Review Article

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Application of nanotechnologies along the food supply chain

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Abstract: Nanoscience and nanotechnology are new frontiers for this century. Nanotechnology translates into the ability to manipulate the material on a nanoscale. As in other sectors, recent developments in the field of nanoscience and nanotechnology offer new opportunities for innovation for food. Nanofoods are considered foods grown, produced, processed or packaged using nanotechnological tools that incorporate nanomaterials to improve nutritional quality, taste or texture, and increase the shelf life of food. Nanotechnology's applications are diverse, going from nanoencapsulated ingredients, such as bioactive compounds, nutrients and food additives that increase the bioavailability of the compounds, to ingredients that constitute nanostructures and nanotextures that provide barriers for physical-chemical protection, which allow modification of flavour and odour. Also, has the potential to be used as biosensors to monitor food conditions during storage and transport, through packaging that includes indicators. This review covers the development and use of nanotechnology along the food supply chain, focusing the agricultural production, industrial processing and protection through packaging, as well as addressing the advantages and disadvantages of using this technology.

Keywords: nanotechnology, nanoscience, food industry, nanofood, agriculture, packaging

1 Introduction

The term nanotechnology was first used by Prof. Norio Taneguchi, from the University of Science of Tokyo, to describe the manufacture of new materials in nanometer size [1,2]. However, the nanotechnology concept was introduced by Richard Feynman in 1959 at a meeting of the American Physical Society [2,3]. Nanotechnology operates in the range between 0.1 and 100 nm [4,5], incorporating the dimensions of atoms and molecules, until values close to the wavelength of visible light [6,7].

Nanoparticles have different behaviours (reactivity, thermal, resistance, etc.) in comparison to the particles of the same material but in micro- or macro-scales [8–10]. The reduction of the particle size improves the material properties, such as the delivery efficiency, solubility and biological activity, due to the higher surface area [7,11]. Therefore, the particle size is strongly important, because it can change the nature of the interactions between molecules, and the impact that the particles can have on the environment, human body and society as a whole [12].

Two construction strategies are used in nanotechnology: "top-down" and "bottom-up" [10,13,14]. Generally, commercial production translates into the "top-down" approach, which involves reducing the size of materials by grinding, nanolithography or precision engineering to form the nanometric structures. On the other hand, the "bottom-up" approach allows the construction of nanostructures from individual atoms or molecules, capable of self-assembly [3,13].

Nanoscale engineering carries the promise of a novel technological revolution [15,16], but technology produced at this scale brings also safety contests, said the Science for Environment Policy Report produced for the European Commission in 2017 [17]. Nanotechnology has been used since the twentieth century [2], and recently, the novelty of the nanoprocesses spread worldwide [8]. Several countries invested in the research and development of nanoproducts in the last few years, which results in a number of products in the food sector commercialized without neither regularization nor identification of its compounds [18].

Nanofoods are food products that have been produced using nanotechnological tools and techniques and have in their composition the presence of nanomaterials [19]. Nanotechnology can provide a useful tool for food

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preservation through the improvement of additives, processing and packages [20,21], which contain nanocomposites capable of preserving the food freshness, quality and taste, ensuring food safety [1,9,22]. Nanotechnology has been incorporated into many food products, and the progression of this technology has helped to improve the processing and storage of food [23].

The increase in the world population results in a greater number of people to feed, while food production does not keep up with this growth and measures are needed to enable food quality for all [24]. Thus, nanofoods appear as a complement to food security [20], due to the facility of transporting foods to different parts of the world, while makings it possible to extend their shelf life [15,22,25]. Additionally, facilitates the tracking and identification of contaminants, allows the intelligent storage of products, and the incorporation of health supplements or antibacterial agents, which in fact is a major contribution to improving the food industry [22].

Nanoscience allows food production with better thermal stability, solubility and oral bioavailability [5,22]. There are several forms of nanosystems, such as solid nanoparticles, nanofibers and nanocapsules, which are examples of compounds that can be applied in food processing, packaging and preservation [17,25]. Several nanocomposites were created to increase the physical characteristics of food, such as colour and aspect [26]. The incorporation of nutraceuticals, nutrients, vitamins and minerals, as well as flavour nanoencapsulation are some of the ways of processing food with nanomaterials [20,22,27].

The questions that involve nanofood production and application are related to human health and the environment, as the consequences can be good or bad [1,12,28]. Thus, the challenges facing nanotechnology applied in the food industry focus on minimizing the toxic effects for consumers, workers in the sector, and ultimately the environment [29,30].

According to Siqueira-Batista et al. [28], nanoscience will result in great advances in medicine and pharmacology, more efficient methods for the chemical and petrochemical industry, computers with a higher degree of sophistication, greater efficiency in the use of energy, and innovations in the area of the environment among several other advances. However, regulation is essential to manage the manufacture, processing, application and disposal of nanomaterials [4]. In addition, efforts are needed to strengthen public awareness about food and agricultural products containing nanocomposites.

In a survey conducted in 2008, in Australia, 86% of the population surveyed stated that they were excited or hopeful about nanotechnology in general. Regarding the food sector, 32% supported nanofoods. There were different attitudes towards the use of nanotechnology directly in food or in packaging, which is more supported, with about 73% of respondents in favour of its use. Considering low levels of awareness about nanotechnology, the study suggests that attitudes tend to change as people become more informed about the subject since in a previous survey conducted in 2005, the support for nanofoods was 49% [31].

In the last decades, hundreds of nanoproducts have been commercialized and applied in the food industry. Most of these products do not contain nanocomposites in the food itself, but within the food industry, that is, materials that are in contact with food but are not directly ingested by the consumers [23]. However, there is a great concern in relation to the intake of nanofoods, so it is essential to investigate the behaviour of nanoparticles within the human body, as well as their possible toxic effects on the organism [4,26]. Little knowledge about their toxicity has been one of the causes for limited regulation, as the risks that new nanomaterials can bring are unknown [32].

Recent studies have shown that nanoparticles such as nanosilver, titanium dioxide and zinc oxide, which are used as nutritional supplements and at food packaging, may be toxic to cells [1]. Likewise, studies focused on the environment have indicated that these substances can also contaminate water [33].

Thus, this review aims to clarify some aspects of nanotechnology, specifically the nanoscience application in the food sector, its advantages and disadvantages, pointing out the current situation of the market, and the evolution of the application of nanocomposites in different sectors of the food industry, such as agriculture, processing, manufacturing and packaging. In addition, some aspects related to the possible toxic and polluting effects of these materials and the lack of legislation and regulation in the sector related to these factors are pointed out.

2 Methodology

The methodology consisted of bibliographic research carried out by consulting the main online scientific communication platforms, which can be accessed through Google Scholar, such as Science Direct, Web of Science, Taylor and Francis and Scielo, which include scientific journals of international circulation. Some information from governmental entities was also considered, to this, the information was accessed through its respective websites.

First, a search was made based on scientific articles present in the previous cited platforms to define and develop aspects related to the theme to be exposed in this review: what are the advantages and disadvantages of applying nanotechnology directly or indirectly in foods; the concerns of consumers; and the safety concerns regarding to the yet unknown long-term effects exposed by the scientific community.

During the bibliographic search, the main keywords used were as follows: nanotechnology, food industry, food packaging, nanofood, toxicity and agri-food sector. Publications dated from 2003 to 2021 were considered for this review. The cloud in Figure 1 was obtained considering the keywords appearing in all the sources effectively used for this review article as they appear in the list of references, and which occurred at least twice, i.e., in two different articles. The size of the circles indicates the frequency of occurrence of each of the keywords, and the curved lines express their links, i.e., co-occurrence. The figure shows that the most frequent keywords were nanotechnology, food packaging and nanoparticles, which is in accordance with the main objective of the review.

The analysis with VOSviewer software selected 28 keywords, grouped in six clusters with 56 links and a total link strength of 72. The clusters are presented in Table 1, and the scores for each item are calculated as the average publication year of the documents in which a keyword or a term occurs. Higher values mean that the keyword in question was cited on average in more recent articles. The most relevant cluster includes six terms: antioxidants, lipid peroxidation, nanoemulsion, nutraceuticals, phospholipids and stability, while the least important cluster includes only two keywords: nanoemulsions and nanosensors. The terms whose average year is most recent, 2019, are nanoparticle, migration and food safety, whereas the term nanotechnologies has an average year of occurrence of 2009, meaning that has been in use with a high frequency for much longer.

The literature review focused on the presentation of information related to the application of nanotechnology in the food industry, in various sectors from cultivation to commercialization, including the applications of nanoscience in agriculture, to food packaging. The information was complemented explaining issues related to toxicity, its possible effects on health and the environment, and the lack of regulations in the sector.

3 Current state of the nanofood sector

The impact of nanotechnology on food has become more apparent in recent years, due to conferences and researches dedicated to this topic [34]. Several companies that were hesitant to reveal their research programs on nanofoods

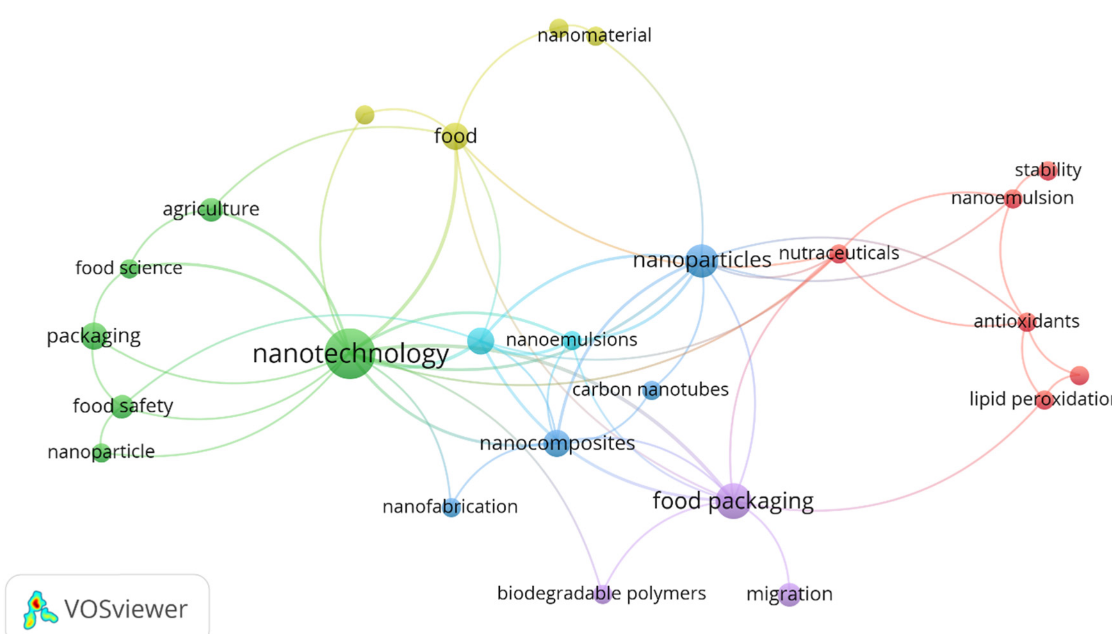

Figure 1: Map of the keywords in the sources used for this review article.

Table 1: Clusters of the keywords in the sources used for this review article

Cluster	Keywords	Weight (Links)	Weight (Total link strength)	Weight (Occurrences)	Score (Avg. pub. year)
1	Antioxidants	5	5	2	2017
	Lipid peroxidation	3	3	2	2012
	Nanoemulsion	4	4	2	2018
	Nutraceuticals	7	7	2	2014
	Phospholipids	2	2	2	2018
	Stability	1	1	2	2018
2	Agriculture	3	4	3	2018
	Food safety	4	4	3	2019
	Food science	3	4	2	2016
	Nanoparticle	2	2	2	2019
	Nanotechnology	15	26	14	2014
	Packaging	3	3	4	2018
3	Carbon nanotubes	2	2	2	2011
	Nanocomposites	7	9	4	2013
	Nanofabrication	2	2	2	2012
	Nanoparticles	10	14	6	2016
4	Food	7	9	4	2014
	Nanomaterial	2	2	2	2016
	Nanotechnologies	2	2	2	2009
	TiO_2	2	2	2	2016
5	Biodegradable polymers	2	2	2	2015
	Food packaging	10	13	7	2016
	Migration	1	1	3	2019
6	Nanoemulsions	5	8	2	2018
	Nanosensors	8	13	4	2017

have made them public to maintain their presence in the market.

The United States of America was the pioneer in the sector, investing around US $3.7 billion at a National Nanotechnology Initiative. In 2008, about US $82 billion was invested in nanoproducts in the global market [31]. It was estimated that the global economic impact of nanotechnology by 2027 would reach values of around US $70.7 billion [35], generating employment for about 6 million workers, employed worldwide in the promising nanotechnology industries [23].

The world is experiencing a technological revolution, which can take years or even decades, and become more impactful than past revolutions [28]. According to Cornick [31], the public perception about nanotechnology is unknown, as well as the nanotechnology risks themselves. Thus, the issues related to this promising technology start to arise, because it is very new and little if nothing is known about their long-term effects.

The Regulation (EU) No 1169/2011 establishes that all engineered nanomaterials used as food ingredients have to be clearly indicated in the list of ingredients to certify consumer information. Additionally, they have to specify the word “nano” in brackets. Also, Regulation (EU) No 1169/2011 refers to “engineered nanomaterials” and not to “nanomaterials,” so in this way, natural and incidental nanomaterials are not included in the definition [36]. This means that a lot of goods were produced and commercialized without the consumers knowing that they were nanoproducts [37].

The nanoscience sector has been optimistic about the potential to change the current agricultural production system, ensuring food security, based on healthier food cultivation [1,38]. It is also hopeful in terms of improving the nutritional quality of products, derived from additives, and in the way, the body can digest or absorb food [20,29,30]. Nevertheless, the consumer preference for “natural” food products has inhibited the implementation of technologies in food, so nanotechnology has been no exception [39].

The Potential Risks Arising from Nanoscience and Nanotechnologies on Food and Feed Safety Report (2009) says that the prospects for nanoscience and nanotechnology applications in the food chain range from antibacterial membranes and packaging, to pathogen and contaminant sensors, tracking devices, reaching the improbable like create food by synthesis at the atomic level [40]. This technology has the potential to revolutionize the food sector based on robust and high-barrier packaging, antimicrobial agents and sensors to detect contaminants, gasses and microbes in food [39].

The nanomaterials implemented in the food industry can be inorganic, organic, natural or combined [20,21,23]. Among the inorganic and produced from metals, the nanosilver is the most commercially applied due to its antimicrobial activity [12], while the use of gold nanoparticles is aimed at the area of sensors [23]. Titanium dioxide nanoparticles are applied as a disinfectant and food additive [41], while natural nanoparticles are widely designed for the food industry, being applied as supplements [23,29].

There are five principal ways to apply nanotechnology in the food chain industry, according to The Potential Risks Arising from Nanoscience and Nanotechnologies on Food and Feed Safety Report (2009): (1) processes that introduce nanoparticles directly on food or that remain in contact with the food, or yet, products that are indirectly part of the manufacturing of food, which are as follows: nanocomposites, materials of active contact with the food, that interact with the food itself or with the environment around it, or surface coatings with nanostructures; (2) foods and ingredients that have been processed or formulated with nanostructures, and include applications that involve processing nanoscale ingredients to improve the taste, texture and consistency of food; (3) nanosized, nanoencapsulated or encapsulated nanomaterial ingredients used in food, including nanoscale ingredients, additives and processing aids or supplements; (4) biosensors for monitoring the condition of food during storage and transportation, including packaging with indicators; and (5) the indirect applications, such as the nanosized agrochemicals, feed, fertilizers, pesticides or veterinary medicines [40].

Thus, it can be said that the application of nanoscience in the food chain is broad [42] and is still under construction, as new research is done every day, and new products are created, translating into constant changes in the market and the industry.

4 Nanoscience and nanotechnology in agriculture

The application of nanotechnology in agriculture is relatively recent compared to the use in other sectors, such as medical and pharmaceutical [20,43]. The appearance of nanoscience in the agriculture industry dates back to 2003 when the United States Department of Agriculture published the first research focused on the theme [23].

The agri-food industry has vital importance since it is one of the main drivers of the world economy [6,18,23]. As such, agricultural practices are generally in the public eye due to climate change, energy and resource limitations, and the rapid growth of the global population that generate unprecedented pressure on food and water resources [43,44].

Currently, some of the main challenges facing agriculture are the accumulation of pesticides and chemical fertilizers, which generate environmental damages of great importance and compromise food security [44]. This problem is intensified with population growth estimated at 9 billion habitants by 2050 [44] increasing the demand for food by 60% [24]. Nevertheless, nanotechnology presents an alternative for these issues, the application of these sciences has the potential to be widely adopted by the agricultural sector worldwide [29].

Science applied to agricultural development has brought many benefits to workers and consumers, through the implementation of improvements, new knowledge and technologies [6,23]. These strategies are known as precision agriculture, used to improve yields in crops, without damaging the environment. Regarding food science, nanotechnology tends to provide a solid atmosphere for understanding the interactions of food components on a microscopic scale, which can influence their structures and the properties of food as a whole [45].

The use of nanoscience in the sector of agricultural inputs aims to improve the functional efficiency of products such as nutrients, chemical or biological pesticides, as well as the safety associated with the use of these products, reducing the risks of toxicity to workers, overdose in crops, and also the consequent environmental contamination [6]. According to Duncan [39], the sectors of agriculture that apply nanoprocesses or nanocomposites are pesticides, fertilizers, vaccines and feed for animals, detection of pathogens and genetic engineering.

The applications of nanotechnology in agricultural practices occur since the beginning of the production chain, through the development of nanoparticles and nanoencapsulation for controlled release of fertilizers and pesticides in soils, and also of drugs for veterinary use, which significantly contribute to improving the performance, efficiency and economy of inputs in this sector [6].

Nanoscale carriers can be used for efficient and thoughtful delivery of pesticides, plant growth regulators, herbicides, fertilizers and others [46]. Some mechanisms involved in the process to improve absorption and provide controlled release of products are encapsulation and trapping, polymers and dendrimers and ionic surface bonds [44]. These advances help to increase the bioavailability of active ingredients for plants, which reduces product waste, and could also reduce the necessary dosages.

Conventional fertilizers are less efficient, offer low nutrient absorption, which translates into high losses in the field [46]. The development of nanofertilizers presents itself as a solution to such problems, as they are capable of increasing the incorporation of nutrients by crops and microorganisms in the soil. The application of nanoencapsulated herbicide can lead to a decrease in dosage, without loss of efficiency, which is economically beneficial, besides being also favourable to the environment [6,23].

The use of nanosensors is aimed at detecting chemicals, such as pesticides and herbicides, as well as pathogens in food and agricultural systems. This real-time monitoring system *in situ* helps to remedy potential losses in the yield, thus improving production, concomitantly with the proper use of nanofertilizers, nanopesticides and nanoherbicides [23].

Nanotechnological techniques have demonstrated efficiency in controlling water quality [18,33]. Silver nanoparticles (Ag) have shown promising results as a disinfectant, due to the production of reactive oxygen species that cut the DNA of bacteria and viruses [44]. The nanoparticles of metal oxides and sulphides, such as titanium dioxide (TiO_2), zinc monoxide (ZnO), tin dioxide (SnO_2), zinc sulphide (ZnS) or cadmium sulphide (CdS), have an oxidizing action, which helps to remove microbial and organic contaminants [33].

The application of nanotechnology directly in food causes safety worries for the consumers [38,45], thus its use is not much expressive in the present [33]. In counterpoint, nanomaterials applied at food packaging that is not meant to be ingested are more acceptable. Nevertheless, potential risks for consumers exist anyway, such as the release of airborne nanoparticles that could result in unintentional consumption from the escape of nanoparticles into the food packaged [26,38].

According to Sekhon [43], risk assessment procedures are not specific for agri-food nanomaterials, resulting in uncertainty of the nature and severity presented by the potential risks in most cases. The use of nanotechnology in the agricultural sector carries dangers, such as the accumulation of nanoparticles in soils, water and the ecosystem in general [18,23]. However, only a few studies are conducted in this area, and the greater part of the evidences is inconclusive, so there is still much to be learned about the topic [47].

Since the release of modified nanoparticles can cause adverse effects on plants, animals, water, soil and other natural resources, and consequently affect the consumers, in 2012, a new regulation for biocidal products was adopted in the European Union (Regulation (EU) no. 528/2012), which specifically requires the evaluation and approval of active nanomaterials as ingredients in biocides [48].

In view of the possible consequences of implementing nanoproducts in agricultural production, it is important that the authorities plan and implement appropriate risk management strategies in advance, as some of the applications of nanotechnologies in the crops may pose a great risk to workers and consumers because they are directly linked to the food chain [29]. Emphasis is that they may offer danger when applied in consumer products that are directly ingested, which means that the use of nanoproducts has been questioned and needs to be properly investigated [11].

5 Nanotechnology within food processing

The development of nanocomposites and nanoparticles, among others, for food processing industries has grown fast [19,47,49]. The nanotechnology applied at food processing includes processes such as encapsulation (flavour or odour), improvement of texture, viscosity or quality of the product and supplements with better stability and bioavailability [39]. Thus, nanoscience can change the nutritional value and bioavailability of food on its basic meaning [38].

According to Prakash et al. [19] nanotechnology allows to expand the quality of food products, changing their physiochemical characteristics, based on nanosized constituents. It can be also used to make interactive and on-demand kinds of food, which allows the consumer to eat modified food constructed on their own nutritional requirements and tastes.

Nanoparticles have been utilized in food processing aiming to improve its nutritional quality [12,29]. It may help to develop healthier food with fewer fat, sugar and salts incorporated, and in the same way aims to help decreasing food-related diseases [25]. Some examples of nutraceuticals are lycopene, beta-carotenes and phytosterols, which can be incorporated at food in nanoscale, being generally part of healthy foods to avoid the rise in cholesterol levels [25,29].

Bioavailability can be defined as the amount of bioactive compound able to enter the bloodstream [50]. When these compounds are taken orally, they pass through the entire gastrointestinal system before reaching the bloodstream. Therefore, protection against the action of digestive enzymes, pH and temperature of the gastrointestinal tract are required, being necessary to increase the stability of bioactive compounds, and improve their absorption by epithelial cells, to increase bioavailability [11,27,50].

Among the main objectives of nanotechnology in the food chain are nanoencapsulation systems. Nanoencapsulation is an encapsulation method in which nanocomponents (vitamins, preservatives or enzymes) are placed inside nanoscopic capsules [51,52].

The nanoemulsion is composed of a water phase and an oil phase, that is, two non-miscible liquids are combined and a single phase is formed with the help of an emulsifying agent, such as surfactants and co-surfactants. A variety of non-polar molecules, such as mineral and essential oils, free fatty acids and other lipophilic nutraceuticals, can be used in the composition of nanoemulsion [53,54]. Phospholipids are surfactants, since they have a fraction of hydrophobic fatty acid and a hydrophilic one containing phosphoric acid in its structure. Therefore, they can be isolated and used as emulsifiers in the food industry [55]. Lecithin is also commonly used as an emulsifier in the food industry, being extracted mainly from soy, egg yolk, milk, sunflower seeds or rapeseed [56]. Hydrocolloids, like some amphiphilic polysaccharides and proteins, are also good natural emulsifiers and can be used in the preparation of nanoemulsions [57]. Dammak et al. [57] also mention proteins, polysaccharides and saponins as possible emulsifiers in the formulation of nanoemulsions. Nirmal et al. [58] cite as an example the nanoemulsions of lemon myrtle and anise myrtle in water, formed by ultrasonication, which demonstrated good antibacterial activity and stability.

Nanocarriers, such as liposomes, micelles or protein-based carriers, have been utilized as additives, nutritional supplements, to cover the undesirable taste of foods, improve bioavailability, and permit better dispersion of insoluble additives without surfactants or emulsifiers added [25]. Commonly, nanocarriers' systems have different roles: they intensify the bioavailability of bioactive in food in many forms, they might maximize the effects of bioactive, improve the bioaccessibility and absorption by the organism, and can modify the molecular structure, which occurs in the digestion process [59].

Deterioration of food caused by bacterial contamination is a main topic in the food chain, from processing to the storage of food products. In contrast, novel nanoantimicrobials have been tested and present promising results on the preservation of food, likewise extending its shelf life [59]. Silicon dioxide (SiO_2), titanium dioxide (TiO_2) and silver (Ag), in the form of nanoparticles, are added to foods for their anti-caking, coating and antimicrobial properties, respectively [12]. TiO_2 nanoparticles are generally applied in chocolates, cheeses, yogurts, meat and other food products [41,60].

Food colourings can also be applied on a nanometric scale, for example, synthetic lycopene (100 nm) which is added to soft drinks [33]. According to He and Hwang [59] a number of silver nanoparticles or nanocomposites have been approved by the United States Food and Drug Administration Agency (FDA), for use in materials that remain in contact with food as a disinfector. Nanosilver can be considered as one of the greatest antimicrobials used in the food industry [39].

Zein nanoparticles carry edible aromatic compounds and can be implemented in the nanoencapsulation of dietary supplements. Likewise, food protein-based nanotubes can be applied to synthesize vitamins or enzymes on food products and to detect biological and chemical contaminants (nanosensors), favouring food safety [38].

Encapsulation is a process of packaging particles into edible capsules, which can be flavours, pigments, acidulants, nutrients, enzymes, preservatives, etc. [20,61]. The encapsulated material is the filling or core, and the material that forms the capsule is the encapsulant. The type and geometry of the particles are determining factors in the release mechanism of the core. Most compounds used as encapsulants are carbohydrates, both hydrophilic and amorphous, capable of forming a structure by removing water [61].

Among the main objectives of nanotechnology in the food chain are nanoencapsulation systems and the controlled release of nutrients [33,61]. To avoid degradation or loss of flavour during food processing and storage, encapsulation has been applied, improving chemical stability and providing controlled release. Flavour encapsulation helps counteract interactions between flavours, light-induced reactions and oxidation [33]. When designing an encapsulation system, attention must be paid to the physicochemical properties of flavour and carrier, which must not react with flavours [11].

These processes are linked to nanometric transporters, which make it possible to increase the absorption and bioavailability of bioactive substances and minerals in the human body. The growing interest in the stability of flavours in foods is linked to their quality and acceptability [11]. The release of substances can happen, for example, through the increase in temperature, which occurs with the addition of hot water in the preparation of hot drinks or soups. Another form of controlled release is through stability in acidic pH, this way, the release takes place by increasing the pH, causing a controlled administration to different regions of the gastrointestinal tract [33].

Polymers are applied in the formation of nanocomposites with nanomaterials of metal or metal oxide, for application in the food industry. Among these polymers, the most used are low-density polyethylene, gelatin, isotactic polypropylene and polylactic acid. Chitosan, polystyrene, polyvinylprolidone and polyvinyl chloride can also be applied as nanocomposite films, bonded to copper (Cu) or zinc oxide (ZnO) nanomaterials to inactivate pathogens [59].

The material to be encapsulated can be a food or some food compounds, such as ingredients or additives. The most common form of encapsulation in food is the conservation of aromatic compounds, which are usually lost through evaporation, oxidation or interactions between compounds [20,22,61]. During nanoencapsulation, additive substances are enclosed in polymeric nanocomposites. Inorganic additives and compounds such as silver, iron, calcium, magnesium, selenium and silica, at the nanoscale, are applied as preservatives, and to improve the flavour of food. Silica gel microspheres mixed with silica thiosulfate have been applied as an antibacterial agent [25].

Encapsulation goals focus on reducing core interactions with the external environment, delaying changes that can result in loss of aroma, colour or nutrients, separating reactive or incompatible components, avoiding premature substrate reactions, masking undesirable flavours, promoting better core solubility and incorporation in dry systems and allowing controlled release of the material present in the core [22,61].

Nanocomposites can have completely different consequences on the body and environment, depending on the type of application, whether in processing, packaging, or as ingredients in food. Therefore, a clear view of the potential hazards associated with their functionality and applicability is needed to provide further guidance on the safety of food nanotechnology [19,49]. Therefore, an emerging challenge to benefiting from nanotechnology is having the vision to develop it and use it wisely [38].

6 Nanotechnology in the food packaging

Food that is not consumed right after production must be stored in packaging. These packages must serve several functions necessary to maintain the quality of the product. In addition to protecting food from external conditions such as dust, oxygen, light and moisture, it should also serve as a barrier to pathogenic microorganisms, among other harmful substances [39,62]. The packaging must also be safe, inert, with low production cost, lightweight, easy to discard or reuse, waterproof, and resistant to storage and transport [40].

In recent decades, the consumer society has become more complex and demanding; therefore, traditional packaging required improvements to extend the shelf-life of food, monitoring product safety and quality [20]. Recently, active and intelligent packaging has been considered the most popular in researches and the industry, creating a great expectation around this innovative nanotechnology system [51].

The use of edible and biodegradable polymers has been limited due to problems related to their performance, processing and final cost. Thus, the application of nanotechnology to these polymers opens up new possibilities for improving their properties and also the cost-price-efficiency ratio [3]. The most developed branch of food nanoscience is the application to packaging [51]. Nanoscience applied to food packaging includes devices for detection of pathogens, gases, UV protection, and also, the development of more resistant and waterproof polymers [39,62].

Zein nanoparticles have properties that improve the resistance of plastic and bioactive materials, which are used in food packaging [38].

The packages can be characterized as active or intelligent, in accordance with the type of material applied and its function when in contact with food [16,26]. Intelligent and active packaging can cover leaks and act against changes in environmental conditions. The intelligent packages can detect the product deterioration and advise the consumer, while active packages can release additives (antimicrobials, flavours, colours or nutritional supplements) to avoid spoiling [51].

The main trend in the sector involves the development of functional packaging, which has additional properties compared to traditional packaging [12]. The active packages incorporate nanocomposites that prolong the lifetime and guarantee the sensory properties and safety of foods. The mechanism of action comprises the interaction with the food, conditioned or absorbing undesirable compounds, or releasing substances that increase stability [59]. On the other hand, intelligent packaging is related to information on food conditions from nanosensors, which is a very important tool for obtaining information about contaminants, or even allergenic substances in food [33].

Biodegradable packaging materials, derived from renewable sources, have been the target of interest in the food industry. Bionanocomposites applied to packaging, in addition to protecting food and increasing its shelf life, can also be considered ecologically correct, as its application in packaging reduces the need for the use of plastic materials, thus reducing environmental pollution [38].

Biodegradable polymers are typically composed of synthetic polymers such as poly(lactic acid), polyglycolic acid, poly(lactic-*co*-glycolic acid), poly(ε-caprolactone), polymethylmethacrylate and poly(amino acid). They can also consist of natural polymers such as agarose, sodium alginate, chitosan, collagen and fibrin [11]. Polylactic acid (PLA) is considered one of the most promising materials, due to its biocompatibility, thermoplasticity and good processability. PLA and clay nanocomposites are used to improve barrier properties against water vapour transmission due to their mechanical properties [19].

Antioxidant substances can be incorporated into plastic films, papers or bags, being later released, preventing oxidative degradation in food and inhibiting oxidation reactions when there is interaction with free radicals and peroxides, consequently extending the shelf life of the product [63,64]

Since packages containing antioxidant substances have commercial potential, but some food safety criteria must be obeyed, the use of some natural antioxidants has gained interest. Substances such as phenolic and organic acids, plant extracts (teas, herbs, etc.) and polyamines can be applied in food packaging. These natural substances generally have a high production and processing value, so the development of these packages always adds the smallest possible amounts of these compounds, to enable their applications and commercialization [51].

Antimicrobial packaging is another promising type of active packaging. It is constructed from antimicrobial agents that are directly incorporated or immobilized in the packaging material [51]. The material with the highest antimicrobial efficiency is silver because it has good stability at high temperatures and low volatility [3]. Silver is claimed to be effective against numerous strains of bacteria, such as *Escherichia coli, Enterococcus faecalis, Staphylococcus* (*aureus* and *epidermidis*), *Vibrio cholerae, Pseudomonas* (*aeruginosa, putida, fluorescens* and *oleovorans*), *Shigella flexneri, Bacillus* (*anthracis, subtilis* and *cereus*), *Proteus mirabilis, Salmonella enteric, Typhimurium, Micrococcus luteus, Listeria monocytogenes* and *Klebsiella pneumoniae* [39,51].

Magnesium dioxide (MgO_2) and zinc oxide (ZnO) nanoparticles are also highly efficient in destroying microorganisms [51]. In addition, they are cheaper than silver and therefore more widely used. Silicon dioxide (SiO_2) and titanium dioxide (TiO_2) nanoparticles can also be incorporated to develop active O_2 absorbent packaging, preventing food spoilage by oxidation [33]. Indeed, the nanoparticles incorporated in food packaging materials can help track any physical, chemical or even biological modification during the food chain [25].

The development of antioxidant packaging is an innovative technology for preserving foods that are sensitive to oxidation. Its application consists of incorporating antioxidant substances into plastic films, papers or bags that will be released to protect food, by inhibiting through the reacting with free radicals and peroxides, extending their shelf life [64]. Some natural antioxidants can be added to packaging, such as phenolic acids, organic acids, plant extracts and polyamines. Since normally, these natural substances are more expensive than synthetic ones, the development of active packages using minimal amounts of these compounds is desirable for their large-scale production [51].

Nanoemulsions are added to foods in the form of functional components. They can be present in small particles, with a unique viscosity, transparent texture and pleasant to the touch [51]. Due to the poor light scattering of the particles in nanoemulsions, they are suitable for incorporation into optically transparent products such as soft drinks and fortified waters, whitening cosmetics, sauces and soups [11]. They are produced by high-pressure homogenizers or microfluidizers with a diameter smaller than 50–1,000 nm [65]. In addition, they reduce the need to add stabilizers, for example in the decontamination of food packaging and equipment's, which can be done with nanomicelles containing natural glycerin. They can also help to remove pesticide residues from vegetables and fruits [51]. A micellar system composed of oil droplets suspended in a water phase is referred to as an oil-in-water nanoemulsion, while a reverse micellar system, composed of water droplets suspended in an oil phase is referred to as a water-in-oil nanoemulsion [11,65].

Packaging is essential in the food industry, as it constitutes an important strategy and a competitive advantage in the market. It becomes a constant challenge to attend to consumer demands and develop modern and practical packaging that preserves food while being economical and environmentally viable [51].

7 Challenges for the sector

The challenges faced by the sector are related to maintaining growth and moving towards commercialization, but research demands time and high investments. Likewise, health and environmental risks are still unknown, restricting their applicability. Although natural nanomaterials have been safely applied to food, nano-engineered products can pose specific risks [18].

The future scenario of the agro-industrial sector lacks the development of public policies combined with social participation, in the sense of following the process of regulation of new technologies, especially those that bring unpredictable impacts, such as nanotechnology [33]. The regulation of nanoenabled agri-food products is still pending in most countries. It is necessary to discuss how this regulation will be carried out. Regulatory options range from self-regulation to authorizations, standards and disclosure requirements, and also limitations on data collection [18].

The advantages of applying nanotechnology are generally well described, as opposed to the potential toxic effects and impacts, which have received less attention. The most dangerous activities related to nanomaterials have an emphasis on industry, such as working in the generation of nanomaterials, handling nanomaterial powder, performing maintenance on equipment used in the creation of nanomaterials, cleaning of sites, waste and dust collection systems, and services for machining, grinding, drilling, or other rupture mechanisms for these materials [66].

The understanding of the potential toxicity after oral ingestion of nanoparticles is still very recent. Related studies that discuss the oral consumption of the products are limited, only a few studies have compared the toxicity of the nanoformulated and conventional forms of the same chemical species. Thus, the data are insufficient to draw general conclusions [40].

The most common exposure routes to nanoparticles are inhalation, oral ingestion and skin contact [32,34,37]. The National Institute for Occupational Safety and Health (NIOSH) emphasizes that the recommended concentration for contact with nanoparticles depends on their type [32]. Dermal contact occurs through the use of hygiene products such as creams and make-up, among others [67]. Ingestion occurs through the consumption of water or foods that contain or remain in contact with nanoparticles, such as in packaging [37,40].

The understanding of the risks of nanomaterials along the food supply chain requires improvements. In the field of nanotechnology, methods should be developed based on the unique properties of nanoparticles, as conventional methods are not efficient in this case. Various cytotoxic evaluation methods may be needed to assess the destiny of nanoparticles in human or animal bodies, which require a precise characterization technique. Another problem is the lack of a regular and systematic classification of nanomaterials. The method of preparation and synthesis of nanoparticles in food products should be classified and published, as the absence of such classifications creates consumer reluctance to use nanoproducts [30].

8 Conclusions

In resume, the advantages of applied nanoparticles in the food industry are well known and well described, also they have a significant contribution to achieving food safety and to growing healthier food.

The packaging is the sector in which nanoscience is more investigated and utilized, moreover the issues based on consumers' safety are smaller, given that the nanoparticles are not directly added to food. Thus, currently, these products are more commercialized, because they are better accepted by the consumers.

Finally, it can be concluded that considering that nanotechnology and nanoscience are still recent, more researches is needed to manage the expansion within the food chain. Same way, knowledge about the long-term effects in the environment, and more importantly, in the human body, is required, because there is a lack of information on this area.

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