Pomeranian J Life Sci 2025;72(2):53-58

doi: 10.21164/pomjlifesci.1256

Nanotechnology in food

Bartłomiej Palmowski[1, A] ✉, Wiktoria Ficoń[1, B], Maksymilian Dobosz[1, C], Beata Całyniuk[2, D]

[1] Medical University of Silesia in Katowice, Student Scientific Association by the Department of Human Nutrition, Jordana 19f, 41-800 Zabrze, Poland
[2] Medical University of Silesia in Katowice, Department of Human Nutrition, Jordana 19f, 41-800 Zabrze, Poland

[A] ORCID: 0009-0003-7712-8627; [B] ORCID: 0009-0002-9903-7892; [C] ORCID: 0009-0001-2427-8731; [D] ORCID: 0000-0002-8192-7160

✉ bartlomiej4palmowski@gmail.com

ABSTRACT
Nanotechnology is a rapidly developing innovation that allows for continuous improvement in the food industry. It plays an important role in the food sector, offering solutions that increase product shelf life, improve packaging properties, and enhance the bioavailability of nutrients through nanoencapsulation, i.e., a technology that allows bioactive substances such as carotenoids or omega-3 fatty acids (EPA/DHA) to be enclosed in nanocarriers, e.g., lipid nanoemulsions, thereby increasing their stability, solubility, and bioavailability, as well as enabling some control over their release in the digestive tract. At the same time, numerous questions arise regarding toxicity and consumer safety, resulting from the possibility of nanomaterials migrating into food, their biological reactivity, and their fate in the human digestive tract. Current research indicates that nanoparticles can cause oxidative stress, DNA damage, mitochondrial dysfunction, and inflammation, which is closely related to their physicochemical properties. Although many toxic effects are mainly observed in *in vitro* studies, there is a lack of clear data on their *in vivo* effects and long-term impact on human health. The conclusions emphasize the need for further research on biotransformation, bioaccumulation, interaction with the gut microbiome, and the development of uniform risk assessment methods to enable the safe and informed use of nanotechnology in food in the future.

Keywords: nanomaterials; food nanotechnology; stability of bioactive ingredients; smart packaging; nanoencapsulation; consumer safety.

INTRODUCTION

The dynamic development of nanotechnology in recent years has brought numerous innovations to the food sector, including improved packaging properties, increased product shelf life, and increased bioavailability of nutrients through nanoencapsulation. Thanks to their unique properties – large specific surface area and high reactivity – nanoparticles have found application in both active and smart foods, as well as in antimicrobial packaging. At the same time, there is growing interest in the potential health risks associated with human contact with nanomaterials. In particular, attention is drawn to the possibility of nanoparticle bioaccumulation, their penetration through biological barriers, and the induction of oxidative stress and cellular damage. For this reason, it is necessary to conduct systematic toxicological studies to understand the mechanisms of action of nanoparticles in the body, their fate in the gastrointestinal tract, and the factors influencing the safety of their use in food. The aim of this study is to present the current state of knowledge on nanoparticles and their toxicity, the possible negative impact of nanoparticles used in food technology on the human body, to discuss their mechanisms of biological interaction and routes of exposure, and to identify the main methodological challenges and directions for further research in this area.

MATERIALS AND METHODS

This study reviews the available scientific literature on the use of nanotechnology. The analysis covers publications from peer-reviewed scientific journals, mainly from 2015–2025, including the "Journal of Toxicology, Nutrients, Heliyon, Scientific Reports, and Annual Reviews of Pharmacology and Toxicology". A narrative review of secondary sources was used, including: searching for articles in the ScienceDirect, PubMed, SpringerLink, Scopus, and MDPI databases, analysis of their content in terms of key categories: toxicity mechanisms, physicochemical factors, routes of exposure, and bioreactivity in the gastrointestinal tract, comparison of *in vitro* and *in vivo* (animal model) study results, and development of synthetic tables presenting the main relationships and conclusions.

NANOMATERIALS – CLASSIFICATION AND PROPERTIES

From a regulatory perspective, nanomaterials intended for use in food and food contact materials are subject to case-by-case safety assessment. According to the European Food Safety Authority (EFSA), nanomaterials are generally defined as materials with at least one external dimension in the size range of 1–100 nm, and their safety evaluation follows standard toxicological risk assessment principles, including hazard identification, hazard characterization, exposure assessment, and risk characterization. It should be noted that while the 1–100 nm range represents the prevailing regulatory and technical definition, broader size ranges extending beyond 100 nm are occasionally considered in a functional context to describe materials exhibiting nanoscale-related properties despite slightly larger dimensions [1]. Growing public awareness of the importance of a healthy lifestyle, healthy eating, and disease prevention contributes to the development of the global economy and improvement of quality of life. At the same time, the rapid development of nanotechnology has created new opportunities for improving human health and quality of life, as well as food safety, increasing the bioavailability of nutrients, and supporting the treatment of chronic diseases [2]. Nanotechnology was conceptually initiated by Richard Feynman in 1959. It involves the study and manipulation of matter on a nanometer scale – which is equal to one billionth (10^{-9}) of a meter – from one to even 1000 nm in a functional context [3]. Materials of this size have different physical, chemical, and biological properties compared to their macroscopic counterparts. Nanomaterials can be inorganic, including metals, metal oxides, and silicates, or organic, such as polymers, lipids, proteins, and peptides [2, 4]. Nanomaterials can take many forms, ranging from nanoparticles and nanotubes to nanofilms, which are thin layers of molecules with low surface energy, reduced friction coefficient, and high selectivity. They are used in many fields, such as solar energy, medicine, and the production of materials intended for contact with food [5]. Their properties are closely related to the chemical composition and molecular structure of the material.

Thanks to these properties, they can be used in various sectors of the food, pharmaceutical, and biomedical industries. Inorganic nanomaterials exhibit unique mechanical, chemical, and physical properties, making them widely used in, among other things, active food packaging, biosensors, and antimicrobial materials that can be used for food packaging. The most commonly used nanoparticles are silver (Ag), zinc oxide (ZnO), titanium oxide (TiO_2), and silica (SiO_2) [2, 6, 7]. These materials have antibacterial, antifungal, and antioxidant properties, which makes them effective in protecting food from spoilage [8]. Organic nanomaterials include polymers, liposomes, nanoemulsions, and lipid nanoparticles, as well as protein and peptide nanostructures [9, 10]. They are characterized by biocompatibility and biodegradability, which makes them useful in bioactive nutrient delivery systems and regenerative medicine. For example, liposomes – phospholipid vesicles – can transport both hydrophilic and hydrophobic substances, protecting them from degradation in the digestive system [9, 10]. Nanotechnology is revolutionizing the food industry by improving the quality, shelf life, and safety of products. The use of nanomaterials in food processing includes: smart packaging, nanoencapsulation, and increased microbiological safety.

NANOTECHNOLOGY IN FOOD

Nanoparticles can act as nanoemulsifiers, preservatives, and flavor enhancers, as well as improve the texture and color of products. An example is the use of fish oil nanoemulsions in dairy products, which increases the bioavailability of EPA/DHA and masks unpleasant odors [10, 11]. Other examples include the use of TiO_2 nanoparticles as a colorant and Ag nanoparticles as an antimicrobial agent in products with a short shelf life [11, 12]. Packaging with the addition of metal nanoparticles, metal oxides, or nanocellulose provides increased mechanical resistance, acting as a barrier to gases and moisture, and also has some antimicrobial properties [12, 13]. Nanocellulose, nanostarch, protein nanoparticles, and chitosan are used as functional fillers and reinforcements in polymer matrices intended for the food industry and the production of bio-packaging. Materials such as nanosilica and nanoclays, thanks to their biocompatibility, biodegradability, and ability to undergo chemical modification, are an environmentally friendly alternative to traditional and synthetic reinforcing fillers [14].

Nanocellulose is one of the most promising bioorganic reinforcements used in packaging materials. It consists of cellulose fibers with a diameter ranging from several to several dozen nanometers and a length reaching several micrometers. Thanks to its high length-to-diameter ratio and large specific surface area, nanocellulose has excellent mechanical and rheological properties. Its inclusion in polymer matrices, such as polylactide (poly(lactic acid), PLA) – a biodegradable polymer belonging to the group of aliphatic polyesters, significantly improves the elasticity, tensile strength, and dimensional stability of finished packaging [15, 16]. One of the most important advantages of nanocellulose is its excellent barrier to oxygen and carbon dioxide, which results from the ordered structure of hydrogen bonds between the fibers. For this reason, nanocellulose composites are used in active food packaging, especially where it is crucial to limit lipid oxidation or vitamin degradation in food products [15, 16].

However, nanocellulose has certain limited properties when it comes to moisture, as its highly hydrophilic nature promotes water absorption. The high content of hydroxyl groups (-OH) on the surface of the fibers means that in conditions of increased humidity, the material can lose its stiffness and transparency. For this reason, in modern bio-packaging technologies, combining nanocellulose with hydrophobic bases (e.g., PLA, PCL, Bio-PE) allows for the creation of composites with balanced barrier properties – high resistance to oxidation while maintaining protection against moisture [15, 16, 17].

Nanostearch is another bioorganic nanofiller of great importance in the biodegradable materials sector. It is obtained from natural plant raw materials through partial enzymatic or acid hydrolysis of starch. It is characterized by low density, non-toxicity, and the ability to form protective films. Nanostearch can be used as a reinforcing agent in matrices such as poly(vinyl alcohol) – PVA or thermoplastic starch (TPS). The introduction of even small amounts (1–5%) of nanostarch into a composite results in a noticeable increase in tensile strength, elasticity, and heat resistance, making it an excellent auxiliary material in eco-friendly food packaging [18]. In addition, nanostarch has the ability to form biodegradable, transparent protective coatings for food products that limit gas exchange and slow down the aging process of products without adversely affecting their taste or smell.

In recent years, there has also been growing interest in protein nanoparticles obtained from sources such as casein, gelatin, whey protein isolate (WPI), and soy protein isolate (SPI). Thanks to their ability to spontaneously form nanostructures through hydrogen and electrostatic bonds, these proteins can serve as both a structural element and a functional factor (e.g., antioxidant or antimicrobial). The incorporation of protein nanoparticles into polymer matrices (PLA, PVA, sodium alginate) increases their cohesion, mechanical resistance, and barrier properties against oxygen and water vapor [14, 19]. In addition, proteins can be functionalized, i.e., other elements can be attached to them, e.g., by coupling with antioxidants or enzymes, thanks to which they play a dual role: they strengthen the material and actively protect the food product against oxidation [14, 19, 20].

Among inorganic nanomaterials, layered nanoclays occupy a special place, especially montmorillonite (MMT) – a mineral from the group of aluminum-magnesium silicates with a 2:1 layered structure. It consists of two layers: SiO_2 layers connected with an aluminum layer Al(OH)3. When properly dispersed in a polymer matrix, these nanoclays form a multilayer system that effectively modifies the physical and barrier properties of the material, limiting the permeability of water vapor and light, including UV radiation, which makes it a very useful component in modern packaging materials [14, 20, 21]. One of the key effects of nanoclays in composites is the so-called tortuous pathway effect. This effect consists in the fact that montmorillonite plates introduced into the polymer form a labyrinthine structure through which gas molecules, i.e., O_2, CO_2, or H_2O, must travel a longer distance to penetrate the material [14, 20, 21, 22, 23]. This significantly reduces the gas permeability and vapor tightness of the polymer, thereby improving the shelf life of food products packaged in such materials.

This phenomenon is confirmed by Mahmoodi et al. in their paper entitled *High-Strength, Low-Permeable, and Light-Protective Nanocomposite Films Based on a Hybrid Nanopigment and Biodegradable PLA for Food Packaging Applications*. The study proved that even a small amount of nanoclays reduced water vapor permeability by 36% and gas permeability by 54%. The films also exhibited very good optical properties – intense coloration and effective protection against light [24]. Among the inorganic nanomaterials used in the food industry, metal nanoparticles (Ag) and metal oxides (ZnO, TiO_2) are of particular importance, as they exhibit antimicrobial, photocatalytic, and UV-protective properties [14, 20].

Silver nanoparticles (AgNPs) are one of the most commonly used antibacterial agents in packaging technology. Their mechanism of action involves the interaction of Ag^+ ions with bacterial cell membranes, which leads to disturbances in cell wall function. In addition, AgNPs can catalyze the formation of reactive oxygen species (ROS), which increases oxidative stress and leads to the death of the microorganism cell. The use of nanosilver in biopolymer packaging, such as PLA, PVA, or thermoplastic starch, has a clear antimicrobial effect against Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*) bacteria [25, 26].

Titanium oxide nanoparticles (TiO_2-NPs) have a dual function. They act as UV radiation blockers and photocatalytic antiseptics. Under the influence of UVA radiation, TiO_2 generates reactive oxygen species that effectively break down organic contaminants and microorganisms on the surface of the packaging [27]. Thanks to this, TiO_2 is used in so-called self-cleaning packaging films and in protective coatings on equipment used in the food industry. Zinc oxide nanoparticles (ZnO-NPs) are another important component of active packaging materials. Their action is based on the release of Zn^{2+} ions and the generation of ROS in the presence of moisture or UV light. The resulting oxygen radicals damage the lipid membranes, DNA, and enzymes of microorganisms, leading to their death. ZnO is also a generally recognized as safe (GRAS) material according to the FDA, which promotes its acceptance in food applications.

The findings of Kim et al. in their paper entitled *Poly(Lactic Acid)/ZnO Bionanocomposite Films with Positively Charged ZnO as Potential Antimicrobial Food Packaging Materials* showed that PLA/ZnO films reduced the growth of *E. coli* by >95% [28]. Smart packaging made from nanomaterials can respond to environmental changes such as temperature and oxygen presence and provide information about product freshness. Nanosilver and nanozinc effectively inhibit bacterial growth on the surface of meat, while titanium oxide nanoparticles exhibit self-cleaning properties [10, 13]. Nanosensors also enable rapid and inexpensive detection of contaminants, toxins, or microorganisms in food [3]. Modern biosensors based on magnetic nanoparticles and conductive materials allow real-time monitoring of, e.g., the presence of aflatoxin B_1, the strongest and most common aflatoxin produced by fungi of the genus Aspergillus [12, 13, 29]. All of them – polymer nanoparticles, liposomes, and nanoemulsions – increase the stability and effectiveness of bioactive compounds such as curcumin and flavonoids [2, 30, 31].

Thanks to their ability to respond to pH changes, these carriers protect substances from stomach acid and release them only in the small intestine, which increases their absorption. Nanotechnology also enables the development of protective coatings for probiotic bacteria such as Lactobacillus and Bifidobacterium, increasing their survival during transport and digestion. The use of liposomes or polysaccharide-protein layers prevents the destruction of probiotics by digestive enzymes [11].

NANOENCAPSULATION AND THE FATE OF SYSTEMS IN THE GASTROINTESTINAL TRACT

Nanoencapsulation is a technology in which bioactive substances – such as carotenoids, omega-3 fatty acids (DHA/EPA) or coenzyme Q10 – are enclosed in nanocarriers (e.g., lipid nanoemulsions or liposomes). This solution increases their stability, solubility, bioavailability, and also enables controlled release in the digestive tract [20, 32]. Two types of systems are most commonly used in food and dietary supplements:

- lipid nanoemulsions – very small fat droplets dispersed in water. They are excellent at transporting fat-soluble substances such as carotenoids or DHA/EPA [20, 32];

- liposomes – microscopic vesicles composed of phospholipids, similar to cell membranes. They are biocompatible, non-toxic, and can transport both water-soluble and fat-soluble substances [20, 32].

After ingestion, nanoemulsions pass through the digestive system, where numerous physicochemical processes take place. In the mouth and stomach, changes in pH and the presence of salts can lead to aggregation or salting out of particles. In the small intestine, bile and lipases break down lipids, leading to the formation of micelles that dissolve digestive products and facilitate their absorption by intestinal cells. Particle size and lipid composition have a key impact on bioavailability – the smaller the droplets, the greater the surface area of contact with enzymes and the higher the bioaccessibility, e.g., of β-carotene or coenzyme Q10 [32, 33, 34].

TOXICITY AND RISKS

The growing use of nanotechnology in food production and processing brings both functional benefits and potential risks to human health. Although most nanoparticles (NPs) in food are considered technologically safe, recent studies indicate the need for a thorough understanding of their toxicity, biodistribution, and impact on metabolism and gut microbiota [35]. The most commonly described mechanism is the induction of oxidative stress through the excessive formation of ROS. High concentrations of ROS lead to damage to membrane lipids, protein denaturation, mitochondrial disorders, and ultimately to apoptosis or necrosis of not only pathogens but also human cells.

In the publication entitled *The safety of nanomaterials in food production and packaging* by Onyeaka H et al. it was proven that nanoparticles have the ability to disrupt many cellular processes and biological pathways, which can lead to unpredictable changes in cell function, such as cell division and DNA strand replication [36]. Some nanomaterials can damage DNA, causing strand breaks, changes in genome structure, and the formation of modified nitrogen bases such as 8-hydroxyguanine or thymine glycol [36, 37]. If not repaired, this damage can lead to gene mutations, chromosomal changes, tumor development, and cell death [37]. In the article by Xuan L et al. *Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models*, the authors point out that nanoparticles can settle in the respiratory system depending on their size, shape, and surface properties [38]. Smaller particles have a greater ability to penetrate the lower respiratory tract, where they can reach the alveoli and interact with lung cells.

Hydrophilic particles, on the other hand, settle less frequently than hydrophobic ones, and elongated particles are more likely to settle than spherical ones. Once deposited in the respiratory system, NPs can be recognized and absorbed by lung cells, such as macrophages, epithelial cells, or fibroblasts, through phagocytosis or pinocytosis. Their absorption can trigger cellular responses such as the production of ROS, the secretion of pro-inflammatory cytokines, and, consequently, inflammatory pathways [38]. Titanium dioxide nanoparticles can cause inflammation and fibrosis of the lungs. The negative effects are exacerbated by comorbidities such as asthma or chronic obstructive pulmonary disease. Silica, carbon particles, nanosilver, and zinc oxides can cause immunotoxicity and inflammatory reactions in the respiratory system [38].

In their study entitled *The neurotoxic threat of micro- and nanoplastics: evidence from* in vitro *and* in vivo *models*, described that NPs may also exhibit neurotoxic effects to some extent by damaging the blood-brain barrier, causing oxidative stress, inflammation, and changes in the proteins responsible for the integrity of this barrier. Nanoparticles are also capable, to some extent, of initiating apoptosis, i.e., programmed cell death. Some particles also cause disturbances in the functioning of dopamine neurons [39]. Researchers Choi JI et al. in their paper entitled *Potential silver nanoparticles migration from commercially available polymeric baby products into food simulants* proved that Ag-NPs, found in some baby products such as bottles, pacifiers, breast milk containers, and other baby products can migrate from these materials and enter the child's body, being toxic to cells, especially in young children whose bodies are still developing [40].

From a food safety perspective, the toxicological data discussed in this section contribute primarily to the hazard identification and hazard characterization steps of the risk assessment process, while comprehensive risk characterization requires integration with exposure assessment data.

METHODOLOGICAL CHALLENGES AND LIMITATIONS

Assessing the toxicity of nanoparticles in the context of food poses a number of methodological challenges due to their unique physicochemical properties. Firstly, the lack of standardization of research methods makes it difficult to compare the results of different studies. Differences in the synthesis, size, shape, and coatings of nanoparticles lead to high variability in biological effects. Secondly, *in vitro* studies often do not reflect actual conditions in the body, e.g., the influence of microbiota, metabolism, and digestive processes. Cell models allow direct toxicity to be determined, but do not take into account interactions between systems or the biotransformation of nanoparticles in the gastrointestinal tract. Thirdly, methods for determining and tracking nanoparticles in tissues are still limited – the detection of small particles and their aggregation in a biological environment is difficult. An additional problem is the lack of long-term *in vivo* studies and data on the accumulation and excretion of nanoparticles, which makes it difficult to assess the risk of chronic human exposure.

SUMMARY

Nanoparticles used in food and packaging technology have both great technological potential and certain toxicological risks. The mechanisms of their toxicity primarily include the induction of oxidative stress, DNA damage, mitochondrial disorders, and possible neurotoxicity. The extent of these effects is strongly dependent on the physicochemical properties of nanoparticles, such as size, shape, surface area, and the presence of protective coatings. Current research results indicate that most toxic effects are observed mainly *in vitro* and at high concentrations, while the actual *in vivo* toxicity (after ingestion with food) remains poorly understood. Therefore, further comprehensive research is needed on: long-term exposure to nanomaterials, their impact on the intestinal microflora, biotransformation and elimination from the body, and the development of standards for risk assessment and safety regulation of nanomaterials in food. Understanding these processes is crucial to fully exploit the potential of nanotechnology in food while minimizing risks to human health.

REFERENCES

1. More S, Bampidis V, Benford D, Bragard C, Hernandez Jerez A, Bennekou S, et al. Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: human and animal health. EFSA J 2021;19(8):e06768. doi: 10.2903/j.efsa.2021.6768.
2. Han K, Yang H, Fan D, Deng J. Advances in Nanotechnology Research in Food Production, Nutrition, and Health. Nutrients 2025;17(15):2443. doi: 10.3390/nu17152443.
3. Mulvaney P. Nanoscience vs nanotechnology – defining the field. ACS Nano 2015;9(3):2215-7. doi: 10.1021/acsnano.5b01418.
4. Li S, Xu X, Xu L, Lin H, Kuang H, Xu C. Emerging trends in chiral inorganic nanomaterials for enantioselective catalysis. Nat Commun 2024;15(1):3506. doi: 10.1038/s41467-024-47657-y.
5. Gavrylyuk DV, Mel'nychenko MM, Zhuk YO. Nanofilms: Structural Features and Nanoindentation Methods. Int Appl Mech 2022;58:545-51. doi: 10.1007/s10778-023-01186-1.
6. Pandit KH, Patil PB, Goswami AD, Pinjari DV. Fabrications from renewable sources and agricultural wastes and characterization strategies of green nanomaterials. In Handbook of Green and Sustainable Nanotechnology: Fundamentals, Developments and Applications. Springer; 2022. p. 1-15. doi: 10.1007/978-3-030-69023-6_74-1.
7. Rohaizad N, Mayorga-Martinez CC, Fojtů M, Latiff NM, Pumera M. Two-dimensional materials in biomedical, biosensing and sensing applications. Chem Soc Rev 2021;50(1):619-57. doi: 10.1039/d0cs00150c.
8. Morais LO, Macedo EV, Granjeiro JM, Delgado IF. Critical evaluation of migration studies of silver nanoparticles present in food packaging: a systematic review. Crit Rev Food Sci Nutr 2020;60(18):3083-102. doi: 10.1080/10408398.2019.1676699.
9. Cheng L, Zhang S, Zhang Q, Gao W, Mu S, Wang B. Wound healing potential of silver nanoparticles from *Hybanthus enneaspermus* on rats. Heliyon 2024;10(17):e36118. doi: 10.1016/j.heliyon.2024.e36118.
10. Yang Z, Wen T, Peng F. Integrating green synthesized lichenan-silver nanoparticles into lichenan/chitosan matrix for photoresponsive multifunctional food packaging application. Chem Eng J 2025;514:163197. doi: 10.1016/j.cej.2025.163197.
11. Ghorbanzade T, Jafari SM, Akhavan S, Hadavi R. Nano-encapsulation of fish oil in nano-liposomes and its application in fortification of yogurt. Food Chem 2017;216:146-52. doi: 10.1016/j.foodchem.2016.08.022.
12. Jacob J, Robert V, Valapa RB, Kuriakose S, Thomas S, Loganathan S. Poly(lactic acid)/polyethylenimine functionalized mesoporous silica biocomposite films for food packaging. ACS Appl Polym Mater 2022;4:4632-42. doi: 10.1021/acsapm.1c01551.
13. Mu Y, Li M, Zhao X, Gong C, Luo Z, Li B, et al. TiO$_2$ Nanotube Implants Modified with Silk Fibroin and Mesoporous Silica Nanocomposite Coatings Enable Efficient Drug Release to Promote Osteogenesis. ACS Appl Mater Interfaces 2025;17(21):30600-12. doi: 10.1021/acsami.5c03599.
14. Ashfaq A, Khursheed N, Fatima SW, Anjum Z, Younis K. Application of nanotechnology in food packaging: Pros and Cons. J Agricult Food Res 2022;7:100270. doi: 10.1016/j.jafr.2022.100270.
15. Abdul Khalil HP, Davoudpour Y, Islam MN, Mustapha A, Sudesh K, Dungani R, et al. Production and modification of nanofibrillated cellulose using various mechanical processes: a review. Carbohydr Polym 2014;99:649-65. doi: 10.1016/j.carbpol.2013.08.069.
16. Azeredo H, Rosa M, Mattoso L. Nanocellulose in bio-based food packaging applications. Indust Crops Products 2017;97:664-71. doi: 10.1016/j.indcrop.2016.03.013.
17. Jonoobi M, Oladi R, Davoudpour Y, Oksman K, Dufresne A, Hamzeh Y, et al. Different preparation methods and properties of nanostructured cellulose from various natural resources and residues: a review. Cellulose 2015;22:935-69. doi: 10.1007/s10570-015-0551-0.
18. Tang X, Alavi S. Recent advances in starch, polyvinyl alcohol based polymer blends, nanocomposites and their biodegradability. Carbohydrate Polymers 2011;85:7-16. doi: 10.1016/j.carbpol.2011.01.030.
19. Rhim JW, Park HM, Ha CS. Bio-nanocomposites for food packaging applications. Progress Polymer Sci 2013;38:1629-52. doi: 10.1016/j.progpolymsci.2013.05.008.
20. Biswas R, Alam M, Sarkar A, Haque MI, Hasan MM, Hoque M. Application of nanotechnology in food: processing, preservation, packaging and safety assessment. Heliyon 2022;8(11):e11795. doi: 10.1016/j.heliyon.2022.e11795.
21. Król-Morkisz K, Pielichowska K. Thermal Decomposition of Polymer Nanocomposites With Functionalized Nanoparticles. In: Pielichowski K, Majka TM, editors. Polymer Composites with Functionalized Nanoparticles. Micro and Nano Technologies. Amsterdam: Elsevier; 2019. p. 405-35. doi: 10.1016/B978-0-12-814064-2.00013-5.
22. Alexe IA, Stan G, Bahaciu G. V. Balancing sustainability and preservation: how new-generation packaging cuts food waste and environmental impact. J Agroaliment Proc Technol 2025;31:219-26. doi: 10.59463/JAPT2025.2.10.
23. Perera KY, Hopkins M, Jaiswal AK, Jaiswal S. Nanoclays-containing bio-based packaging materials: properties, applications, safety, and regulatory issues. J Nanostructure Chem 2023:1-23. doi: 10.1007/s40097-023-00525-5.
24. Mahmoodi A, Ghodrati S, Khorasani M. High-Strength, Low-Permeable, and Light-Protective Nanocomposite Films Based on a Hybrid Nanopigment and Biodegradable PLA for Food Packaging Applications. ACS Omega 2019;4(12):14947-54. doi: 10.1021/acsomega.9b01731.
25. Cushen M, Kerry JP, Morris MA, Cruz-Romero MC, Cummins E. Nanotechnologies in the food industry – Recent developments, risks and regulation. Trends Food Sci Technol 2012;24(1):30-46. doi: 10.1016/j.tifs.2011.10.006.
26. Rodrigues AS, Batista JG, Rodrigues MÁV, Thipe VC, Minarini LAR, Lopes PS, et al. Advances in silver nanoparticles: a comprehensive review on their potential as antimicrobial agents and their mechanisms of action elucidated by proteomics. Front Microbiol 2024;15:1440065. doi: 10.3389/fmicb.2024.1440065.
27. Haque F, Blanchard A, Laipply B, Dong X. Visible-Light-Activated TiO$_2$-Based Photocatalysts for the Inactivation of Pathogenic Bacteria. Catalysts 2024;14(12):855. doi: 10.3390/catal14120855.
28. Kim I, Viswanathan K, Kasi G, Sadeghi K, Thanakkasaranee S, Seo J. Poly(Lactic Acid)/ZnO Bionanocomposite Films with Positively Charged ZnO as Potential Antimicrobial Food Packaging Materials. Polymers 2019;11(9):1427. doi: 10.3390/polym11091427.
29. Gu L, Lin J, Wang Q, Meng F, Niu G, Lin H, et al. Mesoporous zinc oxide-based drug delivery system offers an antifungal and immunoregulatory strategy for treating keratitis. J Control Release 2024;368:483-97. doi: 10.1016/j.jconrel.2024.03.006.
30. Zhang Z, Zhang Y, Jayan H, Gao S, Zhou R, Yosri N, et al. Recent and emerging trends of metal-organic frameworks (MOFs)-based sensors for detecting food contaminants: A critical and comprehensive review. Food Chem 2024;448:139051. doi: 10.1016/j.foodchem.2024.139051.
31. Hosseini SF, Ansari B, Gharsallaoui A. Polyelectrolytes-stabilized liposomes for efficient encapsulation of Lactobacillus rhamnosus and

improvement of its survivability under adverse conditions. Food Chem 2022;372:131358. doi: 10.1016/j.foodchem.2021.131358.

32. Altemimi AB, Farag HAM, Salih TH, Awlqadr FH, Al-Manhel AJA, Vieira IRS, et al. Application of Nanoparticles in Human Nutrition: A Review. Nutrients 2024;16(5):636. doi: 10.3390/nu16050636.
33. Joye IJ, McClements DJ. Biopolymer-based nanoparticles and microparticles: Fabrication, characterization, and application. Curr Opin Coll Inter Sci 2014;19(5):417-27. doi: 10.1016/j.cocis.2014.07.002.
34. Choi SJ, McClements DJ. Nanoemulsions as delivery systems for lipophilic nutraceuticals: strategies for improving their formulation, stability, functionality and bioavailability. Food Sci Biotechnol 2020;29:149-68. doi: 10.1007/s10068-019-00731-4.
35. Egbuna C, Parmar VK, Jeevanandam J, Ezzat SM, Patrick-Iwuanyanwu KC, Adetunji CO. Toxicity of Nanoparticles in Biomedical Application: Nanotoxicology. J Toxicol 2021;2021:9954443. doi: 10.1155/2021/9954443.
36. Onyeaka H, Passaretti P, Miri T, Al-Sharify ZT. The safety of nanomaterials in food production and packaging. Curr Res Food Sci 2022;5:763-74. doi: 10.1016/j.crfs.2022.
37. Biola-Clier M, Beal D, Caillat S, Libert S, Armand L, Herlin-Boime N, et al. Comparison of the DNA damage response in BEAS-2B and A549 cells exposed to titanium dioxide nanoparticles. Mutagenesis 2017;32(1):161-72. doi: 10.1093/mutage/gew055.
38. Xuan L, Ju Z, Skonieczna M, Zhou PK, Huang R. Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models. MedComm (2020) 2023;4(4):e327. doi: 10.1002/mco2.327.
39. Araújo AM, Mota C, Ramos H, Faria MA, Carvalho M, Ferreira IMPLVO. The neurotoxic threat of micro- and nanoplastics: evidence from *in vitro* and *in vivo* models. Arch Toxicol 2025; 99(9):3505-25. doi: 10.1007/s00204-025-04091-3.
40. Choi JI, Chae SJ, Kim JM, Choi JC, Park SJ, Choi HJ, et al. Potential silver nanoparticles migration from commercially available polymeric baby products into food simulants. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 2018;35(5):996-1005. doi: 10.1080/19440049.2017.