of the food chain involves food production, fortification, food processing, preservation, analysis and packaging, while nanotechnological intervention makes the food processing much more precise and tends to ensure safety. The present review aimed to provide an overview of nanotechnology, food processing and nanomaterials used in food processing. Nanocarriers used in the delivery system, such as nanoencapsulation, nanomaterials and nanoencapsulation, production techniques of encapsulation, nanoencapsulated food additives, the role of nanotechnology food safety security in addition to nanotechnology associated health hazards in food processing are highlighted.

Contents

1. Introduction
2. Nanotechnology
3. Food processing
4. Nanomaterials used in food processing
5. Stages of food processing
6. Green synthesized nanoparticles in food processing
7. Nanotechnology in food processing
8. Implementation of nanotechnology in food processing
9. Nanocarriers used in the delivery system
10. Nanoencapsulation
11. Materials used in nanoencapsulation
12. Production technique of encapsulation
13. Nanoencapsulated food additives

14. Nanoemulsion
15. Applications of nanoparticles in food processing technology
16. Role of nanotechnology in food safety and security
17. Nanotechnology-associated health hazards in food processing
18. Conclusion and future perspectives

1. Introduction

The increasing global population is facing challenges with respect to environmental aspects, healthcare issues, optimal food supply and safety. Resolving these issues necessitates the use of innovative technologies and scientific achievements, and with the feasibility of technologies, nanotechnology is a promising field (1). Food products produced must fulfil the satisfaction of the consumers, as the awareness of consumers about food quality and safety is increasing. Worldwide, this urges scientists to develop the strategies with which to boost food quality with health benefits and nutraceutical values. The conventional method of the food chain involves food production, fortification, processing, food preservation, analysis and packaging (2). Of note, 60% of the current world human population is accounted for by Asia, where the current global population is 4 billion. There is a surplus of food in developed countries; however, as a result of environmental impacts, the majority of the population of developing countries faces daily food shortages. Nanotechnology can be applied to various stages of the food sector, initially from agro-practice, post-harvest practice and food processing (3). In the agricultural sector, nanotechnology plays a key role with the use of nanodevices, facilitating the prediction of the functions of pesticides and fertilizers in the growth and yield of crops. Post-harvest aspects include the storage and aggregation of agricultural products, while raw food processing deals with obtaining grains, fruits, vegetables and several other ingredients into consumable processed food. The food processing techniques include all the aspects of the food industry, which begins with the transfer of food from the farm land to the market (1).

2. Nanotechnology

Nanotechnology unites several disciplines of sciences, such as biotechnology, physics, chemistry and engineering; nanotechnology is generally defined as the use of nanomaterials

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whose nanoscale structures range from 1 to 100 nm. The use of nanotechnology has extended to the food sector, which mainly includes the incorporation of specific types of nanomaterials to respective food products to achieve the desired properties (4). As an integral part of research and development, nanotechnology involves the large-scale manufacturing of agricultural feeds and food products, processed foods, as well as high-quality food packaging materials to ensure food safety worldwide (5). Several researchers working in the field of nanotechnology have assured consumers about the successful improvisation of the efficiency of using nanomaterials in food safety by enhancing the efficacy of food packaging, shelf-life and the nutritional value of the food, without altering the original taste and physical characteristics of foods. The main aim of nano-techniques is to produce innovative food formulations and novel nanofoods which are non-toxic for human consumption; however, the implementation of cost-effective methods composed in nanotechnology is a main drawback of this technology. Hence, there is an urgent need to create alarming concerns pertaining to the development of safe, non-toxic, biocompatible nanostructures from food grade ingredients using biological means, and cost-effective and simple strategies. The field of nanotechnology may pave the way to the development of innovative, quality food products, hence possessing a major application in the food industry (6).

3. Food processing

In general, food processing was defined as the culture of developing, manufacturing, handling and preserving food by making use of traditional, innovative methods and technologies to convert unstapled food to an edible form. The field of food processing technology must include key aspects, such as multi-technological industries, which are well-enriched with an immense diversity of raw materials, well-regulated technological processes and high biosafety needs (3). The conventional methods of food processing techniques in practice include ohmic heating, irradiation and high hydrostatic pressure. In order to meet the consumer's requirements with approved food safety standards, a number of challenges have to be resolved; mainly the management of chemical toxins, and microbial hazards by disease-causing microorganisms should always be noted. Since the beginning of the century, the production of nano foods has become a part of food processing with its main objectives being the advancement of food safety, enhancing flavor and nutrition, and reducing costs, in order for these foods to be accessible to all classes of the population. Food processing requires nanotechnology in the manufacturing of metal coatings of the machines used for processing, food preservatives, additives, as well as in the production of nanoencapsulated products to deliver food (7).

Nanofood processing actually begins from farming and food preservation techniques and the process is completed in the food packaging stage. In agricultural farming, nanoparticles are used as fertilizers and pesticides, which alters the growth rate of plants and positively affects the yield of crops. During the post-harvest stage, the food storage and preservation techniques involving nanomaterials have revolutionized the food industry, and the final step in the food processing is food packaging; active packaging using nanocarriers is the currently used packaging system (8).

4. Nanomaterials used in food processing

According to the EU Commission (Recommendation 2011/696/EU) 'Nanomaterial means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in number size distribution, one or more external dimensions is in the size range 1-100 nm'. WHO has reported that material which has one or more dimensions in the nanoscale range is termed as a nanomaterial, whereas if all the three dimensions are in the nanoscale, it is then termed a nanoparticle. Different nanoparticles exhibit different properties, such as surface, small size, quantum size and quantum tunneling effects; these lead to the different functions of nanoparticles (9).

In order for nanoscaled substances to be used in the food industry, they should have good encapsulation capacity and an enhanced level of desired particles released to the target region. Some routinely used nanoparticles include metallic nanoparticles, polymeric micelles, liposomes nanoparticles, polymeric nanoparticles, solid-core mesoporous nanoparticles, branched gold nanoparticles, mesoporous nanoparticles, surface functionalized nanoparticles, nanorods, porous silica nanoparticles, dendrimer and carbon nanotubes (5); these are illustrated in Fig. 1. On an industrial scale, numerous technologies use nanoparticles to increase the diversity of food-related applications, such as the use of silver nanoparticles as antimicrobial agents in food packaging, chopping boards and refrigerators. Zinc and zinc oxide are used in food preservation as a nutritional enhancers and antimicrobial agents. Silicon dioxide and carbon nanoparticles are used as food additives (10). Platinum and gold nanowires are used as biosensors to improve food analysis. The nanoscaled ingredients used in the manufacturing of food products share different properties to improve texture, consistency and taste (11).

The major applications of nanotechnology in food engineering include nanosensing and designing nanostructured ingredients. The developed nanosensing technology increases food quality and safety evaluation, and nanostructured ingredients help improve food processing (12). The application of food processing techniques mainly involves the appropriate delivery of nutrients, bio-separation of proteins, and the rapid sampling of biological and chemical toxins (12).

The expansion of nanostructured food constituents in the delivery of nutrients and supplements is the prime area of interest in current nanotechnology discipline. This eminent standard has become noticeable in the food processing industry, which is promoting the development of a number of nanomicelles, nanoemulsions, liposomes, biopolymeric nanoparticles and cubosome nanoparticles to achieve successful food safety assurance (13). Nanocomposites in the form of novel food, food or feed additives, biocides, pesticides and food contact materials have a bright future in the field of food processing (12).

5. Stages of food processing

The general methods of the food processing technology include physical, chemical and biological methods. Physical processing involves thermal processing the high

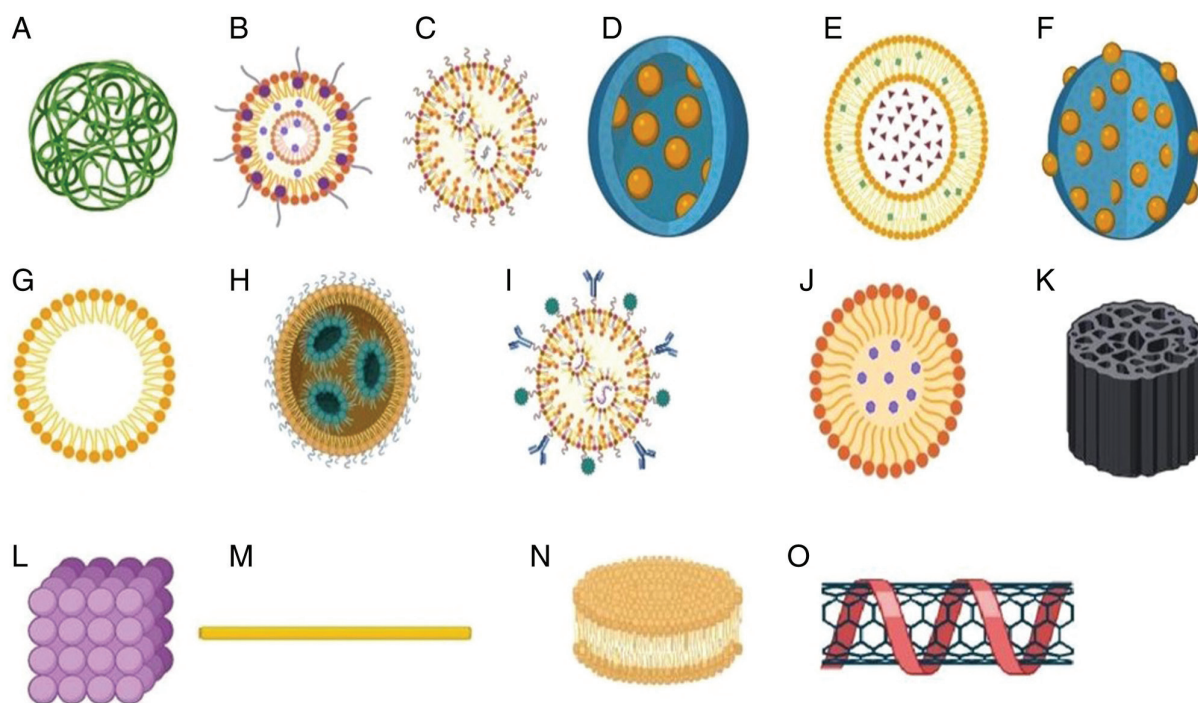


Figure 1. Nanoparticles used in food processing: (A) Polymeric nanoparticle, (B) core shell-type hollow lipid-polymer-lipid hybrid nanoparticle, (C) solid lipid nanoparticle, (D) nanocapsule with drug, (E) liposome with active compound, (F) nanosphere, (G) liposome, (H) lipid nanoparticle, (I) ligand-targeted lipid nanoparticle, (J) nanoemulsion, (K) porous silicon nanoparticle, (L) nanocrystal, (M) gold nanowire, (N) nanodisc and (O) carbon nanotube.

temperature short time (HTST) or long holding temperature (LHT) concept, retorting, cold treatment and or drying) and non-thermal processing (such as the use of radiation, specifically UV radiation). Chemical and biological processing includes the use of chemical preservatives or food additives and pH controlling and fermentation (14). Upon processing, food undergoes a variety of post-harvest and processing-induced modifications that would affect the biological and biochemical consistency of food. In this context, nanotechnology developments in the fields of biology and biochemistry could eventually take great stride in the food industry to retain its molecular integrity. Often, the nanometer length range could affect certain aspects from food safety to molecular synthesis (15).

In general, nanofoods refer to food products that use nanotechnological tools during their production and harvesting, processing and packaging. Nanoparticles employed in food processing industry are commonly distinguished as two forms of nanofoods based on its route of application: i) Food additives (nanoinside); and ii) food packaging (nano outside). Nanoscale food additive substances are used to influence product shelf life, texture, flavor and nutrient composition, or even detect food pathogens and provide functions as food quality indicators. An incremental nanotechnology involves the ability to use nanoscience to improve the quality of materials by understanding and refining their nanoscale structures, which improves food quality during its processing (15).

In food processing, nanoparticle formation can result in homogenization techniques at a high pressure or ultrasonic emulsification, which are used in the production of salad dressings, chocolate syrup, sweeteners, flavored oils and numerous

other foods (16). However, there are certain ethical issues associated with the acceptance of nanotechnology in the food system; for example, various areas in Europe have questioned the incorporation of traceable nano-chips in livestock (17).

6. Green synthesized nanoparticles in food processing

Green synthesis is an eco-friendly, cost-effective harmless approach, and these methods are more efficient than physical and chemical means. Biological synthesis is still considered as a more acceptable, cost-effective method of synthesizing nanoparticles. Various parts of plants, such as roots, fruits, stem, seeds and leaves and other parts, in addition to the use of microorganisms (such as bacteria, yeasts, fungi and actinomycetes) are used to synthesize nanoparticles. Green synthesis is the most skillful, flexible, biologically apt and feasible strategy for the synthesis of nanoparticles (16). Organic acids, proteins, vitamins and secondary metabolites viz alkaloids, flavonoids, terpenoids, polysaccharides are the key biomolecules for the formation of divergent varieties of nanoparticles (18).

Some of the green synthesized nanoparticles used in food processing, using the leaves of *Protium serratum*, silver nanoparticles (AgNPs), have been synthesized, and have exhibited distinct antibacterial activity against food borne pathogens such as *Pseudomonas aeruginosa*, *Escherichia coli* and *Bacillus subtilis* (19). Plant origin AgNPs have been used in a number of consumables, food contact surfaces and food packaging. They are antimicrobial, anti-odorant and health supplements. Similarly, nano-iron also acts as a health supplement, and can be used in the treatment of contaminated water



Figure 2. Schematic representation of the applications of nanotechnology in food processing.

(to break down organic pollutants) and is known to inactivate microbial pathogens (17).

The use of microbiologically produced metal oxide nanoparticles, such as silicon dioxide (SiO_2), magnesium oxide (MgO) and titanium dioxide (TiO_2) are permitted by the US FDA as anti-caking agents, flavor carriers and food color additives (20).

It is evident that green synthesized nanoparticles play a vital role in the food processing industry compared with physical and chemical based nanoparticles, as the biosynthesized nanomaterials present certain advantages, such as: i) A decrease in the use of hazardous materials, as employed in biological systems such as capping, reducing and stabilizing agents; ii) the reduction of energy resources and chemicals, as biosynthesis reactions usually occur at a neutral pH, room temperature and pressure; iii) the biocompatibility and low toxicity of the majority of synthesized materials, due to surface functionalization (20).

7. Nanotechnology in food processing

The recent advent of nanotechnological approaches in food processing has led to numerous advantages. For example, the delivery of colors/additives/flavors using nanoemulsions in the production of functional and adjunct foods. In addition, the controlled release of food through nanoencapsulation and nanodiagnostics (21). A schematic representation of food processing using the nanotechnological approach is presented in Fig. 2.

8. Implementation of nanotechnology in food processing

The implementation of nanotechnology in food processing involves various aspects, such as: i) Carrier materials used in the manufacturing of coatings for food processing machines; ii) nanostructures and nanocarriers applied in the nanodelivery of food additives, preservatives, flavors, colors, taste

Table I. Nanotechnologies and nanomaterials commonly used in food processing and their uses.

No.	Nanotechniques	Nanomaterials/ nanocomposites	Uses	(Refs.)
1	Nanoencapsulation	Nanocapsules	Enhance the taste, stability and bioavailability of food. Protect the food against oxidation. Controlled release of food ingredients under pH and moisture effect.	(13)
		Nanoliposomes	Nanoliposomes have been widely used in food industries for nutrient enrichment and supplements. Deliver food additives, flavors, vitamins and enzymes. Entrap unwanted components and odour of food.	(14)
		Colloidosomes	For the easy delivery of vitamins and minerals.	(15)
		Nanocochleates	Protect the antioxidants from degradation throughout the processing and storage stages.	(16)
		Archaeosome	Protect food from particles from oxidation, enzymatic and chemical degradation.	(17)
		Nanoceuticals	Improve the variety and protection of food products.	(18)
2	Nanoemulsion	Nanoemulsions	Produce food products for flavored oils, salads and sweeteners.	(19)
		Carbohydrates and proteins	Xanthan and guar gum are used to help improve the texture of ice creams.	(20)
		Brominated vegetable oil, dammar gum, ester gum, sucrose-acetate, isobutyrate	Used as a whitening agent, reduces cream formation, also helps in dispersion and availability of nutrients in food.	(20)

enhancers and antimicrobials.; iii) the nano-preservation of food; and iv) nano-food packaging. Details of nanomaterials or nanocomposites used in food processing are presented in Table I (20).

9. Nanocarriers used in the delivery system

Certain criteria should be followed for the proper delivery of food, which include: i) The nanocomposite/nanomaterials to be used in the delivery actions must have the ability to accompany the desired material specifically to the target position in the food system; ii) at a definite rate and definite time, the nanomaterials must be available to reach the target food particle; and iii) most notably, it is critical to maintain the compounds in an active state at appropriate levels for extended phases of time storage. The major nanodelivery systems used in practice are nanoencapsulation and nanoemulsion (22).

10. Nanoencapsulation

The nanoencapsulation technique involves the incorporation of food ingredients, antioxidants, vitamins, slimming agents and enzymes with nanomeric size diameters. The nanoencapsulates increase the bioavailability cargo and also disguise unwanted tastes, colors and odors (23). Over the past few decades, applications in the area of food have focused towards

the safe and controlled delivery of the nanoencapsulates. As regards the human digestive system, for example, the aim is to provide protection for encapsulated materials/nutraceuticals/probiotics against the gastric environment of the colon. The nanoencapsulated materials must satisfy the following criteria, where these materials have to be sustained and retained in the human gastrointestinal tract (GIT) and gradually release the desired products to the target. The systemic understanding of the digestion process and physiological conditions of the GIT are required for the designing of nanoencapsulates. As this nanocarrier faces a turbulent environment in the GIT, a smart design is crucial for the successful delivery of encapsulate materials, which should consider the digestive parameters, such as bile salt composition, electrolyte balance, temperature, pH and mechanical stress to be counteracted in order to achieve the controlled release of nanoencapsulated compounds in the digestive tract (23).

Nanoencapsulation is the process of packing or encapsulating the substances with several coating materials at atomic, molecular and supramolecular level range from 1 to 100 nm. The nanoencapsulated products provides functionality that includes controlled and effective release of the healthy functional bioactive ingredients in to the body cells. Different nanotechnologies are implemented for the encapsulation of food components, which protect from the rigors of food processing and damaging environmental factors (24).

The nanoencapsulation technique enhances the bioavailability of nutrients by shielding them during digestion and are released gently into the body during the digestion process; it also improves the solubility of poorly water-soluble compounds (25).

For the production of mayonnaise, milk, sauces and salad dressings, nanoemulsions are used. The texture of the nanoemulsions allow them to present as a viscous cream at very low concentrations and are used in low-fat foods. The nanoemulsion technique is mostly centered on improving the bioavailability of bioactive compounds, such as curcumin, and polyphenolic compounds with anticancer, anti-inflammatory and antioxidant properties. The use of nano-emulsions has been studied using liposomes, which encapsulate lactoferrin to increase the shelf life of dairy products and vitamin C. It has been observed that encapsulated lactoferrin is active in liposomes for 50 days of refrigeration, without losing vitamin activity in 19 days (26).

11. Materials used in nanoencapsulation

Nanoliposomes. Liposomes are minute sacs of phospholipids generally used as nano-based carrier in the nanoencapsulation technique. Nanoliposomes are well known to deliver essential compounds, such as nutrients, nutraceuticals, vitamins, enzymes, additives and antimicrobials (26). The utilization of digestible lipids in nanodelivery systems enhances the absorption rate of nutrients, since these lipids increase the amount of mixed micelles to be dissolved and also transport hydrophobic materials across the body (25).

Colloidosomes. Colloidosomes are hollow capsule-like structures usually measuring in size $<1/4$ th of a normal human cell. They have been proven to function as efficient carriers of food supplements within biological systems (27).

Nanocochleates. Nanocochleates stabilize and improve the quality of processed food by wrapping the micronutrients to form nanocoils. They are composed of soy-based phospholipids, which can be either phosphatidylserine, phosphatidic acid or di-oleoyl-phosphatidylglycerol etc. (3). Nanocochleates increase the efficiency of cross-membrane diffusion for charged and impermeable molecules, thus having numerous applications in nanoencapsulation. They also possess resistance to degradation by gastrointestinal fluids, which render them suitable for oral delivery (28).

Tocosomes. Colloidal bioactive phosphate-group-bearing alpha tocopherols are known as tocosomes, which can also accommodate sterols, proteins and polymers in their structure, such as nanoliposomes (29). The main purpose of using tocosomes in nanoemulsion is to enhance the antioxidant activities of foods via the synergistic delivery of tocopherols and ascorbic acid into the body, as well as to stabilize minerals, such as calcium and iron, in milk and other drinks (26).

12. Production technique of encapsulation

In order to develop novel food products, it is common to find strategies to supplement the functionality of the desired food

products. Naturally available compounds with high biological activities are used to enrich the food products; these nanofoods have to be non-hazardous to human health, this is the most common strategy incorporated to achieve consumer's attention towards food quality and safety. In this context, several types of nanoencapsulation methods and nanocarrier systems have been devised (14). These involve both colloidal and non-colloidal systems.

Coacervation. The coacervation technique follows the deposition and formation of the coacervation phase around the active food substances by separating a single or poly electrolyte mixture contained in the solution. This hydrocolloid shell may be cross-linked using an appropriate chemical or enzymatic cross-linker, such as glutaraldehyde or transglutaminase, with the main intention of speeding up the process. According to the number and types of polymers used in the process of coacervation, this can be termed as either simple or complex coacervation. Due to the very high payloads achievable (up to 99%) and the possibilities of controlled release based on mechanical stress, temperature, or sustained release, coacervation has its own notable application in the field of nanotechnology (14).

Inclusion complexation. Inclusion complexation is a type of nanoencapsulation, which is associated with the encapsulation of a supramolecular association of a ligand into a cavity containing shell-like substrate formed through hydrogen bonding and least vander Waals forces of attraction. The encapsulation of highly volatile organic molecules, such as essential oils and vitamins follows the inclusion of complexation process; it often also helps to conceal odors and flavors and preserve good aromas. Compared with other techniques, this has the highest encapsulation efficiency with higher stability of the core component; however, the drawback of this technique is that it only encapsulates a few particular molecular compounds, such as β -cyclodextrin and β -lactoglobulin (30).

Nanoprecipitation. The nanoprecipitation method is also known as solvent displacement. It is based on the spontaneous emulsification of the organic internal phase containing the dissolved polymer, drug and organic solvent into the aqueous external phase. The nanoprecipitation technique involves the precipitation of a polymer from an organic solution and the diffusion of the organic solvent in the aqueous medium. The solvent displacement forms both nanocapsules and nanospheres. Biodegradable polymers are commonly used, particularly polycaprolactone, polylactide and poly (lactide-co-glicolide), eudragit and polyalkylcyanoacrylate (31).

Extrusion techniques. The extrusion technique involves a combination of several major operational units, including the mixing, cooking, kneading, shearing, shaping and forming of food, which finally mixes the polymer and bioactive substances into the gelling solution using a dripping tool. After a particular set of time, the gelling solutions become hardened and are collected in the form of beads (32). The types of extrusion technique include the following: i) Spinning disk atomization; ii) jet-cutting; iii) vibrating jet/nozzle extrusion; iv) electrostatic extrusion; and v) coaxial air-flow extrusion (33).

Molecular inclusion. The molecular inclusion technique employs cyclodextrin molecules as a bioactive coating material (34). Among the numerous advantages of the molecular inclusion technique by employing cyclodextrins, the most notable are that it enhances the solubility of poorly water-soluble molecules and also increases their bioavailability.

13. Nanoencapsulated food additives

Conventional methods of food preservation techniques employ hazardous chemical substances that, upon degradation, undergo cross reactions and certain biochemical changes, resulting in sulfite allergies, nitrate toxicity and neurological damage. In addition, uncontrollable processes are initiated inside the food matrix following the addition of conventional preservatives (35). In such problematic situations, the replacement of such toxic preservatives with new advent nanoencapsulated food additives prevents such undesirable changes occurring in food material. The nanocarriers protect the food from thermal degradation and also disguise the flavors of peculiar food additives. Lycopene, citric acid, ascorbic acid, benzoic acid, omega-3 and omega-6 fatty acids, fat-soluble vitamins A and E, iso flavones, lutein, and β -carotene are the commercially available nanoencapsulated food additives listed (36).

14. Nanoemulsion

Nanoemulsions are one of the most notable delivery systems, with a vast number of applications and advantages in the food industry (37,38). Nanoemulsions are the emulsions formed of very small sized particles with an increased surface area. These emulsions are least sensitive to physical and chemical changes, and are thermodynamically unstable due to its positive interfacial tension between oil and water phases (39); all these qualities render them ideal formulas for use in the food industry. Among the basic emulsion compositions, food grade nanoemulsions are widely used in the market commercially due to their highly improved digestibility, efficient encapsulation, increased bioavailability and proper delivery of targeted food ingredients. The aforementioned advantages of nanoemulsions over conventional emulsions have increased the utility of this process in the food industry (37). In order to enhance the delivery of vitamins, fragile micronutrients and medicines, currently, small edible capsules coated with nanoparticles are used in daily foods to provide beneficial health effects (39).

15. Applications of nanoparticles in food processing technology

In the recent past, nanotechnological applications have gained tremendous scope, particularly for improving the properties of packaging/container capacity, the barrier against the flow of gasses and light. Thus, the use of smart sensors has been found to be beneficial to consumers and leads to the rapid identification, producer distribution, and authentication of food products (40).

Due to nano-adhesive properties, nanoparticles can bind to harmful matters in the gastrointestinal GIT and remove them effectively. Pure silver colloid liquid, reduced to a size of 1 nm with atomic particles, has been found to be highly

bactericidal and can inactivate 99.9% of 650 species of micro-organisms within 6 min, when compared to antibiotics which can be effective against only five to six species (15). This new technology platform has provided food quality assurance by detecting *Escherichia coli* in food samples by measuring and detecting light scattering by the cells. This sensor functions based on the principle that a protein of a known and characterized bacterium set on a silicon chip can bind with specific bacteria present in the food sample. The binding process will result in a nano-sized light scattering, which is detectable by the analysis of digital images (18).

Nanotechnology is widely used in the production of healthier foods, which lack or contain low levels of fat, sugar and salt to avoid food-borne diseases, out of which the nanoparticles, SiO_2 and TiO_2 , have been reported to be used as food additives in bulk quantities. Biodegradable poly-D,L-lactide is a quercetin used for bioencapsulation in order to increase the life of tomatoes, and this approach should perhaps extend the shelf life of other fruits and vegetables as well. Other commercialized nanotechnology-based products in the market are nanogreen tea, Neosino capsules as dietary supplements, canola active oil, Aquanova Used as micelles to enhance the solubility of vitamins (A, C, D, E and K), β -carotene, omega fatty acids and nutraceuticals as fortifying nanocarriers to carry nutraceuticals and drugs (41). In line with this, in the USA, Australia, China and Japan the widely sold nano-processed foods in the market are fortified fruit juices, oat nutritional drinks, nanoteas, nanocapsules containing tuna fish oil in breads and nanoceuticals slim shakes (41).

16. Role of nanotechnology in food safety and security

Worldwide, a number of food manufacturing industries are searching for various methodologies which can be used to improve the quality, safety, competence and nutritional properties of food (42). The application of nanotechnology in food safety follows the use of nanoparticles in order to develop nanosensors. The nanosensors are formed to detect spoilage-causing microorganisms and other food contaminants in the food system. Durán and Marcato (43) reported that biosensors have been designed to detect most common food pathogens, such as *Listeria monocytogenes*, *Escherichia coli* and *Salmonella* sp. as well as mycotoxins in food. Magnetic nanogoldimmune sensor, is the nanosensor designed to detect the most common type of mycotoxin termed aflatoxin produced by *Aspergillus flavus* and *Aspergillus parasiticus*, which contaminate numerous foods (44).

17. Nanotechnology-associated health hazards in food processing

The nanoemulsion technique has achieved worldwide application due to various advantages; however, it also has certain drawbacks, such as instances where consumers have to pay the cost for physical ailments, such as the presence of toxic compounds. Several nano-compounds are known to cause cellular damage to biological systems by binding to the receptors of immune cells and confounding them (45). The potential risks associated with meat processing, require the use of a number of tests to be detected, such as skin toxicity,

oral toxicity, oxidative stress, genotoxicity, cytotoxicity and other acute and chronic issues. The nanoscale materials used in food processing also meet production costs, and are complicated methodologies used in synthesis and stability (46). One can reduce the burden of health hazard risks in nanomaterial-assisted food processing by disinfecting equipment and production rooms by using an alkaline solution of 1.5% sodium hydroxide, by using surface biocides for surface sterilization, by wearing protective clothing and by incorporating high-efficiency water and air filters (47).

18. Conclusion and future perspectives

Nanotechnology is one of the most notable technologies involved in manufacturing. Nanomaterials are minute particles ranging from 1 to 100 nm in size, and are used for various purposes; they play a primary role in food and agriculture sectors, particularly in crop development, food quality enhancement and safety, and thus promote human health through novel and innovative approaches. Nanotechnology with its applications in advanced processing, packaging and long-term storage, provides vast growth opportunities to the food industry through the enhancement of food quality by improving its flavor and texture. Nanomaterials incorporated in nanosensors help consumers by providing the inner status of food and its nutritional status with enhanced security, in addition to pathogen detection. The majority of foods that are bioactive against various diseases are hydrophobic in nature, with the least bioavailability and stability; hence, nanotechnology-based delivery systems provide the enhanced bioavailability and targeted delivery of food bioactive compounds.

Nanotechnology-based foods are associated with significant challenges to both governments and industries, ensuring gaining consumer confidence and acceptance and, thus, availability in the market. Furthermore, the effective application of nanocolloidal particles in various sectors in the food industry, such as food quality, safety, nutrition, processing and packaging has been widely reported in recent days.

Nanoparticles are produced worldwide; however, only a limited number of countries have the standard regulatory rules and regulation policies for the implementation of nanotechnology in food products. The lack of sufficient scientific information about nanosystems and nanotechnology creates hurdles in arriving at any conclusions regarding their efficacy. Appropriate labeling and regulations are required for the marketing of nanofoods, which can help to increase consumer acceptability. In this context, the utilization of these nanotechnologies, particularly green nanotechnological approaches, if managed and regulated efficiently, can play a crucial role in improving food processing and product quality; this may benefit human health and the well-being of humans, animals and an ecosystem for a better tomorrow.

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Authors' contributions

DG conceived the study and was also involved in the editing, reviewing and revising of the manuscript, and also communicated the manuscript to the journal. RS and CSP drafted the manuscript, obtained the data acquired for the review and processed the figures. All three authors have read and approved the final manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

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Patient consent for publication

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Competing interests

The authors declare that they have no competing interests.

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