

# GREEN-SYNTHEMIZED ZINC OXIDE NANOPARTICLES IN FOOD AND WATER SYSTEMS: APPLICATIONS IN STORED-PRODUCT PEST CONTROL, GRAIN, BIOCHEMISTRY, AND FOOD SAFETY: A NARRATIVE REVIEW

*Narrative Review*

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**Conflict of Interest:** None

**Grant Support & Financial Support:** None

**Acknowledgment:** The author gratefully acknowledges all researchers whose contributions supported the development of this review.

## ABSTRACT

**Background:** Ensuring sustainable food grain storage and maintaining food and water quality remain global challenges, particularly as conventional preservation and pest-control methods often disrupt ecological balance and raise human health concerns. Nanotechnology has emerged as a promising alternative, with zinc oxide nanoparticles (ZnO NPs) demonstrating notable potential due to their antimicrobial, photocatalytic, and protective functions. Green synthesis approaches offer an environmentally responsible pathway for producing ZnO NPs while reducing reliance on hazardous chemicals.

**Objective:** This narrative review aims to examine the green synthesis of ZnO NPs, evaluate their physicochemical and functional properties, and explore their applications in food systems, water treatment, and stored-grain protection.

**Main Discussion Points:** The review summarizes various plant-, microbe-, and algae-mediated synthesis strategies, highlighting their advantages in terms of cost, safety, and sustainability. It discusses the functional behavior of ZnO NPs in food and water matrices, including interactions with proteins, lipids, and carbohydrates, and outlines their insecticidal actions through physical abrasion, reactive oxygen species (ROS) generation, and enzymatic disruption. Their utility in food packaging, water purification, and post-harvest pest management is emphasized, alongside emerging toxicological insights defining safe exposure thresholds.

**Conclusion:** Green-synthesized ZnO NPs present a promising, eco-friendly alternative to chemical pesticides and preservatives, with broad applicability across food, agricultural, and environmental sectors. However, large-scale field trials and long-term safety assessments remain essential to establish standardized guidelines and fully harness their potential.

**Keywords:** Food Preservation, Green Synthesis, Nanotechnology, Narrative Review, Stored-Grain Protection, Zinc Oxide Nanoparticles.

## INTRODUCTION

Food security has become a critical global concern, largely driven by substantial post-harvest losses that compromise both the quality and availability of food resources (1). These losses are frequently intensified by agricultural pests, microbial contamination, and deteriorating water quality, all of which threaten the stability of food systems (2). Insect pests, in particular, cause extensive degradation of stored grains, while food and water reservoirs are continually exposed to microbial and chemical hazards that further undermine safety and nutritional integrity (3). Traditional pest-management strategies, although widely adopted, increasingly fail to support environmental sustainability. Their prolonged use has contributed to toxicity, the emergence of pest resistance, and contamination of soil and water bodies, highlighting a mismatch between agricultural needs and ecological safety (4). This growing gap underscores the urgent need for innovative, eco-friendly, and sustainable alternatives that can mitigate post-harvest losses without compromising environmental health. Nanotechnology has emerged as a promising frontier in this regard, offering versatile solutions across food preservation, agricultural farming, and pest management (5). Among various engineered nanomaterials, zinc oxide nanoparticles (ZnO NPs) stand out due to their recognized safety profile, with the Food and Drug Administration listing them as generally safe for designated uses. Their unique physicochemical properties, including UV-blocking capacity and environmental compatibility, further enhance their utility in food and water systems (6). Although nanoparticles can be synthesized through physical, chemical, or biological routes, chemical methods often pose limitations related to cost, environmental burden, and scalability. Conversely, green synthesis—utilizing plant extracts, microbes, and other natural precursors—offers a sustainable, cost-effective, and environmentally conscious alternative that has attracted significant research attention (7).

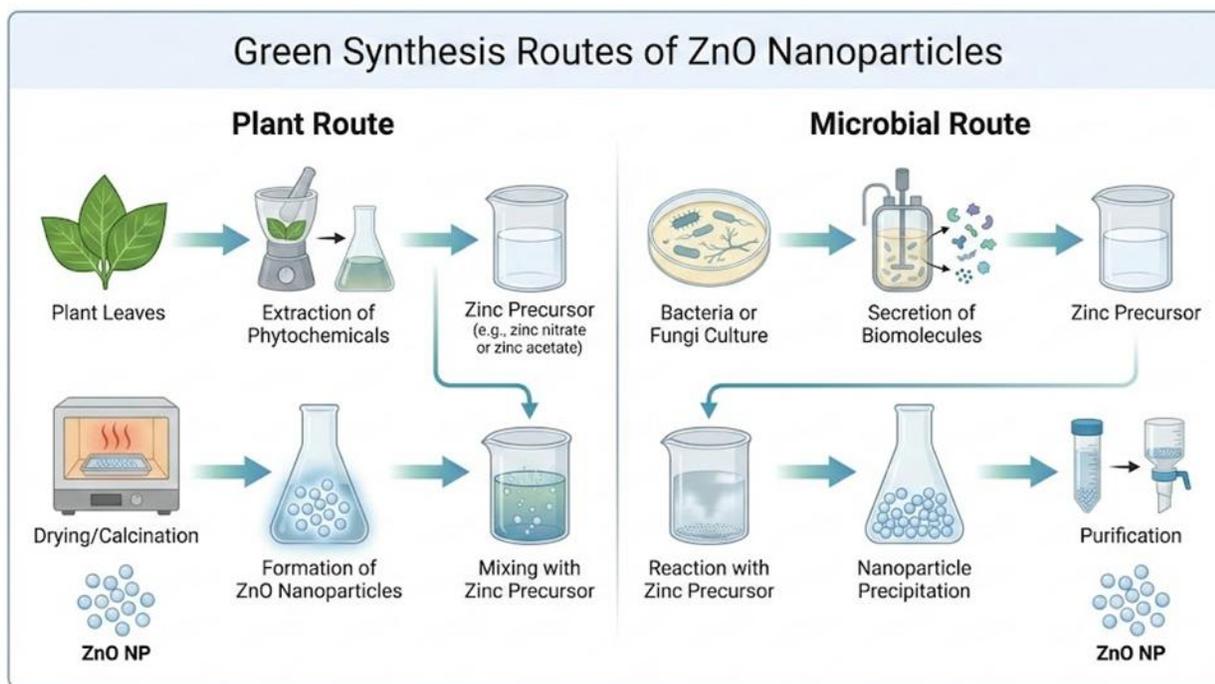
Green-synthesized ZnO NPs are characterized by their incorporation of phytochemicals and bio-waste derivatives, which naturally influence particle morphology and functional behavior (8). These bioactive constituents enable the production of nanoparticles with controlled size, shape, and surface characteristics, making them suitable for diverse applications in food, pharmaceutical, and water-treatment industries (9). Their physicochemical properties—including particle size, band gap, synthesis temperature, and phytochemical interactions—play critical roles in determining their performance in food preservation, antimicrobial activity, and nutrient stabilization (10,11). Within stored-product pest management, ZnO NPs demonstrate multiple modes of action, such as physical abrasiveness and the generation of reactive oxygen species, which disrupt pest cuticles and reduce infestation levels (12). Despite these promising applications, the potential effects of ZnO NPs on grain biochemical properties remain an emerging area of investigation. Their interaction with essential nutrients may alter protein structure, starch gelatinization, and other rheological attributes that define grain quality (13,14). Equally important are safety considerations, as nanoparticles may migrate from packaging materials into food matrices and exert unintended effects on the gut microbiota when exposure exceeds recommended thresholds (15,16). These uncertainties reinforce the necessity for carefully designed studies that examine both the functional benefits and biosafety implications of ZnO NP use within food systems. Given the expanding role of nanotechnology and the growing demand for sustainable, environmentally harmonized solutions, further research is essential to elucidate the green synthesis of ZnO NPs, their multifunctional applications, and their impact on food quality, pest control, and water purification. Therefore, the objective of the present study is to evaluate the sustainability, functional performance, and safety considerations of green-synthesized ZnO nanoparticles within food and water systems, with particular emphasis on their role in stored-grain protection and associated biochemical outcomes.

## GREEN SYNTHESIS OF ZNO NPS

Green synthesis of ZnO nanoparticles (ZnO NPs) has emerged as a cornerstone of green chemistry, driven by the urgent need to develop sustainable nanomaterials with minimal environmental and health hazards (13). Conventional chemical and physical synthesis methods, although effective in generating nanoparticles with defined properties, are often associated with high energy demands, toxic reagents, the generation of harmful by-products, and substantial costs, thereby raising concerns regarding occupational safety, ecological toxicity, and long-term public health impact (7,13,14). In contrast, green synthesis strategies seek to replace hazardous chemicals with biologically derived reducing and capping agents, utilizing readily available plant materials, microbes, and bio-waste to produce ZnO NPs in a cost-effective, time-efficient, and environmentally responsible manner (7,15). Plant-mediated synthesis is widely regarded as one of the most promising routes because it combines high yield with enhanced stability of the final nanoparticles. A broad range of plant parts—including leaves, roots, shoots, grains, and tissue cultures—have been employed, with the embedded secondary metabolites (such as phenolics, flavonoids, and alkaloids) acting as both reducing and stabilizing agents (16,17). These phytochemicals not only drive the reduction of zinc salts to ZnO but also impart stability and functional surface properties, resulting in nanoparticles with distinct

sizes, morphologies, and bioactivities depending on the botanical source used (18–20). Bio-waste-based synthesis extends this concept by valorizing agricultural and food-processing residues, which are washed, dried, pulverized, and boiled in water or ethanol to extract phytochemicals, followed by reaction with zinc precursors to form ZnO NPs (21). This approach simultaneously addresses waste management and reduces the environmental burden, aligning strongly with circular economy principles (22).

Microbial synthesis provides an additional biologically driven route with distinct mechanistic and functional advantages. Bacteria can mediate ZnO NP formation through extracellular or intracellular processes; extracellular synthesis is often favored as it circumvents complex downstream extraction and is generally faster and more scalable (14). Strains such as *Escherichia coli* and *Rhodococcus pyridinivorans* have demonstrated the ability to reduce metal ions to ZnO NPs, with particle sizes ranging from approximately 100–130 nm and documented applications in environmental remediation (21,22). Fungi, including *Penicillium* species, and yeasts such as *Pichia kudriavzevii* have also been employed, offering high biosorption capacity and the ability to generate nanoparticles with diverse and intricate structures due to their rich enzyme systems (23,24). These organisms not only transform toxic metallic ions into less harmful nanoparticulate forms but also chelate, detoxify, and sequester metals, thereby contributing to bioremediation alongside nanoparticle synthesis (25,26). Algae have further expanded the green synthesis toolkit. Macro- and microalgal species serve as reservoirs for metals such as zinc, silver, and copper and can accumulate and biotransform them into NPs (15,25). Species such as *Sargassum muticum* and *Sargassum myricocystum* have been reported to produce ZnO NPs around 36 nm in size, which exhibit promising biomedical properties, including cytotoxic, anticancer, biogenic, and biostatic activities (25,26). These algae-derived ZnO NPs have been investigated in the context of cancer diagnostics, immune-related disorders, biosensing, drug delivery, and hyperthermia (27). Collectively, the literature highlights green synthesis as a credible alternative to conventional methods, offering benefits in terms of reduced toxicity, lower energy consumption, and dual functionality in waste valorization and nanoparticle production (28). However, important gaps remain, particularly regarding standardization of protocols, control of particle size and morphology, reaction times, and scalability of raw material supply chains (14). These limitations underscore the need for harmonized methodologies and comparative studies across plant-, microbe-, and algae-based systems to better define the optimal routes for food- and water-related applications.



### Physicochemical and Functional Properties of ZnO NPs in Food & Water

ZnO NPs exhibit a broad spectrum of physicochemical properties that govern their behavior and utility in food and water systems. Typically, nanoparticle sizes range from 5 to 100 nm, with many preparations falling between 5 and 50 nm, and they can adopt hexagonal, spherical, or rod-like morphologies (15). Surface area is a critical determinant of reactivity; values may reach up to ~140 m<sup>2</sup>/g for ZnO when particle radii approach the nanometer scale, significantly amplifying surface-mediated processes compared to bulk materials (16).

These nanoscale properties underpin their antimicrobial, photocatalytic, and barrier functions, making ZnO NPs attractive candidates for food preservation, packaging, and water purification (8,27). Mechanical attributes such as rigidity, brittleness, tensile strength, hardness, and fatigue resistance are central when ZnO NPs are incorporated into composite matrices, including polymeric films for food packaging (27). As nanofillers, ZnO NPs can enhance the mechanical strength and durability of films while simultaneously providing UV-blocking and antimicrobial functions (5,27). This multifunctionality differentiates them from conventional additives and aligns with the growing demand for active and intelligent packaging systems. In agricultural applications, ZnO NPs are increasingly examined as nano-fertilizers and nano-pesticides (8). Compared with conventional chemical fertilizers that are often applied in bulk and prone to leaching, ZnO nano-fertilizers can be delivered at lower doses, with more controlled and sustained release, reducing nutrient losses into water bodies and mitigating greenhouse gas-related effects (2,8). Their small size and high surface reactivity facilitate improved foliar uptake and soil interaction, potentially enhancing micronutrient delivery, particularly zinc, which is essential for plant enzyme systems and human nutrition (8,25). Nevertheless, optimal dosing windows are narrow; excessive concentrations may impair enzymatic activity, promote oxidative stress, or induce toxicity in plants and non-target organisms (26–28). Functionally, ZnO NPs exhibit notable UV-blocking capacity, photocatalytic activity, and the ability to generate reactive oxygen species (ROS), which are directly linked to their antimicrobial and pollutant-degrading actions (8,28). These properties are highly desirable in water purification, where photocatalytic degradation of organic contaminants and microbial inactivation are needed, but they must be balanced against potential risks of ROS-mediated damage in other settings, particularly in dermal and mucosal exposures (13). Therefore, the physicochemical and functional attributes of ZnO NPs are both an asset and a source of concern, necessitating careful design, surface modification, and context-specific optimization for safe food and water applications (5,27).

**Table 1: Physical and chemical Properties of ZnO NPs**

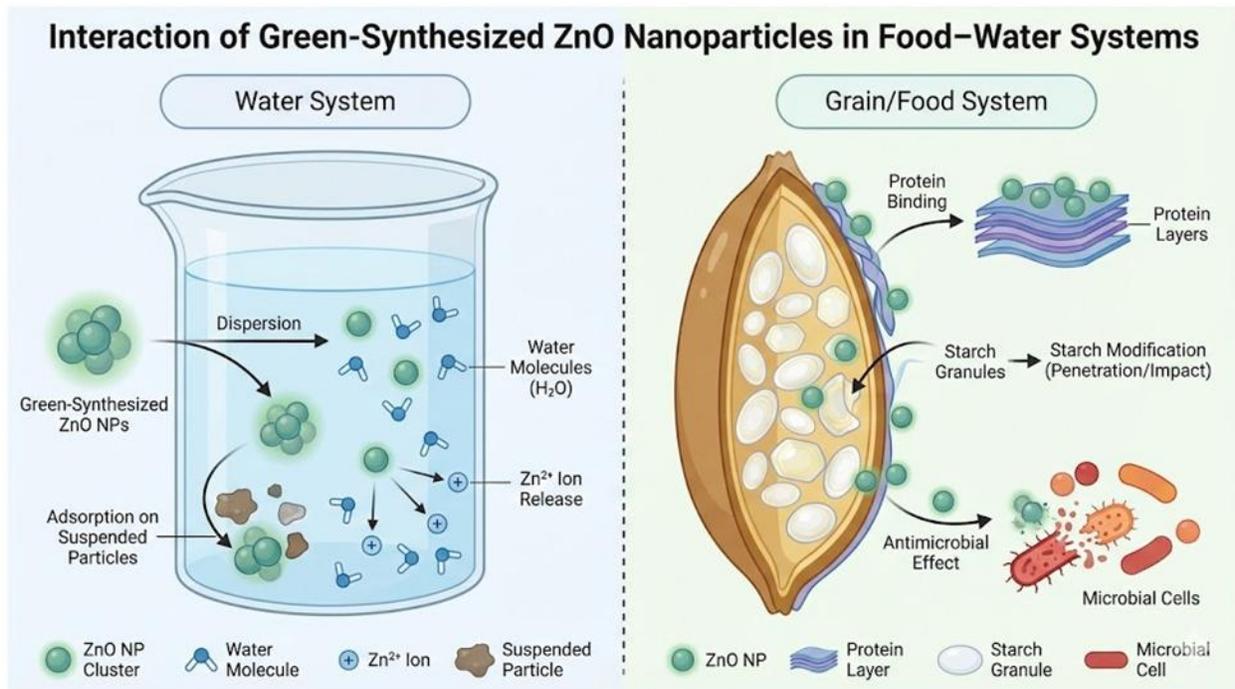
Source	Size (µm)	Band-Gap (eV)	Shape	Temperature-Synthesis (Celsius)	Reference
Extract of Aloe-vera	0.452	3.37	Rod	26-200	(11)
Extract of Green Tea	54.84	3.4	-	100	(4)
Moringa	452	3.2-3.3	Cubic, Hexagonal	140-390	(12)
Bacteria	30-60	3.2-3.3	Rod-shaped	40-50	(13)

### ZnO NPs in Food and Water Systems

Within food and water systems, the interaction of ZnO NPs with biomolecules and aqueous media is central to their behavior, efficacy, and safety. At the nanoscale, ZnO facilitates water molecule adsorption and can promote water splitting, leading to ROS generation that enhances antibacterial activity beyond what is observed with bulk ZnO (17). The efficiency of this catalytic process is influenced by particle size, morphology, and surface chemistry, with smaller particles generally offering higher reactivity but potentially higher toxicity (15,28). In complex food matrices, ZnO NPs interact with carbohydrates, lipids, and proteins, often through surface binding and complex formation (18). These interactions can modulate the bioavailability and stability of both the nanoparticles and food components. For example, protein binding may sequester ZnO NPs without necessarily disrupting primary protein structure or digestive processes, while interactions with saccharides can alter nanoparticle dispersion and reactivity, thereby influencing their functional performance and zinc release (8,10). Importantly, solubility is highly pH-dependent; ZnO NPs dissolve more readily in acidic environments, such as gastric fluids, supporting controlled zinc ion release and targeted delivery, particularly relevant in fortification strategies and oral exposure scenarios (3,13).

Encapsulation technologies, including lipid-based carriers, have been explored to harness these properties while mitigating cytotoxicity. Such systems allow slow or stimuli-responsive release of ZnO NPs or zinc ions, triggered by changes in pH, temperature, or light, and may reduce direct contact between nanoparticles and sensitive tissues or microbiota (11,18). In water treatment, green-synthesized ZnO NPs have been investigated for their ability to remove or degrade pollutants originating from pharmaceutical, textile, and construction industries, offering a more efficient and potentially less energy-intensive alternative to traditional purification methods (22,25). Leaves of *Elaeagnus indica*, for example, have been used to produce ZnO NPs that act as stabilizing and reducing agents, illustrating how plant-derived systems can support both synthesis and application in wastewater treatment (22). Despite these advantages, ZnO NPs are

classified as dangerous to aquatic ecosystems, and their environmental handling requires stringent controls (19). Their persistence, tendency to aggregate or dissolve, and potential to accumulate in sediments and biota all contribute to ecological risk. Regulatory frameworks emphasize the need for wastewater treatment and monitoring of dissolved zinc levels, which vary in permissible limits across regions (18). This tension between utility and risk highlights a key area of ongoing research: how to maximize the benefits of ZnO NPs in food and water systems while minimizing environmental and human health impacts through better design, controlled use, and effective end-of-life management.



### Applications of ZnO NPs in Stored Grain Treatment

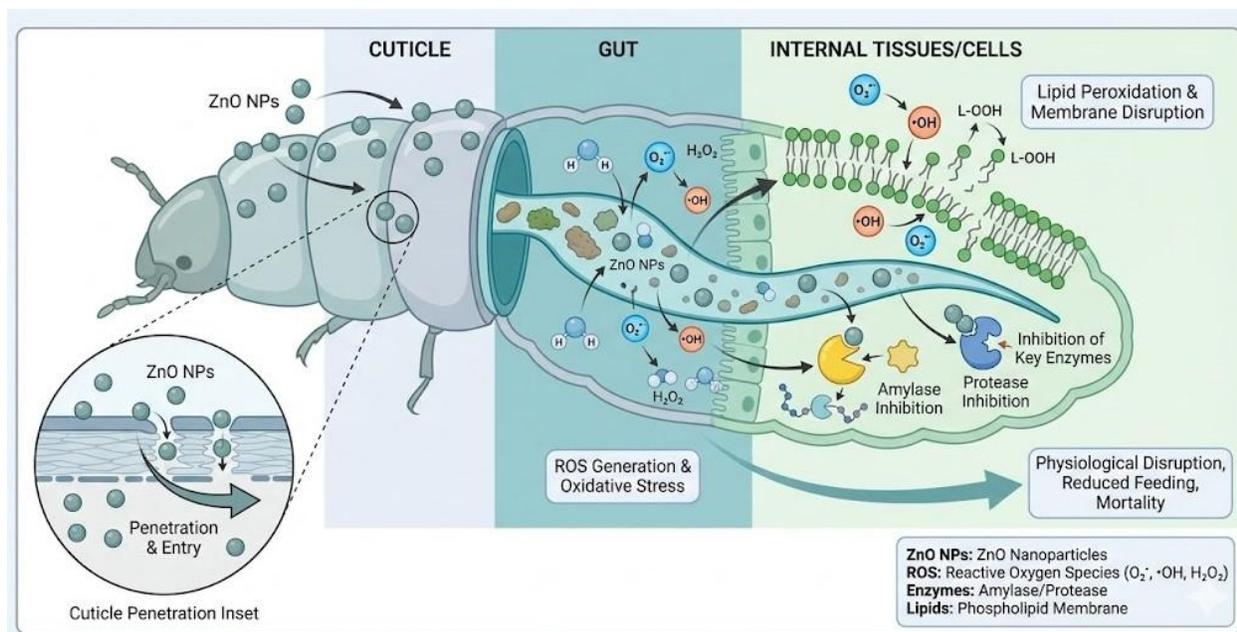
Post-harvest losses in stored grains are a major contributor to food insecurity, particularly in low- and middle-income settings where storage infrastructure and pest control may be suboptimal (1,2). In this context, ZnO NPs have emerged as promising candidates for integrated pest management due to their multi-pronged insecticidal mechanisms and compatibility with food systems (4,10). Unlike conventional synthetic pesticides, which are often associated with residue concerns, resistance development, and environmental contamination, nanoparticle-based formulations offer the potential for lower doses, targeted delivery, and novel modes of action (3,4). ZnO NPs exert their insecticidal effects through several pathways. First, their abrasive nature can physically damage insect exoskeletons, compromising the protective cuticle and leading to dehydration and death (20). Second, ROS generated at the nanoparticle surface induce oxidative stress in insect tissues, damaging cellular components and disrupting physiological functions (11,20). Third, zinc ions released from ZnO NPs may interfere with enzymatic systems critical for metabolism and detoxification, further weakening the pests (20). Collectively, these mechanisms contribute to increased mortality, delayed development, reduced fecundity, and impaired lifecycle progression in key stored-product pests. Empirical studies have documented high mortality rates in species such as *Sitophilus oryzae*, *Acanthoscelides obtectus*, and *Tribolium castaneum* when exposed to ZnO NPs in dust or coating formulations, with dose- and time-dependent effects (4,10,11).

For instance, near-complete mortality has been reported at specific concentrations and exposure durations, underscoring the potential of ZnO NPs as effective alternatives or adjuncts to conventional insecticides (10,11). These nanoparticles can be applied as dusts to storage surfaces, incorporated into coatings on bins or sacks, or integrated into packaging films, enabling sustained and localized exposure of pests while reducing overall chemical load (3,4). Moreover, synergistic strategies that combine ZnO NPs with essential oils or plant extracts have gained attention. In such formulations, essential oils contribute fumigant and repellent properties, while ZnO NPs provide oxidative and mechanical damage, allowing lower doses of each component and thereby potentially reducing toxicity and resistance development (13,19). This multi-modal approach aligns with integrated pest management principles and supports more sustainable

control strategies. However, important concerns remain regarding the non-target effects of ZnO NPs. The same mechanisms that harm insect pests—physical abrasion, oxidative stress, and microbial disruption—may also adversely affect beneficial insects, soil organisms, and aquatic life if nanoparticles disperse beyond intended targets (3). Accumulation of ZnO NPs in the environment and their interactions with ecological networks are not yet fully characterized, necessitating comprehensive risk assessments and long-term field-based studies to complement laboratory evidence (3,19). These gaps highlight the need for exposure modelling, environmental monitoring, and guidelines tailored to nanoparticle-based grain protection.

**Table 2: Insecticidal effects of ZnO NPs on Insect Pests**

Pest	ZnO Nanoparticle Size (nm)	Concentration	Exposure Duration	Mortality Rate (%)	Reference
Sitophilus Oryzae	Less than 100	0.8% (w/w)	17 weeks	100%	(8)
Acanthoscelides obtectus (Coleoptera: Chrysomelidae)	100	1000 mg/kg	10 days	93.3%	(3)
Clavibacter michiganensis	51.8	-	72 hours	78%	(15)
Triboleum Castaneum	433.2-458.4	2.15-2.45 g/kg	-	100%	
Sitophilus Oryzae	Up to 100	2.5 g/kg	14-24 days	100%	(9)



## EFFECTS ON GRAIN BIOCHEMISTRY

Beyond pest control, ZnO NPs have measurable impacts on grain biochemistry, with implications for nutritional quality, processing characteristics, and shelf-life. Their interaction with grain proteins has been reported to enhance the solubility of key protein fractions

such as globulins and albumins under stress conditions, potentially improving protein formation, stability, and bioavailability (12). Amino acid profiles, including levels of serine, leucine, and glutamic acid, may be favorably modulated, contributing to improved nutritional quality while maintaining the structural integrity of storage proteins (22). ZnO NPs also influence carbohydrate metabolism and starch architecture. By promoting the accumulation of starch granules in chloroplasts, they can increase starch content and redirect photosynthates toward grains and leaves (23). During processing, ZnO NP-assisted modification of starch through mechanisms such as sonication and alkali hydrolysis may lead to more amorphous structures, enhanced thermal stability, and altered gelatinization properties—features that are relevant for baking, cooking, and industrial utilization (13). These changes may translate into improved textural and functional properties of cereal-based products. Lipid peroxidation, a key driver of rancidity and quality deterioration in stored grains, appears to be attenuated by ZnO NP application in certain contexts. By modulating ROS levels and lipid-peroxidase activity through antioxidant enzyme systems, ZnO NPs can limit oxidative damage to lipids, helping preserve membrane integrity and extending shelf life under diverse storage conditions (24). Additionally, ZnO NPs have been associated with improved photosynthetic efficiency, stomatal function, transpiration, and respiration under stress, thereby contributing to better grain filling, enhanced zinc biofortification, reduced grain breakage, and improved milling efficiency in crops such as wheat, rice, maize, and barley (12,14). However, these benefits are dose-dependent and context-specific. At higher concentrations, ZnO NPs have been linked to reductions in enzyme activity, increased lipid oxidation, and signs of phytotoxicity, particularly in wheat exposed to elevated nanoparticle concentrations (16). Studies in rice, maize, and barley indicate that while moderate doses may enhance zinc content, pigment accumulation, and germination, excessive application risks tipping the balance toward toxicity (12,15). Moreover, interspecies variation in nanoparticle uptake, translocation, and biochemical responses remains poorly understood. These observations underscore the importance of defining safe and effective concentration ranges and elucidating the long-term impact of ZnO NPs on grain composition and downstream food products.

**Table 3: Effect of ZnO NPs on Different Grains**

Grain Type	Nanoparticle Size	Concentration	Parameters	Effects	Reference
Wheat	100 nm	0 to 200 mg per liter	Enzymes, lipids, proteins	Higher concentration lead to enzyme activity reduction, toxicity, and oxidation of lipid	(19)
Rice	20-50	3.8-60 kg/hm <sup>2</sup>	Nutrition, grain color, fertilizer application	Zinc concentration enhanced, brown color rice grains, fertilizer application decreased	(18)
Maize		25-50 mg/kg	Carotenoid and chlorophyll content	Carotenoid and chlorophyll contents are increased with direct proportion	(20)
Barley		300 to 2000 mg per liter	Enzymatic activity		(21)
Maize	20-100 nm	5-15 g per liter	Germination, nutritional parameters	15 g/l conc. Increased carbohydrates, protein, zinc, and germination percentage	(10)

## FOOD SAFETY AND TOXICOLOGICAL CONSIDERATIONS

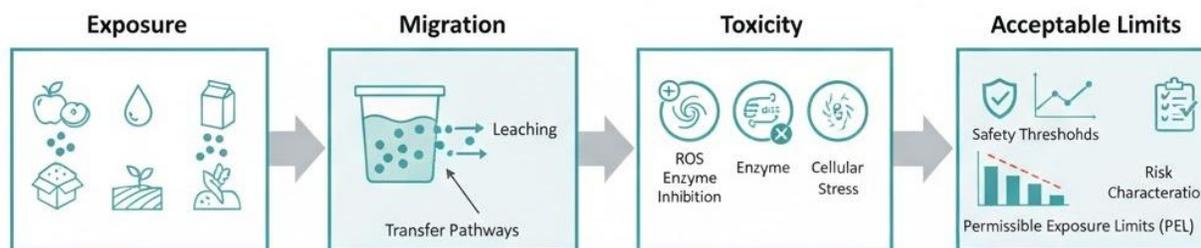
The incorporation of ZnO NPs into food-contact materials and agro-food applications raises critical questions about human exposure, gut health, and systemic toxicity. Migration of ZnO NPs from packaging films into food is particularly pronounced under acidic conditions, where increased solubility and changes in film integrity lead to pore formation and altered barrier properties (3,19). In simulated gastrointestinal models, only a limited fraction of zinc may reach the intestinal lumen, suggesting controlled and compartmentalized translocation across biological membranes; however, this does not preclude localized effects on mucosal tissues and microbiota (19,15). The dissolution of ZnO NPs into zinc ions is heavily influenced by pH and the composition of biological media, with acidic environments promoting higher ion release (10). Released zinc ions are essential micronutrients that support metabolic pathways but may accumulate and contribute to cytotoxicity if exposure exceeds physiological thresholds (20). Particle size, surface characteristics, and storage conditions affect migration and dissolution dynamics, making it challenging to generalize risk without context-specific data (3,10). A growing body of evidence suggests that ZnO NPs can disrupt gut microbiota composition, reducing microbial population size, diversity, and community structure (21). Interestingly, healthy individuals may be more susceptible to certain microbiome shifts than patients with pre-existing gut conditions, and the profile of resistant bacterial species differs between these groups (11). At higher exposures, geno-toxicity, cytotoxicity, and oxidative stress have been documented through pathways involving ROS generation, DNA damage, mitochondrial dysfunction, cell cycle arrest, and apoptosis in various in vitro and in vivo models (12). Observed outcomes include chromosomal aberrations, reduced membrane potential, and altered tissue histology, with toxicity severity influenced strongly by nanoparticle morphology, concentration, and exposure duration (24–26).

Regulatory agencies have responded cautiously. The U.S. Food and Drug Administration has recognized ZnO as generally safe for certain uses, while the European Food Safety Authority has approved its use in packaging under conditions that minimize migration (9). International guidelines, including those aligned with Codex, emphasize limiting exposure, establishing specific migration limits, and defining safe incorporation levels in food-contact materials (9,19). For example, permissible levels of ZnO in packaging films for acidic foods are restricted to about 1%, and movement into aqueous environments may be restricted to 5% or less, with further constraints on zinc ion concentrations associated with cytotoxic or antimicrobial thresholds (19,23). Toxicological studies in human cell lines, aquatic systems, and animal models reinforce the need for careful dose selection. For instance, human Caco-2 cells exhibit increased cytotoxicity at higher ZnO NP concentrations, with suggested safer limits below 12.5 µg/ml, while aquatic ecosystems experience marked reductions in fungal diversity at concentrations above 10 mg/l (24,25). In rodent models, high doses have been associated with histopathological changes in organs such as the pancreas, eye, stomach, and prostate, with suggested no-effect levels near the lowest tested doses (26). Microalgae such as *Dunaliella tertiolecta* demonstrate growth inhibition in a concentration-dependent manner, indicating ecological sensitivity even at low mg/liter levels (19). These findings collectively indicate that while ZnO NPs can be used safely within defined exposure limits, they are not inherently risk-free. Future work must refine safe concentration thresholds for different applications, elucidate chronic exposure effects, and integrate microbiome and systems biology perspectives into food safety assessments.

**Table 4: Toxicity of ZnO NPs in Evaluated in Different Models**

Model	Dose	Effects	Safe limit	Reference
Coca-cells (Human cells)	6 to 25 mg/ml	Increase in cytotoxicity, damaging brain,	Less than 12.5 µg/ml	(25)
Aquatic System	10 to 1000 mg/liter	Affected badly fungal diversity with increased concentration	Less than 10 mg/liter	(26)
Rat Model	31.25 to 500 mg/kg	Higher conc. Affected pancreases, eye, stomach, prostate gland tissues	Less than 31.25 mg/kg	(27)

Model	Dose	Effects	Safe limit	Reference
Dunaliella tertiolecta	0.1 to 3 mg/liter	Growth inhibition increased with increased concentration	0.1 to 1 mg/liter	(14)



### Integrated Perspective: Food, Entomology, Nanotechnology, and Safety

From an integrated standpoint, green-synthesized ZnO NPs sit at the intersection of food science, entomology, nanotechnology, and public health. Their capacity to function simultaneously as antimicrobial agents, insecticidal tools, nano-fertilizers, and active packaging components positions them as powerful instruments for addressing post-harvest losses, enhancing crop yield, and extending shelf life (4,7,8). When appropriately designed and dosed, ZnO NPs can support food security by reducing spoilage, limiting pest-induced damage, and improving nutritional delivery, particularly through zinc biofortification and improved grain quality (2,8). However, this technological promise must be balanced against safety and ecological considerations. Optimizing nanoparticle concentration to achieve robust pest control while limiting zinc ion release to within permissible limits is a central challenge (19,27). Formulation science, including the development of coatings, dusts, and packaging-embedded ZnO NPs, must be guided by rigorous risk assessments that account for human dietary exposure, occupational contact, and environmental dissemination (3,27). Green synthesis using plants and microbes has an important role in reducing upstream toxicity and energy consumption, thereby aligning nanoparticle production more closely with sustainability goals (7,20).

Synergistic formulations that combine ZnO NPs with biopesticides, such as essential oils, illustrate how multifunctional materials can reduce reliance on conventional chemical pesticides while maintaining or enhancing efficacy against key grain pests (13,19). At the same time, the broad-spectrum bioactivity of ZnO NPs demands careful evaluation of non-target impacts on beneficial insects, soil biota, and aquatic ecosystems, as well as downstream consequences for gut microbiota and human tissues (3,11). Current evidence highlights several gaps that warrant further investigation. These include the long-term environmental fate of ZnO NPs, their cumulative effects across trophic levels, standardized toxicity profiles for green-synthesized versus chemically synthesized particles, and real-world field trials that validate laboratory findings under commercial storage and distribution conditions (17–19). Moreover, harmonized regulatory frameworks and international consensus on testing protocols, labelling, and safe-use thresholds are needed to guide responsible innovation. In summary, the integration of ZnO NPs into food and water systems offers a compelling opportunity to tackle post-harvest losses and enhance food security, provided that nanotechnology advances are anchored in robust safety science, environmental stewardship, and evidence-based regulation.

### IMPLICATIONS AND FUTURE DIRECTIONS

The expanding evidence on green-synthesized ZnO nanoparticles (ZnO NPs) carries meaningful implications for human health, food safety, agricultural practice, and regulatory frameworks. As these nanomaterials increasingly enter food and water systems, their clinical relevance becomes more apparent, particularly in relation to gut microbiota modulation, systemic exposure, and potential oxidative or inflammatory responses. Recent studies highlight that ZnO NPs can alter microbial diversity, with implications for gastrointestinal integrity, nutrient metabolism, and immune homeostasis, suggesting the need for clinicians to remain aware of possible dietary or

packaging-derived nanoparticle exposures when assessing unexplained gastrointestinal symptoms or dysbiosis-related disorders (21,22). At the same time, their antimicrobial and antioxidant functions offer potential applications in food preservation and water sanitation that may indirectly support public health by reducing microbial contamination, lowering foodborne illness risk, and improving access to safer food supplies (23). From a policy perspective, the findings underscore the need for clearer regulatory guidance on the permissible concentration, migration limits, and physicochemical attributes of ZnO NPs used in food-contact materials. Although various international bodies have acknowledged their benefits, emerging toxicological evidence highlights gaps in exposure modelling, dose–response thresholds, and cumulative risk assessments (24). Regulatory harmonization is therefore essential to ensure that innovation in nanoparticle-enabled technologies proceeds without compromising consumer safety. Guidelines should prioritize standardized toxicity testing, clearer labelling requirements, and stricter monitoring of nanoparticle release into food, water, and the environment.

Despite substantial progress, several unanswered questions persist. Key uncertainties include the long-term fate of ZnO NPs in biological systems, their organ-specific accumulation, and potential interactions with proteins, lipids, and carbohydrates in stored grains and processed foods. Current *in vitro* data show promising antimicrobial and pest-management performance, yet translational gaps remain concerning how environmental variables—humidity, temperature, grain type, and microbial diversity—modify their real-world efficacy and safety (25). The need for large-scale, controlled field assessments is evident, as laboratory mortality rates in stored-grain pests may not fully reflect ecological variability or non-target species exposure (26). Furthermore, reproducibility challenges in plant- and microbe-mediated synthesis continue to limit scalability, calling for more rigorous optimization of precursor selection, reaction conditions, and nanoparticle characterization (27). Future research will benefit from well-designed *in vivo* toxicological investigations, using tiered dosing studies to define safe upper limits, biodistribution patterns, and reversible versus irreversible effects, particularly in mammalian models relevant to human exposure (11,24). Longitudinal cohort designs could clarify chronic low-level ingestion outcomes, while advanced omics approaches (metabolomics, metagenomics, proteomics) may help elucidate nanoparticle–microbiome–host interactions. For agricultural and entomological applications, multi-location field trials, dose-response modelling, and life-cycle environmental impact assessments are needed to validate the sustainability of ZnO NP-based pest control. Additionally, standardized, universally accepted protocols for green synthesis—including solvent systems, extraction procedures, and particle stabilization—would greatly improve reproducibility and allow meaningful comparison across studies (28). Taken together, the incorporation of ZnO NPs into food, water, and storage systems offers considerable promise but demands thoughtful integration grounded in safety science, regulatory oversight, and methodological rigor. Strengthening these areas will ensure that nanotechnology continues to progress in a manner that enhances, rather than jeopardizes, human and environmental health.

## CONCLUSION

The evidence reviewed highlights that green-synthesized ZnO nanoparticles represent a versatile and impactful advancement with applications spanning food preservation, active packaging, agricultural productivity, water purification, and biomedical fields. Their antimicrobial, photocatalytic, and functional properties position them as promising alternatives to conventional chemical agents, offering enhanced efficacy with reduced environmental burden. Although laboratory findings consistently demonstrate strong potential across sectors, the current body of evidence is predominantly experimental, with limited real-world validation. Clinicians and researchers should therefore interpret existing data cautiously, recognizing both the benefits and the unresolved safety considerations, particularly regarding human exposure, microbiome effects, and ecological impact. Moving forward, multidisciplinary research—with emphasis on *in vivo* toxicity profiling, long-term environmental assessments, standardized green-synthesis protocols, and large-scale field trials—remains essential to translate laboratory success into safe, sustainable, and widely applicable technologies.

## AUTHOR CONTRIBUTIONS

Author	Contribution
Rehab Mangot	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Sana Aslam	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
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