The Sustainability Challenge of Food and Environmental Nanotechnology: Current Status and Imminent Perceptions

Gitishree Das 1, Jayanta Kumar Patra 1,*, Spiros Paramithiotis 2,*, and Han-Seung Shin 3

1 Research Institute of Biotechnology & Medical Converged Science, Dongguk University-Seoul, Ilsandong-gu, Gyeonggi-do 10326, Korea; gdas@dongguk.edu
2 Department of Food Science and Human Nutrition, Agricultural University of Athens, GR-11855 Athens, Greece
3 Department of Food Science and Biotechnology, Dongguk University-Seoul, Ilsandong-gu, Gyeonggi-do 10326, Korea; spartan@dongguk.edu
* Correspondence: jkpatra@dongguk.edu (J.K.P.); sdp@aua.gr (S.P.)

Received: 8 November 2019; Accepted: 29 November 2019; Published: 2 December 2019

Abstract: Nanotechnology is a connection among various branches of science with potential applications that extend over a variety of scientific disciplines, particularly in the food science and technology fields. For nanomaterial applications in food processing, such as antimicrobials on food contact surfaces along with the improvement of biosensors, electrospun nanofibers are the most intensively studied ones. As in the case of every developing skill, an assessment from a sustainability point of view is necessary to address the balance between its benefits to civilization and the unwanted effects on human health and the environment. The current review aimed to provide an update regarding the sustainability of current nanotechnology applications in food science technology, environment, and public health together with a risk assessment and toxicity evaluation.

Keywords: antimicrobials; biosensors; electrospun nanofiber; food processing; nanotechnology; sustainability; environment; human health

1. Introduction

Nanotechnology was first hinted at by Richard Feynman during a speech at the annual meeting of the American Physical Society in December 1959. Nanotechnology concerns the use of nanomaterials at a nanometric scale in order to take benefit of the specific physico-chemical properties occurring in this size range. Over the next two decades, the theoretical knowledge and analytical tools for nanotechnology were established, which led to the discovery of fullerenes and carbon nanotubes a few years later. Nanotechnology, being the intersection between physics, chemistry, materials science, engineering, and modern molecular biotechnology, has a number of prospective uses. However, every emerging technology needs to be balanced between the benefits for human civilization and its unwanted effects on environment and life. In the following paper, an attempt was made to present this balance with reference to food nanotechnology by discussing the most typical applications and also discussing advances in green biotechnology together with risk assessments and toxicity evaluations of novel nanomaterials for the purpose of legislation as well as public acceptance in terms of food.
2. Nanotechnology and Its Potential Applications in Food Science Technology, Environment, and Human Health

Nanotechnology is extensively applied in the everyday life of human beings in almost all fields. It has appeared as a high-tech development in the field of agriculture and food with the potential to increase global food production along with an increase in the nutritional value, quality, and safety of food [1–3]. Progress in the arena of nanotechnology has enabled a quite wide and diverse variety of applications in food technology which includes food additives, food safety, nano-delivery systems, biosecurity, nanotoxicity, etc. [1,4–7]. A number of potential applications for nanotechnology in the food and agriculture sector has been presented by He et al. [5] (Table 1, Figure 1). The use of nanomaterials as processing aids, antimicrobials for surface contact with foodstuffs, and also in the manufacture of biosensors and electrospun nanofibers are the most expansively studied factors which are discussed in the current review along with their pros and cons.

![Diagram of Food Nanotechnology Applications](image_url)

**Figure 1.** Application of food nanotechnology in various fields. Reproduced with permission from He et al. [5] (originally Figure 1).
### Table 1. Different examples of nano-based food products.

| Sector                     | Application                  | Nanomaterials                                                                 | Manufacturer                        | Current Status                                         | Note                                                                 | Reference |
|----------------------------|------------------------------|------------------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------|----------------------------------------------------------------------|-----------|
| Food processing            | Color additives              | TiO<sub>2</sub>                                                               | Exempt from certification           | <1% by weight of the food                              |                                                                    | [8]       |
|                            | Synthetic iron oxide         | Exempt from certification                                                    |                                     | <0.25% (for dogs and cats) and 0.1% (for human) % by weight of the finished food |                                                                    | [8,9]     |
|                            | ZnO, iron oxide, aluminum oxide, silicon dioxide, cobalt oxide, manganese oxide (E530) | Authorized by EC 10/2011                                                      |                                    | Authorization based on conventional particle size       |                                                                    | [10]      |
|                            | Additive or polymer production aid | Titanium nitride                                                             | Authorized by EC 10/2011           | No migration reported. Only to be used in PET bottles up to 20 mg/kg |                                                                    |           |
|                            | Food processing              | Carbon black                                                                 | Authorized by EC 10/2011; no longer authorized by the US FDA as additives | <2.5% w/w in the polymer                              |                                                                    |           |
|                            | Preservatives                | Silver-silica                                                               | Nanox Intelligent Materials        | FCN No. 1235. <4 ppm by weight of silver as an antimicrobial agent blended into polymers |                                                                    | [11]      |
|                            | Flavor carrier               | Silicon dioxide (E551)                                                       | Authorized by EC1334/2008           | <10,000 mg/kg, excluding foods for infants and young children |                                                                    | [12]      |
|                            | Marking fruit and vegetables | Silicon dioxide (E551)                                                       | Exempt from certification           | <2% of the ink solids                                  |                                                                    | [8]       |
|                            | Anticaking agents            | Silicon dioxide (E551)                                                       | REG<sup>b</sup>                     | <2% by weight of the food                              |                                                                    | [13]      |
|                            | Nutritional dietary supplement | Copper oxide, iron oxide                                                     | Approved for animal feed            |                                                        |                                                                    | [14]      |
|                            |                               | ZnO                                                                          | GRAS<sup>c</sup>                   |                                                        |                                                                    |           |
|                            | Pesticides detection         | Zinc Oxide QDs                                                               | R&D                                 |                                                        |                                                                    | [15]      |
|                            | Pathogens detection          | Magnetic nano-sensors                                                        | R&D                                 |                                                        |                                                                    | [16,17]   |
|                            |                               | Plasmonic nano-sensors                                                       |                                     |                                                        |                                                                    | [18]      |
|                            |                               | Fluorescent nano-sensors                                                     |                                     |                                                        |                                                                    | [19]      |
Table 1. Cont.

| Sector                        | Application                                      | Nanomaterials                          | Manufacturer                      | Current Status            | Note                                                                 | Reference |
|-------------------------------|-------------------------------------------------|----------------------------------------|-----------------------------------|---------------------------|----------------------------------------------------------------------|-----------|
|                               | Toxins detection                                | Fluorescent nano-sensors               | R&D                               |                           |                                                                      | [20]      |
|                               |                                                  | Plasmonic nano-sensors                 |                                   |                           |                                                                      | [21]      |
|                               |                                                  | Phosphorescent QDs                     |                                   |                           |                                                                      | [22]      |
|                               | Food contact packaging                          | Chitosan/nano-silica coating           | Tested on longan fruit            |                           |                                                                      | [23]      |
|                               |                                                  | Poly-ε-caprolactone                    | Tested on fresh-cut “Red Delicious” apples |                           |                                                                      | [24]      |
|                               | Edible film/coating                             | Nano-emulsion/quinoa protein/chitosan  | Tested on fresh strawberries      |                           |                                                                      | [25]      |
|                               |                                                  | Bio-nano-hybrid pectins and LDH-salicylate | Tested on fresh apricots         |                           |                                                                      | [26]      |
|                               |                                                  | Nano-emulsion with lemongrass essential oil | Tested on fresh-cut Fuji apples |                           |                                                                      | [27]      |
|                               |                                                  | Bentonite (Al₂O₃SiO₂nH₂O)               | GRAS                              | US FDA 21CFR184.1155     |                                                                      | [28]      |
|                               | Flame retardation additives, gas barrier, etc. | Montmorillonite                        | PolyOne Corporation Nanocor® Inc. | FCS Inventory            | FCN No. 1163                                                         | [11]      |
|                               | Prevent abrasive wear                           | Montmorillonite chromium (III) oxide   | Toyo Seikan Kaisha Limited and Nanocor Incorporated | FCS Inventory | FCN No. 932                                                        | [26]      |
|                               |                                                  | Nano-emulsion with lemongrass essential oil | Oerlikon Balzers Coating AG, Oerlikon Surface Solutions AG | FCN No. 1839. For use at a thickness not to exceed 200 nm, not for use in contact with infant formula and human milk | [27]      |
|                               | Prevent abrasive wear Heating enhancer in      | Titanium aluminum nitride              | Balzers Aktiengesellschaft         | GRAS                      | FCN No. 302. The maximum thickness of the surface coating shall not exceed 5 mm | [28]      |
|                               | polyethylene terephthalate (PET) polymers       |                                        |                                   |                           |                                                                      |           |
|                               |                                                  | Tin antimony oxide                     | Nyacol Nano Technologies, Inc.    | FCS Inventory             | FCN No. 1437. <0.05% by weight of the polymer                        | [11]      |

- FCS: Effective Food Contact Substance (FCS) Notifications;
- REG: Food additives for which a petition has been filed and a regulation issued;
- GRAS: Generally Recognized as Safe;
- E numbers are codes of specific substances used as food additives approved by the European Food Safety Authority (EFSA).
- EC: European Commission;
- FDA: United States Food and Drug Administration;
- R & D: Research & Development;
- Layered double hydroxide. Reproduced with permission from He et al. [5].
2.1. Nanomaterials in the Food Processing Sector

There have been enormous uses of nanotechnology in the food processing sector which include the formulation of novel functional nanomaterials for applications in the food, microscale and nanoscale processing, manufacture of new foodstuffs with enhanced properties and various design of instruments and methods for their possible use in bio-safety and food security [29]. Nanotechnology offers effective approaches in food processing regarding improvement of physico-chemical characteristics of foodstuffs along with improvement in nutrient constancy and bioavailability. Some of the uses of nanotechnology in food sector industries are discussed below. Titanium dioxide and silica dioxide have been exclusively used as processing aids and their use as food additives is allowed within the European Union under the codes E171 and E551, respectively. Titanium dioxide is used mostly as a color enhancer. Weir et al. [30] reported that the highest TiO$_2$ content (normalized per serving) was estimated in candies, including chewing gums, chocolate, etc., reaching as higher as 100 mg Ti, whereas dairy products contained less than 0.06 mg Ti. Silicon dioxide, in contrast, is basically used as an anti-caking agent; however, its use in food model preparation for xenobiotic analysis offers significant advantages [31]. Recently, the French government has banned the sale of food products containing TiO$_2$ starting from 1 January 2020 [32]. Nanoencapsulation (i.e., encapsulation in a protective envelope of a nanometric scale) may offer significant advantages and new possibilities. The variety of nanocarriers, nanoencapsulation approaches, conditions, and formulae must be nominated as per the food matrix characteristics and the type of encapsulated compound [33]. Research is primarily dedicated to the effective incorporation of lipophilic compounds such as fatty acids, antioxidants, carotenoids, and vitamins [34,35]. A wide range of delivery systems has been described to expand the compatibility between the food matrix and the bioactive compound, provide adequate protection against chemical and physicochemical degradation during specific processing or storage conditions, enhance controlled release upon specific environmental stimuli, and to prolong the antimicrobial potential of the encapsulated antimicrobial compounds. These are the principles on which the structural design of systems for effective delivery of bioactive compounds have been comprehensively studied [36,37].

2.2. Nanomaterials in Food Contact Surfaces

The use of nanocomposites for food contact surfaces has become an area of intensive research. More accurately, the antimicrobial potential of metals and their oxides currently employed as well as their consequences on the mechanical and thermal properties on packaging has been studied at length. Regarding the former, the antibacterial potential of nanoscale silver is already known. There are numerous instances of silver incorporation in glass and graphene oxide-inhibiting biofilm formations [38] and in packaging ingredients, like polyvinylpyrrolidone (PVP), cellulose, low-density polyethylene, etc., that exhibit good antibacterial activity against both Gram-positive and Gram-negative species and, in some cases, enhancing the physicochemical stability of the foodstuffs. Another class of compounds, termed photocatalytic nanoparticles, has also been extensively considered. Moreover, the uses of TiO$_2$-based polymer coating are effectively applied against biofilm-forming foodborne pathogens [39]. Apart from using metals and their oxides, nano-emulsions have been utilized in improving the antimicrobial potential of compounds. Otoni et al. [40] have described the development of edible films from pectin, papaya puree, and cinnamaldehyde emulsions. Donsi et al. [41] created a film consisting of modified chitosan and containing a nano-emulsion of mandarin essential oil. Besides the antimicrobial activities, nanocomposites are also being utilized to significantly improve basic packaging properties. These properties include protection from physico-chemical or microbiological quality deterioration that is generated from exposure to environmental stimuli. This improvement is accredited to the enhancement of the barrier properties against gases, volatile compounds, and moisture migration along with mechanical and heat resistance [42].
2.3. Nanotechnology in Quality and Safety Management of Food

The invention of improved biosensor-based nanotechnology has enabled its potential applications in food-based safety management for detecting both the chemical and biological contaminants. The most extensively studied approaches involve the exploitation of silicon-based nanowires on the basis of their biocompatibility and tunable electrical properties and gold nanoparticles due to the fact of their biocompatibility, ideal optical performance, controlled manufacture, and carbon nanotubes, and their dual application in electrodes and transducer components.

Contaminants, such as allergens, toxins, and pesticides, have been efficiently detected using such biosensors. Regarding allergen detection, improvements have included methods for the discovery of the Ara h1 peanut allergen in chocolate candy bars through a nanobead-enhanced optical fiber surface plasmon resonance biosensor [43], foreign protein contamination (ovalbumin) in whole milk by combining immunomagnetic separation and surface-enhanced Raman scattering [44], and soy protein in soy products by a long-wavelength fluoroimmunoassay by means of a conjugate made up of anti-soy protein antibodies bound to Nile blue color doped silica nanoparticles [45].

The enhancement of biosensor technology for bacterial and mycotoxin detection has drawn specific attention [46,47]. Efficient mycotoxin detection was also conveyed by many authors [48,49]. Several biosensors have been developed for pesticide detection also [50].

2.4. Electrospun Nanofiber of Food Interest

There is a growing interest in the use of electrospun nanofibers in food sector industries, particularly in the encapsulation of new food ingredients, enzymes, and other types of bioactive compounds along with the electrospinning of biopolymers for food additives, novel packaging, food sensors, food coatings, and flavor enhancement, etc. (Figure 2) [51–56].
These applications include active food packaging and preservation of nutrients, enhancing the texture and nature of the food, etc. There are a number of examples of the use of electrospun fibers in the food sectors, such as the addition of antimicrobial agents to electrospun fibers and the use of them in packaging materials for increasing the shelf-life of foods. Natural polymers, such as alginate, chitosan, collagen, gelatin, etc., are being electrospun and tested for their medical applications. Furthermore, food materials, such as zein, soy protein, whey protein, etc., are also being electrospun for their potential applications in the food sector [57,58]. Additionally, intelligent active packaging materials are also being created by electrospun processes for the integration of biosensors into fibers to indicate the expiry date of food products [59]. Fabra et al. [60] reported the use of a bio-based polyester multilayer packaging material with high barrier interlayer electrospun zein nanofibers for food packaging applications. Another application of electrospinning technology is in the case of chocolate making, where the use of electrospinning results in a lower amount of chocolate sauces and the production of fiber particles give varied texture and mouth feeling as compared to bulk chocolate particles [53]. Kriegel et al. [61] introduced eugenol into polyvinyl alcohol and cationic chitosan blended with a Gemini surfactant (Surfynol 465) and tested its promising antibacterial activities [61]. Conservation of active bioactive compounds through a process of encapsulation in the electrospun fibers is one of the most extensively studied fields in the application of electrospun nanofibers in food technology, and it is considered...
one of the most efficient techniques to protect highly sensitive compounds from various adverse environmental conditions [55]. Folic acid is one example of this application and its beneficial effects, as without any coating it is vulnerable to degradation when exposed to light and acidic conditions. However, when it is encapsulated within sodium alginate-pectinpoly nanofibers, almost 100% of the folic acid is retained after 41 days of storage in the dark at pH 3 as presented by Alborzi [62]. Apart from encapsulation of vitamins and minerals, electrospun fibers techniques are also used for delivery of probiotic bacteria [55,63]. Liu et al. [64] used an aqueous solution containing two edible polysaccharides, pectin and pullulan, for encapsulation of probiotic bacteria Lactobacillus rhamnosus GG [64].

2.5. Antimicrobial-Rich Nanoparticles in the Food Sector

Spoilage of food materials is caused due to the contamination of food that leads to the growth and proliferation of pathogenic microorganisms, such as bacteria, fungi, food- and water-borne pathogens, etc., which results in the loss of quality of the food [65,66]. Basically, the contamination of food materials is caused due to the fact of exposure to the environment, faulty food processing, and low-quality packaging [65,66]. In order to tackle such issues, there is a need for the development of effective antimicrobial food processing and packaging material which should be safe, effective, and low cost. Besides, the safety evaluations for the active antimicrobial food packaging materials equipped with nanoparticles which can effectively prevent the proliferation of pathogens and protect food from the adverse environment along with increasing the shelf-life of the foods is essential for the future. In such cases, nanomaterials can play a significant role in contending with harmful pathogens and in protecting food [65,67]. Recently, a number of nano-based antimicrobial agents have been tested as food packaging materials, and they have been proven to show enhanced properties such as thermal stability, pH resistance, and other physico-chemical potentials [65,67–70]. There are several ways of using the antimicrobial compounds as packaging materials in food packaging systems which include the addition of a packet of volatile antimicrobial agents in the packing system which will diffuse slowly into the packet and provide protection to the food from external contaminations. Another way is to directly mix the antimicrobial agents into the polymers used as packaging materials. The other way is to coat the antimicrobial compounds on the surface of the packaging materials or utilize antimicrobial packaging materials directly [66,70,71]. However, effective safety management of these materials is essential in order to protect human health and the environment. Possible mechanisms of action for the effectiveness of antimicrobial agents depends on the controlled release of the active compounds into a system that can provide a durable antimicrobial packaging material, and this can be achieved by the use of nano—micro-structures, such as nanofibers, nano-capsules, and micro-capsules, in the packaging system which helps in the gradual release of the active compounds and also provides mechanical potential for the packaging materials [70]. These types of improved materials are also equipped with smart technologies, such as indicators and dyes, which shows the quality of the product, durability, temperature, pH, and degree of contamination of the food [70,72].

3. Sustainability of Food Nanotechnology

A rapid development in novel nanomaterials and related applications has been witnessed over the last decade. Moreover, this tendency is likely to continue further in the future. A number of promising opportunities have been identified for nano-based technologies which are intended for the improvement of sustainability in agriculture and food systems (Figure 3) [73,74]. These include sensors for testing chemicals, measuring physical, chemical, or biological properties, and for detecting pathogens or toxins in products; advanced techniques for detection and control of harmful pathogens and to increase food safety; technology for water treatment in agricultural fields; nano-based fertilizers, etc. [73–75]. However, there are many apprehensions concerning their influence on the environment and human health. Addressing these concerns, the European Food Safety Authority (EFSA) has developed and published a practical approach for real risk assessment on the use of engineered
nanomaterials in food and food chain [76]. Within this document, the lack of consistent detection methods, identification, and classification of engineered nanomaterials, especially in multifaceted ecological samples, is mentioned. This issue was also recently talked about by the Organization for Economic Co-operation and Development [77].

The aim of green nanobiotechnology has been adequately presented by Hutchison [78] and Maksimovic and Omanovic-Miklicanin [79]. These may be abridged into two cornerstones: the enlargement of positive effects on the health of humans and well-being and the diminishment of the hostile effects on the environment. Nevertheless, this attitude is significantly hindered by the aforementioned lack of reliable methodology and our inadequate knowledge of the factors which are responsible for the toxic properties of nanomaterials. Study of the structure of various food products at the nanoscale range is a developing area in the field of nanotechnology and, in the near future, it will be a reality to assess the food structure and develop new food materials at the nanoscale range.

3.1. Nano-Based Sensors

Nano-based sensors and probes have proved to be beneficial for the improvement of agricultural productivity as well as in food protection and preservation [73,74,80–82]. There are numerous examples of nano-based sensors and devices that detect various types of pathogens, toxins, and contaminants in food products and in packaging materials [74,75,82,83]. Regardless of several remarkable achievements, accomplishing the careful and delicate recognition of specific pathogens and toxicants in food remains challenging. The capacity to differentiate between live and dead pathogenic microbes in the food system among a large number of pathogens is always challenging, and it needs to be studied extensively [84]. Furthermore, the manufacture of specific types of nanosensors targeting specific functions in the food system is also challenging [85].

3.2. Nano-Based Control of Pathogens

The application of nano-based materials in food packaging, for protection against harmful pathogens and to increase the shelf-life of food materials by nano-coating and smart packaging,
is commercially used [86–88]. However, there are a number of issues which prevent the smooth implementation of these nano-based materials for food safety. The exact mechanism of such effects on pathogens is not fully understood. Furthermore, the effect of environmental parameters, such as temperature, pH, light, and excretes from food, while packaging is also not properly explained [89]. Finally, the safety of nano-empowered packaging materials which are used straightway on food products and food processing equipment needs to be proved in order to avoid any unintentional negative results on human health [86,89].

3.3. Nano-Based Fertilizers

There is a current and growing body of literature on the development of nano-based materials as nano-fertilizers for agrochemical delivery [90–93]. Notwithstanding being an extremely active research field, approaches to ensuring targeted delivery to specific organisms through the use of biological materials, such as antibiotics and other hormones or materials, to be triggered at extreme environmental conditions are usually lacking. A number of challenges, such as the nature of interactions between plants and nanomaterials, the effect of nanomaterials on plant growth, the nutritional value of the food as well the quality, are still not clear and, thus, prevents the effective use of smart nano-based fertilizers in agriculture [73,92].

3.4. Nanoparticle Toxicity

The cause of nano-toxicity and its future nature has been extensively studied recently. There are numerous entrance points for release of engineered nanomaterials into the environment which includes direct application to an environmental compartment (either intentionally or through unintentional product degradation), wastewater treatment plant effluent, and wastewater treatment plant sludge [94,95]; yet, it is hard to guess the pertinent absorptions of nanoparticles that are released at any given point of time [94]. The amplified nanoparticle utilization in a number of applications including food industries has raised a major concern for food safety and the potential consequences on public health and the environment [96]. The effects on aquatic and terrestrial systems along with associated factors have been recently reviewed by Bundschuh et al. [97]. A number of portions of the human body, especially the skin, lungs, and the intestinal tracts, are in continuous exposure to the outside environment and these parts are vulnerable to nanoparticle exposure [98]. In such cases, the importance of size, shape, chemical composition, solubility, surface properties, and aggregation have been very early recognized [99]. Size-dependent toxicity has also been exhibited in numerous studies involving human lung cells [100]. Nanoparticle shape also significantly affects exerted toxicity [101–103]. A variety of nanoparticles, with respect to their size and configuration, could be highly lethal to cells by causing oxidative stress or/and organelle damage [98]. The effect of surface properties on toxicity level has also attracted significant attention, since a variety of coating ingredients, such as proteins, polysaccharides, various surfactants, and citric acid, have been effectively applied [104]. A better understanding of the effect of nanoparticles on various parts of the human body is presented in Figure 4. It is shown that exposure of nanoparticles to various organs may cause specific diseases in that particular organ; for example, when nanoparticles are inhaled, they may cause diseases like emphysema, bronchitis, lung cancer, and neurodegenerative diseases, and further, when intestinal tracts are affected by these nanoparticles, they may result in cancer-related diseases [98,103].
Figure 4. Various types of contact paths linked to nanoparticles and various diseases as proven by epidemiological and clinical studies. Reproduced with permission from Buzea et al. [98] (originally Figure 7).

Besides, a number of risk assessment efforts have been undertaken in order to predict the amount of nanoparticles exposed to the environment from various sources, and a summary of this has been presented [94,105,106] which shows that a large dynamic range of nanoparticles are exposed to the environment, and it requires an accurate methodology to measure it. A multidisciplinary tactic which merges experimental, computational, and theoretical methods could be helpful in finding a risk assessment method in order to confirm the eco-toxicological issues linked with the engineered nanoparticles and their exposure to food and the environment.

3.5. Operational Approaches

Detection of nanomaterials in the food and various environmental products is a very challenging task, mostly due to the fact of their reactive nature and the concomitant transformations. An effective analysis would include a sample preparation step that would facilitate detection and characterization. Ideally, it should remove any interfering substances and preserve the state and nature of the nanomaterial; however, it is influenced by the analytical step that follows. In general, sample preparation includes a number of steps such as the homogenization of the sample, extraction, and stabilization of the nanomaterials. The type of solvents used in the initial step may affect the second step significantly. Thus, apart from the matrix, the morphological characteristics of the nanomaterial and the subsequent separation technique need to be considered. In Table 2, representative studies for the detection of inorganic and organic nanoparticles in the biological samples are summarized. In the case of inorganic nanoparticles, matrix interference is removed by chemical or enzymatic digestion that may be assisted by microwaves or sonication followed by solid or liquid phase extraction process. After extraction has taken place, a fractionation method precedes and is united with a detection one.
Table 2. Representative studies for the recognition of nanomaterials in biological entities.

| Target Nanoparticle (NP) | Matrix         | Sample Preparation                                                                 | Detection/Quantification Method | Comments                                                                                                                                                                                                 | Reference |
|--------------------------|----------------|------------------------------------------------------------------------------------|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Ag NPs                   | chicken meat   | sonication followed by proteinase K treatment                                       | SP-ICP-MS                      | The established method exhibited good performance with respect to trueness, repeatability, reproducibility, and ability to determine Ag NPs transformed into silver sulfide.                                                | [107]     |
| Ag NPs                   | sock fabric    | HNO$_3$/H$_2$O$_2$ digestion                                                        | ICP-OES                        | The sock manufacturing process may control silver release; high silver concentration will end with the wastewater treatment facility limiting the disposal of the biosolids as agricultural fertilizers.                     | [108]     |
| Cu NPs                   | topsoil        | colloidal soil suspensions digested by HNO$_3$/HCl/H$_2$O$_2$ and microwaves       | ICP-MS                         | The significance of dwell time, background removal, and sample dilution as methods for optimization and recovery maximization were highlighted.                                                            | [109]     |
| TiO$_2$ NPs              | water suspended particulate matter | filtration                                                       | SP-ICP-MS                      | TiO$_2$ NPs from sunscreens are possibly released into the water but settle into the sediment.                                                                                                         | [110]     |
| TiO$_2$ NPs, Ag NPs, Au NPs | water | none                                                                                           | SP-ICP-MS                      | Lime softening followed by alum coagulation collected with powdered activated carbon adsorption resulted in removal of Au and Ag NPs and almost complete of TiO$_2$ NPs in wastewater.               | [111]     |
| Various fullerenes       | wastewater     | filtration followed by sonication-assisted toluene extraction and partial evaporation | LC-QqLIT-MS                     | The established method was characterized as very effective.                                                                                                                                              | [112]     |
| C$_{60}$ and C$_{70}$ fullerenes | soil and sediment | sonication-assisted toluene extraction and partial evaporation                             | UHPLC-HRMS                     | A fast and sensitive method suitable for the analysis of very complex matrices.                                                                                                                            | [113]     |
| Various fullerenes       | water and sediment | LLE with toluene (water samples); ultrasound extraction and PLE (sediment samples) | UHPLC-MS/MS                   | An effective approach for fullerene analysis in biological entities.                                                                                                                                   | [114]     |
| Graphene and graphene oxide | wastewater biomass | solubilization followed by thermal digestion and reduction | PTA                            | The proposed approach provided had promising results.                                                                                                                                                     | [115]     |
| SWCN                     | sediment       | sonication in the presence of surfactants                                            | NIRF Spectroscopy              | The applicability of this tactic was exhibited.                                                                                                                                                         | [116]     |

NPs: NanoParticles; SP-ICP-MS: single particle inductively coupled plasma mass spectrometry; OES: Optical Emission Spectroscopy; LC-QqLIT-MS: liquid chromatography coupled to a hybrid triple quadrupole linear ion trap mass spectrometry; UHPLC-HRMS: Ultra High Performance Liquid Chromatography coupled with High Resolution Mass Spectrometry; LLE: liquid-liquid extraction; PLE: pressurized solvent extraction; PTA: Programmed Thermal Analysis; SWCN: Single-Walled Carbon Nanotubes; NIRF: Near InfraRed Fluorescence.
Detection was mostly achieved through microscopic and spectrometric techniques. Regarding the microscopic techniques, electron microscopy may provide information on the morphological characteristics and nature of the nanomaterials. However, sample preparation introduces high uncertainty [117]. This issue was addressed, at best, in the liquid samples by application of environmental (or atmospheric) scanning electron microscopy which can be carried out with a basic sample preparation method. Light scattering was initially regarded as a harmonizing approach. However, unequal distribution of the size of the nanoparticles hinders the potential in the complicated samples. This limitation was only partially addressed, at least in liquid samples, by nanoparticle tracking analysis (NTA) [118]. As far as spectrometric techniques are concerned, they may be provided with detection, identification, and quantification of nanoparticles. Inductively coupled plasma-mass spectroscopy (ICP-MS), single-particle ICP-MS (spICP-MS) as well as matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) are mostly used due to the satisfactory size and concentration limit of detection [119] but no information regarding size, shape or aggregation may be obtained. However, this limitation is overruled by coupling with a fractionation technique [120].

Specific characterization of organic nanoparticles, such as fullerenes and carbon nanotubes, have been comprehensively assessed; however, graphene and graphene oxides have not been so exclusively studied. In the latter case, only limited literature is currently available. The most effective approach was described by Doudrick et al. [115] which included chemical reduction of graphene oxide, allowing a competent extraction and separation from background carbon and reliable quantification by programmed thermal analysis (PTA). Information on the size, shape, and degree of accumulation of organic nanoparticles is acquired as in the case of inorganic ones through electron microscopy, light scattering, and NTA techniques. Regarding fullerenes, the separation and extraction process together with the detection and quantification approaches were appraised by Astefanei et al. [121]. In brief, in complex matrices, removal of proteins and surfactants precedes liquid–liquid extraction that is usually employed as such or in combination with ultrasounds using oxidizing agents or salts and toluene. Liquid chromatography coupled with mass spectrometry (LC-MS) is the detection step that is mostly employed. A widespread extraction, separation, and detection process has been described for effective detection and quantification of carbon nanotubes and comprehensively reviewed [122]. Depending on the matrix, a pre-treatment involving chemical or enzymatic digestion, either sonication-assisted or not, is essential. Then, extraction and separation through a variety of approaches, such as asymmetric flow field-flow fractionation (AF4), chromatographic or electrophoretic techniques may take place followed by quantification strategies such as spICP-MS, thermal gravimetric analysis-mass spectrometry (TGA-MS), etc.

Finally, a major challenge is to distinguish between anthropogenic contamination and naturally occurring nanoparticles. In the case of inorganic ones, this may be achieved through the calculation of specific ratios such as Ti to Fe and Ce to La [123,124].

3.6. Measurement Issues

The capacity to quantify the presence of nanomaterials in the food system at a particular time period is a very critical issue for its potential application in the food system [125,126]. These quantifications of the nanomaterials comprise both the preparation and storage of the food products, along with its digestion and channel through the alimentary canal of the digestive system of the humans which is itself a various complicated issue due to the multifaceted nature of the human body and the thermodynamic instability of the nanomaterials [125]. It is also not clear what factors in specific are needed to be quantified. A number of factors are accountable for the establishment of a highly applicable method in the measurement of nanomaterials in the food system that comprise the case of how nanomaterials are added, and it is always essential to identify them whether they are natural or added from external sources as food additives, enhancers or emulsions. Besides, the multifaceted nature of the human alimentary canal also creates further concerns in the measurement and classification of the nanomaterials [125]. A number of analytical methods particularly in a combined form are applied to basically measure
the nanomaterials in the food [125,127]. These methods include microscopy (transmission electron microscopy, scanning electron microscopy), chromatography, spectroscopy (X-ray powder diffraction spectroscopy, energy-dispersive X-ray spectroscopy), centrifugation, chromatography, and other related methodologies [128].

4. Conclusions

There is numerous evidence for the involvement of the science of nanotechnology in almost all steps of the food chain. In addition, novel nanomaterials along with their applications are expected to emerge within the upcoming years. Consequently, it is imperative to discuss these advancements through a green biotechnology perspective. The essential first step towards this direction is the improvement of the analytical tools that will allow accurate and reliable quantification of the planned nanomaterials in a multifaceted environmental sample. Then only will our understanding regarding their conversions and bio-kinetics be improved, allowing for the design of safer nanomaterials with reduced environmental impact.

Author Contributions: Conceptualization, G.D., J.K.P. and S.P.; resources, G.D., J.K.P. and S.P.; writing—original draft preparation, G.D., J.K.P. and S.P.; writing—review and editing, G.D., J.K.P., S.P. and H.-S.S.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful for their respective institutes for the support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Peters, R.J.B.; Bouwmeester, H.; Gottardo, S.; Amenta, V.; Arena, M.; Brandhoff, P.; Marvin, H.J.P.; Mech, A.; Moniz, F.B.; Pesudo, L.Q.; et al. Nanomaterials for products and application in agriculture, feed and food. *Trends Food Sci. Technol.* 2016, 54, 155–164. [CrossRef]

2. King, T.; Osmond-McLeod, M.J.; Duffy, L.L. Nanotechnology in the food sector and potential applications for the poultry industry. *Trends Food Sci. Technol.* 2018, 72, 62–73. [CrossRef]

3. Duefroi, W.; Villares, A.; Peyron, S.; Moreau, C.; Ropers, M.-H.; Gontard, N.; Cathala, B. Nanoscience and nanotechnologies for biobased materials, packaging and food applications: New opportunities and concerns. *Innov. Food Sci. Emerg. Technol.* 2018, 46, 107–121. [CrossRef]

4. Chau, C.-F.; Wu, S.-H.; Yen, G.-C. The development of regulations for food nanotechnology. *Trends Food Sci. Technol.* 2007, 18, 269–280. [CrossRef]

5. He, X.; Deng, H.; Hwang, H.-M. The current application of nanotechnology in food and agriculture. *J. Food Drug Anal.* 2019, 27, 1–21. [CrossRef]

6. Yu, H.; Park, J.-Y.; Kwon, C.W.; Hong, S.-C.; Park, K.-M.; Chang, P.-S. An Overview of Nanotechnology in Food Science: Preparative Methods, Practical Applications, and Safety. *J. Chem.* 2018, 2018, 10. [CrossRef]

7. Dwivedi, C.; Pandey, I.; Misra, V.; Giulbudagian, M.; Jungnickel, H.; Laux, P.; Luch, A.; Ramteke, P.; Singh, A. The prospective role of nanobiotechnology in food and food packaging products. *Integr. Food Nutr. Metab. IFNM* 2018, 5, 1–5. [CrossRef]

8. Code of Federal Regulations (CFR). *Electronic Code of Federal Regulations.* *Title 21: Food and Drugs.* Part 73—Listing of Color Additives Exempt from Certification; The United States Office of the Federal Register (OFR) and The United States Government Publishing Office: Washington, DC, USA, 2018.

9. U.S. FDA. *Color Additive Status List*; United States Food & Drug Administration: Washington, DC, USA, 2015.

10. The European Commission. Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food Text with EEA relevance. *Off. J. Eur. Union* 2011, 12, 1–89.

11. U.S. FDA. *Inventory of Effective Food Contact Substance (FCS) Notifications*; Administration USFaD: Washington, DC, USA, 2018. Available online: https://www.accessdata.fda.gov/scripts/fdcc/?set=IFCN (accessed on 8 August 2018).
12. European Commission. Regulation (EC) No. 1333/2008 of the European Parliament and of the Council of 16 December 2008 on Food Additives. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008R1333 (accessed on 16 December 2008).

13. Code of Federal Regulations (CFR). Title 21–food and drugs. Chapter i–food and drug administration. Department of health and human services. Subchapter B–food for human consumption (continued). Part 172–food additives permitted for direct addition to food for human consumption. Subpart E–Anticakingagents. Sec. 172.480 Silicon Dioxide. Available online: https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfCFR/CFRSearch.cfm?fr=172.480 (accessed on 8 August 2018).

14. U.S. FDA. Food Additive Status List; US FDA/CFSAN Office of Food Additive Safety: Washington, DC, USA, 2018. Available online: https://www.fda.gov/IngredientsPackagingLabeling/FoodAdditivesIngredients/ucm091048.htm (accessed on 7 August 2018).

15. Sahoo, D.; Mandal, A.; Mitra, T.; Chakraborty, K.; Bardhan, M.; Dasgupta, A.K. Nanosensing of Pesticides by Zinc Oxide Quantum Dot: An Optical and Electrochemical Approach for the Detection of Pesticides in Water. J. Agric. Food Chem. 2018, 66, 414–423. [CrossRef]

16. Sun, Y.; Fang, L.; Wan, Y.; Gu, Z. Pathogenic detection and phenotype using magnetic nanoparticle-urease nanosensor. Sens. Actuators B Chem. 2018, 259, 428–432. [CrossRef]

17. Kearns, H.; Goodacre, R.; Jamieson, L.E.; Graham, D.; Faulds, K. SERS detection of multiple antimicrobial-resistant pathogens using nanosensors. Anal. Chem. 2017, 89, 12666–12673. [CrossRef] [PubMed]

18. Perçin, I.; Idil, N.; Bakhshpour, M.; Yilmaz, E.; Mattiasson, B.; Denizli, A. Microcontact imprinted plasmonic nanosensors: Powerful tools in the detection of Salmonella paratyphi. Sensors 2017, 17, 1375. [CrossRef] [PubMed]

19. Banerjee, T.; Sulthana, S.; Shelby, T.; Heckert, B.; Jewell, J.; Woody, K.; Karimnia, V.; McAfee, J.; Santra, S. Multiparametric magneto-fluorescent nanosensors for the ultrasensitive detection of Escherichia coli O157:H7. ACS Infect. Dis. 2016, 2, 667–673. [CrossRef] [PubMed]

20. Sun, A.; Chai, J.; Xiao, T.; Shi, X.; Li, X.; Zhao, Q.; Li, D.; Chen, J. Development of a selective fluorescence nanosensor based on molecularly imprinted-quantum dot optosensing materials for saxitoxin detection in shellfish samples. Sens. Actuators B Chem. 2018, 258, 408–414. [CrossRef]

21. Zhang, C.-H.; Liu, L.-W.; Liang, P.; Tang, L.-J.; Yu, R.-Q.; Jiang, J.-H. Plasmon coupling enhanced raman scattering nanobeacon for single-step, ultrasensitive detection of cholera toxin. Anal. Chem. 2016, 88, 7447–7452. [CrossRef]

22. Zhang, W.; Han, Y.; Chen, X.; Luo, X.; Wang, J.; Yue, T.; Li, Z. Surface molecularly imprinted polymer capped Mn-doped ZnS quantum dots as a phosphorescent nanosensor for detecting patulin in apple juice. Food Chem. 2017, 232, 145–154. [CrossRef]

23. Shi, S.; Wang, W.; Liu, L.; Wu, S.; Wei, Y.; Li, W. Effect of chitosan/nano-silica coating on the physicochemical characteristics of longan fruit under ambient temperature. J. Food Eng. 2013, 118, 125–131. [CrossRef]

24. Zambrano-Zaragoza, M.; Mercado-Silva, E.; Gutiérrez-Cortez, E.; Cornejo-Villegas, M.; Quintanar-Guerrero, D. The effect of nano-coatings with α-tocopherol and xanthan gum on shelf-life and browning index of fresh-cut “Red Delicious” apples. Innov. Food Sci. Emerg. Technol. 2014, 22, 188–196. [CrossRef]

25. Robledo, N.; López, L.; Bunger, A.; Tapia, C.; Abugoch, L. Effects of antimicrobial edible coating of thymol nanoemulsion/quinoa protein/chitosan on the safety, sensorial properties, and quality of refrigerated strawberries (Fragaria × ananassa) under commercial storage environment. Food Bioprocess Technol. 2018, 11, 1566–1574. [CrossRef]

26. Gorrasi, G.; Bugatti, V. Edible bio-nano-hybrid coatings for food protection based on pectins and LDH-salicylate: Preparation and analysis of physical properties. LWT Food Sci. Technol. 2016, 69, 139–145. [CrossRef]

27. Salvia-Trujillo, L.; Rojas-Graü, M.A.; Soliva-Fortuny, R.; Martín-Belleso, O. Use of antimicrobial nanoemulsions as edible coatings: Impact on safety and quality attributes of fresh-cut Fuji apples. Postharvest Biol. Technol. 2015, 105, 8–16. [CrossRef]
28. Code of Federal Regulations (CFR). Electronic Code of Federal Regulations. Title 21: Food and Drugs. Part 184—Direct Food Substances Affirmed as Generally Recognized as Safe. Subpart b-Listing of Specific Substances Affirmed as GRAS; The United States Office of the Federal Register (OFR) and the United States Government Publishing Office: Washington, DC, USA, 2018. Available online: https://www.ecfr.gov/cgi-bin/text-idx?SID=/z9a76b1d7e7a98ae9459d88005ab7058&mc=1&node=pt21.1.73&rgn=div5 (accessed on 8 August 2018).

29. Augustin, M.A.; Sanguansri, P. Chapter 5 Nanostructured Materials in the Food Industry. In Advances in Food and Nutrition Research; Academic Press: Cambridge, MA, USA, 2009; Volume 58, pp. 183–213.

30. Weir, A.; Westerhoff, P.; Fabricius, L.; Hristovski, K.; Von Goetz, N. Titanium dioxide nanoparticles in food and personal care products. Environ. Sci. Technol. 2012, 46, 2242–2250. [CrossRef] [PubMed]

31. Casado, N.; Pérez-Quintanilla, D.; Morante-Zarcero, S.; Sierra, I. Current development and applications of ordered mesoporous silicas and other sol–gel silica-based materials in food sample preparation for xenobiotics analysis. TrAC Trends Anal. Chem. 2017, 88, 167–184. [CrossRef]

32. France bans Titanium Dioxide in food products by January 2020|Sanitary/Phytosanitary/Food Safety, SP2-Prevent or Resolve Barriers to Trade that Hinder U.S. Food and Agricultural Exports|Paris|France (May 09, 2019) FR2019-2431. Available online: https://apps.fas.usda.gov/newsgainapi/api/report/downloadreportbyfilename?filename=France%20bans%20Titanium%20Dioxide%20in%20food%20products%20by%20January%202020_Paris_France_5-3-2019.pdf (accessed on 9 May 2019).

33. Assadpour, E.; Mahdi Jafari, S. A systematic review on nanoencapsulation of food bioactive ingredients and nutraceuticals by various nanocarriers. Crit. Rev. Food Sci. Nutr. 2018, 59, 1–23. [CrossRef]

34. Rodriguez-Ruiz, V.; Salatti-Dorado, J.; Barzegari, A.; Nicolas-Boluda, A.; Houaoui, A.; Caballo, C.; Caballero-Casero, N.; Sicilia, D.; Bastias Venegas, J.; Pauthe, E. Astaxanthin-Loaded Nanostructured Lipid Carriers for Preservation of Antioxidant Activity. Molecules 2018, 23, 2601. [CrossRef]

35. Singh, H.; Kumar, C.; Singh, N.; Paul, S.; Jain, S.K. Nanoencapsulation of docosahexaenoic acid (DHA) using a combination of food grade polymeric wall materials and its application for improvement in bioavailability and oxidative stability. Food Funct. 2018, 9, 2213–2227. [CrossRef]

36. Singh, H. Nanotechnology Applications in Functional Foods; Opportunities and Challenges. Prev. Nutr. Food Sci. 2016, 21, 1–8. [CrossRef]

37. Shishir, M.R.I.; Xie, L.; Sun, C.; Zheng, X.; Chen, W. Advances in micro and nano-encapsulation of bioactive compounds using biopolymer and lipid-based transporters. Trends Food Sci. Technol. 2018, 78, 34–60. [CrossRef]

38. De Faria, A.F.; Martinez, D.S.T.; Meira, S.M.M.; de Moraes, A.C.M.; Brandelli, A.; Souza Filho, A.G.; Alves, O.L. Anti-adhesion and antibacterial activity of silver nanoparticles supported on graphene oxide sheets. Colloids Surf. B Biointerfaces 2014, 113, 115–124. [CrossRef]

39. Weng, X.; van Niekerk, J.; Neethirajan, S.; Warriner, K. Characterization of antimicrobial efficacy of photocatalytic polymers against food-borne biofilms. LWT Food Sci. Technol. 2016, 68, 1–7. [CrossRef]

40. Otoni, C.G.; de Moura, M.R.; Aouada, F.A.; Camilloto, G.P.; Cruz, R.S.; Lorevisco, M.V.; de FF Soares, N.; Mattoso, L.H. Antimicrobial and physical-mechanical properties of pectin/papaya puree/cinnamaldehyde nanoemulsion edible composite films. Food Hydrocoll. 2014, 41, 188–194. [CrossRef]

41. Donsi, F.; Marchese, E.; Maresca, P.; Pataro, G.; Vu, K.D.; Salmieri, S.; Lacroix, M.; Ferrari, G. Green beans preservation by combination of a modified chitosan based-coating containing nanoemulsion of mandarin essential oil with high pressure or pulsed light processing. Postharvest Biol. Technol. 2015, 106, 21–32. [CrossRef]

42. Ghanbarzadeh, B.; Oleyaei, S.A.; Almasi, H. Nanostructured materials utilized in biopolymer-based plastics for food packaging applications. Crit. Rev. Food Sci. Nutr. 2015, 55, 1699–1723. [CrossRef] [PubMed]

43. Pollet, J.; Delport, F.; Janssen, K.; Tran, D.; Wouters, J.; Verbist, T.; Lammertyn, J. Fast and accurate peanut allergen detection with nanobead enhanced optical fiber SPR biosensor. Talanta 2011, 83, 1436–1441. [CrossRef]

44. He, L.; Haynes, C.L.; Diez-Gonzalez, F.; Labuza, T.P. Rapid detection of a foreign protein in milk using IMS–SERS. J. Raman Spectrosc. 2011, 42, 1428–1434. [CrossRef]

45. Godoy-Navajas, J.; Caballos, M.A.; Gómez-Hens, A. Heterogeneous immunoassay for soy protein determination using nile blue-doped silica nanoparticles as labels and front-surface long-wavelength fluorimetry. Anal. Chim. Acta 2011, 701, 194–199. [CrossRef]
46. Goldman, E.R.; Clapp, A.R.; Anderson, G.P.; Uyeda, H.T.; Mauro, J.M.; Medintz, I.L.; Mattoussi, H. Multiplexed toxin analysis using four colors of quantum dot fluororeagents. *Anal. Chem.* 2004, 76, 684–688. [CrossRef]

47. Tang, D.; Tang, J.; Su, B.; Chen, G. Gold nanoparticles-decorated amine-terminated poly (amidoamine) dendrimer for sensitive electrochemical immunoassay of brevetoxins in food samples. *Biosens. Bioelectron.* 2011, 26, 2090–2096. [CrossRef]

48. Feng, R.; Zhang, Y.; Li, H.; Wu, D.; Xin, X.; Zhang, S.; Yu, H.; Wei, Q.; Du, B. Ultrasensitive electrochemical immunosensor for zeronal detection based on signal amplification strategy of nanoporous gold films and nano-montmorillonite as labels. *Anal. Chim. Acta* 2013, 758, 72–79. [CrossRef]

49. Gan, N.; Zhou, J.; Xiong, P.; Hu, F.; Cao, Y.; Li, T.; Jiang, Q. An ultrasensitive electrochemiluminescent immunoassay for Aflatoxin M1 in milk, based on extraction by magnetic graphene and detection by antibody-labeled CdTe quantum dots-carbon nanotubes nanocomposite. *Toxins* 2013, 5, 865–883. [CrossRef]

50. Zhang, S.P.; Shan, L.G.; Tian, Z.R.; Zheng, Y.; Shi, L.Y.; Zhang, D.S. Study of enzyme biosensor based on carbon nanotubes modified electrode for detection of pesticides residue. *Chin. Chem. Lett.* 2008, 19, 592–594. [CrossRef]

51. Mcdonnell, G.E.; Fiorello, A.; Smith, D. Indicator Device Having an Active Agent Encapsulated in an Electrospun Nanofiber. U.S. Patent No. 7,569,359, 4 August 2009.

52. Torres-Giner, S. Electrospun nanofibers for food packaging applications. In *Multifunctional and Nanoreinforced Polymers for Food Packaging*; Lagarón, J.-M., Ed.; Woodhead Publishing: Cambridge, UK, 2011; pp. 108–125.

53. Doyle, J.J.; Choudhari, S.; Ramakrishna, S.; Babu, R.P. Electrospun Nanomaterials: Biotechnology, Food, Water, Environment, and Energy. 2013. Available online: http://dx.doi.org/10.1155/2013/269313 (accessed on 8 August 2019).

54. Noruzi, M. Electrospun nanofibres in agriculture and the food industry: A review. *J. Sci. Food Agric.* 2016, 96, 4663–4678. [CrossRef] [PubMed]

55. Nikmaram, N.; Roohinejad, S.; Hashemi, S.; Koubaa, M.; Barba, F.J.; Abbaspourrad, A.; Greiner, R. Emulsion-based systems for fabrication of electrospun nanofibers: Food, pharmaceutical and biomedical applications. *RSC Adv.* 2017, 7, 28951–28964. [CrossRef]

56. Wang, C.; Wang, J.; Zeng, L.; Qiao, Z.; Liu, X.; Liu, H.; Zhang, J.; Ding, J. Fabrication of electrospun polymer nanofibers with diverse morphologies. *Molecules* 2019, 24, 834. [CrossRef]

57. Shankar, A.; Seyam, A.-F.; Hudson, S. Electrospinning of soy protein fibers and their compatibility with synthetic polymers. *J. Text. Appar. Technol. Manag.* 2013, 8, 1–14.

58. Sullivan, S.T.; Tang, C.; Kennedy, A.; Talwar, S.; Khan, S.A. Electrospinning and heat treatment of whey protein nanofibers. *Food Hydrocoll.* 2014, 35, 36–50. [CrossRef]

59. Kriegel, C.; Arrechi, A.; Kit, K.; McClements, D.; Weiss, J. Fabrication, functionalization, and application of electrospun biopolymer nanofibers. *Crit. Rev. Food Sci. Nutr.* 2008, 48, 775–797. [CrossRef]

60. Fabra, M.J.; Lopez-Rubio, A.; Lagaron, J.M. High barrier polyhydroxyalcanoate food packaging film by means of nanostructured electrospun interlayers of zein. *Food Hydrocoll.* 2013, 32, 106–114. [CrossRef]

61. Kriegel, C.; Kit, K.M.; McClements, D.J.; Weiss, J. Nanofibers as Carrier Systems for Antimicrobial Microemulsions. Part I: Fabrication and Characterization. *Langmuir* 2009, 25, 1154–1161. [CrossRef]

62. Alborzi, S. Encapsulation of Folic Acid in Sodium Alginate-Pectin-Poly (Ethylene Oxide) Electrospun Fibers to Increase Its Stability. Ph.D. Thesis, University of Guelph, Guelph, ON, Canada, 2012.

63. Ghorani, B.; Tucker, N. Fundamentals of electrospinning as a novel delivery vehicle for bioactive compounds in food nanotechnology. *Food Hydrocoll.* 2015, 51, 227–240. [CrossRef]

64. Liu, S.-C.; Li, R.; Tomasula, P.M.; Sousa, A.M.; Liu, L. Electrospun food-grade ultrafine fibers from pectin and pullulan blends. *Food Nutr. Sci.* 2016, 7, 636. [CrossRef]

65. Malhotra, B.; Keshwani, A.; Kharkwal, H. Antimicrobial food packaging: Potential and pitfalls. *Front. Microbiol.* 2015, 6, 611. [CrossRef] [PubMed]

66. Appendini, P.; Hotchkiss, J.H. Review of antimicrobial food packaging. *Innov. Food Sci. Emerg. Technol.* 2002, 3, 113–126. [CrossRef]

67. De Azeredo, H.M. Antimicrobial nanostructures in food packaging. *Trends Food Sci. Technol.* 2013, 30, 56–69. [CrossRef]
68. Tunç, S.; Duman, O. Preparation of active antimicrobial methyl cellulose/carvacrol/montmorillonite nanocomposite films and investigation of carvacrol release. *LWT Food Sci. Technol.* 2011, 44, 465–472. [CrossRef]

69. Dobrucka, R.; Ankiel, M. Possible applications of metal nanoparticles in antimicrobial food packaging. *J. Food Saf.* 2019, 39, 12617. [CrossRef]

70. Huang, T.; Qian, Y.; Wei, J.; Zhou, C. Polymeric antimicrobial food packaging and its applications. *Polymers* 2019, 11, 560. [CrossRef]

71. Sadeghizadeh-Yazdi, J.; Habibi, M.; Kamali, A.A.; Banaei, M. Application of Edible and Biodegradable Starch-Based Films in Food Packaging: A Systematic Review and Meta-Analysis. *Curr. Res. Nutr. Food Sci.* J. 2019, 7. Available online: https://www.foodandnutritionjournal.org/volume7number3/application-of-edible-and-biodegradable-starch-based-films-in-food-packaging-a-systematic-review-and-meta-analysis/(accessed on 8 August 2019).

72. Sofi, S.; Singh, J.; Rafiq, S.; Ashraf, U.; Dar, B.; Nayik, G.A. A Comprehensive Review on Antimicrobial Packaging and its Use in Food Packaging. *Curr. Nutr. Food Sci.* 2018, 14, 305–312. [CrossRef]

73. Rodrigues, S.M.; Demokritou, P.; Dokoozlian, N.; Hendren, C.O.; Karp, B.; Mauer, M.S.; Sadik, O.A.; Safarpour, M.; Unrine, J.M.; Viers, J. Nanotechnology for sustainable food production: Promising opportunities and scientific challenges. *Environ. Sci. Nano* 2017, 4, 767–781. [CrossRef]

74. Prasad, R.; Bhattacharyya, A.; Nguyen, Q.D. Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives. *Front. Microbiol.* 2017, 8, 1014. [CrossRef] [PubMed]

75. Cerqueira, M.; Pastrana, L. Does the future of food pass by using nanotechnologies? *Front. Sustain. Food Syst.* 2019, 3, 16. [CrossRef]

76. Committee, E.S. Guidance on the risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain. *EFSA J.* 2011, 9, 2140. [CrossRef]

77. OECD Environment Directorate Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology: Alternative Testing Strategies in Risk Assessment of Manufactured Nanomaterials: Current State of Knowledge and Research Needs to Advance Their Use. Available online: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/JM/MONO(2016)63&doclanguage=en (accessed on 19 December 2018).

78. Hutchison, J.E. The Road to Sustainable Nanotechnology: Challenges, Progress and Opportunities. *ACS Sustain. Chem. Eng.* 2016, 4, 5907–5914. [CrossRef]

79. Maksimović, M.; Omanović-Mikličanin, E. Towards green nanotechnology: Maximizing benefits and minimizing harm. In *CMBEBIH 2017*; IFMBE Proceedings; Badnjevic, A., Ed.; Springer: Singapore, 2017; Volume 62, pp. 164–170.

80. Sekhon, B.S. Nanotechnology in agri-food production: An overview. *Nanotechnol. Sci. Appl.* 2014, 7, 31. [CrossRef]

81. Rai, V.; Acharya, S.; Dey, N. Implications of nanobiosensors in agriculture. *J. Biomater. Nanobiotechnol.* 2012, 3, 315. [CrossRef]

82. Neethirajan, S.; Ragavan, V.; Weng, X.; Chand, R. Biosensors for sustainable food engineering: Challenges and perspectives. *Biosensors* 2018, 8, 23. [CrossRef]

83. Xiang, K.; Li, Y.; Ford, W.; Land, W.; Schaffer, J.D.; Congdon, R.; Zhang, J.; Sadik, O. Automated analysis of food-borne pathogens using a novel microbial cell culture, sensing and classification system. *Analyst* 2016, 141, 1472–1482. [CrossRef]

84. Yazgan, I.; Noah, N.M.; Toure, O.; Zhang, S.; Sadik, O.A. Biosensor for selective detection of E. coli in spinach using the strong affinity of derivatized mannose with fimbrial lectin. *Biosens. Bioelectron.* 2014, 61, 266–273. [CrossRef]

85. Farahi, R.H.; Passian, A.; Tetard, L.; Thundat, T. Critical issues in sensor science to aid food and water safety. *ACS Nano* 2012, 6, 4548–4556. [CrossRef]

86. Bradley, E.L.; Castle, L.; Chaudhry, Q. Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries. *Trends Food Sci. Technol.* 2011, 22, 604–610. [CrossRef]

87. Falguera, V.; Quintero, J.P.; Jiménez, A.; Muñoz, J.A.; Ibarz, A. Edible films and coatings: Structures, active functions and trends in their use. *Trends Food Sci. Technol.* 2011, 22, 292–303. [CrossRef]
106. Hegde, K.; Brar, S.K.; Verma, M.; Surampalli, R.Y. Current understandings of toxicity, risks and regulations.

105. Handy, R.D.; Shaw, B.J. Toxic e...

103. Sahu, S.C.; Hayes, A.W. Toxicity of nanomaterials found in human environment: A literature review.

102. Tarantola, M.; Pietuch, A.; Schneider, D.; Rother, J.; Sunnick, E.; Rosman, C.; Pierrat, S.; Sönnichsen, C.; Wegener, J.; Janshoff, A. Toxicity of gold-nanoparticles: Synergistic effects of shape and surface functionalization on micromotility of epithelial cells. Nanotoxicology 2011, 5, 254–268. [CrossRef]

101. Jain, A.; Ranjan, S.; Dasgupta, N.; Ramalingam, C. Nanomaterials in food and agriculture: An overview on their safety concerns and regulatory issues. Crit. Rev. Food Sci. Nutr. 2018, 58, 297–317. [CrossRef] [PubMed]

100. Gliga, A.R.; Skoglund, S.; Wallinder, I.O.; Fadeel, B.; Karlsson, H.L. Size-dependent cytotoxicity of silver nanoparticles in human lung cells: The role of cellular uptake, agglomeration and Ag release. Part. Fibre Toxicol. 2014, 11, 11. [CrossRef]

99. Nel, A.; Xia, T.; Mädler, L.; Li, N. Toxic potential of materials at the nanolevel. Science 2006, 311, 622–627. [CrossRef] [PubMed]

98. Buzea, C.; Pacheco, I.I.; Robbie, K. Nanomaterials and nanoparticles: Sources and toxicity. Biointerphases 2007, 2, 17–71. [CrossRef] [PubMed]

97. Bundschuh, M.; Filser, J.; Lüderwald, S.; McKee, M.S.; Metreveli, G.; Schaumann, G.E.; Schulz, R.; Wagner, S. Nanomaterials in food and agriculture: An overview on their safety concerns and regulatory issues. Science 2007, 315, 254–268. [CrossRef] [PubMed]

96. Jain, A.; Ranjan, S.; Dasgupta, N.; Ramalingam, C. Nanomaterials in food and agriculture: An overview on their safety concerns and regulatory issues. Science 2007, 315, 254–268. [CrossRef] [PubMed]

95. Mueller, N.C.; Nowack, B. Exposure modeling of engineered nanoparticles in the environment. Anal. Bioanal. Chem. 2017, 409, 1219–1228. [CrossRef] [PubMed]

94. Maurer-Jones, M.A.; Gunsolus, I.L.; Murphy, C.J.; Haynes, C.L. Toxicity of engineered nanoparticles in the environment. Anal. Chem. 2013, 85, 3036–3049. [CrossRef]

93. Kashyap, P.L.; Xiang, X.; Heiden, P. Chitosan nanoparticle based delivery systems for sustainable agriculture. Crit. Rev. Food Sci. Nutr. 2018, 297–317. [CrossRef] [PubMed]

92. Bindraban, P.S.; Dimkpa, C.; Nagarajan, L.; Roy, A.; Rabbinge, R. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. Biol. Fertil. Soils 2015, 51, 897–911. [CrossRef]

91. Liu, R.; Lal, R. Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). Sci. Rep. 2014, 4, 5686. [CrossRef]

90. Monreal, C.; DeRosa, M.; Mallubhotla, S.; Bindraban, P.; Dimkpa, C. Nanotechnologies for increasing the crop use efficiency of fertilizer-micronutrients. Biol. Fertil. Soils 2016, 52, 423–437. [CrossRef]

89. Hossain, F.; Perales-Perez, O.J.; Hwang, S.; Roman, F. Antimicrobial nanomaterials as water disinfectant: Applications, limitations and future perspectives. Sci. Total Environ. 2014, 466, 1047–1059. [CrossRef]

88. Silvestre, C.; Duraccio, D.; Cimmino, S. Food packaging based on polymer nanomaterials. Prog. Polym. Sci. 2011, 36, 1766–1782. [CrossRef]
10. Gondikas, A.P.; Kammer, F.V.D.; Reed, R.B.; Wagner, S.; Ranville, J.F.; Hofmann, T. Release of TiO$_2$ Nanoparticles from Sunscreens into Surface Waters: A One-Year Survey at the Old Danube Recreational Lake. Environ. Sci. Technol. 2014, 48, 5415–5422. [CrossRef]

11. Donovan, A.R.; Adams, C.D.; Ma, Y.; Stephan, C.; Eichholz, T.; Shi, H. Single particle ICP-MS characterization of titanium dioxide, silver, and gold nanoparticles during drinking water treatment. Chemosphere 2016, 144, 148–153. [CrossRef]

12. Farré, M.; Pérez, S.; Gajda-Schrantz, K.; Osorio, V.; Kantiani, L.; Ginebreda, A.; Barceló, D. First determination of C60 and C70 fullerenes and N-methylfulleropyrrolidine C60 on the suspended material of wastewater effluents by liquid chromatography hybrid quadrupole linear ion trap tandem mass spectrometry. J. Hydrol. 2010, 383, 44–51. [CrossRef]

13. Carboni, A.; Helmus, R.; Parsons, J.R.; Kalbitz, K.; de Voogt, P. A method for the determination of fullerenes in soil and sediment matrices using ultra-high performance liquid chromatography coupled with heated electrospray quadrupole time of flight mass spectrometry. J. Chromatogr. A 2016, 1433, 123–130. [CrossRef]

14. Astefanei, A.; Nuñez, O.; Galceran, M.T. Analysis of C60-fullerene derivatives and pristine fullerenes in environmental samples by ultrahigh performance liquid chromatography–atmospheric pressure photoionization-mass spectrometry. J. Chromatogr. A 2014, 1365, 61–71. [CrossRef]

15. Doudrick, K.; Nosaka, T.; Herckes, P.; Westerhoff, P. Quantification of graphene and graphene oxide in complex organic matrices. Environ. Sci. Nano 2015, 2, 60–67. [CrossRef]

16. Schierz, A.; Parks, A.N.; Washburn, K.M.; Chandler, G.T.; Ferguson, P.L. Characterization and Quantitative Analysis of Single-Walled Carbon Nanotubes in the Aquatic Environment Using Near-Infrared Fluorescence Spectroscopy. Environ. Sci. Technol. 2012, 46, 12262–12271. [CrossRef] [PubMed]

17. Dukd一二Ο, A.; Boxxal, A.B.; Chaudhry, Q.; Mølhave, K.; Tiede, K.; Hofmann, P.; Linsinger, T.P. Uncertainties of size measurements in electron microscopy characterization of nanomaterials in foods. Food Chem. 2015, 176, 472–479. [CrossRef] [PubMed]

18. Jarzębski, M.; Bellich, B.; Białopiotrowicz, T.; Sliwa, T.; Kościński, J.; Cesário, A. Particle tracking analysis in food and hydrocolloids investigations. Food Hydrocoll. 2017, 68, 90–101. [CrossRef]

19. Laborda, F.; Bolea, E.; Cepría, G.; Gómez, M.T.; Jiménez, M.S.; Pérez-Arante-gui, J.; Castillo, J.R. Detection, characterization and quantification of inorganic engineered nanomaterials: A review of techniques and methodological approaches for the analysis of complex samples. Anal. Chim. Acta 2016, 904, 10–32. [CrossRef]

20. Mattarozzi, M.; Suman, M.; Cascio, C.; Celestani, D.; Weigel, S.; Undas, A.; Peters, R. Analytical approaches for the characterization and quantification of nanoparticles in food and beverages. Anal. Bioanal. Chem. 2017, 409, 63–80. [CrossRef]

21. Astefanei, A.; Nuñez, O.; Galceran, M.T. Characterisation and determination of fullerenes: A critical review. Anal. Chim. Acta 2015, 882, 1–21. [CrossRef]

22. Petersen, E.J.; Flores-Cervantes, D.X.; Bucheli, T.D.; Elliott, L.C.C.; Fagan, J.A.; Gogos, A.; Hanna, S.; Kägi, R.; Mansfield, E.; Bustos, A.R.M.; et al. Quantification of Carbon Nanotubes in Environmental Matrices: Current Capabilities, Case Studies, and Future Prospects. Environ. Sci. Technol. 2016, 50, 4587–4605. [CrossRef]

23. Montaño, M.D.; Lowry, G.V.; von der Kammer, F.; Blue, J.; Ranville, J.F. Current status and future direction for examining engineered nanoparticles in natural systems. Environ. Chem. 2014, 11, 351–366. [CrossRef]

24. Praetorius, A.; Gundlach-Graham, A.; Goldberg, E.; Fabienke, W.; Navratilova, J.; Gondikas, A.; Kaegi, R.; Günther, D.; Hofmann, T.; von der Kammer, F. Single-particle multi-element fingerprinting (spMEF) using inductively-coupled plasma time-of-flight mass spectrometry (ICP-TOFMS) to identify engineered nanoparticles against the elevated natural background in soils. Environ. Sci. Nano 2017, 4, 307–314. [CrossRef]

25. Szakal, C.; Roberts, S.M.; Westerhoff, P.; Bartholomaeus, A.; Buck, N.; Illuminato, I.; Canady, R.; Rogers, M. Measurement of Nanomaterials in Foods: Integrative Consideration of Challenges and Future Prospects. ACS Nano 2014, 8, 3128–3135. [CrossRef]

26. Cockburn, A.; Bradford, R.; Buck, N.; Constable, A.; Edwards, G.; Haber, B.; Hepburn, P.; Howlett, J.; Kampers, F.; Klein, C.; et al. Approaches to the safety assessment of engineered nanomaterials (ENM) in food. Food Chem. Toxicol. 2012, 50, 2224–2242. [CrossRef] [PubMed]
127. Gallocchio, F.; Belluco, S.; Ricci, A. Nanotechnology and Food: Brief Overview of the Current Scenario. *Procedia Food Sci.* **2015**, *5*, 85–88. [CrossRef]

128. Tiede, K.; Boxall, A.B.A.; Tear, S.P.; Lewis, J.; David, H.; Hassellöv, M. Detection and characterization of engineered nanoparticles in food and the environment. *Food Addit. Contam.* **2008**, *25*, 795–821. [CrossRef] [PubMed]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).