

TOXICOLOGICAL RISK ASSESSMENT OF ZINC OXIDE AND SILVER NANOPARTICLES IN FOOD PACKAGING

Daniela GRIGORESCU¹, Rodica Mariana ION^{1,2,3*}

¹ Valahia University of Targoviste, Materials Engineering Dept., 13 Alea Sinaia, 130004, Targoviste, Romania

² ICECHIM, 202 Splaiul Independentei, 060021, Bucharest, Romania.

³ Academy of Romanian Scientists, 3 Ilfov Street, 050044 Bucharest, Romania.

E-mail: rodica_ion2000@yahoo.co.uk

Abstract: The integration of nanotechnology into the food packaging sector has generated a paradigm shift in food preservation, offering superior antimicrobial and barrier properties. However, the transition from conventional materials to nanocomposites raises fundamental questions regarding "nano-safety" and the potential impact on human health. This review paper critically analyzes current scientific literature on the toxicological risk associated with metallic nanoparticles, with a particular focus on zinc oxide (ZnO NPs) and silver (AgNPs). The complex mechanisms through which these submicroscopic entities can interact with biological systems—from inhalation and dermal contact to ingestion through the gastrointestinal tract—are explored. The analysis focuses on the importance of rigorous physicochemical characterization—including morphology, surface charge, and adsorption capacity—as a mandatory prerequisite in toxicity assessment. Furthermore, the paper examines current testing methodologies, drawing a parallel between the efficiency of in vitro models (oxidative stress, apoptosis, genotoxicity) and the complexity of in vivo studies (biodistribution, clearance, histopathology). A significant segment is dedicated to the dynamics of migration from the polymer matrix into food, evaluating influencing factors such as pH, temperature, and contact time. Finally, directives and guidelines issued by the European Food Safety Authority (EFSA) and REACH regulations are reviewed, providing a theoretical perspective on how scientific and political consensus attempts to define safety limits for the modern consumer.

Keywords: nanotoxicology, active packaging, migration, ZnO, AgNPs, EFSA, risk assessment, bio-interface

1. INTRODUCTION

Nanomaterials offer numerous advantages but have raised many concerns at both public and scientific levels regarding risks to human health and the environment. In the human body, nanoparticles can affect the respiratory system, the central nervous system, as well as the gastrointestinal tract and the skin. For toxicity assessment, the methods used must account for the physicochemical properties of nanoparticles, as they possess different properties from larger particles of identical chemical composition. Therefore, a complete characterization of nanoparticles is needed, including surface charge, porosity, agglomeration, crystallinity, solubility, size, distribution, as well as adsorption capacity, optical properties, and catalytic activity. The term "nano-safety" is associated with "nano-toxicology." Nano-safety deals with the classification of conducted toxicity studies, understanding the importance of results, and the criteria by which they will be classified [1]. However, these results are often not given due importance because we are accustomed to classifying a material in only two ways: safe or poisonous. When results are contradictory, it is

necessary to carefully investigate the cause leading to those results, whether the issue is the chosen methodology, working conditions, or the type of material used. It is impossible not to ask: what does nanotoxicology represent for each of us, and what expectations do we have? Non-governmental institutions want safe products for both consumers and the environment; scientists want more research funding to answer various questions; politicians want to know if this research is necessary. Each institution has different expectations, making it very difficult to reach a common agreement. The toxicological risk of a substance is always a combination of the toxicity of the substance itself and the consumer's exposure to it. Thus, it is important to establish whether the nanomaterial is used as a food additive or if it is incorporated into a polymeric material in direct contact with the contained product. The question all researchers ask is: "Is there a possibility of nanoparticles migrating from the material in which they were incorporated into the contained food product?". Based on the European Commission's request, the

European Food Safety Authority (EFSA) has developed a Guide establishing criteria for assessing the presence of nano-sized particles in food, animal feed, and food contact materials (Nano-RA) and a Guide establishing technical requirements for regulated food and feed applications to establish the presence of small particles, including nanoparticles (Particle-TR). In the first Guide, assessment criteria are divided into three groups:

- **The first group** addresses solubility and dissolution rate to determine whether consumers will be exposed to particles after food consumption. According to current standards, the risk of particle exposure is considered eliminated if the substance exhibits high solubility of at least 33.3 g/L, or if the dissolution process in water is accelerated, with a half-life of at most 10 minutes (corresponding to a dissolved fraction of over 88% in the first half-hour). In the context of commercial products, safety is confirmed when the substance dissolves completely in the food matrix or when present residues are below the reported solubility threshold, thus transforming the "nano" assessment into a conventional one.
- **The second group** evaluates and characterizes conventional material to determine if it contains or consists of small-sized particles. A material is considered outside the scope of specific assessment for small fractions if the majority of its particles exceed 500 nm, and the fraction below this threshold represents less than 10% of the total number. This logic also applies to liquid formulations, where the absence of suspended particles is monitored, as well as the internal composition of the fine fraction: if less than one-tenth of the particles making up the fraction below 500 nm are smaller than 250 nm, the risk profile is considered covered. It is important to note that these size-related routes are not applicable to materials with intrinsic nanostructure.
- **The last group** includes information on the proper conduct of assessments. Researchers must demonstrate that materials used in toxicological tests included these fine fractions and that the experimental design ensured a level of dispersion or degree of agglomeration representative of correctly addressing potential hazards. Thus, risk assessment becomes an integrated process where physicochemical data confirm the relevance of the biological studies conducted [2].

The Particle-TR Guide's role is not to determine if a substance is toxic, but to measure if it contains particles small enough to be treated with special rigor. According to these Technical Requirements, a specialized assessment becomes mandatory if the material:

- Falls under the legal definition of a manufactured nanomaterial.
- Is used in food contact materials (packaging) and exhibits a nanometric form or has been intentionally modified to have different properties from its usual form.
- Belongs to the category of plant protection products (pesticides) and contains very small-sized fractions.

Is a nanostructured material which, although it may appear to consist of large particles, retains its reactivity at a microscopic scale.

Contains a fraction of small particles (where at least 10% of particles are below the 500-nanometer threshold).

If the technical filter confirms the presence of small particles, the process moves to the Nanomaterial Risk Assessment. This stage investigates: behavior in the digestive system (whether particles persist or dissolve rapidly into ions—high solubility equals low risk); toxicity at the cellular level (analyzing if particles can cause oxidative stress, inflammation, or direct DNA damage); bioaccumulation (studying if these particles can cross biological barriers such as the intestinal wall and deposit in organs like the liver, spleen, or brain). The system imposed by the European Food Safety Authority ensures strict control: Technical Requirements identify the presence of particles through physical and mathematical methods, while Risk Assessment guarantees, through biological studies, that these particles do not affect the body's integrity. This approach ensures that technological innovations in packaging and food are safe for long-term human consumption [3].

2. STRATEGIES FOR IN VITRO AND IN VIVO EVALUATION OF TOXICITY INDUCED BY METALLIC NANOPARTICLES

According to the Guide on risk assessment of nanomaterials, the European Food Safety Authority (EFSA) recommends for insoluble nanomaterials, such as those with added antimicrobial nanoparticles like metal oxides, an assessment of effects on the intestinal microbiome, primarily in vitro, followed by in vivo evaluation using animal models [4]. Since nanoparticles have sizes similar to viruses and bacteria, but their absorption and transport in tissues do not rely on molecular mechanisms, in vitro and in vivo tests are necessary.

The first choice is always in vitro tests because they provide results in a short time, have low costs, and do not raise ethical issues. Animal cells are used to evaluate, on one hand, the induction of genetic mutation, and on the other hand, structural and numerical chromosomal lesions. In vivo tests involve the use of live animals. European Union Directive 2010/63/EU on the protection of animals, as well as other regulations such as Regulation (EC) No. 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), have proposed that toxicity tests no longer be performed on live animals but rely on in vitro tests and computational methods [5]. However, in vivo testing is necessary when in vitro genotoxicity test results are positive or inconclusive.

The most commonly used in vitro tests are:

Proliferation tests, based on non-invasive, long-term monitoring of cell viability. Viability and lethality are the most important parameters when testing nanoparticle toxicity.

- **Apoptosis test.** The generation of large amounts of free radicals (oxidative stress) is one of the causes of apoptosis and DNA damage.
- **Necrosis test,** a test to determine cell viability and death.
- **Oxidative stress test,** determining reactive oxygen and nitrogen species [6], [7].

In vivo toxicity tests are generally performed on mice and rats and include biodistribution (the path of nanoparticles to an organ or tissue), clearance (a pharmacokinetic parameter describing the removal of a substance from systemic circulation), hematology, histopathology (establishing the level of toxicity induced by nanoparticles on tissues), and serum chemistry (changes in cell and serum chemistry after exposure to nanoparticles) [8]-[12].

2.1. ZINC OXIDE NANOPARTICLES (ZNO NPS)

Currently, metallic nanoparticles are the most used in the field of nanotechnology due to their excellent antimicrobial activity, even though their real influence on human health and the environment is still an area where relatively little is known. Among these, zinc oxide nanoparticles occupy a central place in food packaging production, being valued for their stability and ability to fight fungi or Gram-positive and Gram-negative bacteria. Moreover, they act as a barrier against UV radiation, protecting light-sensitive foods, and are recognized as safe by the US Food and Drug Administration, while also being an essential source of zinc for the human body. For large-scale production, the most used synthesis methods are mechanochemical ball milling and physical vapor deposition. In the mechanochemical process, precursors such as zinc chloride and sodium carbonate are milled together with an inert diluent, and the mixture is then heat-treated at temperatures of 170-380°C to obtain zinc oxide with sizes of 20-30 nm [13]. On the other hand, the physical method involves injecting precursors into plasma, where the energy of the electric arc leads to the formation of atoms which, through controlled cooling, condense into nanoparticles of 8-75 nm [14]. Although methods like sol-gel or hydrothermal synthesis exist, they can use large amounts of toxic chemicals, which is why "green synthesis" is increasingly being developed. This utilizes sources such as plants, algae, or bacteria, where extracts rich in flavonoids and amino acids reduce toxicity and protect the environment [15].

When added to food contact materials, these particles improve mechanical properties and the water vapor barrier, extending shelf life. Although their mechanism is not fully elucidated, three main modes of action are accepted: the production of reactive oxygen species that cause oxidative stress and destroy the microorganism's membrane, the release of zinc ions that affect bacterial respiration, and direct contact through which nanoparticles penetrate and accumulate inside the cell wall, leading to loss of its integrity [16]. On the other hand, nanoparticles are intended to migrate from the packaging into the contained food, thus being ingested as part of the diet. This can be related to nanoparticle

characteristics (such as concentration, dispersion, shape, size), environmental factors (temperature, mechanical stress, etc.), food type, physicochemical properties of the polymer used, and duration of contact with the food. As there is no standard procedure for testing nanoparticle migration, each nanomaterial must be evaluated on a case-by-case basis [17]. Zinc oxide nanoparticles represent some of the most used materials in consumer products, from cosmetics and sunscreens to biomedical applications and food packaging, frequently exposing the human body through dermal routes, inhalation, or oral ingestion. This extensive presence has become a public health concern because particles can enter the body through the respiratory and digestive systems, as well as through parenteral routes. Many in vitro and in vivo tests have demonstrated that these nanoparticles are toxic to animals, their effects being closely linked to solubility. Unlike other metallic structures, zinc oxide tends to dissolve in aqueous solutions, releasing zinc ions (Zn^{2+}), a process that critically depends on the solution's pH, particle size, and the presence of organic compounds [18]. The effect of pH, size, and nanoparticle shapes on solubility has been tested by researchers using aqueous solutions at body temperature (37°C) and pH between 1.5-7, reproducing human biological fluids (gastric, intestinal, and plasma fluids). Results showed an increase in solubility at low pH. Also, particle size and shape influence solubility. It was observed that larger and agglomerated particles dissolve more slowly in aqueous solutions [19]. Another important aspect regarding nanoparticle toxicity is the interaction with the food matrix, which can have an acidic or alkaline pH in aqueous solution [20].

Researchers have studied the toxicity of zinc oxide nanoparticles based on age, observing that these particles can reach the brain, causing inflammation and affecting long-term and spatial memory, effects more pronounced in elderly subjects. However, the addition of antioxidants such as hesperidin from citrus could reduce this inflammatory response [21]. Human activities have disrupted the natural nanoparticle cycle, which can have a negative impact on soil. Man-made nanoparticles have specific nanotechnological properties regarding size, behavior, and properties, and their sorption process is influenced by soil composition and pH. It was seen that the toxicity of zinc oxide nanoparticles is higher in acidic soil compared to neutral soil, with the lowest being in alkaline soil. These metallic nanoparticles can have a negative impact on biodiversity and soil bacterial activity because their antibacterial effects affect microorganisms that contribute to the decomposition of organic matter and the nutrient cycle [22].

Nanomaterials often discarded in sea, ocean, and lake waters represent a risk to the health of aquatic animals and plants. Studies on the cytotoxicity of zinc oxide nanoparticles on zebrafish investigated metabolic and bioenergetic responses in the liver, the main organ that metabolizes any foreign substance. Following a 28-day exposure, a loss of adenosine triphosphate (ATP), the chemical compound that provides cells with the energy needed to carry out any biological activity, was observed [23].

But if we talk about food packaging, nanoparticles are incorporated into the polymer matrix. Chinmayee Parida and collaborators analyzed the migration of nanoparticles from a gelatin-based biopolymer matrix into fresh bread slices. The research quantified migration as a function of temperature, time, and concentration, with toxicity assessment based on European Food Safety Authority (EFSA) studies on low-density polyethylene. The European Food Safety Authority (EFSA) concluded that the substance does not migrate in nano form, but as soluble ionic zinc [24]. As long as migration respects the specific limit of 5 mg/kg food or 25 mg/person/day, the products are considered safe for consumption. Chinmayee et al. obtained the bionanocomposite material through the casting method, characterizing nanoparticles by SEM, TEM, FTIR, and XRD to determine size, morphology, and interaction with the gelatin matrix. The study of migration into food showed that the process is influenced by concentration, temperature, and time, reaching maximum values on the fifth day. Since the results fall within the 50 mg/day limit established by the EFSA Scientific Panel, the tests did not indicate adverse effects, and the product is safe for consumption [25]. Francisco A.G. Soares Silva et al. studied the migration of zinc oxide nanoparticles from a bacterial cellulose film produced by bacteria of the genus *Komagataeibacter*. Due to high porosity and water retention capacity, this material is ideal for active substances. Migration tests were performed in food simulants (10%, 20%, 50% ethanol) according to EU Regulation 10/2011 and in contact with chicken skin at various temperatures. Results indicated higher migration of zinc ions in solutions with lower ethanol concentration, as zinc is more soluble in water. However, after 72 hours, a reabsorption of zinc by nanocellulose was observed in all simulants. The specific migration limit (SML) for ionic zinc remained below the 5 mg/kg food threshold established by EU Regulation 2016/1416, confirming the material's compliance for food contact [26]. Yaqing Xiao, Yingnan Liu et al. developed an active film for pork meat based on soy protein isolate, cellulose nanocrystals, and zinc oxide nanoparticles. This addition improved mechanical and thermal properties and the gas barrier, while demonstrating effective biocidal activity against *E. coli* and *S. aureus*. Crucially, cellulose nanocrystals prevented zinc migration into the food, confirming the success of using this material in the packaging industry [27]. Nattinee Bumbudsanpharoke et al. investigated zinc migration from a low-density polyethylene (LDPE) and zinc oxide nanoparticle nanocomposite film. Tests used various food simulants (50% ethanol, distilled water, 4% acetic acid, n-heptane) at a temperature of 70°C for 30 minutes [28]. Hatice Kavuncuoglu et al. evaluated nanoparticle migration from a low-density polyethylene film with added ZnO and TiO₂ used for beef preservation. Tests performed for 7 days at temperatures of 1°C, 7°C, and -18°C showed that titanium nanoparticle migration was higher than that of zinc. However, it was concluded that the nanocomposite film represents a viable solution for food packaging [29]. Therefore, the presented data lead us to the idea that we can use zinc oxide nanoparticles in active food packaging and consumer products, as they offer superior mechanical, thermal, and antimicrobial

properties. However, their integration requires rigorous risk assessment. As long as production processes respect authorized concentrations (up to 2%) and specific migration limits established by Regulation (EU) No. 10/2011, these materials are considered safe for human health.

2.2 SILVER NANOPARTICLES (AgNPs)

Silver nanoparticles occupy a central place in nanotechnology due to their optical, thermal, and electrical properties, but especially for their remarkable biocidal capacity. This antimicrobial property is essential in the context of increasing bacterial resistance to antibiotics. In the food industry, they are incorporated into both thermoplastic polymers (PE, PP, PS, PA) and biopolymers such as cellulose, chitosan, or starch. The synthesis of these nanoparticles is carried out through three main routes: physical methods (evaporation-condensation produces spherical particles of 6.2-21.5 nm), laser ablation (20-50 nm, without chemical reagents), and ion sputtering; chemical methods (chemical reduction with organic/inorganic agents, microemulsion, and laser irradiation); ecological methods (Green Synthesis, using extracts from plants, fungi (*Fusarium*, *Aspergillus*), algae, or bacteria (*Bacillus*, *Pseudomonas*) for sustainable production). Despite the benefits, silver nanoparticles present toxicity risks for the human body. They can enter the body through dermal contact, inhalation, ingestion, or injection, having the potential to induce cell necrosis, apoptosis (programmed cell death), or even genetic mutations. In a study led by Wim H. De Jong and collaborators, rats exposed intravenously for 28 days to AgNP doses (6 mg/kg body weight) with sizes of 20 nm and 100 nm showed significant physiological changes. Regardless of particle size, an increase in spleen weight and almost total suppression of Natural Killer (NK) cell activity, essential components of the immune system, were observed [30]. Rayhaneh Amooaghaie and collaborators demonstrated that the toxicity of silver nanoparticles (AgNP) depends directly on the synthesis method used. The study compared the chemical method (using sodium borohydride and sodium citrate) with the green method (using *Nigella sativa* leaf extract as a reducing and stabilizing agent). Monitoring effects on rat bone stem cells and plant germination revealed that nanoparticles obtained through green synthesis are considerably less toxic. The research concluded that cell viability is significantly higher when using green chemistry principles compared to conventional chemical methods [32]. In vitro and in vivo tests confirm that the cytotoxic and genotoxic effects of silver nanoparticles are closely linked to concentration, duration of exposure, and especially their size, with smaller particles being the most harmful. The study led by Muthu Irulappan Sriram et al. on bovine endothelial cells clearly demonstrated this correlation [33]. Silver nanoparticles can enter the body through diffusion, endocytosis, and phagocytosis, generating reactive oxygen species which leads to the onset of oxidative stress. However, the generation of reactive oxygen species can be reduced by pre-treating

cells with N-acetylcysteine, which is a powerful antioxidant [34].

Studies on the migration of silver nanoparticles (AgNP) from packaging into food remain limited, although the process is well-defined as a three-stage mass transfer: diffusion through the material, dissolution, and final dispersion in the food product. Although standard analysis methods (such as electron microscopy or mass spectrometry) are extremely precise, they are limited by high costs, the need for sophisticated equipment, and specialized personnel. As an efficient alternative, Ana I. Corpul Ricardo et al. validated a rapid qualitative method based on chemiluminescence. This technique uses the reaction between luminol and silver ions in an alkaline medium, generating light in the presence of nanoparticles, allowing for a rapid and accessible evaluation of migration. The method was applied to silver-colored beads containing additive E174 (silver) or E173 (aluminum) used for decorating sweet pastry products [35]. Aiga Mackevica et al. investigated the migration of silver nanoparticles from four types of packaging into different simulants (purified water, 10% ethanol, 3% acetic acid) at 40°C for 10 days. Results indicated that 3% acetic acid caused the highest migration rate (3.1 ng/cm²), highlighting an increased risk of particle transfer into food products with acidic pH. These observations confirm the need for careful evaluation of the interaction between active packaging and the type of food product, acidity being a critical factor that accelerates the migration of ions or nanoparticles from the polymer matrix [36]. Amal M. Metak et al. compared silver nanoparticle migration in orange juice, testing two types of packaging: those with nanoparticles incorporated into the matrix and those only surface-coated. Results showed significantly higher migration in the case of coated packaging (28.92 ± 0.01 µg/L) compared to nanocomposite ones (5.66 ± 0.02 µg/L). However, both values were within safety limits, without altering the sensory, chemical, or biochemical properties of the juice [37]. Susana Addo Ntim et al. evaluated silver nanoparticle migration from commercial packaging (with concentrations between 0.001 and 36 mg/kg polymer) into water and 3% acetic acid. The study concluded that in the tested simulants, no intact nanoparticles were detected, only ionic silver (Ag⁺). This is gradually released through the oxidation of the nanoparticle surface during contact with the environment, confirming that mass transfer from packaging to food occurs predominantly in ionic form, and not as solid particles [38]. M. Cushen et al. analyzed silver migration from polyethylene packaging directly into boneless chicken breast. Results indicated constant values between 0.003 and 0.005 mg/dm², with time and temperature having no significant influence on the process in this real food matrix [39]. In contrast, Min Hee Kim et al. tested migration from LDPE into simulants (distilled water and 4% acetic acid), observing that the acidity of the medium considerably accelerates silver diffusion, with values being much higher in acetic acid than in water [40].

Fewer studies have been conducted regarding nanoparticle migration from biodegradable packaging. Soumya B. Nair et al. tested nanoparticle migration from

a food film obtained from chitosan/glucomannan (a soluble vegetable fiber derived from the root of the perennial herbaceous plant *Amorphophallus konjac*)/silver nanoparticles/granular cassava starch into the packaged food product, in this case using bread. Conducted tests demonstrated nanoparticle migration below the limit established by current legislation (10 mg/L) [41]. Nicolli Grecco Marchiore et al. studied the migration of "green" synthesized silver nanoparticles (AgNP) (with starch and dextrose) applied as an edible coating on chicken sausages. The study highlighted the following aspects: biocidal activity (the coating delayed the development of microorganisms by up to 15 days compared to control samples); reduced migration (no significant migration inside the product was recorded, the concentration of metallic silver (Ag⁰) remaining constant (4.10⁻³ µg/g) after 30 days); safety (the value was well below the limit of 0.01 mg/kg established by Regulation (EC) No. 450/2009); consumer impact (washing and cooking the product considerably reduce the silver concentration on the surface, eliminating risks to consumer health) [42]. M. El. Mouzahim et al. studied the effect of kaolin clay and silver nanoparticles on food film obtained from chitosan, used for packaging fresh apple slices. The film thus obtained showed nanoparticle migration below the limit established by the European Food Safety Authority (EFSA), so it could be used for packaging fresh fruit without endangering consumer health [43]. Nesrine Amiri et al. optimized the ICP-MS technique to precisely quantify silver in beverages (orange juice, milk powder) and simulants. Results showed that nanoparticle stability depends directly on the contact medium. The highest migration rate was recorded in 3% acetic acid, as low pH favors solubilization, while high pH stabilizes silver on the surface of containers. In all cases, values remained below the detection limit [44]. On the other hand, Florencia Ortega et al. compared migration from starch films with nanoparticles synthesized in situ versus those through green chemistry (with lemon juice). Tests (7 days at 35°C) highlighted that green synthesis reduces migration because lemon juice acts as a cross-linking agent and plasticizer. Both methods generated migration values compliant with current legislation [45]. Ludmila Motelica et al. developed an innovative biodegradable film based on alginate, enriched with silver nanoparticles and lemongrass essential oil, for packaging soft cheese. This solution extended the product's shelf life from 4 to 14 days, demonstrating high biocidal efficiency against Gram-positive (*B. cereus*, *S. aureus*) and Gram-negative (*E. coli*, *S. Typhi*) bacteria. Researchers emphasize that the combined use of antimicrobial agents allows for reducing the concentration of each substance, thus minimizing toxicity risks for the consumer [46].

The EFSA Scientific Panel established following conducted studies that silver nanoparticles incorporated into polymers (such as polyolefins or polyesters) do not migrate into food as nano-objects, thus eliminating the toxicological risk associated with this form. The only observed migration is in soluble ionic form, but the recorded values (up to 6 µg/kg) are well below the safety

limit of 50 µg/kg established by the AFC Panel. Therefore, an addition of 0.025% silver in packaging materials is considered safe for consumer health [47].

3. CONCLUSIONS

In recent years, we have witnessed an accelerated expansion of nanoparticle use in diverse fields, from the cosmetic and pharmaceutical industries to the food industry; however, this evolution is accompanied by essential questions regarding their toxicity to the body and the environment. Due to their extremely small dimensions, nanoparticles behave differently in the body compared to large particles, having the ability to penetrate through ingestion, respiration, or skin and subsequently accumulate in various organs. In vitro and in vivo studies conducted to date put forth considerable efforts to elucidate the mechanisms triggering harmful effects and to identify ways in which these materials can become less toxic. In this context, it becomes imperative to establish a safe maximum dose, an objective that can only be achieved by defining a standardized toxicological profile

that takes into account both the nature of the nanoparticles and the characteristics of the polymer matrix in which they are incorporated. Correct risk assessment requires advanced analytical characterization methods, as establishing specific regulation represents, currently, the number one challenge for researchers worldwide. On the other hand, the addition of metallic nanoparticles with biocidal properties—such as silver, zinc, or copper—in food packaging allows for obtaining materials with global properties superior to traditional ones, offering improved protection against gases, moisture, UV radiation, and bacteria. Results regarding the migration of these particles are encouraging, indicating that only a minute amount passes into food or simulants, suggesting low consumer exposure and a reduced health risk. However, the lack of appropriate regulation persists even in developed countries, which is why it is vital to invest financial resources, time, and technological means to answer current uncertainties. Only through a rigorous risk assessment regarding human toxicity will we be able to ensure a safe framework for the use of nanomaterials, allowing their approval as reliable solutions for food packaging.

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