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EMERGING APPLICATIONS OF NANOTECHNOLOGY IN THE FOOD INDUSTRY: INNOVATIONS IN FOOD PACKAGING, SAFETY, QUALITY AND PRESERVATION**P. Jayamma¹Dr.G.Deepika Kumari²**¹Assistant professor, Department of Food Safety and Quality Assurance, College of Food Technology, ANGRAU, Pulivendula, A.P.²Associate Professor in Microbiology, College of Veterinary Science, Garividi, A.P.Corresponding author: p.jayamma@angrau.ac.in**Abstract**

Nanotechnology, the design and application of materials with at least one dimension in the nanometre range, has become one of the most active areas of food science and technology. This narrative review synthesises peer-reviewed literature on the use of engineered nanomaterials (ENMs) in five domains: (i) active, intelligent and barrier-improved food packaging; (ii) food preservation and shelf-life extension; (iii) food safety, pathogen detection and biosensing; (iv) food processing, nanoencapsulation and quality monitoring; and (v) the toxicological, regulatory and societal issues that condition commercial adoption. Evidence indicates that polymer nanocomposites containing layered silicates, nanocellulose, silver, zinc oxide and titanium dioxide can improve gas and moisture barrier properties, mechanical strength and antimicrobial performance. Nanoemulsions and other nanocarriers improve the dispersibility, stability and delivery of lipophilic bioactives and antimicrobials, and nanoparticle-based biosensors (gold, quantum dots, magnetic and carbon-based materials) offer rapid, sensitive detection of pathogens, toxins and chemical contaminants. However, migration of nanoparticles from packaging, uncertain gastrointestinal fate, and incomplete toxicological datasets remain key concerns, exemplified by the European Union's withdrawal of titanium dioxide (E171) as a food additive. Most published evidence derives from laboratory-scale or in vitro studies, and standardised characterisation, migration testing and life-cycle assessment are needed before widespread commercialisation. Priorities for future research include biodegradable and bio-based nanomaterials, safe-and-sustainable-by-design strategies, and harmonised regulation.

Keywords: nanotechnology; food packaging; nanocomposites; antimicrobial packaging; nanoemulsions; nanoencapsulation; biosensors; food safety; shelf life; nanotoxicology; regulation

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Introduction

Nanotechnology concerns the manipulation of matter at the nanoscale, conventionally 1–100 nm, where materials often display physicochemical properties (large specific surface area, enhanced reactivity, quantum and optical effects) that differ from their bulk counterparts (Sozer and Kokini, 2009; Weiss et al., 2006). In the food sector, these properties are exploited to improve the functionality of

packaging, to deliver and protect sensitive ingredients, to inhibit spoilage and pathogenic microorganisms, and to detect contaminants at low concentrations (Duncan, 2011; Neethirajan and Jayas, 2011; He and Hwang, 2016).

Food loss and food-borne disease provide strong motivation for such technologies. Spoilage, oxidation and microbial contamination reduce shelf life and safety, while conventional packaging and preservation approaches may be

International Conference on Ensuring Global Food Safety-ICEGFS-2026

insufficient for highly perishable products or may rely on additives that consumers increasingly wish to avoid. Nanomaterials may allow lower-dose, targeted and multifunctional solutions, such as packaging that simultaneously acts as a gas barrier, an antimicrobial surface and a freshness indicator (Duncan, 2011; Bajpai et al., 2018).

A useful distinction in the literature separates nano-applications into those in which nanomaterials are (a) added to food (e.g., nanoemulsions, nanocarriers, anti-caking agents and pigments), (b) in contact with food (food-contact materials and coatings), and (c) used outside food for analysis and monitoring (sensors, filters, detection assays) (Cushen et al., 2012; Peters et al., 2016). This classification is important because exposure routes, and therefore risk assessment requirements, differ markedly among these categories.

Several earlier reviews have addressed individual aspects: nanocomposite packaging (Azeredo, 2009; Silvestre et al., 2011; Rhim et al., 2013), nanosensors and pathogen detection (Lazcka et al., 2007; Vanegas et al., 2018), nanoemulsions and encapsulation (McClements and Rao, 2011; Ezhilarasi et al., 2013; Assadpour and Jafari, 2019) and safety and regulation (Bouwmeester et al., 2009; McClements and Xiao, 2017). The present review integrates these strands into a single framework linking material class, mechanism, application and risk, and highlights evidence gaps that are important for translation to industry.

Applications of Nanotechnology in Food Packaging

Nano-enabled packaging is conventionally divided into improved (barrier) packaging, active packaging and intelligent (smart) packaging (Duncan, 2011; Bumbudsanpharoke and Ko, 2015).

Improved barrier and mechanical properties

Incorporating high-aspect-ratio nanofillers into polymers creates a tortuous diffusion path for gases and water vapour. Layered silicates (nanoclays such as montmorillonite) are the most widely studied fillers, and numerous reviews report improvements in oxygen and water-vapour barrier, stiffness and thermal stability when clays are well dispersed (Sorrentino et al., 2007; Azeredo, 2009; Silvestre et al., 2011). Natural biopolymer-based nanocomposites, including starch, chitosan, gelatin and cellulose-based systems reinforced with clays or nanocellulose, have been reviewed as environmentally friendlier alternatives to petroleum-derived films (Rhim and Ng, 2007; Rhim et al., 2013). Performance depends strongly on exfoliation, filler–matrix compatibility and processing, and improvements are not universal across polymer–filler pairs (Azeredo, 2009).

Active antimicrobial packaging

Metal and metal-oxide nanoparticles are the most common antimicrobial agents in nano-active packaging. Silver nanoparticles (AgNPs) show broad-spectrum antibacterial activity (Sondi and Salopek-Sondi, 2004; Morones et al., 2005), commonly attributed to membrane damage, release of Ag⁺ ions and generation of reactive oxygen species. Zinc oxide (ZnO) nanoparticles are antimicrobial and are generally regarded as safe in bulk form by the US FDA for specified uses, which has encouraged their study in packaging (Espitia et al., 2012). Titanium dioxide (TiO₂) acts through photocatalytic generation of reactive oxygen species under UV light (Maneerat and Hayata, 2006; Bodaghi et al., 2013). Chitosan nanoparticles have also shown antibacterial effects in vitro (Qi et al., 2004). Llorens et al. (2012) reviewed metallic micro- and nanocomposites in food-contact materials and highlighted their antimicrobial

International Conference on Ensuring Global Food Safety-ICEGFS-2026

potential together with the need for migration assessment.

The release that drives antimicrobial efficacy also drives migration risk

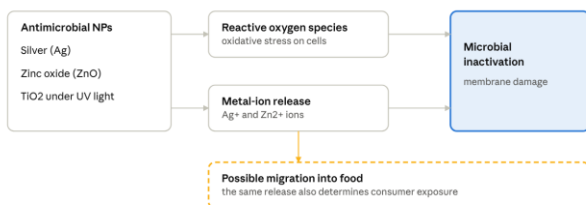


Figure 1. Commonly proposed antimicrobial pathways of Ag, ZnO and TiO₂ nanoparticles, and the associated migration trade-off (after

Sondi and Salopek-Sondi, 2004; Morones et al., 2005; Espitia et al., 2012; Llorens et al., 2012).

Intelligent packaging and sensing

Nanomaterials are used in indicators and sensors that report oxygen, humidity, temperature, gases from spoilage, or microbial growth, often through colorimetric or fluorescent changes (Duncan, 2011; Bumbudsanpharoke and Ko, 2015). Such systems are largely at the laboratory or pilot stage, and their robustness in real supply chains requires further evidence.

Representative studies

Table 1. Selected published studies on nano-enabled food packaging and related migration research.

Nanomaterial / system	Application or matrix	Principal reported finding (qualitative)	Reference
Ag and ZnO in polymer nanocomposite	Fresh orange juice packaging	Nanocomposite packaging assessed for its effect on microbial quality and shelf life during storage	Emamifar et al. (2010)
Silver–montmorillonite	Fresh fruit salad	Antimicrobial nanoparticles used to prolong shelf life	Costa et al. (2011)
TiO ₂ photocatalysis	<i>Penicillium expansum</i> in vitro and in fruit	Photocatalytic antifungal activity demonstrated	Maneerat and Hayata (2006)
TiO ₂ nanocomposite film	In vitro and in vivo tests on produce	Photocatalytic antimicrobial effect evaluated	Bodaghi et al. (2013)
Nano-ZnO coating	Fresh-cut 'Fuji' apple	Active packaging effects on quality of fresh-cut apple evaluated	Li et al. (2011)
Nano-silver food containers	Food simulants	Nanoparticle and silver release from containers detected	Echegoyen and Nerín (2013)
Nanoparticles in food-contact plastics	Critical review	Migration potential of nanoparticles critically assessed	Störmer et al. (2017)

Nano-Based Food Preservation and Shelf-Life Extension

Antimicrobial nanoparticles and coatings

Beyond packaging films, nanoparticles are applied as edible coatings or incorporated in matrices to slow microbial growth, respiration and moisture loss in fresh produce (Bajpai et al., 2018; Pathakoti et al., 2017). TiO₂

photocatalysis has been investigated for fungal control on fruit (Maneerat and Hayata, 2006), and nano-ZnO and nano-silver systems have been evaluated for fresh-cut fruit and juices (Emamifar et al., 2010; Li et al., 2011; Costa et al., 2011). Antimicrobial nanomaterials are also discussed more generally in the context of microbial control (Li et al., 2008).

International Conference on Ensuring Global Food Safety-ICEGFS-2026

Nanoemulsions of essential oils and antimicrobials

Essential oils have well-documented antimicrobial properties but are hydrophobic, volatile and organoleptically intense. Food-grade nanoemulsions reduce droplet size to the nanometre range, which can improve dispersion in aqueous foods, physical stability and, in several studies, antimicrobial efficacy (McClements and Rao, 2011; Donsì and Ferrari, 2016). The same reviews caution that the fate of the lipid carrier and the sensory impact must be considered.

Nanoencapsulation of protective and bioactive compounds

Nanocarriers (liposomes, solid lipid nanoparticles, biopolymer nanoparticles, nanoemulsions, nanofibres) protect antioxidants, vitamins, polyphenols and probiotics from degradation and can control release (Ezhilarasi et al., 2013; Assadpour and Jafari, 2019). Delaying lipid oxidation and preserving bioactive stability contribute indirectly to shelf-life extension and nutritional quality.

Limitations

Efficacy in simplified media does not always translate to complex food matrices, where proteins, lipids and ions may reduce nanoparticle activity or alter dispersion (Weiss et al., 2006; He and Hwang, 2016). Dose, particle characterisation and regulatory acceptability therefore remain decisive.

Applications in Food Safety, Pathogen Detection and Biosensors

Conventional culture-based detection is reliable but slow, whereas PCR and immunoassays are faster but may require trained personnel and laboratory infrastructure (Lazcka et al., 2007). Nanomaterials contribute through signal

amplification, high surface area for biorecognition elements, and distinctive optical, magnetic or electrochemical properties.

- **Gold nanoparticles (AuNPs):** localised surface plasmon resonance enables colorimetric assays and lateral-flow formats (Saha et al., 2012). Nanoparticle–enzyme conjugates have been used for colorimetric bacterial sensing (Miranda et al., 2011).
- **Quantum dots (QDs):** bright, photostable fluorescence suited to multiplexed labelling and sensing (Medintz et al., 2005); toxicity of cadmium-containing QDs limits direct food contact.
- **Magnetic nanoparticles:** used for separation and pre-concentration of target cells from complex food matrices before detection (Vanegas et al., 2018).
- **Plasmonic substrates for SERS:** surface-enhanced Raman spectroscopy with metallic nanostructures has been applied to detect contaminants and pathogens in food (Craig et al., 2013).
- **Electrochemical nanosensors:** carbon-based and metallic nanomaterials improve electrode sensitivity for pathogens, toxins, pesticides and veterinary-drug residues (Vanegas et al., 2018; Neethirajan and Jayas, 2011).

Overviews of rapid-detection strategies for foodborne pathogens are provided by Lazcka et al. (2007) and Vanegas et al. (2018). Reported limits of detection are assay- and matrix-specific, and comparisons across studies should be made cautiously because of differences in matrices, sample preparation and validation.

Table 2. Nanomaterial-based sensing platforms for food safety (conceptual summary from cited reviews).

Platform	Transduction principle	Typical targets	Key advantages	Key limitations	Sources
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International Conference on Ensuring Global Food Safety-ICEGFS-2026

Platform	Transduction principle	Typical targets	Key advantages	Key limitations	Sources
Gold nanoparticles	Colorimetric / plasmonic / lateral flow	Bacteria, toxins, adulterants	Simple, visual readout, portable	Matrix interference; sensitivity varies	Saha et al. (2012); Miranda et al. (2011)
Quantum dots	Fluorescence	Pathogens, toxins	Multiplexing, photostability	Heavy-metal composition raises safety concerns	Medintz et al. (2005)
Magnetic nanoparticles	Separation / concentration	Bacterial cells	Reduces matrix effects	Needs coupling to a detection step	Vanegas et al. (2018)
SERS substrates	Raman enhancement	Contaminants, pathogens	Fingerprint specificity	Substrate reproducibility	Craig et al. (2013)
Electrochemical nanosensors	Current / impedance	Pathogens, residues	Miniaturisable, low cost	Electrode fouling in complex foods	Vanegas et al. (2018)

Nanotechnology in Food Processing and Quality Monitoring**Delivery systems and texture/functional ingredients**

Nanoemulsions and nanostructured delivery systems can incorporate lipophilic nutraceuticals, flavours and colours into clear beverages and low-fat products, and may modify texture and bioavailability (Weiss et al., 2006; McClements and Rao, 2011; Ezhilarasi et al., 2013). Nano-sized additives such as silicon dioxide (E551) as an anti-caking agent and TiO₂ as a whitening pigment have long been used, and their nano-fractions have been quantified in food products (Dekkers et al., 2011; Weir et al., 2012; Peters et al., 2014).

Nano-enabled processing aids

Nanostructured membranes and filters are applied for separation, clarification and removal of contaminants, and nanomaterials are explored as enzyme supports and catalysts (Neethirajan and Jayas, 2011; Rossi et al., 2014).

Quality and authenticity monitoring

Nanosensors and nanostructured indicators can monitor freshness, detect adulterants and measure residues, supporting real-time quality control and traceability (Neethirajan and Jayas, 2011; Bajpai et al., 2018). SERS and optical nanosensors in particular are being developed for rapid on-site analysis (Craig et al., 2013).

Table 3. Comparison of major nanomaterial classes in food-related applications.

Nanomaterial	Main functions	Typical food uses	Maturity / status	Principal concerns	Key sources
Silver (AgNPs)	Antimicrobial	Packaging films, containers, coatings	Commercial in food-contact items in some regions; restricted in others	Ag release, ecotoxicity, antimicrobial resistance debate	Sondi and Salopek-Sondi (2004); Echegoyen and Nerin (2013); EFSA (2016)

International Conference on Ensuring Global Food Safety-ICEGFS-2026

Nanomaterial	Main functions	Typical food uses	Maturity / status	Principal concerns	Key sources
Zinc oxide (ZnO)	Antimicrobial, UV block	Packaging films, coatings	Research to pilot	Zn ²⁺ release; migration	Espitia et al. (2012)
Titanium dioxide (TiO ₂)	Whitening; photocatalysis; UV barrier	Pigment in foods (E171); packaging	E171 no longer authorised in the EU	Genotoxicity uncertainty; accumulation	EFSA (2021a); Weir et al. (2012); Bettini et al. (2017)
Silicon dioxide (SiO ₂)	Anti-caking, carrier	Powders, spices	Long-standing additive (E551)	Nano-fraction exposure data	Dekkers et al. (2011)
Nanoclays (montmorillonite)	Barrier, mechanical reinforcement	Polymer films, bottles	Commercial in some packaging	Migration of clay-associated metals/organo modifiers	Azeredo (2009); Silvestre et al. (2011)
Nanocellulose / biopolymer nanofillers	Barrier, reinforcement; biodegradable	Bio-based films, coatings	Research to pilot	Scale-up cost; moisture sensitivity	Rhim et al. (2013)
Chitosan nanoparticles	Antimicrobial, carrier	Coatings, encapsulation	Research	Variable performance in foods	Qi et al. (2004)
Nanoemulsions / lipid nanocarriers	Delivery, dispersion, antimicrobial	Beverages, functional foods	Commercial for some ingredients	Gastrointestinal fate of carriers	McClements and Rao (2011)
Gold nanoparticles	Sensing, signal amplification	Rapid detection assays	Used in diagnostics; limited food-contact use	Cost; not intended for ingestion	Saha et al. (2012)
Quantum dots	Fluorescent labels	Laboratory detection	Research	Cd/Pb-based toxicity	Medintz et al. (2005)

Note: "Maturity" entries are qualitative syntheses from the cited reviews and regulatory documents, and the status of individual products varies by jurisdiction.

Results and Discussion Based on Published Literature

This section synthesises the literature cited above. No new experimental data are reported, and statements about efficacy reflect the cited studies' own conclusions.

Packaging: consistent barrier gains, variable antimicrobial translation

Reviews agree that well-dispersed nanoclays and other high-aspect-ratio fillers improve barrier and mechanical properties of both synthetic and biopolymer matrices (Sorrentino et al., 2007; Azeredo, 2009; Silvestre et al., 2011; Rhim et al., 2013). The principal limitation is processing: achieving exfoliation and compatibility at industrial scale, and managing the hydrophilicity of many bio-based matrices. Antimicrobial nanocomposites based on Ag, ZnO and TiO₂ are

International Conference on Ensuring Global Food Safety-ICEGFS-2026

effective in vitro and in several food models (Emamifar et al., 2010; Costa et al., 2011; Maneerat and Hayata, 2006; Bodaghi et al., 2013; Li et al., 2011), but performance in real foods depends on contact between film and product, water activity and the diffusion of active species. Where activity relies on ion release, there is an inherent link between efficacy and migration, which is the central trade-off for regulators (Llorens et al., 2012; Echegoyen and Nerín, 2013; Störmer et al., 2017).

Preservation: carriers and coatings extend the toolbox

Nanoemulsions and nanoencapsulation address a different limitation, namely the poor solubility, volatility or instability of natural antimicrobials and antioxidants (McClements and Rao, 2011; Ezhilarasi et al., 2013; Assadpour and Jafari, 2019). Their advantage is that they use food-

grade lipids, proteins and polysaccharides, which are generally easier to position within existing regulatory frameworks than inorganic ENMs, although the carrier's gastrointestinal fate must still be considered (McClements and Xiao, 2017).

Detection: strong analytical promise, limited field validation

Nanomaterial-enabled sensors repeatedly demonstrate improvements in speed and sensitivity compared with culture-based methods (Lazcka et al., 2007; Vanegas et al., 2018). Gaps include validation against standard methods in diverse real foods, sample preparation, shelf-stable reagents and cost. These are engineering and standardisation challenges rather than scientific barriers, but they explain why laboratory demonstrations outnumber commercial food-testing products.

Table 4. Synthesis of evidence maturity by application domain

Domain	Evidence base	Strengths	Main evidence gaps
Barrier nanocomposites	Many in vitro and film-property studies; some commercial use	Reproducible barrier and mechanical gains	Scale-up; end-of-life and recyclability
Antimicrobial packaging	Laboratory and model-food studies	Broad-spectrum activity	Long-term migration; efficacy in real supply chains
Nanoemulsions and encapsulation	Extensive laboratory work; commercial ingredients exist	Food-grade materials; improved dispersion and stability	Fate in the gut; sensory effects
Biosensors and detection	Predominantly proof-of-concept	Speed and sensitivity	Matrix effects; multi-laboratory validation
Nano-additives (TiO ₂ , SiO ₂)	Long-established use	Technological functionality	Exposure, toxicity uncertainty, regulatory restriction

Cross-cutting observations

Three themes emerge. First, **characterisation is inconsistent**: many studies do not report particle size distribution in the matrix, dissolution or aggregation, which limits comparability (Peters

et al., 2014; Rossi et al., 2014). Second, **migration and toxicity are often studied separately from efficacy**, so benefit-risk balance is rarely evaluated within a single study. Third, **sustainability is under-addressed**: the

International Conference on Ensuring Global Food Safety-ICEGFS-2026

life-cycle impact of ENMs and the effect of nanofillers on recyclability or compostability are seldom quantified in the food-packaging literature reviewed here.

Safety Concerns, Toxicity, Regulatory Issues and Future Prospects

Exposure and migration

Human exposure arises from ingestion of nano-sized additives and carriers, and from migration of nanoparticles or their dissolution products from food-contact materials. Studies of nano-silver food containers have detected release of silver into food simulants, including particulate forms (Echegoyen and Nerín, 2013), and a critical review of nanoparticle migration from food-contact plastics concluded that migration depends on the polymer, particle type and conditions, and that analytical characterisation of released particles is challenging (Störmer et al., 2017). Nano-fractions of established additives are also present in foods: nanosilica (Dekkers et al., 2011) and TiO₂ (Weir et al., 2012; Peters et al., 2014) have been quantified in commercial products.

Gastrointestinal fate and toxicity

Particle size, surface chemistry, dissolution and interaction with the food matrix and digestive fluids determine absorption, distribution and effects, and these differ between organic (lipid, biopolymer) and inorganic (metal, metal-oxide) nanoparticles (McClements and Xiao, 2017). General nanotoxicology frameworks describe mechanisms such as oxidative stress and inflammation arising from high surface reactivity (Oberdörster et al., 2005; Nel et al., 2006). A rodent study reported that food-grade TiO₂ affected intestinal and systemic immune homeostasis and promoted preneoplastic lesions (Bettini et al., 2017). Reviews of nanomaterial safety in food emphasise that data on chronic oral exposure, accumulation and effects on the gut microbiota remain limited (Bouwmeester et al., 2009; He and Hwang, 2016; McClements and Xiao, 2017).

Regulatory landscape

Regulation is evolving and differs by jurisdiction; the following summary should be checked against current texts before publication.

Table 5. Selected regulatory instruments relevant to nanomaterials in food and food-contact materials.

Jurisdiction	Instrument	Relevance
European Union	Regulation (EU) No 1169/2011 on food information to consumers	Requires engineered nanomaterial ingredients to be labelled, with the word "nano" in brackets
European Union	Regulation (EU) 2015/2283 on novel foods	Foods containing or consisting of engineered nanomaterials fall under novel-food authorisation
European Union	Regulation (EU) No 10/2011 on plastic food-contact materials	Substances in nanoform may only be used if explicitly authorised and specified
European Union	EFSA Scientific Committee guidance on nanomaterials in the food and feed chain (EFSA, 2021b)	Sets out the risk-assessment approach, including characterisation and testing
European Union	Commission Regulation (EU) 2022/63	Removed titanium dioxide (E171) from the list of authorised food additives, following EFSA (2021a)

International Conference on Ensuring Global Food Safety-ICEGFS-2026

Jurisdiction	Instrument	Relevance
United States	FDA guidance on emerging technologies and significant manufacturing-process changes (2014)	Advises manufacturers to assess the safety and regulatory status of nanotechnology-derived ingredients and food-contact substances

In its 2021 re-evaluation of E171, EFSA concluded that genotoxicity concerns could not be ruled out and that the additive could no longer be considered safe (EFSA, 2021a). This outcome illustrates that safety conclusions for a long-used additive can change when evidence on nano-fractions and genotoxicity accumulates. EFSA's 2016 re-evaluation of silver as a food additive (E174) likewise reported a need for additional data (EFSA, 2016). Regulatory divergence between regions, and the absence of a single internationally accepted definition of nanomaterial for food, complicate global trade and consumer communication (Cushen et al., 2012; Peters et al., 2016).

Consumer perception and sustainability

Consumer acceptance of nanotechnology in food is closely tied to perceived benefit, trust in regulators and transparent labelling, and is generally lower for ingredients that are added to food than for applications outside food (Cushen et al., 2012). Environmental fate, including release of metal nanoparticles from discarded packaging, requires life-cycle assessment.

Future prospects

1. **Safe-and-sustainable-by-design materials:** prioritising bio-based, biodegradable and organic nanocarriers, and designing out dissolution or release where it is not required.
2. **Harmonised characterisation and testing:** standard protocols for size distribution in complex matrices, migration, in vitro digestion models and chronic oral toxicity.
3. **Integrated benefit–risk studies:** efficacy, migration and toxicity evaluated together in real foods.

4. **Multifunctional smart packaging:** combining barrier, antimicrobial and sensing functions with validated, low-migration systems.
5. **Translational validation of biosensors:** multi-laboratory validation, portable readers and integration with digital traceability.
6. **Regulatory convergence and transparent communication** to build consumer trust (EFSA, 2021b; McClements and Xiao, 2017).

Conclusion

Nanotechnology offers credible solutions to persistent challenges in food packaging, preservation, safety testing and quality control. The strongest evidence supports nanoclay and biopolymer nanocomposites for barrier improvement, nanoemulsions and nanocarriers for delivering and stabilising functional ingredients, and nanoparticle-based sensing for rapid analysis. Antimicrobial metal and metal-oxide systems are promising, but their reliance on release of active species makes the balance between efficacy and migration decisive. The regulatory withdrawal of E171 in the European Union shows that adoption depends on robust, matrix-relevant safety evidence. Future progress will depend on standardised characterisation, integrated benefit–risk assessment, sustainable material design and harmonised regulation, so that innovation proceeds with consumer trust and public-health protection.

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International Conference on Ensuring Global Food Safety-ICEGFS-2026

Conflict of interest

Authors declare that there is no conflict of interest.

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International Conference on Ensuring Global Food Safety-ICEGFS-2026

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