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Review

Food Safety Promotion via Nanotechnology: An Argumentative Review on Nano-Sanitizers

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Abstract

Nano-sanitizers, which exploit the unique physicochemical properties of nanomaterials, are being increasingly investigated as innovative tools to promote food safety. In this argumentative review, we compare and contrast nano-sanitizers with conventional sanitation methods by examining their underlying antimicrobial mechanisms, multifaceted benefits, inherent challenges, and wide-ranging public health implications. We evaluate regulatory conundrums and consumer perspectives alongside future outlooks for integration with advanced technologies such as artificial intelligence. Through selective synthesis of the published literature, our argumentative discussion demonstrates that nano-sanitizers not only promise superior performance in pathogen inactivation but could also contribute to overall food system sustainability, provided safety and regulatory concerns are adequately addressed.

Keywords: nanomaterials; surface decontamination; antimicrobials; food pathogens; regulations; public health

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1. Introduction

Prevention of foodborne illness is a critical global public health challenge of the 21st century. Global foodborne illness burden is estimated at 600 million cases and 420,000 deaths annually [1]. Common pathogens, including *Escherichia coli*, Shiga toxin-producing *E. coli* (STEC), nontyphoidal *Salmonella*, *Listeria monocytogenes*, *Toxoplasma gondii*, *Clostridium perfringens*, *Campylobacter* spp., and norovirus, are predominantly responsible for the foodborne outbreaks, and are estimated to cost over USD 17.6 billion in 2018 dollars [2]. Thus, there is an unmet need for novel, safer, and effective methods to address rising foodborne illnesses caused by common pathogens.

Food packaging and material characteristics play a role in the food supply chain for prevention efforts to be established in mitigating foodborne disease outbreaks. Common packaging materials, including several types of plastic, oriented polyethylene terephthalate (OPET), oriented polypropylene (OPP), nylon 6, cardboard, and wood, have been shown to harbor bacteria and survive from a few hours to several days [3–5]. Previous research has shown that bacteria such as *E. coli* may survive in cardboard for 1–2 h [3] and up to 15 days in plastics [4]. The combination of food packaging materials and environmental conditions (temperature; humidity) during packaging and transportation offers an opportunity for common foodborne pathogen growth, particularly affecting raw food supplies [5]. The current gold standard in food decontamination prior to food packaging is to remove pathogens by washing, with or without additional sanitizers such as bleach and peroxides [6,7]. While

such practices can be cost-effective and safer when protocols are strictly adhered to, there is an opportunity for human error during sanitizer dilution or when equipment sanitation downtime is ignored [8], potentially increasing the risk of foodborne outbreaks.

Nano-sanitizers—products that utilize nanoparticles or nanomaterials to enhance antimicrobial efficacy—are gaining attention for their potential to transform food sanitation practices and promote public safety, as traditional sanitation practices have failed to fully mitigate the risk of foodborne pathogens [9,10]. Over the last decade, research has demonstrated that varied nanomaterials have the potential to serve as potent antimicrobial agents against resistant food microbes [10,11]. Considering these advances, the integration of nano-sanitizers into food processing, packaging, and storage systems has emerged as a promising strategy to enhance food quality and consumer safety [11,12]. Moreover, the academic discourse surrounding nano-applications is enriched by studies that integrate conventional chemical disinfectants with nano-solutions in terms of efficacy, scalability, and regulatory oversight [13]. This review builds on compelling evidence and discusses how nano-sanitizers might revolutionize food safety standards while also addressing ongoing debates over potential health risks and environmental impacts [14].

In addition to their antimicrobial potency, nano-sanitizers are increasingly seen as essential components in the broader context of food safety innovation [13]. As foodborne illnesses continue to pose a formidable public health burden, particularly in regions where conventional sanitation interventions are suboptimal [15], recent reviews have advocated for the adoption of emerging technologies that offer improved precision and sustainability [14]. The problem is further compounded by global trends, such as increasing urbanization and complex supply chains, which render food contamination a multifaceted challenge [14]. Against this backdrop, experiments comparing conventional sanitizers with nano-enabled systems have identified significant gaps in our understanding of pathogen inactivation kinetics and the implications for microbial resistance [16]. Therefore, it is imperative to rigorously examine the benefits and limitations of nano-sanitizer technology through an evidence-based, interdisciplinary lens.

Furthermore, consumer safety and regulatory considerations are at the forefront of current debates regarding the deployment of nanomaterials in food applications [17] (Figure 1). Public perceptions, influenced by concerns over label transparency and product acceptability, contribute to the policy challenges that often hinder the adoption of novel technologies [18]. At the same time, alternative biological approaches, such as the use of probiotics, have been proposed as competitors to nano-sanitizers. However, though evidence suggests that nano-enabled antimicrobial platforms offer more rapid and targeted pathogen inactivation [19], comparisons between traditional disinfectants and these emerging nano-solutions indicate that conventional methods struggle to achieve the same level of efficacy under extreme conditions [20]. Utilizing these multifaceted perspectives, the present review argues that nano-sanitizers may significantly reshape food safety practices, contingent upon effective policy frameworks and more focused food safety research [21].

Recent insights into global food safety challenges in both artisanal and industrial production settings reveal widespread deficiencies and inconsistent practices that nano-sanitizers might help alleviate [22]. Moreover, risk–benefit assessments underscore that the potential health risks of foodborne contaminants far outweigh those associated with properly regulated nanomaterial applications [23]. Integrated within the One Health framework, nano-sanitizer interventions have the potential to deliver cross-sectoral benefits, improving not only human health but also animal and environmental outcomes [24]. Against this dynamic and evolving backdrop, the following sections provide an in-depth analysis of the underlying mechanisms, evidenced benefits, regulatory challenges, and prospective future directions for nano-sanitizers in food safety.

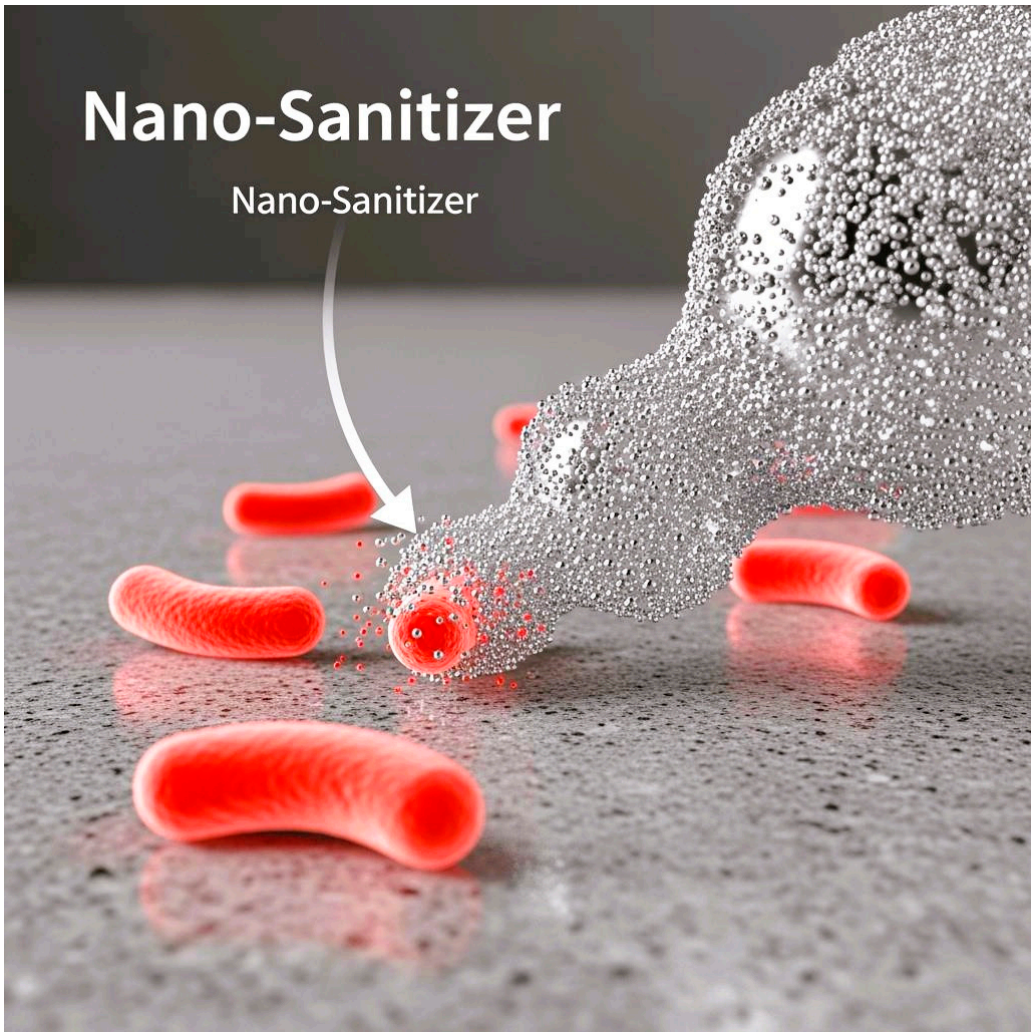


Figure 1. Three-dimensional depiction of a nano-sanitizer applied to a bacteria-contaminated surface used for food preparation. Red structures denote rod-shaped Enterobacteria (e.g., *E. coli*, *Salmonella*). The image was generated in Imazen-4-ultra-generate-05-20 model, a text-to-image generation model developed by Google.

As advances in nanotechnology coincide with broader trends toward digitalization and innovative smart processing systems, there exists an unprecedented opportunity for integrating nano-sanitizers into comprehensive food safety management systems [9,11]. This convergence of technologies, augmented by real-time data and analytics, promises not only to detect but also prevent microbial contamination more effectively than ever before [10]. The ensuing debate among industry experts, regulatory bodies, and consumer groups sets the stage for our argument that nano-sanitizers, while offering remarkable promise, also necessitate balanced scrutiny. By presenting both the supportive and contradictory evidence from the recent body of literature, this argumentative review aims to provide a cogent argument for a cautious yet optimistic trajectory toward the widespread adoption of nano-sanitizer technologies.

While the synthesis and characterization of nano-sanitizers/nanomaterials are critical steps in nanotoxicological research, several recent reviews have adequately described various methods of synthesis and characterization [25–29] and thus are not discussed here, as the main objectives of this review were to compare and contrast nano-sanitizers with conventional sanitation methods by evaluating their underlying antimicrobial mechanisms, multifaceted benefits, regulatory conundrums, and other challenges, as well as wide-ranging public health implications. Through this argumentative review, our central goal

was to initiate a discussion around the many benefits that nano-sanitizers may promise over conventional sanitizers, including their limitations, among nano-researchers, food safety experts, regulatory agencies, and other stakeholders.

An argumentative review was conducted of the peer-reviewed literature published in English spanning 1999–2025 using databases such as PubMed, Web of Science, and Google Scholar, including relevant websites related to the topic. The Boolean logic method was utilized to retrieve relevant articles for inclusion in this review. Keywords used were "food safety AND nanotechnology", "food safety AND nano-sanitizers", "conventional sanitizers AND challenges", "biofilms AND nanoparticles", "adaptive bacterial response AND sanitizers", "metabolomics AND nanoparticles", "food metabolomics AND safety", "nanotoxicity mechanisms AND bacteria", "biofilms inactivation AND metabolite profile", and/or "nanomaterials AND regulations". A total of 753 articles were retrieved, title-reviewed, and 176 articles were retained for abstract review. Upon review of the abstracts, 90 articles were included in this argumentative review.

2. Mechanisms of Action of Nano-Sanitizers

Nano-sanitizers operate by harnessing unique antimicrobial mechanisms that are fundamentally influenced by the nanoscale dimensions of the materials used (Figure 2) [9,11]. One primary mechanism involves direct interaction with microbial cell membranes, whereby nanomaterials cause physical disruption of the lipid bilayer, leading to cell lysis and irreversible damage [15,30]. The small particle size vis-à-vis surface charge may allow for penetration into biofilms and intracellular spaces, enhancing the inactivation of pathogens that might otherwise evade conventional treatments [12,17,31]. For instance, nano-titanium dioxide (TiO_2NP) has been shown to exhibit photocatalytic properties under ultraviolet light, generating reactive oxygen species (ROS) that induce oxidative stress in bacteria [30]. Such ROS generation can accelerate lipid peroxidation and cellular damage, ensuring that even resistant strains are effectively neutralized [32]. Furthermore, direct physical interactions due to contrasting surface charge have been documented to disintegrate bacterial cell wall, leading to cell death in multidrug-resistant *E. coli* strains (Figure 3) [33].

Additional mechanisms include the controlled release of active agents through nanocarrier systems, which deliver antimicrobial compounds with high precision and at minimal effective doses [14,17]. In some formulations, nanostructures are designed to mimic enzymatic barriers, thereby interfering with essential metabolic pathways within pathogens [34]. Moreover, the surface charge and functionalization of nanomaterials can be tailored to promote specific interactions with microbial cell wall, leading to electrostatic disruption of the cell wall [33,35]. These tailored interactions are supported by studies that demonstrate enhanced binding affinity and increased microbial uptake of metal-based nanoparticles, such as silver or copper, resulting in the rapid inactivation of pathogens [16,31,33,36]. Such mechanistic insights are critical, as they provide the scientific basis for comparing nano-sanitization with conventional chemical disinfectants, whose mechanisms are often less targeted and thus more prone to resistance development [13].

Furthermore, the dynamics of nano–microbe interactions are influenced by the physicochemical characteristics of the nanoparticles, including size, shape, and surface functional groups (Figure 2) [14,31,33]. These parameters govern not only the antimicrobial efficacy but also performance variations in different food matrices [14,35]. Experimental evidence suggests that by modulating synthesis conditions, researchers can optimize nano-sanitizer formulations to achieve improved contact with pathogens and to overcome some of the limitations inherent to bulk materials [14,34]. In addition, the integration of artificial intelligence in modeling interaction kinetics has further refined our understanding of these mechanisms, demonstrating that nano-sanitizers can achieve disinfection at much lower

dosages compared to their conventional counterparts [11,36]. Such mechanistic advantages are essential in contexts where minimal chemical residues are desired to maintain food quality and consumer safety [17].

The interplay between nanoparticle surface properties and environmental factors such as pH, temperature, and the presence of organic matter also plays a pivotal role in determining in situ antimicrobial action [37]. Advanced spectroscopic techniques have revealed that under specific conditions, nano-sanitizers can be activated to produce localized, high-intensity ROS, thereby achieving rapid microbial inactivation even in the presence of biofilm structures [30]. Additionally, the potential for synergistic effects with other preservation methods, such as mild heat treatment or low-dose irradiation, has been documented, underscoring the flexibility of these nanosystems in multi-hurdle interventions [33]. Such synergies highlight the promise of nano-sanitizers as both standalone agents and as part of integrated food safety protocols. In summary, the mechanistic profile of nano-sanitizers, supported by recent advances in materials science and microbiology, positions them as potent, adaptable solutions for modern food safety challenges. However, it is important to emphasize the potential adaptive response of pathogenic microbes against novel nano-sanitizers.

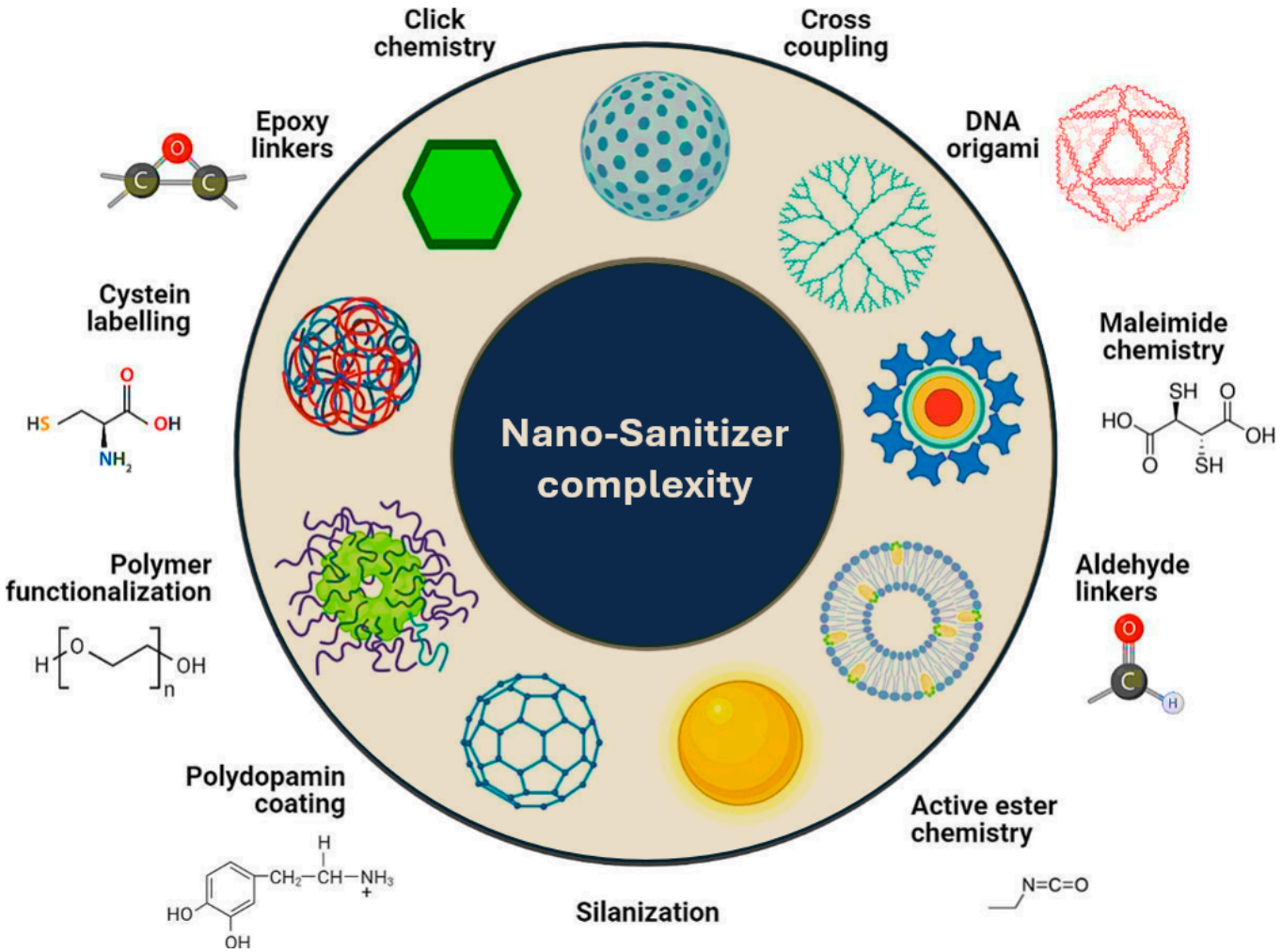


Figure 2. Variations in nano-sanitizers can be tailored according to particle size, shape, and/or surface ligands, collectively demonstrating different particle behaviors and potential toxicities against foodborne pathogens. Image adapted from Kaymaz et al. [38], with permission from Elsevier (https://creativecommons.org/licenses/by-nc/4.0/ accessed on 14 July 2025).

Bacterial adaptive responses to disinfectants emerge through a convergence of stress-induced mutagenesis and selection pressures [39]. Even low-intensity exposures can trigger general stress responses that may increase the mutation rate and facilitate the evolution of resistant variants [40–42]. The vast reproductive capacity of bacterial populations, capable of expanding rapidly, statistically ensures that even rare mutation events—ranging from single-base substitutions to large genomic rearrangements—can occur and be selected for under such stresses [40,41]. This evolutionary process is further compounded by horizontal gene transfer, which allows bacteria to rapidly distribute resistance genes via mobile genetic elements, including plasmids, integrons, and transposons, thereby reinforcing their adaptive plasticity [40,43].

Sublethal exposure to disinfectants has been shown to induce overexpression of efflux pumps and alterations in membrane permeability, mechanisms that collectively increase the survival probability of resistant mutants in environments, such as the food industry, with continuous antimicrobial pressure [40,43]. Moreover, such adaptive modifications may extend to the re-engineering of key cellular proteins, thus optimizing bacterial cellular functions to circumvent the inhibitory actions of disinfectants [39,41,42].

Additionally, bacterial biofilm is another adaptive mechanism for conferring resistance against disinfectants. The metabolic profile of bacterial biofilms undergoes significant reprogramming after exposure to antibiotics or disinfectants, with notable shifts in substrate utilization and energy allocation [44]. Biofilm cells can continue to consume glucose and maintain certain biosynthetic activities even when growth is halted, suggesting that metabolic fluxes are redirected rather than entirely suppressed [44]. This phenomenon is accompanied by an accumulation of stress-induced metabolites and a transition toward alternative metabolic pathways that support survival under unfavorable conditions, as demonstrated in studies investigating the effects of chlorhexidine on oral biofilms [45] and sodium hypochlorite treatments on *Klebsiella pneumoniae* biofilms [46]. Concurrently, these metabolic adaptations integrate with structural and genetic resistance mechanisms—such as changes in extracellular polymeric substances and reduced permeability—that further protect biofilm cells from antimicrobial agents [47]. Overall, the dynamic metabolic adjustments observed underscore the resilience of biofilms and highlight the complexities involved in eradicating these persistent microbial communities. In summary, the misuse and extensive application of disinfectants not only promote the selection and survival of these rare resistant phenotypes but also drive rapid and dynamic evolution in bacterial populations, underscoring the complexity and resilience of microbial adaptive mechanisms [40,41,43,44,48].

Nonetheless, detailed kinetic studies have elucidated that the rate of microbial inactivation by nano-sanitizers often exceeds that achieved by conventional disinfectants [10,12]. At the heart of these studies is the understanding that the nanoscale interface facilitates rapid electron transfer events, which markedly expedite the ROS generation process [49]. This advanced mode of action not only results in immediate microbial cell disruption but also decreases the probability of pathogens developing resistance over time [11]. Furthermore, the engineering of nanomaterials with specific geometric configurations, such as rod-shaped or star-shaped nanoparticles, has been shown to further enhance their antimicrobial potency through increased surface contact [34,35]. These findings are corroborated by computational modeling and real-world testing in controlled food-processing environments [14,50]. Collectively, the evidence supports that nano-sanitizers represent a fundamentally different and enhanced approach to microbial inactivation, with the potential to address some of the persistent challenges facing conventional sanitation methodologies.

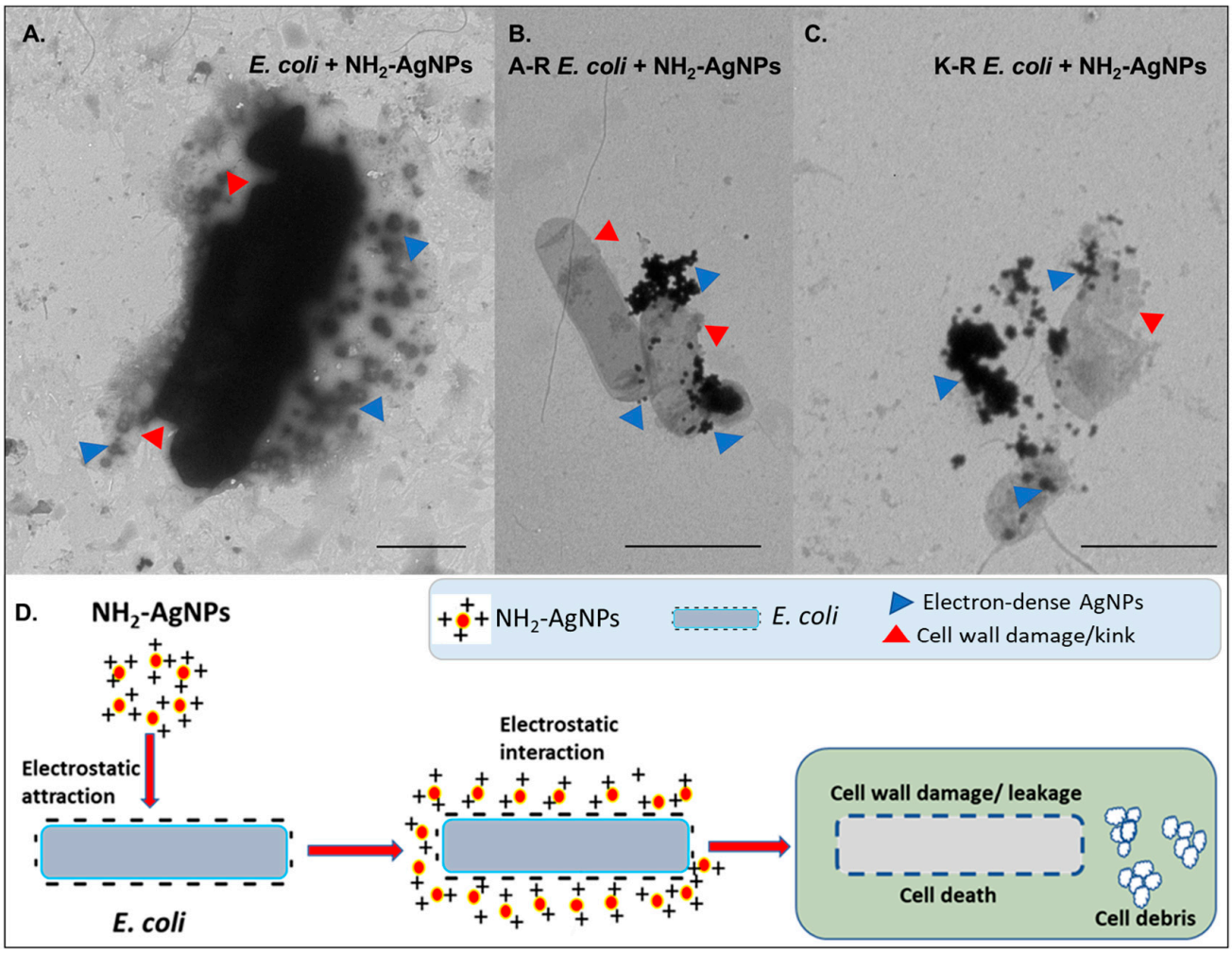


Figure 3. Schematic depicting mechanism of action of amino-functionalized silver nanoparticles (NH_2-AgNPs) against three strains of *E. coli* DH5α: susceptible *E. coli* DH5α (**A**), ampicillin-resistant *E. coli* DH5α (**B**), and kanamycin-resistant *E. coli* DH5α (**C**). Red triangles denote cell wall damage and/or kinks on cell walls (**A**–**C**), and blue triangles denote electron-dense nanoparticles around *E. coli* cells (**A**–**C**), confirming direct physical electrostatic interactions between high positively charged NH_2-AgNP (10 μg/mL) and negatively charged *E. coli* cell surfaces (**D**). Scale bar denotes 2 μm. Image adopted from [33] (copyright with the authors).

Recent investigations have employed high-resolution imaging and spectro-electrochemical measurements to validate these mechanisms, thus bridging the gap between in vitro and in situ conditions [10,30]. These multidisciplinary approaches involving materials scientists, microbiologists, and food technologists have provided robust evidence that the nanoscale effects observed in laboratory settings can be effectively translated into practical food safety applications [32]. Such integration of mechanistic studies with applied research is central to understanding not only how nano-sanitizers work but also how they can be fine-tuned for optimal performance in diverse food systems [14]. Overall, mechanistic insights into nano-sanitizers offer strong support for their potential to transform current food safety practices by harnessing advanced, tunable antimicrobial actions that are difficult to achieve using conventional methods.

3. Benefits of Nano-Sanitizers over Conventional Sanitizers

The benefits of nano-sanitizers in food safety extend to antimicrobial efficacy, environmental sustainability, and process efficiency [9,49]. First and foremost, nano-sanitizers have been shown to work at much lower effective doses compared to traditional chemical sani-

tizers, thereby reducing the risk of chemical residues and potential human toxicity [10,11]. Due to their high surface area and tailored reactivity, these materials can achieve rapid and broad-spectrum inactivation of foodborne pathogens, including bacteria, viruses, and fungi, thus significantly reducing the incidence of contamination [11,12]. In addition, the ability of nano-sanitizers to disrupt biofilms, which are notoriously resistant to conventional disinfectants, represents a critical advancement in ensuring high levels of hygiene in complex food processing environments [13,15].

Another significant benefit lies in the enhanced functionality offered by nano-enabled formulations. For instance, the controlled-release properties of nano-carrier systems facilitate the sustained delivery of antimicrobial agents over time, thereby extending the duration of protection on food surfaces and packaging materials [14,51]. This controlled release is particularly advantageous in dynamic food supply chains where product exposure to contaminants may vary throughout processing, distribution, and retail stages [14]. Moreover, the incorporation of nano-sanitizers into food packaging materials not only improves microbial safety but also contributes to preserving quality by inhibiting oxidative degradation and spoilage reactions [52]. Such multifunctional benefits position nano-sanitizers as integral components of intelligent smart packaging systems that actively monitor and respond to microbial challenges [35].

Environmental considerations further underscore the advantages of nano-sanitizers. Because these materials can be effective at low concentrations, their overall ecological footprint is reduced, a benefit that aligns with the principles of green chemistry and sustainability [16,53]. Minimizing the use of harsh chemical agents helps mitigate the risk of environmental contamination while also decreasing the likelihood of selecting for antimicrobial resistance among environmental microbes [36]. In addition, nano-sanitizers offer the prospect of energy-efficient operation by shortening treatment times, thereby reducing energy consumption during the sanitization process [30,32]. These factors collectively suggest that nano-sanitizers can contribute to both enhanced food safety and improved sustainability metrics across food-processing systems [17].

The benefits of nano-sanitizers become even more compelling when weighed against traditional sanitization methods, which often require high dosages and prolonged exposure times to achieve comparable levels of microbial inactivation [37]. In contrast, recent studies utilizing advanced nano-platforms have consistently demonstrated superior outcomes in reducing bacterial load, even in challenging matrices such as biofilm-embedded pathogens or in the presence of organic matter [18]. Furthermore, the rapid action of nano-sanitizers can lead to significant operational cost savings in industrial food processing, as it enables faster turnaround and increased production throughput [19]. These economic advantages, combined with enhanced product quality and consumer safety, create a strong impetus for industry adoption of nano-enabled approaches.

Beyond efficacy and efficiency, nano-sanitizers offer benefits in terms of flexibility and adaptability. Their physicochemical properties can be modified to suit specific applications, ranging from direct surface sanitization to integration within packaging materials or as coatings for processing equipment [20,21]. This versatility has spurred innovative formulations that are now being tailored for various food products and environmental conditions [22,23]. Moreover, nano-sanitizers have the potential to work synergistically with other technological interventions, such as smart sensors and automated quality control systems, to create an integrated food safety architecture [54]. Such integration not only increases the reliability of sanitation processes but also elevates the overall performance of food safety management systems.

It is also worth noting that the use of nano-sanitizers can contribute to reducing food waste by prolonging the shelf-life of perishable products [24]. By minimizing residual

microbial contamination during storage and transportation, these advanced sanitizers help maintain food quality and reduce spoilage losses [9]. In a world where food security is an ever-growing concern, the dual benefits of improved microbial control and waste reduction render nano-sanitizers particularly attractive [49]. At the same time, risk–benefit analyses indicate that when developed and applied under stringent regulatory frameworks, the potential risks associated with nano-sanitizers are outweighed by the significant improvements in food safety and overall public health outcomes [10,54].

Recent strategies to minimize food product contamination increasingly leverage nanomaterials to improve food packaging and detection systems. Nanomaterials such as silver nanoparticles, zinc oxide nanoparticles, and titanium dioxide nanoparticles are incorporated into packaging materials to impart superior barrier properties and inherent antimicrobial effects, thereby mitigating microbial proliferation and chemical degradation [12]. In addition, chitosan-based nanofibers have demonstrated the capacity to reduce bacterial viability on meat products by synergistically combining antimicrobial agents, which extend shelf life and enhance food safety [55]. Furthermore, advanced optical detection techniques employ multifunctional nanomaterials integrated with antibodies, aptamers, and biomimetic polymers to facilitate rapid and precise identification of foodborne contaminants [56]. Nanomaterial-enabled packaging also benefits from polymer–clay nanocomposites that act as physical barriers to prevent oxygen and moisture ingress, further minimizing spoilage and contamination risks [57]. These innovations not only reduce the potential for microbial contamination but also allow for real-time monitoring of food quality through sensor-based assays, thereby offering a dual approach to food preservation and safety [58]. Consequently, the integration of nanomaterials into both active packaging solutions and sophisticated detection systems represents a promising frontier to ensure food integrity, sustain shelf life, and comply with evolving regulatory safety standards [56–58]. By harnessing the unique physicochemical properties of nanomaterials, researchers continue to develop cost-effective, scalable, and robust strategies that protect food products from a diverse array of contaminants. For example, silver nanoparticles have been widely incorporated into food packaging and surface coatings due to their potent antimicrobial properties, yet their potential toxicity and migration concerns need to be addressed [12,33,55–57]. Nanoemulsions and polymeric nanoparticles have been exploited for their ability to encapsulate and deliver bioactive compounds, potentially enhancing nutritional value and sensory stability [59–61]. In addition, nanocomposites created by dispersing nano-fillers such as silica and nanocellulose within polymer matrices may offer improved barrier properties and mechanical strength in packaging, although migration risks and regulatory issues remain [61–64]. Moreover, slightly acidic, low-concentration electrolyzed water (SALCEW) represents a novel nano-sanitizer that can be generated on-site with minimal chemical additives, effectively reducing microbial loads in meat processing; however, its efficacy against resilient organisms and potential equipment corrosion are areas for further optimization [65]. A list of various nanomaterials with potential use in the food industry has been summarized, including material names, chemical compositions, usages/applications, associated benefits, and the challenges encountered in their implementation, in Table 1. These innovations, underpinned by rigorous research and regulatory assessments, promote sustainability and offer significant economic benefits by reducing food waste and effectively protecting consumer health in practical applications [12,58].

Table 1. Varied types of nanomaterials or nano-sanitizers used in the food industry, including their names, chemical composition, how they are used, benefits, and challenges.

Type of Nanomaterial	Chemical Composition	How Used	Benefits	Challenges	References
Silver/Silver-based Nanoparticles					
Silver Nanoparticles	Silver (Ag)	Food packaging and preservation	Antimicrobial properties; extends shelf life	Potential toxicity and environmental concerns	[66]
Silver Nanoparticles	Ag	Antimicrobial agent in packaging	Effective against a wide range of pathogens; extends shelf life	Potential toxicity concerns; regulatory issues	[67]
Silver Nanoparticles	Ag	Antimicrobial coatings	Effective against a broad range of bacteria	Potential leaching into food; toxicity concerns	[68]
Silver Nanoparticles	Ag	Antimicrobial agents in food packaging	Effective against bacteria; extends shelf life	Potential toxicity; regulatory hurdles	[63]
Silver Nanoparticles	Ag	Antimicrobial agent in food packaging	Effective against a broad range of pathogens	Potential toxicity and environmental concerns	[62]
Silver Nanoparticles	Ag	Antimicrobial coatings in packaging	Effective against a broad range of pathogens	Potential toxicity and environmental concerns	[64]
Silver Nanoparticles	Ag	Food packaging and surface treatment	Strong antimicrobial properties; reduces spoilage	Potential toxicity; regulatory concerns	[69]
Silver Nanoparticles	Ag	Incorporated into packaging to provide antimicrobial properties	Effective against a wide range of pathogens	Potential toxicity and regulatory concerns	[70]
Silver-Cellulose Nanoparticles	Ag + cellulose	Preservative in meat and fish products	Enhances antimicrobial activity; biodegradable	Sourcing cellulose; stability in packaging	[63]
Silver-Starch Nanoparticles	Ag + starch	Food preservative	Effective against spoilage microorganisms	Shelf life and interaction with food	[63]
Chitin-Derived Silver Nanoparticles (AgNPs)	Ag + chitin	Incorporated into chitin films for food preservation.	Antimicrobial activity against pathogens like Vibrio spp.; extends shelf life of perishable foods	Control of nanoparticle size and uniformity; potential consumer acceptance issues	[71]
Titanium Dioxide Nanoparticles					
Titanium Dioxide Nanoparticles	Titanium dioxide (TiO_2)	UV protection and antimicrobial coatings	Protects against UV degradation and bacterial growth	Potential for phototoxicity under certain conditions	[66]
Titanium Dioxide Nanoparticles	TiO_2	Photocatalytic properties in packaging	Provides UV protection, enhances shelf life	Production cost; potential environmental impact	[67]
Titanium Dioxide Nanoparticles	TiO_2	Acts as a photocatalyst in food packaging to degrade contaminants.	Self-cleaning properties; reduces foodborne pathogens	Limited effectiveness in low-light conditions; potential toxicity issues	[71]
Titanium Dioxide Nanoparticles	TiO_2	UV protection in packaging	Enhances food safety by preventing spoilage	Regulatory approval for food contact materials	[68]
Titanium Dioxide Nanoparticles	TiO_2	UV protection in food packaging	Protects food from sunlight-induced degradation	Health effect uncertainties and regulatory hurdles	[62]
Titanium Dioxide	TiO_2	Applied to food packaging films for UV protection	Protects food from light degradation	Potential health concerns and environmental impact	[70]
Titanium Dioxide	TiO_2	UV-blocking agents in food packaging	Enhances shelf life and safety	Concerns over potential accumulation in the body	[64]
Titanium Dioxide Nanoparticles	TiO_2	Photocatalytic food safety applications	Antimicrobial effects; photocatalytic activity	Safety concerns associated with ingestion	[69]
Zinc Oxide Nanoparticles					
Zinc Oxide Nanoparticles	Zinc oxide (ZnO)	Antimicrobial agent in food coatings	Effective against a range of pathogens	Limited solubility in various food matrices	[66]
Zinc Oxide Nanoparticles	ZnO	Antimicrobial in food packaging	Non-toxic; effective against bacteria and fungi	Limited solubility; variable effectiveness	[67]
Zinc Oxide Nanoparticles	ZnO	Used in food packaging films to inhibit microbial growth and UV radiation	Enhances barrier properties and protects food from spoilage	Regulatory challenges and stability concerns under various conditions	[71]
Zinc Oxide Nanoparticles	ZnO	Active food packaging	UV-filtering, antimicrobial, and improves product safety	Stability and reusability issues	[68]
Zinc Oxide Nanoparticles	ZnO	Antimicrobial in coatings and active packaging	Enhances food safety by reducing microbial load	Possible cytotoxicity and regulatory issues	[62]
Zinc Oxide Nanoparticles	ZnO	Food packaging and coatings	UV protection; antimicrobial properties	Regulatory approvals and health impacts	[64]
Zinc Oxide Nanoparticles	ZnO	Active packaging films	Enhances shelf life; UV protection	Environmental impact; nanoparticle leaching	[69]
Zinc Oxide Nanoparticles	ZnO	Used in coatings and food packaging for antimicrobial effects	Enhances shelf life and prevents mold growth	Stability in formulations and UV degradation	[70]

Table 1. *Cont.*

Type of Nanomaterial	Chemical Composition	How Used	Benefits	Challenges	References
Other Metal-based Nanoparticles					
Copper Nanoparticles	Copper (Cu)	Applied to food packaging to prevent microbial contamination.	Broad-spectrum antimicrobial activity	Corrosive properties; potential for waste accumulation.	[71]
Copper Nanoparticles	Cu	Antimicrobial coatings on surfaces	Broad spectrum of antimicrobial activity; reduces spoilage	Corrosion issues; potential leaching	[67]
Gold Nanoparticles	Gold (Au)	Biosensors for food contamination	High sensitivity in detection; biocompatible'	High cost; limited scalability	[67]
Gold Nanoparticles	Au	Used in biosensors to detect food contaminants	High sensitivity and specificity in contaminant detection	Costly production; stability in food matrices.	[71]
Aluminum Nanoparticles	Aluminum (Al)	Food preservative containers	Antimicrobial properties extend shelf life and reduce spoilage	Environmental impact of nanoparticles; regulatory hurdles	[68]
Nanosilica	Silicon dioxide (SiO_2)	Carrier for nutrients and stabilizer in food products	Improves texture and prevents clumping	Potential for leaching and regulatory concerns	[62]
Silicon Dioxide	SiO_2	Anti-caking agents in powdered foods	Improves flowability and storage	Long-term health effects need further study	[64]
Iron Oxide Nanoparticles	Fe_2O_3	Food additives and fortification	Provides nutritional benefits	Possible toxicity and bioaccumulation risks	[64]
Bio-based Nanomaterials					
Chitosan-Based Nanoparticles	Chitosan ($C_6H_{11}NO_4S$)	Active packaging material	Biodegradable, antimicrobial properties	Cost of sourcing chitosan	[67]
Chitosan Nanoparticles (CNP)	$C_6H_{11}NO_4S$	Encapsulation of antimicrobial agents like nisin, lupulone, and xanthohumol	Broad spectrum antibacterial activity; biodegradable	Susceptibility to degradation; potential variability in efficacy	[72]
Chitosan Nanofibers	$C_6H_{11}NO_4S$	Used as packaging material with antimicrobial properties	Biodegradable and safe; enhances food preservation	Variability in antimicrobial activity	[70]
Chitosan Nanofibers	$C_6H_{11}NO_4S$	Bioactive food packaging	Reduces bacterial viability; biodegradable	Sourcing of raw materials; consistency in production	[68]
Chitosan Nanofibers	$C_6H_{11}NO_4S$	Bioactive packaging for meats	Reduces bacterial growth and extends shelf life	Limited water solubility and mechanical strength	[62]
Chitosan Nanoparticles	$C_6H_{11}NO_4S$ (from crustacean shells)	Edible coatings for fruits and vegetables	Biodegradable; enhances antimicrobial effects	Limited solubility; potential allergenicity	[69]
Chitosan–Nisin Nanocomposite (CNPN)	$C_6H_{11}NO_4S$ + Nisin	Food preservation to inhibit microbial growth	Effective against a variety of pathogens	Stability under heat and processing conditions	[72]
Chitosan–Lupulone Nanocomposite (CNPL)	$C_6H_{11}NO_4S$ + Lupulone	Enhancing food safety and extending shelf life	Natural antimicrobial; reduces foodborne pathogens	Variable release rates; sourcing of raw materials	[72]
Chitosan–Xanthohumol Nanocomposite (CNPX)	$C_6H_{11}NO_4S$ + Xanthohumol	Food preservation and quality maintenance	Competitively inhibits microbial growth	Limited solubility in certain food matrices	[72]
Gelatin-Based Nanoparticles	$C_{68}H_{88}N_{18}O_{39}S$ (derived from collagen)	Edible coating for food	Biocompatible; improves food preservation	Texture and stability issues	[67]
Nanofibers	Polymer-based structures (e.g., cellulose, chitosan)	Food wrapping and antimicrobial surfaces	Enhanced mechanical properties; effective against pathogens	Production challenges and cost	[67]
Lipid Micro/Nanoparticles	Lipid-based nanoparticles	Encapsulation of bioactive compounds in food packaging	Enhances stability and functional properties	Stability during storage and processing	[62]
Nanoemulsions	Various lipid-based materials	Used to enhance flavor and texture in food applications	Improved bioavailability and stability of bioactive compounds	Formulation complexity and stability over time	[70]
Lipid-Based Nanoparticles	Lipids (e.g., phospholipids)	Delivery systems for bioactive compounds	Enhanced bioavailability of nutrients	Stability and scalability issues	[64]
Protein Nanoparticles	Proteins (e.g., whey)	Emulsifiers and stabilizers in food formulations	Improved texture and stability	Allergic reactions in sensitive individuals	[64]
Ternary Nanoparticles (TNPs)	Rosemary essential oil, Nisin, *Lycium barbarum* polysaccharides	Beef preservation	High antibacterial activity; effective against foodborne pathogens	Stability under varying conditions; consumer acceptance	[69]
Biogenic Nanoparticles	Various plant extracts	Synthesis of nanoparticles from natural sources	Eco-friendly; reduces reliance on synthetic chemicals	Variability in effectiveness based on plant source	[66]

Table 1. *Cont.*

Type of Nanomaterial	Chemical Composition	How Used	Benefits	Challenges	References
Graphene/Carbon-based Nanomaterials					
Graphene Oxide Nanomaterials	Graphene oxide (GO)	Food safety sensors	Exceptional conductivity for real-time monitoring	Scaling up production; potential risks in environment	[68]
Graphene Oxide	GO	Food packaging with barrier and antimicrobial properties	High electrical and thermal conductivity	Cost and scalability of production	[62]
Carbon Nanotubes	C	Sensors for contaminant detection	High sensitivity for detecting pathogens and toxins	Cost and complexity of production	[68]

Furthermore, the economic implications of adopting nano-sanitizer technology are notable. Industry reports suggest that operational costs can be lowered through reduced chemical usage and lower energy inputs, thereby enhancing profitability while maintaining high safety standards [11,12]. In summary, the multi-dimensional benefits of nano-sanitizers, ranging from superior antimicrobial efficacy and environmental sustainability to improved cost-effectiveness and adaptability, strongly support their transformative potential in modern food safety systems.

4. Challenges, Regulations, and Implications for Public Health

Despite their promising benefits, the adoption of nano-sanitizers also poses significant challenges that require careful consideration [9,10]. A significant issue is the potential toxicity of nanomaterials to human health, as their small size might facilitate absorption across biological membranes, leading to cytotoxicity or bioaccumulation [10,49]. Research comparing nano-sanitizers with conventional sanitizers highlights that while lower effective doses are beneficial, the long-term health effects of chronic, low-level exposure to nanomaterials remain incompletely understood [11,12]. In addition, variability in particle size, shape, and surface charge (Figure 2) can lead to unpredictable interactions within complex food matrices or even within the human body [13,15]. These uncertainties necessitate a cautious regulatory approach and rigorous risk–benefit assessments [50,51].

Regulatory oversight is one of the most significant challenges facing nano-sanitizers. International Organization for Standardization (ISO) guidelines for evaluating nanomaterials establish a comprehensive, standardized framework that defines the physical, chemical, and toxicological parameters essential for characterizing nanomaterials. These guidelines specify key criteria, including nanoparticle size (typically 1–100 nm, as indicated in ISO standards) [73,74], surface characteristics, aggregation behavior, and stability (assessed as zeta potential changes) [75], to ensure consistent and reproducible evaluation across different laboratories and product applications. Such standardization is pivotal for both basic research and practical applications, such as the development and regulation of nano-sanitizers. A central tenet of the ISO approach is the precise physicochemical characterization of nanomaterials. Standard measurement techniques, including dynamic light scattering (DLS) for determining particle size distribution and electrophoretic light scattering for calculating zeta potential, offer a robust means to quantify crucial properties in aqueous suspension that influence material performance and biological interactions [75]. For nano-sanitizers, where the efficacy hinges on the antimicrobial properties of nanoparticles (e.g., silver, titanium dioxide, and biobased nanomaterials; for a detailed list, see Table 1), these parameters dictate critical aspects such as dispersion stability and reactivity. A stable dispersion minimizes aggregation, which, in turn, preserves the intended antimicrobial mechanism and lowers potential toxicity risks when materials interact with human tissues or environmental components.

In parallel, ISO guidelines extend to standardized toxicological assessments, ensuring that both direct biological effects and environmental impacts are adequately characterized. For instance, the ISO/TS 20787 protocol for aquatic toxicity—a procedure developed to assess nanomaterial ecotoxicity using model organisms like *Artemia nauplii*—provides a repeatable method to gauge the environmental risks associated with nano-enabled products [76]. The ecological safety of nano-sanitizers is particularly critical, as these products may, during use or end-of-life disposal, introduce nanoparticles into environmental matrices, where they can affect aquatic life [77]. Complementary frameworks, such as nanoCRED, enhance the regulatory assessment of ecotoxicity data by offering clear criteria for data relevance and reliability [77]. Together, these approaches ensure that environmental safety assessments align with the rigorous protocols mandated by ISO, establishing confidence in the sustainable deployment of nano-sanitizers.

Additional decision-making frameworks, such as the DF4nanoGrouping proposed by Arts et al. [78], integrate seamlessly with the ISO guidelines by providing a tiered strategy to classify nanomaterials based on intrinsic properties and potential life cycle hazards. Such groupings facilitate risk identification and streamline the testing process by suggesting targeted evaluations for subcategories of nanomaterials. When applied to nano-sanitizers, this grouping concept may aid in tailoring safety assessments to the specific characteristics of the incorporated nanoparticles, whether their biopersistence, uptake, or cellular effects, thus ensuring comprehensive risk management throughout the product's life cycle.

The correlation between these ISO evaluation guidelines and the development of nano-sanitizers is multifaceted. On a fundamental level, adherence to standardized procedures for size, surface charge, and dispersion stability guarantees that the active nanomaterials in sanitizers consistently deliver their antimicrobial function without undue variation. Furthermore, standardized environmental and toxicological testing protocols assist manufacturers and regulators in identifying potential adverse effects early in the product development process. This dual approach—incorporating both physicochemical characterization and toxicity testing—ensures that nano-sanitizers are effective in their intended disinfection roles and safer for users and the environment. In summary, the ISO guidelines provide a rigorous foundation for the evaluation of nanomaterials by defining key measurement techniques and safety-testing protocols. These guidelines are directly applicable to nano-sanitizers, where the determination of particle size, zeta potential, and toxicity forms the basis for ensuring both product efficacy and safety. The integration of complementary frameworks—such as DF4nanoGrouping for nanomaterial classification [78] and nanoCRED for ecotoxicity evaluation [77]—further augments the ISO approach, establishing a robust and holistic risk assessment model that bridges laboratory evaluation with real-world application. This synergy between standardized guidelines and innovative product design is essential for the continued safe development and regulatory acceptance of nano-sanitizers.

Existing food safety frameworks were conceived primarily for conventional chemicals and may not fully accommodate the unique behaviors of nanomaterials [14,79]. Recent discussions have emphasized the need for regulatory agencies to evolve and to include standardized testing protocols, labeling requirements, and post-market surveillance to manage potential risks effectively [34,52]. Moreover, public perceptions, shaped by past controversies over nanotechnology in consumer products, can lead to resistance against adoption unless robust educational initiatives are implemented [16,35]. The divergence between scientific consensus and consumer beliefs often results in calls for precautionary measures and even outright bans, as evidenced by some proposals to label or ban nano-enabled food applications [17,37].

Another challenge arises from the potential environmental impacts of nano-sanitizers. Given their widespread use, even trace amounts of nanomaterials may accumulate in soil and water, with unknown repercussions for ecosystems and human health [18]. Comparative studies suggest that conventional sanitizers, although used at higher doses, have a more established profile regarding environmental fate. In contrast, the unique properties of nanomaterials complicate the prediction of their behavior in natural systems [19]. Moreover, establishing a reliable life cycle analysis methodology for nano-sanitizers is difficult due to the rapid pace of innovation and variability in nanomaterial formulations [20]. This complexity is further compounded by insufficient data on the interactions between nanomaterials and complex food components, limiting the ability to extrapolate laboratory findings to real-world scenarios [21].

In industrial settings, the scalability and cost-effectiveness of nano-sanitizer production pose additional challenges that might hinder widespread adoption [22]. Although research has demonstrated impressive in-lab efficacy, translating these results into commercial products that meet regulatory requirements while maintaining affordability remains challenging [23]. Arguments have been made by some experts that the current infrastructure supporting food safety practices may not be adequately prepared to integrate advanced nanotechnologies without substantial investment in research, training, and quality control systems [54]. Furthermore, comparative risk–benefit analyses indicate a delicate balance: while the enhanced antimicrobial activity of nano-sanitizers offers public health advantages, the unknown long-term impacts on human health and the environment could offset these benefits if not properly managed [24].

The complexities of public perception and regulatory fragmentation are further exacerbated by the fact that many traditional food sectors, such as artisanal processes or street food vending, lack the means to monitor and enforce nano-sanitizer usage effectively [80,81]. For example, studies on street food safety in regions like Kampala have revealed challenges in consistent hygienic practices, a scenario where the controlled deployment of nano-sanitizers could offer significant improvements but also raise concerns about consumer consent and labeling [82]. In parallel, the risk of unintended interactions between nano-sanitizers and native food components, as well as their potential to induce allergenic or inflammatory responses, remains a topic of active research and debate [83,84]. Such concerns call for interdisciplinary studies that bridge food science, toxicology, and materials engineering.

Beyond these technical and regulatory barriers, socio-economic factors also come into play. The integration of nano-sanitizers into food safety systems may require substantial modifications to existing processing infrastructures, which could be cost-prohibitive for small and medium enterprises [85,86]. Moreover, the global nature of food supply chains means that regulatory standards and market acceptance vary considerably between regions, making a unified strategy difficult to achieve [87,88]. In addition, while some economic analyses predict that nano-sanitizers could reduce costs by lowering chemical usage and energy expenditure, these benefits must be balanced against the potential costs associated with additional monitoring and safety testing [89,90]. Ultimately, the successful integration of nano-sanitizers into food safety management will depend on overcoming these multifaceted challenges through enhanced research, cooperative regulatory efforts, and proactive stakeholder engagement.

5. Looking into the Future

Looking ahead, the future of nano-sanitizers in food safety appears promising yet contingent upon addressing key technical, regulatory, and social challenges [9,10]. Researchers are already exploring novel nanomaterial formulations and functionalizations that are

designed to optimize antimicrobial efficacy while minimizing toxicity [10,49]. For instance, emerging work on bio-inspired and biodegradable nanomaterials is expected to mitigate concerns regarding bioaccumulation and environmental persistence, thereby offering a more sustainable approach to food sanitization [11,12]. In tandem with these material innovations, ongoing studies are integrating advanced modeling and artificial intelligence techniques to predict nano-microbe interactions and to fine-tune dosage regimens, ensuring that the sanitizing effects are optimized with minimal adverse outcomes [13,15].

The evolution of regulatory frameworks will be pivotal to unlocking the full potential of nano-sanitizers [14,77,79]. Future policies are likely to adopt adaptive, risk-based approaches that incorporate continuous monitoring and updated guidelines as new evidence emerges [34,52]. Global harmonization of nano-specific safety standards would facilitate broader market acceptance and expedite commercial deployment [52]. Moreover, public–private partnerships and international collaborative networks are essential to bridging the current gaps between laboratory research and field application [16,35]. Active engagement with stakeholders, including food producers, regulatory agencies, and consumers, is expected to foster transparency and build trust in nano-enabled food safety technologies [17,37].

From an industrial perspective, the integration of nano-sanitizers with "Industry 4.0 technologies" is poised to transform food safety management systems [18]. Innovative smart packaging that incorporates nano-sanitizers along with sensors and real-time data analytics can provide continuous monitoring of food quality, thereby enhancing traceability and enabling rapid responses in case of contamination [19,20]. Such integration would not only improve the safety profile of food products but also contribute to operational efficiencies and cost reductions [21,22]. Moreover, as the food industry increasingly embraces digital transformation, nano-sanitizers could be embedded within automated cleaning and sanitation protocols to ensure consistent application across diverse processing environments [23]. The alignment of nano-tech innovation with digital monitoring promises to deliver a more resilient and adaptive food safety framework.

In the academic arena, future research is expected to delve deeper into understanding the long-term impacts of chronic nano-exposure, both at the human health level and in environmental contexts [23]. Interdisciplinary efforts, combining nanotechnology, toxicology, and food science, are essential to designing next-generation nano-sanitizers with improved safety profiles [9,10]. Moreover, emerging techniques in high-throughput screening and omics technologies will likely play a significant role in elucidating the molecular mechanisms and potential side effects of these materials [10,49]. Such research not only informs best practices for nano-sanitizer deployment but also aids in tailoring formulations to meet the diverse needs of global food supply chains [11,12].

Consumer education and transparent labeling will also be critical components of future nano-sanitizer strategies [13,15]. Studies on public perceptions suggest that acceptance of nano-enabled products is closely linked to clear communication about safety measures, benefits, and potential risks [50,51]. Therefore, future policy and industry practices should incorporate robust educational programs and standardized labeling practices that convey nano-related information in an accessible manner [14,79]. In doing so, the food industry can preempt undue skepticism and ensure that consumers are well informed about the benefits of nano-sanitizers.

Furthermore, emerging market trends and global food security challenges will continue to drive innovation in nano-sanitizer technology [34,52]. With climate change and expanding global populations straining conventional food production systems, the need for effective, energy-efficient, and sustainable sanitization methods is more urgent than ever [16,35]. The development of multifunctional nanomaterials that combine antimicrobial

action with antioxidant and anti-spoilage properties is a promising avenue that could redefine food preservation standards [36,53]. These innovations hold the potential not only to enhance food safety but also to contribute to an overall reduction in food waste, thereby addressing both economic and environmental concerns [30,32].

Finally, collaborations between academia, industry, and regulatory bodies will be crucial for success in this area [17,37]. International consortia and research partnerships can facilitate the exchange of best practices, expedite technology transfer, and promote the development of harmonized safety protocols [18,19]. Considering the rapidly evolving threats from foodborne pathogens, a proactive and cooperative approach will be essential to ensuring that nano-sanitizers contribute positively to public health outcomes and food security on a global scale [20,21]. The convergence of technological innovation, regulatory reform, and strategic stakeholder engagement thus offers a hopeful outlook for the transformative role of nano-sanitizers in future food safety systems.

6. Conclusions

In summary, nano-sanitizers represent a paradigm shift in the approach to food safety. Their unique antimicrobial mechanisms, ranging from membrane disruption and ROS generation to controlled active agent release, offer advantages that are not readily achievable with conventional chemicals or biological sanitizers [9–11]. The benefits extend from enhanced microbial inactivation and reduced chemical usage to improved environmental sustainability and potential cost savings in food processing operations [11,12,51]. The integration of advanced digital technologies and smart systems into food safety practices holds promise for creating robust, real-time monitoring and sanitization processes that significantly reduce the risk of foodborne disease outbreaks [23,54]. Ultimately, harnessing the full potential of nano-sanitizers will require a coordinated effort among researchers, industry stakeholders, and regulatory authorities to ensure that these technologies are developed and implemented safely, ethically, and efficiently [18,21]. With a balanced focus on innovation, risk management, and consumer education, the adoption of nano-sanitizers could lead to transformative improvements in food safety and public health outcomes.

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