processes

MDPI

Review

Applications of Green Synthesis of Nanoparticles Using Microorganisms in Food and Dairy Products: Review

Shayma Thyab Gddoa Al-Sahlany [1], Alaa Kareem Niamah [1,*], Deepak Kumar Verma [2,*], Pawan Prabhakar [3,4], Ami R. Patel [5], Mamta Thakur [6] and Smita Singh [7]

1 Department of Food Science, College of Agriculture, University of Basrah, Basra City 61004, Iraq; shayma.gddoa@uobasrah.edu.iq
2 Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India
3 Bio-Research Laboratory, Rajendra Mishra School of Engineering Entrepreneurship, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India; pawanprabhakar1@gmail.com
4 School of Business, Woxsen University, Hyderabad 502345, Telangana, India
5 Division of Dairy Microbiology, Mansinhbhai Institute of Dairy and Food Technology—MIDFT, Dudhsagar Dairy Campus, Mehsana 384002, Gujarat, India; ami@midft.com
6 Department of Food Processing Technology, College of Dairy and Food Technology (CDFT), Rajasthan University of Veterinary & Animal Sciences, Jaipur 303301, Rajasthan, India; thakurmamtafoodtech@gmail.com
7 Department of Allied Health Sciences, Chitkara School of Health Sciences, Chitkara University, Rajpura 140401, Punjab, India; sweetsmita1004@gmail.com
* Correspondence: alaa.niamah@uobasrah.edu.iq (A.K.N.); rajadkv@rediffmail.com (D.K.V.); Tel.: +96-4770-904-2069 (A.K.N.); +91-7407-170-260 (D.K.V.)

Abstract: The swift progression of nanotechnology has transformed the food and dairy industries through the facilitation of functional foods, nutraceuticals, and antimicrobial systems. This review examines the environmentally friendly synthesis of nanoparticles (NPs) through the utilization of microorganisms, offering a sustainable and biocompatible alternative to traditional physical and chemical approaches. This study primarily aims to investigate the contemporary trends, mechanisms, and microbial species associated with NP biosynthesis, as well as to evaluate NPs' techno-functional applications in food and dairy processing. The specific objectives encompass analysis of the synthesis pathways—both intracellular and extracellular—utilized by bacteria, fungi, yeasts, and algae. Additionally, an evaluation of the physicochemical properties and biological activities (including antibacterial, antioxidant, and antifungal effects) of synthesized NPs will be conducted, alongside the identification of their potential applications in food preservation, packaging, and fortification. The review emphasizes notable advancements in laboratory-scale applications, especially concerning yogurt fortification, biofilm suppression, and antimicrobial food coatings. Nonetheless, commercial application is constrained by issues related to scalability, purification, stability, regulatory adherence, and toxicity evaluation. Future investigations ought to focus on enhancing bioreactor systems, leveraging microbial consortia, utilizing food and agricultural waste as substrates, and implementing omics technologies to elucidate biosynthetic mechanisms. Furthermore, the standardization of synthesis protocols and the improvement of regulatory frameworks will be crucial in closing the divide between experimental achievements and NPs' application in industry. In a nutshell, the microbial-mediated green synthesis of NPs offers a promising pathway for the advancement of safe, sustainable, and functional innovations within the food and dairy sectors.

Academic Editors: Navid Aslfattahi, Kumaran Kadirgama, Lingenthiran Samylingam and Mohammad Reza Chalak Qazani

Received: 1 April 2025
Revised: 13 May 2025
Accepted: 16 May 2025
Published: 18 May 2025

Citation: Al-Sahlany, S.T.G.; Niamah, A.K.; Verma, D.K.; Prabhakar, P.; Patel, A.R.; Thakur, M.; Singh, S. Applications of Green Synthesis of Nanoparticles Using Microorganisms in Food and Dairy Products: Review. *Processes* **2025**, *13*, 1560. https://doi.org/10.3390/pr13051560

Keywords: green synthesis; nanoparticles; microorganisms; food and dairy applications; biocompatibility; nanoencapsulation; sustainable nanotechnology

1. Introduction

Nanotechnology has significant potential to revolutionize food systems by enabling the development of innovative products and expanding their range of applications, including bioactive compounds (BACs), nutraceuticals, functional food and dairy products, and pharmaceutical foods [1–9]. This technology offers advanced methods for detecting pathogens in milk and milk products, thereby enhancing the quality and safety standards of dairy products [7,9–12]. In the domain of food and dairy processing, nanoencapsulation is utilized to incorporate nano-sized elements and nutritional supplements, including proteins and antioxidants, along with additives such as flavors and colors, into functional foods [8,13]. This methodology effectively masks undesirable tastes and off-flavors, creates protective barriers, facilitates controlled release, and improves the bioavailability of various vitamins and their precursors.

Additionally, nanotechnology is being utilized to address food-related health challenges, including diabetes and obesity, and to develop specialized nutritional diets tailored for specific demographic groups, especially older people and individuals with diverse lifestyles [4,14–17]. Furthermore, it enhances the sustainability of food production systems [3]. This technology facilitates the creation of devices designed for precise nutrient delivery through nutritional nano therapy [2,18,19], as well as the development of advanced systems for controlled nutrient release via nanoencapsulation [13]. The development of nanoscale enzymatic reactors signifies a novel application, enabling the incorporation of new food products via fortification [1,20,21]. Furthermore, electrospun nanofibers are garnering significant interest as materials for packaging and encapsulation, offering structured polymeric films with improved functionality [13,22–25]. Thus, nanotechnology represents a multidisciplinary domain that investigates innovative approaches to address issues at the molecular and atomic scale through the manipulation of materials at the nanoscale [4,9,25–27]. Nanotechnology involves the investigation, creation, production, and incorporation of intricate and accurately defined structures. The increasing prevalence of nanotechnology has led to significant advancements in sectors such as agriculture [28–30], food production [4,22,25,31], and healthcare [4,26,32]. The emergence of antibiotic resistance in bacterial populations represents a significant challenge within global health systems.

Within the last decade, nanoparticles (NPs) have come to represent highly effective nanomaterials utilized in the earlier specified fields [24], exhibiting significantly enhanced biological properties such as antioxidant [33–35], antibacterial [34–40], antifungal [33,40–42], antiviral [43,44], and anticancer [35,39,44] effects. Additionally, NP formulations enhance the delivery and dispersion of BACs and water-insoluble components [2]. The synthesis of green NPs using biological extracts is being increasingly recognized for its environmentally sustainable and economically viable processing methods, scalability, and, crucially, its applications in various fields, including the food [1,2,4,6], environment [45–47], biological [40,43,48], and healthcare and medical sectors [4,47,49–53]. The green synthesis of NPs employs various biological sources, including bacteria [41,54,55], yeast [56–60], fungi [57,58,61], algae [58,62–65], plants [48,66–69], and agro-industrial waste [70,71]. The characteristics of the NPs generated from these biological sources are subsequently examined in terms of size, morphology, chemical composition, and stability within a medium.

NPs are materials with minuscule dimensions, generally ranging from 1 to 100 nm in diameter, and display distinct properties when contrasted with their micron-scale counterparts (1–100 μm) [4,18,24,27,72]. The nanoscale dimensions and high surface-area-to-volume ratio of NPs provide significant benefits, such as heightened chemical reactivity, improved energy absorption, and enhanced biological mobility [18,24,26,27]. A range of established methodologies are utilized for the synthesis of NPs, encompassing chemical, physical, and environmentally sustainable (green) synthesis techniques [73–75]. This last method is frequently favored because of its ability to attain elevated purity levels, a manageable morphology, and a significant yield. The techniques employed include plasma chemical processes [76], vapor deposition [77–79], microwave irradiation [80], pulsed laser techniques [81,82], sonochemical reduction [82–84], ultrasound irradiation [74], and gamma radiation [85,86].

The techniques developed for NP synthesis present distinct advantages and limitations, contingent upon the specific physicochemical properties of the NPs and their intended applications. Plasma chemical processes facilitate the generation of NPs that are both highly pure and uniformly sized via ionized gas-phase reactions [76]. However, scalability poses a challenge due to the intricate requirements of the instrumentation involved [76,87]. Vapor deposition techniques, such as chemical vapor deposition (CVD) and physical vapor deposition (PVD), offer atomic-level precision and are widely utilized in the semiconductor and coating industries [77–79,88]. Nevertheless, their elevated costs and reliance on vacuum processes restrict their use in the synthesis of bulk NPs. Microwave irradiation provides a swift and energy-efficient method that improves reaction kinetics and crystalline quality; however, achieving uniform scalability continues to pose challenges [80,89]. Pulsed laser techniques, including pulsed laser ablation in liquid (PLAL), enable the surfactant-free production of ultrapure NPs [81,82]. However, their limited yield and elevated operational costs confine their use to specialized applications [82,90,91]. Sonochemical reduction, facilitated by acoustic cavitation, enables straightforward synthesis under ambient conditions while providing a degree of control over morphology; however, the reproducibility and uniformity of particles may fluctuate between different batches [82–84]. Gamma radiation techniques employ ionizing energy for the synthesis of NPs without the need for reductants, presenting benefits in biomedical and sterile contexts. Nonetheless, issues pertaining to radiation safety and necessary infrastructure limit their application to regulated environments [86]. Consequently, the choice of synthesis method must be methodically aligned with the targeted characteristics of the NPs, the scale of production, and the particular industrial or biomedical application.

In contrast, chemical synthesis, a commonly employed technique, utilizes reducing agents in various environments, including polyol, microemulsions, thermal decomposition, and electrochemical reactions [71,73,92,93]. Nonetheless, both physical and chemical synthesis methodologies encounter obstacles, such as the necessity for high-purity materials, strict compliance with procedural protocols, significant financial expenditure, and possible biological risks associated with toxic byproducts. In contrast, green synthesis methods offer a sustainable and biocompatible alternative by utilizing natural reducing agents sourced from nonpathogenic or non-toxic microorganisms, such as bacteria [94–97], fungi [98–100], yeast [58,101], and extracts derived from plants [48,67,68]. Green synthesis presents significant benefits in terms of environmental impact and technical efficiency, as it reduces reliance on the toxic chemicals and harsh synthetic conditions traditionally used in NP fabrication [40,48,102,103].

In recent years, the synthesis of metallic NPs through eco-friendly methods has been increasingly incorporated food waste, especially in regions like West Asia. West Asia is commonly known as the Middle East. Turkey, Iran, Israel, Jordan, and Lebanon represent

West Asian nations where such research and applications are presumably taking place, informed by the regional agricultural context and existing evidence [70,104–106]. These regions generate significant quantities of agricultural and food waste, thus providing a substantial and sustainable source of natural reducing agents for the synthesis of NPs. For example, extracts obtained from botanical sources, such as fruit peels, leaves, seeds, and vegetable byproducts, have effectively enabled the production of various metallic NPs [69–71,104,106]. In a comparable context, various tropical countries with significant agricultural waste have utilized substances like papaya leaves, orange peels, and coffee grounds for the eco-friendly production of metallic NPs [71,106]. These organic sources contain a wealth of BACs, such as polyphenols, flavonoids, and antioxidants, which facilitate the reduction of metal ions and contribute to the stabilization of the resulting NPs.

Through the critical discussion in the preceding paragraphs based on the integration of results and findings from the previously published scientific literature, it can be inferred that there exist specific research gaps and a deficiency of consolidated papers presented on a singular platform. Such a compilation could provide valuable information aimed at aiding scientists in improving their critical thinking and analytical perspectives concerning their scientific projects and experimental endeavors. Consequently, this review paper aims to address various aspects to fill these research gaps and fulfill the requirements identified by the scientific community in the preceding discussion. This study seeks to outline current trends in the use of green nanotechnology, with a particular emphasis on the development of functional dairy products utilizing NPs produced via environmentally sustainable techniques. This study aims to thoroughly examine the synthesis of NPs utilizing biological sources, including bacteria, fungi, yeast, algae, and agro-industrial waste, highlighting their environmentally friendly and sustainable characteristics in contrast to conventional physical and chemical approaches. Furthermore, the review emphasizes the utilization of agricultural and food waste, especially in areas such as West Asia, as viable sources of natural reducing agents for the synthesis of metallic NPs. The paper further investigates the role of microbially synthesized NPs in improving food safety, quality, shelf life, and functionality within food packaging, preservation, nutrient delivery, pathogen detection, and quality enhancement in dairy products such as milk, yogurt, cheese, and meat. The discussion encompasses potential risks such as toxicity, environmental impacts, and consumer perception, while emphasizing the necessity for regulatory frameworks and safety assessments to guarantee safe implementation. Additionally, the paper aims to delineate future research developments, encompassing progress in synthetic biology, cohesive bioreactor systems, AI-enhanced optimization, and the utilization of waste-derived substrates to enhance the scalability, safety, and sustainability of NP applications within food systems.

2. Synthesis of Green Nanoparticles

NPs undergo comprehensive investigation through various physical and chemical methodologies (Figure 1); however, they exhibit unpredictability, high costs, and the potential to produce hazardous byproducts. Table 1 presents a comparative analysis of the high-cost factors associated with using physical and chemical methodologies for NP synthesis, emphasizing aspects such as equipment, energy consumption, material requirements, scalability, and operational complexity. Each method undergoes an assessment focused on its cost determinants, accompanied by estimated cost ranges where relevant and substantiated. A variety of synthetic methodologies have been employed to produce NPs with diverse morphologies and dimensions. As a result, the primary principle directing this research initiative is to carefully synthesize nanostructured particles using a methodology that is both efficient and mindful of environmental sustainability [107]. The literature has extensively documented that resources linked to green synthesis can function as bioresearch centers, enabling the synthesis of metallic and metal oxide NPs via a biomimetic approach that emulates natural processes [40,48,102]. A diverse array of microorganisms, such as bacteria, fungi, and actinomycetes [41,54,55,57,58,61,108], as well as extracts obtained from plants [48,66–69], have been recognized as effective and environmentally sustainable precursors for the successful synthesis of NPs aimed at particular applications [40,43,46–48,51–53]. Figure 2 demonstrates that biological sources such as plants and microorganisms (including bacteria, fungi, algae, and yeast), along with various waste materials, are utilized for the environmentally sustainable synthesis of green NPs. These biological agents provide a sustainable and non-toxic alternative to traditional chemical and physical methods for NP synthesis, in accordance with the principles of green chemistry and environmental sustainability [44,68,70,107].

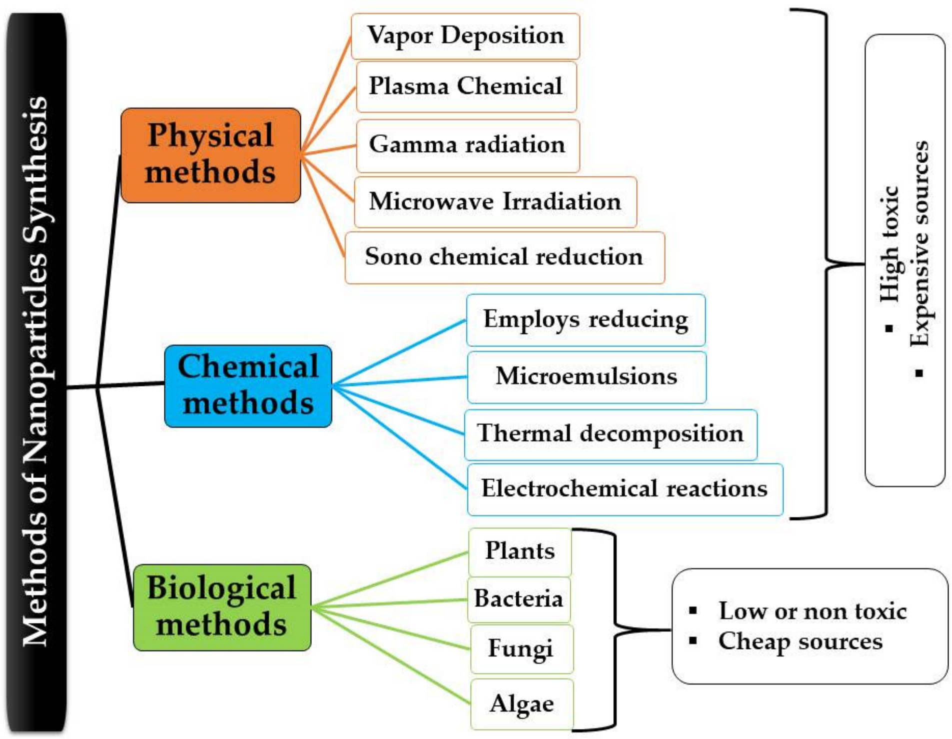

Figure 1. Overview of nanoparticle synthesis techniques ranging from conventional physical and chemical approaches to eco-friendly biological methods employing microorganisms and plant extracts for reduced toxicity and environmental impact.

Table 1. Comparative cost analysis of physical and chemical methods for nanoparticle synthesis.

Method	Equipment Cost	Energy Cost	Material Cost	Scalability	Operational Complexity	Overall Cost Summary	References
(A) Physical Methodologies							
Vapor Deposition (CVD/PVD)	Very High (USD 100,000–USD 1M+ for reactors, vacuum systems)	High (500–1000 °C, vacuum maintenance)	High (volatile precursors, high-purity substrates)	Limited (reactor size, high setup costs)	High (skilled operators, maintenance)	Very High (equipment, energy)	[77,79,88,109]
Plasma Chemical (PECVD, RF Plasma)	High (USD 50,000–USD 500,000 for plasma generators, chambers)	High (plasma generation, electrical power)	Moderate to High (pure gases, precursors)	Moderate (energy, equipment limits)	High (complex systems, skilled labor)	High (plasma systems, energy)	[76,110,111]
Gamma Radiation	Extremely High (USD 500,000–USD 2M for Co-60 facilities)	Moderate (facility maintenance)	Moderate (precursors affordable, radioactive waste costly)	Low (safety, infrastructure limits)	Very High (safety, regulatory compliance)	Extremely High (facilities, safety)	[85,86]
Microwave Irradiation	Moderate (USD 10,000–USD 100,000 for reactors)	High (rapid heating, short duration)	Moderate (precursors, surfactants)	High (fast reactions, simple setups)	Moderate (precise control systems)	Moderate to High (energy, equipment)	[80,112,113]
Sonochemical Reduction	Low to Moderate (USD 5000–USD 50,000 for ultrasonic systems)	Moderate (acoustic cavitation)	Low to Moderate (reducing agents, precursors)	High (one-step, eco-friendly)	Low (simple systems)	Low to Moderate (equipment, energy)	[82–84,114]
(B) Chemical Methodologies							
Chemical Reduction (Reducing Agents)	Low (USD 1000–USD 10,000 for lab setups)	Low (ambient/moderate temperatures)	Moderate (reducing/capping agents, e.g., $NaBH_4$, PVP)	High (simple processes)	Low to Moderate (waste disposal)	Low to Moderate (materials, waste)	[115–117]
Microemulsions	Low (USD 1000–USD 10,000 for lab equipment)	Low (room temperature)	High (surfactants, solvents, e.g., AOT)	Low (material costs, complex processing)	Moderate (washing, purification)	Moderate to High (surfactants, processing)	[118,119]
Thermal Decomposition	Moderate (USD 5000–USD 50,000 for furnaces/autoclaves)	High (200–500 °C heating)	Moderate (metal precursors, e.g., alkoxides)	Moderate (energy, material limits)	Moderate (safety for high temperatures)	Moderate to High (energy, equipment)	[120,121]
Electrochemical Reactions	Low to Moderate (USD 1000–USD 20,000 for cells, electrodes)	Low to Moderate (voltage application)	Moderate (electrolytes, noble metal electrodes)	Moderate (electrode/electrolyte costs)	Moderate (electrode maintenance)	-	[92,93]

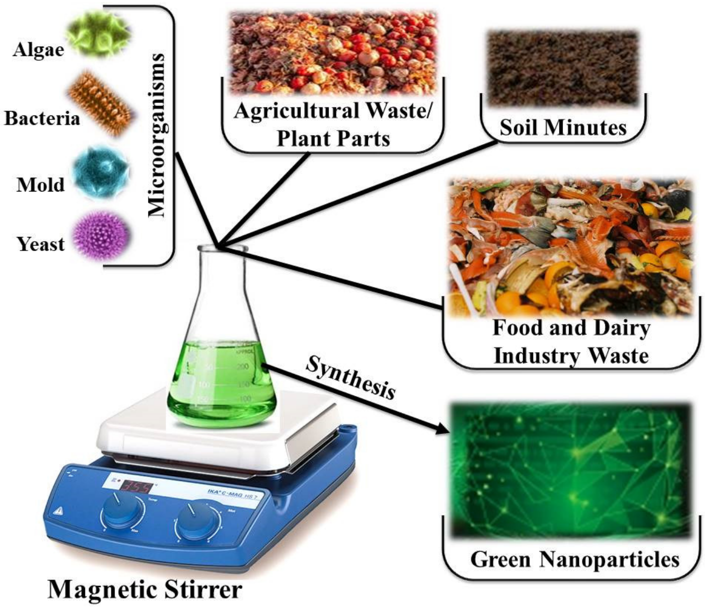

Figure 2. Various biological sources such as plants, microorganisms (bacteria, fungi, algae, and yeast), and different wastes are utilized for the eco-friendly synthesis of green nanoparticles, offering a sustainable alternative to conventional chemical methods.

The mechanism of green synthesis for NPs primarily takes place in aqueous solutions, rather than employing other chemical solvents [102], thus entirely eliminating the introduction of hazardous substances that may present considerable threats to environmental and human health (Figure 1). To enhance the stability of NPs synthesized via green methodologies, various capping agents are utilized [44,48,68,70]. A prominent example is polysaccharides like dextran, which is composed of glucose molecules that can differ in length [122]. These agents are recognized for their affordability, intrinsic stability, biodegradability, and non-toxic properties. Amino cellulose fiber was utilized in the synthesis of zinc oxide NPs (ZnO-NPs), serving effectively as both a reducing agent and a stabilizing agent in the process [123]. The nitrogen group in the amino cellulose acted as a functional group that was indirectly involved in the formation of NPs, especially during the crucial reduction phase of the synthesis process. A significant advantage associated with the utilization of biological molecules as stabilizing agents in the NP synthesis process is the enhancement of biocompatibility, especially when compared to NPs generated through other methods [124]; this characteristic renders biocompatible NPs suitable for a variety of important applications across multiple fields, including the agriculture, food, health, and biomedical sectors [20,125–129].

3. Formation of Nanoparticles

The biogenic synthesis of NPs through the utilization of bacteria [34,108,130], fungi (molds) [131,132], yeast [133], and algae [64,132,134] represents a sustainable and environmentally friendly approach compared to traditional methods. This process harnesses microbial metabolic processes to synthesize biocompatible NPs suitable for various applications. Recent developments highlight the utilization of various microorganisms, such as *Pseudomonas aeruginosa*, *Aspergillus niger*, *Saccharomyces cerevisiae*, and *Chlamydomonas reinhardtii*, in the synthesis of metallic NPs (Ag and Au), metal oxide NPs (TiO_2 and ZnO), and semiconductor NPs [60,94,130,132–136]. Recent investigations emphasize the synthesis of NPs using microalgae, the implementation of sustainable purification techniques, and the utilization of renewable resources. Advancements in technology encompass both intracellular and extracellular synthesis mechanisms, where extracellular methods facilitate the collection of NPs [130,134,137,138]. The process of purification is complex, necessitating several stages, including centrifugation, filtration, dialysis, and chromatography, to eliminate biological contaminants such as proteins and polysaccharides [137,139,140]. Innovative approaches, including magnetic separation, NP immobilization on solid substrates, and enzyme optimization, effectively tackle challenges related to scalability and purity [138,141,142]. Utilizing advanced characterization techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) facilitates accurate quality control of NPs [137,138].

Furthermore, various challenges arise, including intricate purification processes, especially for intracellular NPs, necessitating multiple stages (centrifugation, dialysis, and chromatography) to eliminate biological contaminants [132,140,143]. The scalability of such processes is adversely affected by the variability in NP size and shape, as well as fluctuations in microbial growth at the industrial scale [134,140]. NP aggregation, potential toxicity to non-target organisms, insufficient mechanistic insights, and the elevated costs associated with enzymes and equipment present significant challenges to widespread adoption [36,139,144]. In order to address the challenges outlined previously, a range of solutions can be considered, including the prioritization of extracellular synthesis, the implementation of advanced separation techniques such as magnetic separation and nanofiltration, and the automation of purification processes to improve overall efficiency [132,139,140,145,146]. Enhancements in scalability can be achieved via the optimization of bioreactors, the utilization of microbial consortia, and the implementation of standardized protocols [132,147,148]. The stability of NPs is examined through the use of polymeric matrices, natural stabilizers, and surface functionalization [58,142,145]. The mitigation of toxicity can be achieved through the application of biodegradable NPs and controlled release systems [36,139,141,144,146]. Additionally, the utilization of omics technologies and waste-based media contributes to cost reduction and enhances mechanistic understanding [132,143,149]. A comprehensive summary in Table 2 delineates the challenges and corresponding solutions associated with the biosynthesis of NPs utilizing bacteria, fungi, yeast, and algae, with a particular emphasis on the complex purification process and other pertinent issues involved.

Table 2. Challenges and solutions in the microbial biosynthesis of nanoparticles concerning purification, scalability, and stability for sustainable applications.

Challenge	Description	Solutions	References
Complexity of Purification	Intracellular NPs necessitate cell lysis and a series of procedures, such as centrifugation and filtration, to achieve the isolation of pure NPs. Extracellular synthesis produces NPs that contain biological impurities, such as proteins and lipids, which require complex purification processes.	• Emphasize the extracellular synthesis process to enhance recovery efficiency, for instance, by utilizing marine fungi such as *Penicillium fellutanum*. • Utilize sophisticated separation methodologies such as magnetic separation or nanofiltration. • Employ enzyme-assisted purification methods, such as cellulase and protease, to effectively degrade impurities. • Deploy automated purification systems (e.g., continuous flow centrifugation).	[140,150]
Scalability Issues	Synthesis conducted at the laboratory scale	• Enhance bioreactor configu-	[151,152]

	demonstrates effectiveness; however, the transition to industrial-scale production is impeded by the variability in NP size, shape, and yield, which is influenced by fluctuating microbial growth conditions.	rations through continuous observation of pH levels, thermal conditions, and oxygen concentration. • Employ microbial consortia, such as bacteria–algae systems, to achieve improved yield. • Establish standardized protocols for cultivation and synthesis to guarantee uniformity.	
NP Stability and Aggregation	NPs may aggregate as a result of insufficient capping or environmental conditions (such as pH and ionic strength), which diminishes their effectiveness in applications such as water purification.	• Secure NPs on polymeric or graphene-derived matrices to inhibit aggregation. • Employ polysaccharides or proteins derived from microorganisms as natural capping agents. • Modify NP surfaces with ligands or surfactants throughout the synthesis process.	[153,154]
Toxicity and Environmental Concerns	NPs such Ag-NPs and TiO_2 have the potential to exhibit toxicity towards non-target organisms, including algae and fish, thereby presenting significant ecological risks. Insufficient purification processes can result in the presence of hazardous residues.	• Formulate biodegradable NPs (e.g., nanocellulose derived from algae) to mitigate environmental persistence. • Perform extensive nanotoxicology investigations to guarantee safety. • Encapsulate NPs within enzyme-sensitive carriers to facilitate controlled release mechanisms.	[13,152,154]
Mechanistic Understanding	The limited understanding of NP formation mechanisms, including specific enzymes and pathways, impedes the optimization of NP size, shape, and functionality.	• Utilize omics technologies (genomics, proteomics, metabolomics) to clarify underlying mechanisms. • Employ rigorously defined model organisms (e.g., *Chlamydomonas reinhardtii*, *Sa. cerevisiae*) for in-depth mechanistic investigations. • Implement precise genetic alterations to improve synthesis efficiency.	[140,155,156]
Cost and Infrastructure	Enzymatic functionalization and purification necessitate the use of costly enzymes and specialized equipment, such as ultracentrifuges. Algae-based systems require expensive photobioreactor technology.	• Utilize agro-wastes or wastewater as substrates for microbial growth to reduce expenses. • Implement enzyme immobilization or recycling techniques to decrease overall enzyme expenditures. • Cultivate algae in wastewater or marine environments to reduce infrastructure requirements.	[150,151,155]

A critical discussion in the following sections presents the biosynthesis of NPs utilizing bacteria, fungi (molds), yeast, and algae as sustainable and eco-friendly alternatives to conventional methods.

3.1. By Bacteria

There are two methodologies for synthesizing NPs utilizing bacterial cells, as follows: intracellular and extracellular processes. Nonetheless, the precise mechanical process underlying the production of NPs remains unidentified [69,149,153,157,158]. However, it is hypothesized that their formation occurs through the initial entrapment of metal ions either on the bacterial cell surface or within its interior [54,69,71,153,158,159]. Secondly, the ion is subjected to multiple enzymatic processes (reduction reactions) facilitated by bacterial enzymes [54,86,106,155,159]. The extracellular production method is typically favored due to its more straightforward purification process and higher yield in comparison to intracellular synthesis [160]. Bacteria function as a reducing agent in the presence of ionic solutions, such as those containing silver or gold, during the synthesis of NPs [52,86,159,161]. The bacterial metabolic enzymes nicotinamide adenine dinucleotide (NADH) and nicotinamide adenine dinucleotide phosphate hydrogen (NADPH) facilitate the transfer of an electron to the metal atom, thereby enhancing its stability [149,155,159]. Following the proliferation of bacterial cells, the synthesis of NPs commences. The synthesis of NPs during the reduction phase of silver metal ions is critically dependent on a key enzyme. This process involves the electron transfer mechanism facilitated by NADH and NADH-dependent nitrate reductase (NADH-DNR) present in *Bacillus* spp., highlighting the complex biochemical interactions at play [54,149].

The bacterial-mediated biosynthesis of metallic NPs through a pathway reliant on the enzyme nitrate reductase [159] is illustrated in Figure 3. Nitrate ions (NO_3^+) are taken up by the bacterial cell, prompting the activation of nitrate reductase, an intracellular enzyme that employs NADH as an electron donor, transforming it into NAD^+ while releasing electrons (e^-) [155,159]. These electrons are subsequently transferred through NADH-DNR to facilitate the reduction of metal ions (M^+) into their zero-valent metallic state (M^0), resulting in the formation of metallic NPs [68,159,162]. This method exemplifies an environmentally sustainable approach for the synthesis of NPs, utilizing bacterial enzymatic systems under standard conditions [46]. The NPs produced may be classified as either intracellular or extracellular, contingent upon the specific bacterial species and metal precursor utilized [58].

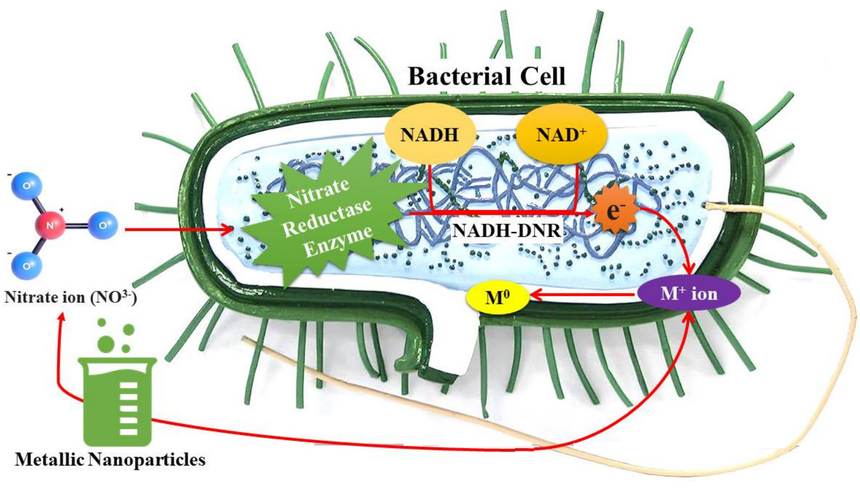

Figure 3. Schematic representation of bacterial nanoparticle synthesis. During bacterial growth, metal ions (M^+) are reduced to their elemental form (M^0) through microbial redox reactions, leading to the formation and accumulation of metallic nanoparticles around or within the cells.

In 1999, *Ps. stutzeri* was utilized for the production of NPs through the accumulation and aggregation of silver ions on the bacterial outer membranes [163]. Silver ions aggregated within the bacterial cell membrane due to their interaction with hydrogen sulfide (H_2S) generated by the bacteria [163–165]. This reaction transformed the gas into a non-toxic compound suitable for bacterial utilization. Nitrate reduction enzymes and cofactors are integral to the process of reducing silver NPs (Ag-NPs) in bacterial systems. Certain proteins have been identified as participants in the reduction of silver nitrate ($AgNO_3$), resulting in the formation of Ag-NPs [40,66,153,155,164–166].

Cell-free culture supernatants obtained from seven bacterial strains, namely *Phaeocystis antarctica*, *Ps. proteolytica*, *Ps. meridiana*, *Arthrobacter kerguelensis*, *A. gangotriensis*, *Bacillus indicus*, and *Bhargavaea cecembensis*, were utilized for the biosynthesis of Ag-NPs with sizes ranging from approximately 6 to 13 nm (refer to Table 3). The NPs demonstrated stability for a duration of eight months when stored in a dark environment. The synthesis and subsequent stability of the Ag-NPs were found to be affected by variables including temperature, pH, and the particular bacterial species from which the supernatant originated [58,159,161,167]. It was observed that the supernatant of A. kerguelensis did not promote the production of Ag-NPs at the temperature optimal for the synthesis of these NPs by *Phaeocystis antarctica* [52,157,159,168]. As a result, this study presents substantial evidence indicating that the components found in cell-free culture supernatants that facilitate the synthesis of Ag-NPs differ among various bacterial species.

Table 3. Important studies on different bacterial species as biological nanofactories to produce metal nanoparticles for different applications in food and dairy products.

Bacterial Species	NPs	Size	Characterization Methods	Applications	Utilization at Commercial Scale and/or Laboratory Scale of NPs	Future Prospects	References
Aeromonas hydrophila	ZnO-NPs	57 nm	UV–Vis spectroscopy, XRD, FTIR, AFM, NC-AFM and FESEM with EDX	Antibacterial and antifungal	ZnO-NPs produced through the utilization of *A. hydrophila* demonstrated significant antibacterial and antifungal properties in laboratory settings, suggesting their potential applicability in the domains of food preservation and safety.	Nonetheless, additional investigation and advancement are required to convert these discoveries into applications at a commercial scale, guaranteeing effectiveness, safety, and adherence to regulatory standards in practical food and dairy product conditions.	[36,126,127,169–171]
Bacillus subtilis	Fe_3O_4-NPs + Au-NPs	18 nm + 20 nm	UV–Vis spectroscopy, FTIR, SEM, EDX and XRD	Antibacterial	The synthesis of Fe_3O_4-NPs and Au-NPs mediated by *B. subtilis* offers a promising approach for the development of antimicrobial agents in food and dairy applications. The combined incorporation of these NPs in food and dairy applications represent a developing field of study, which is predominantly conducted at the laboratory level.	Although laboratory studies have indicated their potential, additional research is necessary to evaluate their safety, efficacy, and scalability for commercial applications.	[172–174]
B. paramycoides	Ag_2O-NPs	25–70 nm	UV–Vis spectroscopy, X-ray, and SEM	Inhibition of biofilm-forming bacteria	The application of Ag_2O-NPs synthesized using *B. paramycoides* in inhibiting biofilm-forming bacteria within food and dairy products remains at the laboratory research stage. There was no evidence of their commercial-scale utilization in these industries. The promising antibacterial and antibiofilm properties of *B. paramycoides*-synthesized Ag_2O-NPs indicate potential for future applica-	However, further research is necessary to assess their safety, efficacy, and feasibility in real-world food systems. Studies focusing on their interaction with food matrices, potential toxicity, and regulatory compliance will be crucial steps toward commercial adoption.	[170,175,176]

					tions in the food and dairy industries.		
Bifidobacterium bifidum	TiO_2-NPs	81 nm	SEM, and (AFM)	Antibacterial	The utilization of *B. bifidum*-mediated TiO_2-NPs in food and dairy products is currently confined to laboratory research, with no significant commercial application documented. The antibacterial properties of TiO_2-NPs mediated by *B. bifidum* showed significant promise in laboratory environments, suggesting potential applications for improving food safety.	Nevertheless, owing to safety considerations, compliance with regulatory standards, and various technical obstacles, their application in commercial food and dairy products has not yet been achieved. Additional investigations and thorough risk evaluations are crucial to assess the practicality of incorporating these nanomaterials within the food sector.	[18,170,177]
Lactobacillus gasseri	ZnO-NPs	22 nm	UV–Vis spectroscopy, TEM, SEM, DLS, FTIR, and XRD	Yogurt fortification	The application of ZnO-NPs produced through *L. gasseri* for the enhancement of yogurt is presently confined to laboratory research. Although encouraging outcomes have been documented, there is currently no substantiation for application at a commercial scale. As a result, laboratory investigations demonstrated that ZnO-NPs synthesized by *L. gasseri* can improve the nutritional and antimicrobial characteristics of yogurt.	However, additional research and development are necessary to facilitate the transition from laboratory settings to commercial-scale production.	[20,21,178,179]
Lacticaseibacillus rhamnosus	TiO_2-NPs	3–7 nm	UV–Vis spectroscopy, FTIR, XRD, TEM, SEM, EDX, DLS, and zeta potential	Biocontrol of mold strains	The utilization of *L. rhamnosus*-synthesized TiO_2-NPs for the biocontrol of mold strains in food and dairy products is predominantly confined to laboratory conditions. Although encouraging outcomes were documented in controlled experiments, commercial-scale implementation has not	Subsequent investigations must prioritize the enhancement of production capacities, the evaluation of long-term safety parameters, and the analysis of effects on food quality and human health to promote the integration of this technology within the food	[41,180,181]

					yet been achieved. Laboratory studies showed the efficacy of *L. rhamnosus*-mediated TiO_2-NPs in inhibiting mold proliferation and lowering mycotoxin concentrations. However, advancing to commercial-scale applications necessitates thorough assessments.	and dairy sectors.	
Pseudomonas aeruginosa	ZnO-NPs	6–21 nm	UV–Vis spectroscopy, FTIR, TEM, and XRD	Antimicrobial	The utilization of ZnO-NPs produced via *Ps. aeruginosa* for antimicrobial applications in food and dairy products is predominantly confined to research, with no notable commercial-scale applications documented. ZnO-NPs demonstrated significant antimicrobial efficacy against a range of foodborne pathogens in controlled laboratory environments, suggesting their potential utility in enhancing food preservation and safety measures.	Nonetheless, the shift from experimental investigation to market application necessitates the resolution of regulatory challenges, the assurance of consumer safety, and the advancement of economically viable, scalable synthesis techniques. Ongoing investigation and cooperation among researchers, industry participants, and regulatory authorities are crucial for the implementation of ZnO-NPs in the food and dairy industries.	[10,94,135,170,182,183]
Nocardiopsis dassonvillei	Ag-NPs	29 nm	UV–Vis spectroscopy, FTIR, and TEM	Antimicrobial, antioxidant, insecticidal, and anticancer	The biosynthesis of Ag-NPs using *N. dassonvillei* predominantly remains within the realm of laboratory research. Their integration into commercial food and dairy applications has not been achieved, primarily due to unresolved concerns regarding safety, regulatory compliance, and scalable production methods.	Despite their potential for enhancing food and dairy preservation, transitioning from laboratory findings to real-world applications requires rigorous safety assessments, the development of cost-effective and scalable synthesis protocols, and targeted research focusing on food matrix interactions and functionality. Future studies should aim to address these critical gaps to facilitate the safe and effective incorpora-	[161,163,170,184–186]

						tion of *N. dassonvillei*-derived Ag-NPs in food and dairy systems.	
Oscillatoria limnetica	Fe_2O_3-NPs	-	UV–Vis spectroscopy, FTIR, SEM, EDX and XRD	Antimicrobial, antifungal, and antioxidant	The utilization of *O. limnetica*-mediated Fe_2O_3-NPs in food and dairy products is presently confined to laboratory research activities. These NPs exhibited significant antimicrobial, antifungal, and antioxidant properties in vitro. However, their application at a commercial scale within the food industry remains unachieved. At the laboratory scale, *O. limnetica*-mediated Fe_2O_3-NPs exhibited considerable potential for antimicrobial, antifungal, and antioxidant applications in food and dairy products, with proven effectiveness against pathogens, fungi, and oxidative processes.	Nonetheless, the implementation of commercial-scale applications is obstructed by regulatory, scalability, and safety challenges. Continued investigation is essential to tackle these obstacles, facilitating the implementation of practical applications, including active packaging and fortification in dairy products. Currently, these NPs are considered a promising yet predominantly experimental approach for enhancing food safety and preservation.	[1,97,170,187,188]
Serratia marcescens	Ag-NPs	14–20 nm	EDX and FTIR	Antibacterial and biofilm inhibition	At the laboratory scale, Ag-NPs derived from *S. marcescens* exhibited considerable potential for applications in antibacterial and biofilm inhibition within food and dairy environments, demonstrating effectiveness against critical pathogens and biofilms. Nonetheless, the implementation of their commercial-scale application has not been achieved, mainly owing to challenges related to regulation, scalability, and safety.	Current investigations must prioritize the integration of laboratory achievements with market feasibility, especially by tackling safety issues and creating functional applications such as disinfectants or active packaging for dairy products.	[189–191]
Streptomyces spp.	Ag-NPs	11–63 nm	UV–Vis spectroscopy, XRD, FTIR, SEM-EDX, and TEM	Antimicrobial, and antioxidant	At the laboratory scale, Ag-NPs derived from *Streptomyces* spp. exhibited considerable potential for	Future investigations should prioritize the enhancement of NP stability, undertake thor-	[55,170,192,193]

	antimicrobial and antioxidant applications in food and dairy products, demonstrating effectiveness against foodborne pathogens and oxidative spoilage. Nonetheless, the implementation of commercial-scale applications is constrained by regulatory limitations, challenges in scalability, and safety considerations related to the release of Ag+ ions.	ough toxicity assessments, and establish regulatory frameworks to facilitate commercial implementation, potentially in antimicrobial coatings or natural preservative systems for the food and dairy sectors.	

The synthesis of NPs by bacteria represents a novel technological advancement that yields a significant quantity of NPs. However, this approach encounters several challenges, including the purification process, which is intricate, necessitating multiple steps and considerable effort to achieve pure particles. Furthermore, there is a limitation in the ability to regulate the size of the NPs produced. The primary obstacle lies in the production and purification of these particles at an industrial scale. To address the previously identified challenges, several strategic solutions have been proposed (Table 2). Emphasis on extracellular synthesis, along with the adoption of advanced separation techniques, such as magnetic separation and nanofiltration, and the automation of purification processes, can significantly enhance overall process efficiency. Scalability improvements can be achieved through the optimization of bioreactors, incorporation of microbial consortia, and implementation of standardized protocols. To enhance NP stability, approaches such as the use of polymeric matrices, natural stabilizers, and surface functionalization are commonly employed. Toxicity reduction is facilitated through the development of biodegradable NPs and the incorporation of controlled release systems. Moreover, the integration of omics technologies and the utilization of waste-derived media will contribute to cost reduction while simultaneously providing deeper mechanistic insights.

3.2. By Fungi (Molds)

The formation of NPs through fungal processes closely resembles the particle synthesis mechanisms employed by bacteria, encompassing both intracellular and extracellular methodologies [58]. NPs are synthesized through the combination of metallic precursors and fungal metabolites, which encompass various compounds, including cyclosporine, griseofulvin, lovastatin, and mevastatin, as well as oxidation-reduction enzymes such as acetyl-CoA carboxylase (ACCases), NADH, NADPH, and peroxidases [155,194,195]. Metabolic products facilitate the conversion of metal ions into a reduced state, resulting in the synthesis of NPs (Figure 4).

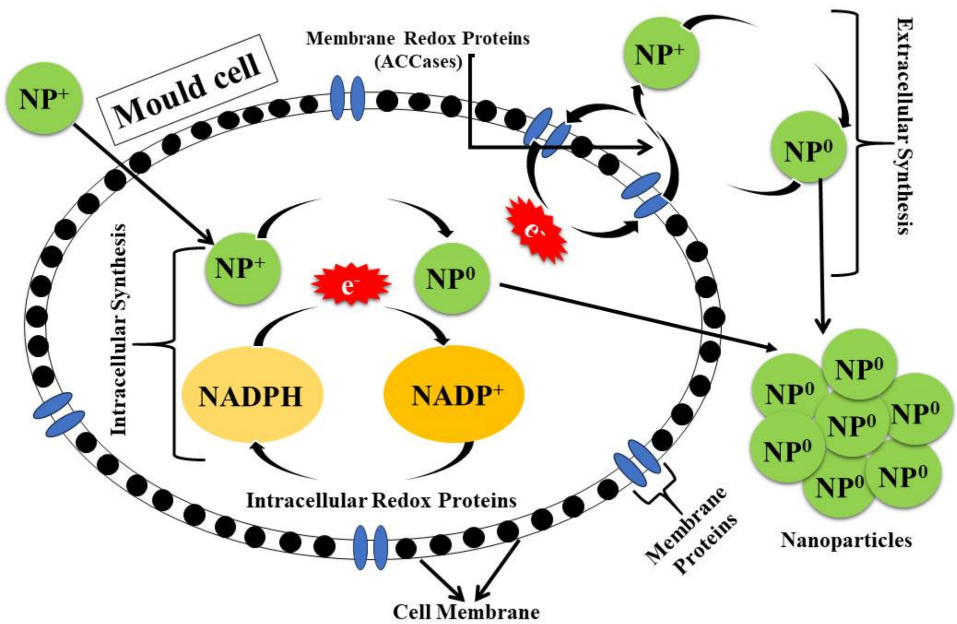

Figure 4. Biosynthesis of nanoparticles by molds via intracellular and extracellular routes offers an eco-friendly, cost-effective, and scalable approach for producing metal nanoparticles with potential applications in food, medicine, and environmental sectors.

In the intracellular approach, metallic precursors are introduced into the fungal growth medium, where the activity of reducing enzymes facilitates the synthesis of NPs

[155]. In both methodologies, the synthesized NPs can be isolated from metabolites through centrifugation, chemical washing, and filtration techniques. Fungi exhibit significant resistance to agitation and flow forces within bioreactors, thereby enhancing their application in the production of NPs ((A) in Table 4). A variety of fungal species have been utilized for the synthesis of NPs, including *A. flavus* [101,196,197], *A. fumigatus* [198,199], *A. niger* [136,200–202], *Fusarium pseudonygamai* [203], *Penicillium solitum* [204], *P. citrinum* [61], *Rhizopus arrhizus* [61], and *Trichoderma viride* [99,205].

Table 4. Important studies on metal nanoparticle synthesis from diverse fungal species, including molds (**A**) and yeasts (**B**), which show wide-ranging applications, with emphasis on food and dairy products due to their biocompatibility and eco-friendly production methods.

(A) Molds							
Mold Species	**NPs**	**Size**	**Characterization**	**Applications**	**Utilization at Commercial Scale and/or Laboratory Scale of NPs**	**Future Prospects**	**References**
Aspergillus flavus	Se-NPs	100 nm	UV–Vis spectroscopy, FTIR, FESEM, EDX, XRD, and Zeta potential	Antifungal	Se-NPs produced by *A. flavus* exhibited potential for use in the food and dairy sectors, attributed to their antimicrobial, antioxidant, and nutritional characteristics. In laboratory conditions, *A. flavus* synthesized Se-NPs that exhibited significant efficacy against pathogens such as *Salmonella* and *Candida*, making them appropriate for use as preservatives or for selenium enrichment in dairy products. Commercial scaling necessitates the optimization of bioreactors and purification processes to achieve cost-effective, food-grade Se-NPs suitable for applications in packaging, additives, or functional foods	Future prospects encompass genetic engineering aimed at developing safer strains, the implementation of smart packaging solutions, and the exploration of probiotic synergy, all underpinned by the use of sustainable media such as agricultural by-products. Challenges encompass the assurance of aflatoxin-free production, the attainment of regulatory approval, and the execution of long-term safety studies. The increasing demand for natural preservatives and functional foods suggests that Se-NPs have the potential to transform dairy preservation and enhance nutritional value, contingent upon standardization and clinical validation.	[6,8,44,59,101,167,170,197,206–208]
A. fumigatus	ZnO-CuO NPs	85–92 nm	UV–Vis spectroscopy, DLS, HR-TEM, SEM, and XRD	Antifungal	ZnO-CuO NPs using *A. fumigatus* present potential applications in the food and dairy sectors. At the laboratory scale, their antimicrobial and antifungal properties demonstrated efficacy in controlling pathogens such as *E. coli* and *Aspergillus* spp., inhibiting aflatoxins,	Future prospects encompass genetically optimized synthesis, biodegradable intelligent packaging, and nanosensors designed for the detection of mycotoxins. The incorporation of artificial intelligence and the Internet of Things has the potential to enhance efficiency in production processes and improve quality control measures. It is	[8,16,42,129,170,209–211]

					and improving food packaging films, thereby extending shelf life. In commercial applications, they functioned as natural preservatives in dairy products such as cheese and yogurt, as well as in active packaging materials. However, challenges persist regarding production costs, stability, and the attainment of regulatory approval.	essential to address issues related to toxicity, sensory effects, and consumer skepticism. Through enhancements in safety and scalability, these NPs have the potential to transform food safety, sustainability, and preservation, thereby decreasing dependence on synthetic additives.	
A. niger	Ag-NPs	9–50 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM	Antimicrobial, anticancer, and antiangiogenic	Ag-NPs produced by *A. niger* provide environmentally sustainable antimicrobial alternatives for use in the food and dairy sectors. At the laboratory scale, they addressed pathogens such as *E. coli* and spoilage fungi in dairy products, thereby improving preservation and packaging methods. The application of Ag-NP-coated containers and films in commercial settings enhanced the shelf life of dairy products such as cheese and milk; however, widespread adoption is constrained by financial considerations and regulatory frameworks.	Future prospects encompass intelligent packaging solutions, synergistic formulations incorporating natural antimicrobials, and customized applications for dairy products. Progress in fungal synthesis, genetic modification, and AI-enhanced optimization indicates potential for scalability. Clear regulatory frameworks and comprehensive long-term safety data are essential for mitigating toxicity concerns and addressing consumer skepticism. The sustainable synthesis and innovative applications of Ag-NPs, such as edible coatings, have the potential to transform food safety practices, in accordance with clean-label trends, assuming that cost and regulatory challenges are addressed.	[8,136,161,164,165,168,170,201,202,210,212]
Fusarium oxysporum	Se-NPs	42 nm	TEM, XRD, UV–Vis spectroscopy, FTIR, and PL spectrometer	Antifungal and in-vivo biodistribution	Se-NPs produced by *F. oxysporum* exhibit potential for applications in food and dairy, attributed to their antimicrobial, antioxidant, and nutritional characteristics. At the laboratory scale, Se-NPs demonstrated the ability to inhibit pathogens	Future prospects encompass intelligent packaging solutions, eco-friendly manufacturing utilizing agricultural by-products, and tailored nutritional approaches. Regulatory approval necessitates comprehensive long-term toxicity assessments and purification processes to remove fungal residues.	[6,30,167,170,207,213–215]

					such as *Listeria* and fungi, extend shelf life through antioxidant activity, and enrich products with bioavailable Se. Commercial applications encountered obstacles related to yield, cost, and safety; however, their applications may encompass active packaging, food additives, and Se-enriched dairy products such as yogurt.	The integration of Se-NPs with probiotics or alternative NPs may improve their effectiveness. Progress in fermentation techniques and biosafety measures, potentially through genetic engineering, is expected to facilitate widespread implementation in the food and dairy sectors.	
Penicillium oxalicum	SiO_2-NPs	20–50 nm	TEM, FTIR, XRD, and DLS	Phytotoxicity, heavy metal bioremediation, and photocatalytic activity against crystal violet and Ribazol black dye	SiO_2-NPs produced by *P. oxalicum* present environmentally friendly applications in the food and dairy sectors. At the laboratory scale, these NPs demonstrated antimicrobial and photocatalytic characteristics, improving biodegradable packaging films and functioning as anticaking agents or flavor carriers. They have the potential to substitute synthetic silica (E551) in dairy powders and enhance packaging barriers, thereby prolonging shelf life. Their challenges encompass regulatory obstacles, expenses associated with scalability, and consumer apprehensions regarding nanotechnology.	Future prospects encompass the development of intelligent packaging systems, targeted nutrient delivery mechanisms, and effective mycotoxin management, utilizing environmentally friendly synthesis methods derived from agricultural waste. Progress in toxicology, uniform characterization methods, and bioreactor technology are essential for commercial implementation. Although SiO_2-NPs show potential for enhancing sustainable food systems, it is essential to conduct thorough investigations into their long-term health and environmental effects to guarantee safety and market feasibility, thereby establishing them as cutting-edge solutions for the dairy and food sectors.	[25,170,216–220]
P. polonicum	Ag-NPs	54 nm	UV–Vis spectroscopy, FTIR, XRD, and TEM	Antimicrobial and seed germination advancements	Ag-NPs produced by *P. polonicum* exhibit significant potential for applications in the food and dairy sectors, attributed to their strong antimicrobial characteristics and environmentally sustainable	Future developments encompass intelligent packaging integrated with sensors, low-dose coatings specifically designed for dairy products, and synergistic antimicrobial approaches that combine silver NPs with probiotics or essential oils. Innovations in bioreactor	[33,100,161,168,170,217,221,222]

					synthesis methods. At the laboratory scale, Ag-NPs demonstrated efficacy against pathogens such as *Salmonella* and *Acinetobacter*, showing promise for applications in biodegradable packaging and dairy preservation. From a commercial perspective, there is potential to improve active packaging or to disinfect equipment; however, challenges related to regulatory approval and scalability persist. Concerns regarding safety, such as cytotoxicity and environmental effects, necessitate thorough evaluation.	design and the utilization of sustainable nutrient sources have the potential to reduce costs. Additionally, the implementation of standardized protocols may facilitate regulatory compliance, thereby establishing *P. polonicum*-derived Ag-NPs as a significant advancement in ensuring food and dairy safety.	
Trichoderma asperellum	ZnO-NPs	3–9 mm	UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM	Antibiofilm and antibacterial	ZnO-NPs produced through the action of *T. asperellum* exhibit potential utility in the food and dairy sectors. At the laboratory scale, these environmentally friendly NPs demonstrated antimicrobial properties against *E. coli*, *St. aureus*, and fungi, positioning them as suitable candidates for food packaging and preservation applications. They improved shelf stability and enriched products with bioavailable Zn. Commercial scaling encounters obstacles such as suboptimal yields, elevated costs, and regulatory challenges; however, the implementation of bioreactor systems and the utilization of waste-based substrates will	Future developments encompass intelligent packaging solutions, dairy products enhanced with probiotics, and sustainable production methods utilizing genetically modified fungal strains. Notwithstanding challenges related to scalability and consumer acceptance, ZnO-NPs have the potential to revolutionize food safety and nutrition. Progress in toxicology, environmentally friendly synthesis methods, and international regulatory frameworks will facilitate their integration, presenting considerable market opportunities within high-end food industries.	[36,125,128,129,170,209,223–225]

					enhance feasibility.		
T. viride	Ag-NPs	1–50 nm	UV–Vis spectroscopy, SEM and TEM	Antimicrobial	Ag-NPs produced by *T. viride* exhibit potential for use in the food and dairy sectors owing to their antimicrobial characteristics. At the laboratory scale, sodium alginate films were utilized to enhance the shelf life of fruits and vegetables by effectively inhibiting pathogens such as *E. coli* and *St. aureus*. In the dairy industry, Ag-NPs have the potential to regulate spoilage microorganisms and biofilm formation. The implementation of commercial-scale applications encounters obstacles such as maintaining production consistency, managing costs, and navigating regulatory requirements; however, environmentally sustainable synthesis methods will facilitate scalability.	Future developments encompass intelligent packaging solutions, coatings tailored for dairy applications, and synergistic formulations incorporating natural antimicrobials. Improvements in bioreactor design and encapsulation may lead to increased safety and efficacy. Although toxicity and environmental issues require attention, Ag-NPs synthesized by *T. viride* correspond with the requirements for sustainable food safety, presenting significant potential for transformation if regulatory and public acceptance challenges are surmounted.	[13,99,161,168,170,205,226,227]
(B) Yeasts							
Candida albicans	Se-NPs	100 nm	UV–Vis spectroscopy, FTIR, FESEM, EDX, XRD, and Zeta potential	Antifungal	Se-NPs produced by *C. albicans* present significant potential for applications in the food and dairy industries, attributed to their antimicrobial, antioxidant, and nutritional characteristics. Studies conducted at the laboratory scale indicated successful synthesis, with Se-NPs exhibiting inhibitory effects on pathogens such as *E. coli*, thereby prolonging shelf life. The pathogenic characteristics of the	Future prospects encompass genetic engineering, hybrid synthesis utilizing chitosan, and applications in sustainable packaging or enhanced dairy products. Approval requires the implementation of long-term toxicology studies and adherence to standardized protocols. Se-NPs correspond with the increasing demand for environmentally sustainable additives; however, their implementation is contingent upon addressing safety, scalability, and consumer acceptance challenges,	[6,34,59,81,101,207,214]

					yeast necessitate rigorous purification measures to address safety concerns. Commercial scalability encounters obstacles, such as regulatory constraints and competition from non-pathogenic microorganisms, exemplified by *Bacillus* spp.	thereby establishing them as an emerging yet promising technology within food systems.	
Pichia fermentans	Ag-NPs and ZnO-NPs	-	UV–Vis spectroscopy, XRD, and FE–SEM–EDX	Antibiogram	Ag-NPs and ZnO-NPs produced by *P. fermentans* present effective antimicrobial agents for applications in the food and dairy industries. Laboratory-scale investigations validated their effectiveness against pathogens such as *E. coli* and *Listeria*, facilitating food preservation and the development of active packaging solutions. Spherical NPs that were stabilized by microbial enzymes exhibited synergistic interactions with antibiotics, specifically aimed at multidrug-resistant strains. The utilization of commercial applications is constrained by factors such as expense, reproducibility, and regulatory frameworks; however, potential uses encompass antimicrobial coatings and packaging films.	Future prospects encompass intelligent packaging utilizing nanosensors, sustainable manufacturing through genetic engineering, and the incorporation of probiotics. The use of biocompatible matrices for encapsulation may address issues related to toxicity. Improvements in bioreactor technology and waste utilization strategies could potentially increase scalability. Standardized protocols and safety assessments are essential for regulatory approval, establishing these NPs as environmentally friendly instruments for enhancing food safety and extending shelf life within sustainable food systems.	[13,14,30,36,48,56,129,161,168,170]
Rhodotorula glutinis	Ag-NPs	15 nm	UV–Vis spectroscopy, DLS, FTIR, XRD, EDX, SEM, TEM, and AFM	Antifungal and cytotoxicity activities	Ag-NPs synthesized by *R. glutinis* offer eco-friendly, antimicrobial solutions for the food and dairy industries. Laboratory studies confirmed their	Future prospects include bionanocomposite films, synergistic antimicrobial blends, and sensors for spoilage detection. Advances in bioreactor design and genetic engineering could	[30,40,57,131,161,168,170,228–230]

					size, stability, and efficacy against pathogens like *E. coli* and *C. albicans*, ideal for preserving dairy products and controlling mycotoxins. In packaging, Ag-NPs extended shelf life by inhibiting spoilage. Commercially, they were used in antimicrobial films and equipment coatings, but scaling faces challenges like cost, regulatory hurdles, and stability.	enhance production efficiency. While less toxic than chemical Ag-NPs, long-term safety and resistance risks need study. With regulatory clarity and sustainable practices, *R. glutinis*-synthesized Ag-NPs could revolutionize food safety and preservation.	
Rhodotorula mucilaginosa	Ag-NPs	13 nm	UV–Vis spectroscopy, DLS, FTIR, XRD, EDX, SEM, TEM, and AFM	Antifungal and cytotoxicity activities	Ag-NPs produced by *R. mucilaginosa* exhibit potential for applications in the food and dairy industries, attributed to their antimicrobial characteristics and environmentally sustainable synthesis methods. At the laboratory scale, these Ag-NPs demonstrated inhibitory effects on pathogens such as *St. aureus* and *E. coli*, facilitating applications in food preservation, dairy safety, and antimicrobial packaging. In commercial applications, these materials were utilized in packaging and disinfectants; however, challenges related to scalability, cost, and regulatory compliance (such as those imposed by the FDA and EFSA) remain significant.	Future prospects encompass intelligent, biodegradable packaging solutions, synergistic formulations incorporating natural antimicrobials, and the synthesis of bioremediation-integrated processes utilizing deceased biomass. Issues such as toxicity, environmental consequences, and microbial resistance necessitate the optimization of low-dose applications and the education of consumers. The progress in genetic engineering and the automation of bioreactors suggests that Ag-NPs derived from *R. mucilaginosa* have the potential to transform food safety practices, while also supporting sustainability objectives and tackling worldwide spoilage issues.	[40,57,131,161,168,170,228,229]
Saccharomyces cerevisiae	Se-NPs	34–125 nm	UV–vis spectroscopy, TEM, DLS, FTIR, and XRD	Antiradical, antiradical, and anti-inflammatory	Se-NPs produced by *Sa. cerevisiae* demonstrate potential utility in the food and dairy sectors. Laboratory investiga-	Future prospects encompass sustainable production, advanced packaging solutions, and personalized nutrition, utilizing the eco-friendly synthesis	[6,8,59,60,126,170,207,208,214,215]

					tions demonstrated their antibacterial properties (e.g., against *E. coli* and *St. aureus*), antioxidant capacity (up to 48.5%), and nutritional advantages. Dairy products such as enriched yogurt and food packaging were enhanced to prolong shelf life. Se-NPs encounter obstacles in terms of scalability, control over particle size, and obtaining regulatory approval; however, they remain a feasible option for functional foods and animal feed applications.	capabilities of *Sa. cerevisiae*. Advancements in bioreactor design and genetic modification have the potential to enhance yield and ensure standardization. Through additional safety and mechanistic investigations, Se-NPs have the potential to transform dairy fortification and enhance food safety, effectively tackling global selenium deficiency and advancing sustainability objectives.	
Yarrowia lipolytica	Se-NPs	110 nm	XRD, zeta potential, FESEM, EDX, FTIR, and DLS	Antimicrobial, antioxidant, and inhibition of biofilm	Se-NPs produced by *Y. lipolytica* demonstrate potential utility in the food and dairy sectors. In laboratory settings, these substances demonstrated antimicrobial properties against pathogens such as *E. coli* and *C. albicans*, impeded biofilm formation, and acted as bioavailable sources of selenium for nutritional enhancement. Their antioxidant characteristics and Generally Recognized as Safe (GRAS) designation endorse their application in dairy products such as yogurt and cheese. Se-NPs have the potential to improve food packaging, prolong shelf life, and enrich animal feeds, utilizing the capability of *Y. lipolytica* to utilize inexpensive substrates. Chal-	Future prospects encompass intelligent packaging systems, tailored nutritional solutions, and eco-friendly manufacturing processes that utilize food waste. Progress in metabolic engineering and regulatory harmonization may position Se-NPs as a fundamental component of environmentally sustainable, health-oriented dairy products, while also offering cross-industry applications in nutraceuticals.	[6,126,167,170,207,231,232]

	lenges encompass production expenses, regulatory obstacles, and consumer approval.	

The synthesis of Ag-NPs utilizing the fungus *Macrophomina phaseolina* has been reported. The reduction of silver ions was facilitated by the exoenzymes located on the surface of the mold cells [98,155,165]. In another investigation, extracellular proteins and polysaccharides facilitated the reduction of gold ions (Au^{+3}) present in $AuCl_4$ via electrostatic interactions, aided by the presence of positively charged lysine. The transport of Au^{+3} ions into the cell was observed to occur via ionic pathways across the cell membrane, followed by reduction facilitated by cytoplasmic oxidation-reduction enzymes [155,233]. *M. phaseolina* exhibited elevated oxidation-reduction enzyme activity compared to other fungi, facilitating the synthesis of Au-NPs and Ag-NPs. This characteristic is economically advantageous, as it requires a reduced amount of enzymes to produce Au-NPs and Ag-NPs [226,233,234]. The production of NPs through fungal methods is hindered by challenges related to low yield, necessitating purification processes to achieve pure particles. These processes elevate production expenses.

3.3. By Fungi (Yeasts)

Yeasts, classified as unicellular eukaryotic microorganisms, exhibit a notable capacity to absorb and concentrate considerable amounts of hazardous metallic cations from their environment [58,60,144,235]. This ability is linked to their extensive cell surface area and substantial cytosolic volume, which, together, enhance the efficient uptake of these toxic elements [144]. These eukaryotic organisms demonstrate a wide range of advanced detoxification processes, such as chelation, bioprecipitation, and biosorption, which, together, make them highly effective as bio-factories for the production of metal NPs from metallic precursors via different biochemical pathways [58,60,236]. The inherent differences in the detoxification mechanisms utilized by various yeast species significantly influence the production of bio-metal NPs, which exhibit a diverse array of tunable characteristics, such as particle size, morphology, and chemical composition [60,144]. These variations result in a range of physicochemical properties that can be customized for specific applications. As a result, the capacity of these microorganisms to modify their detoxification mechanisms not only increases the adaptability of the synthesized metal NPs, but also creates a wide range of opportunities for their application across various domains, such as nanotechnology and environmental remediation [60]. Baker's yeast (*Sa. cerevisiae*) was employed to synthesize highly stable Ag-NPs, utilizing yeast extract as both a reducing and coating agent for the synthesized nanoparticles due to the presence of numerous reducing enzymes within the yeast extract [59,155,237]. Lead NPs (Pb-NPs) were synthesized through the adsorption technique on the external surfaces of *Rhodotorula mucilaginosa* in acidic conditions, resulting in particle sizes ranging from 10 to 20 nm [57,238]. Various yeast strains were employed to synthesize NPs from a range of metal ions, including lead, silver, gold, and others ((B) in Table 4).

3.4. By Algae

Algae are eukaryotic organisms characterized by their significant ability to absorb and concentrate heavy metals, subsequently transforming them into various forms. Due to these unique characteristics, algae have been employed in the synthesis of NPs composed of various metals [49,58,63,239]. The biosynthesis of NPs commences with the formulation of an initial metal ion solution that is subsequently combined with algal extracts [58,65]. The BACs found in algae extracts, including pigments, fats, starches, unsaturated oils, and proteins, effectively neutralize the charge of the ionic solution to a state of zero valence [63,240–242]. The biosynthesis of natural products by algae occurs in three distinct stages. The initial phase, referred to as the activation stage, involves the reduction of metal ions facilitated by oxidation-reduction enzymes that are secreted by algal cells [155]. This phase induces a modification in the chromatic properties of the solution. The second stage involves the growth phase, during which metal ions aggregate to produce NPs of various geometries and dimensions that exhibit stability. During the third stage, the NPs are acquired in their definitive configuration [49,58,65,241,242]. The biosynthesis of particles is influenced by variables such as temperature, pH, solution concentration, and the method of stirring [58,236]. The biosynthesis of NPs from algae can take place either within the cells (intracellularly) or outside the cells (extracellularly) [63,65,155,239]. The intracellular approach is contingent upon the concentration of ion dosage in the growth medium and the production of NADH or NADPH-dependent reductase enzymes during metabolic activities, including nitrogen fixation, respiration, and photosynthesis (Figure 5).

The algae-mediated green synthesis of metal NPs offers an eco-friendly, sustainable, and cost-effective alternative to conventional chemical methods [48,58,65,239]. The biosynthesis process is depicted in Figure 5, which typically involves the following three sequential stages: activation, growth, and termination [63]. During the activation stage, metal ions (M^+) are absorbed by the algal biomass through interactions with functional groups such as hydroxyl, carboxyl, and amino groups present on the cell surface [66,243]. In the growth stage, intracellular enzymes—particularly NADH or NADPH-dependent reductases—facilitate the reduction of metal ions to their zero-valent forms (M^0) [58,63,155,158]. A variety of algal-derived biomolecules, including proteins, polysaccharides, carboxylic acids, amino acids, and tyrosinated peptides, contribute to reduction and stabilization processes [65]. This intracellular transformation is complemented by the termination stage, wherein BACs such as polysaccharides, phenolics, and pigments act as capping agents, promoting biomineralization and ensuring NP stability [58,63,239]. Additionally, extracellular synthesis pathways also play a significant role, wherein metabolites secreted by algae reduce and cap metal ions outside the cell, a process that can be optimized using magnetic stirring for an enhanced dispersion and yield [65,239,244]. This dual mechanism of intracellular and extracellular synthesis not only enhances NP stability and functionality, but also supports broad applicability in the biomedical, agricultural, and environmental domains due to the biocompatibility and low toxicity of the synthesized metal NPs [52,58,64,158].

The intracellular synthesis of gold NPs (Au-NPs) was accomplished by incubating chloroauric acid with *Rhizoclonium fontinale* algae at a temperature of 20 °C for a duration of 72 h [245]. A noticeable change in the coloration of the algal thallus from green to purple indicated the successful biosynthesis of Au-NPs. Furthermore, incubation of the gold metal solution with the biomass did not lead to any change in color, indicating the absence of intracellular enzymes or metabolites participating in the bio-reduction process [155,245]. In another experiment, gold/cellulose NPs (Au/cellulose-NPs) were synthesized using *Chlorella vulgaris* [246]. The synthesized Au/cellulose NPs were evaluated using UV–Vis spectroscopy, TEM, zeta potential analysis, and FTIR. Au/cellulose NPs have been employed in the treatment of lung cancer cells, leading to a notable enhancement in the relative expression of tumor suppressor genes when compared to control cells [246].

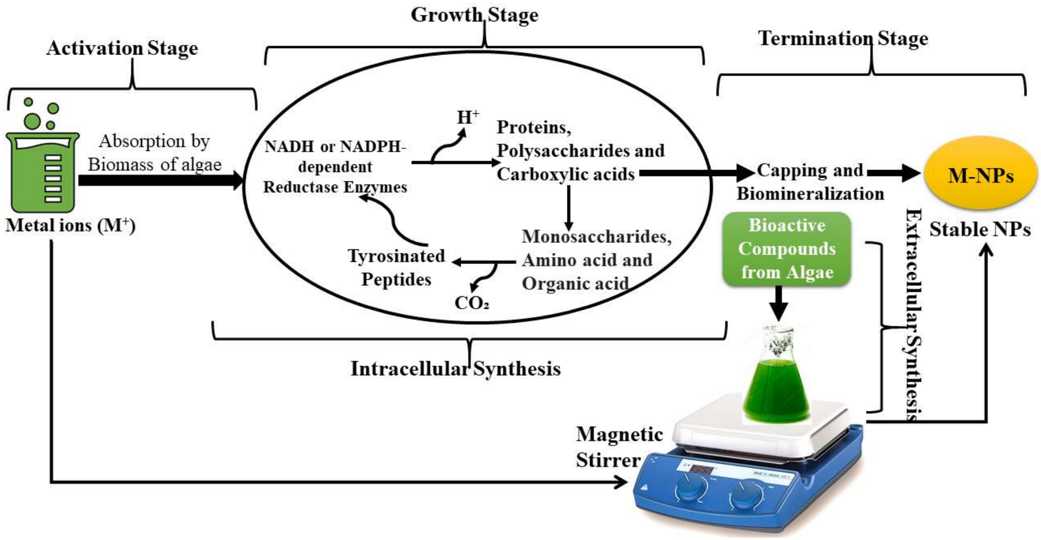

Figure 5. Schematic diagram illustrating the dual mechanism of metal nanoparticle synthesis by algae through intracellular and extracellular pathways. In intracellular synthesis, metal ions penetrate algal cell walls and are reduced by intracellular biomolecules, leading to nanoparticle formation inside the cells. In extracellular synthesis, algal-secreted enzymes and metabolites in the surrounding medium reduce metal ions externally, resulting in the formation of nanoparticles outside the cells.

The extracellular synthesis pathway occurs when metal ions bind to the surfaces of algal cells, where a range of metabolites—such as proteins, lipids, RNA, DNA, polysaccharides, pigments, and enzymes—aid in their reduction at these surfaces [155]. The extra-cellular synthesis pathway offers significant benefits, particularly in the ease of purifying NPs [58,247]. Nonetheless, it is crucial to perform specific preliminary treatments, including the washing and homogenization of algal biomass, to ensure optimal results. The dimensions, morphology, and aggregation of NPs are influenced by several variables, such as pH, temperature, and metal concentration. An elevated pH level inhibits the agglomeration of NPs by augmenting the reductive capacity of functional groups present in metals [58,236,248]. An elevated pH level (greater than 7) enhances the stability of NPs generated externally to the cell by facilitating the interaction between metal ions and the amino acids located in the cell wall [249]. The extracellular synthesis of Au-NPs utilizing *Spirulina maxima* polysaccharides at different concentrations of chloroauric acid $H[AuCl_4]$ was evidenced by the detection of a surface plasmon resonance (SPR) peak at 530 nm, suggesting the participation of proteins, enzymes, and biomolecules in the algal-mediated formation of NPs [240]. Algae, as photosynthetic organisms, exhibit a remarkable capacity to thrive across diverse aquatic environments [241,242]. Their significance in nanotechnology is underscored by their exceptional ability to facilitate the biosynthesis of various metal NPs and metal oxides [240]. This capability is primarily due to their rapid growth rates, ease of cultivation and manipulation, and a biomass accumulation rate that is, on average, ten times more accelerated than that of higher terrestrial plant species [241]. A diverse array of algal strains have undergone extensive investigation and analysis regarding their capacity for the eco-friendly synthesis of various NPs, thereby underscoring the adaptability and prospective applications of these organisms in the progression of sustainable nanomaterials production (Table 5).

Table 5. Some key studies reporting on the involvement of algal species in the biosynthesis of metal nanoparticles, emphasizing their distinct properties and various applications with emphasis on food and dairy products.

Algae Group	Algae	NPs	Location	Size	Characterization Methods	Applications	Utilization at Commercial Scale and/or Laboratory Scale of NPs	Future Prospects	References
Brown algae	*Dictyota indica*	Pd-NPs	Extracellular	19 nm	UV–Vis spectroscopy, SEM, TEM, XRD, and FTIR	Heavy metal removal	Pd-NPs produced from *D. indica* demonstrate environmentally sustainable potential for applications in the food and dairy sectors. In laboratory settings, these PdO-NPs exhibited antimicrobial activity (55.2–99% inhibition) and antioxidant properties, making them suitable for food preservation and pathogen control, particularly against pathogens such as *E. coli* in dairy products and processing, as well as in the catalytic synthesis of food additives. They have the potential to improve active packaging, prolong shelf life, and apply coatings to equipment to inhibit the formation of microbial biofilms. Challenges encompass the assurance of safety, adherence to regulatory standards, scalability, and the stability of food matrices.	Future prospects encompass intelligent packaging, functional dairy products, and sustainable processing, utilizing the catalytic and antimicrobial properties of Pd-NPs. Investigations should focus on toxicity assessment, synthesis optimization, and the establishment of consumer confidence. The synthesis of Pd-NPs from *D. indica* has the potential to transform food safety and quality, in accordance with the principles of green nanotechnology and the circular economy.	[53,161,170,250–252]
	Ecklonia cava	Ag-NPs	Extracellular	43 nm	UV–Vis spectroscopy, FTIR, XRD, and TEM	Antimicrobial, antioxidant, and anticancer	Ag-NPs produced from *E. cava* exhibit antimicrobial and antioxidant characteristics suitable for applications in the food and dairy sectors. Laboratory investigations revealed the green synthesis of spherical NPs that exhibit activity against *E. coli* and *St. aureus*, making them suitable for active packaging and prolonging shelf life. The application of Ag-NPs in commercial settings is constrained by factors such as scalability, cost considerations, and regulatory challenges, despite their utilization in certain packaging solutions.	The future outlook encompasses enhanced synthesis methods, the development of hybrid materials, and the implementation of intelligent packaging solutions, all in accordance with sustainable trends. Nonetheless, challenges arise from toxicity risks, environmental issues, and delays in regulatory processes. Although environmentally sustainable, it is essential to examine their safety and economic feasibility closely. Progress in high-throughput synthesis and safety evaluations may facilitate wider implementation, improving food safety and minimizing waste, especially in the dairy sector, contingent upon the resolution of regulatory and scalability challenges.	[31,46,62,65,132,161,168,170]

Fucus vesiculosus	ZnO-NPs	Extracellular	12–17 nm	FTIR, TEM, XRD, and zeta potential	Antibacterial	The microbial synthesis of ZnO-NPs utilizing *F. vesiculosus* provides environmentally sustainable alternatives for applications in the food and dairy sectors. At the laboratory scale, Fu/ZnO-NPs and their alginate-coated variants demonstrated significant antibacterial efficacy against pathogens such as *E. coli* and *St. aureus*, thereby improving food packaging and dairy preservation methods. Nonetheless, the issues of low yields and the optimization of synthesis processes continue to pose significant challenges. ZnO-NPs are utilized in commercial applications such as antimicrobial packaging and as GRAS additives in dairy products. However, challenges related to scalability, cost, and regulatory issues, including cytotoxicity and NP migration, hinder their widespread adoption.	Future prospects encompass intelligent packaging solutions, enhanced functional dairy products, and optimized synthesis processes utilizing bioreactors or extremophilic microorganisms. Progress in safety evaluations and sustainable methodologies, utilizing *F. vesiculosus* as a renewable resource, has the potential to enhance commercialization, revolutionizing food preservation and aligning with environmentally friendly technology trends.	[30,36,38,125,129,170,224]
Gelidiella acerosa	Au-NPs	Extracellular	5–117 nm	HRTEM, UV–visible, SEM, and XRD	Antidiabetic, antibacterial, and antioxidant	Au-NPs produced from *G. acerosa* present environmentally sustainable applications in the food and dairy sectors. At the laboratory scale, these Au-NPs demonstrated antibacterial activity against *St. aureus*, possess antioxidant properties, and show potential for biosensing applications in the detection of contaminants such as pathogens in dairy products. Challenges encompass issues related to size uniformity and concerns regarding toxicity. They have been investigated for applications in antimicrobial packaging and colorimetric sensors aimed at improving food safety and extending shelf life; however, regulatory challenges and issues related to scalability hinder widespread adoption.	Future prospects encompass advanced packaging technologies, multiplex biosensors, and the delivery of nutraceuticals in dairy products, all facilitated by sustainable biorefineries. Addressing barriers related to toxicity, regulatory compliance, and consumer acceptance is essential. Utilizing standardized protocols and safety data, Au-NPs derived from *G. acerosa* have the potential to transform food safety and enhance functional dairy products, in accordance with sustainability objectives.	[52,102,170,233,253–257]

Sargassum myriocystum	Ag-NPs	Extracellular	20 nm	UV–Vis spectroscopy, XRD, SEM, and TEM	Antibacterial, anticancer, and photocatalytic activity	Ag-NPs produced from *S. myriocystum* exhibit antimicrobial and antioxidant characteristics suitable for applications in the food and dairy sectors. Laboratory investigations validated their effectiveness against pathogens such as *E. coli* and *St. aureus*, facilitating their application in active packaging and preservatives to prolong shelf life. Their green synthesis, employing algal phyco-molecules, guarantees environmental sustainability. Scalable production in bioreactors for commercial applications, along with the integration into biodegradable films, offers potential cost-effective solutions; however, challenges arise regarding regulatory compliance and consumer skepticism.	Future developments encompass intelligent packaging solutions, targeted antimicrobial agents, and eco-friendly production methods through algal cultivation, all contributing to food security and the principles of circular economies. Nonetheless, the issues of toxicity, microbial resistance, and environmental consequences necessitate meticulous oversight. Advancements in safety and technology suggest that Ag-NPs derived from *S. myriocystum* have the potential to revolutionize food preservation, contingent upon the resolution of regulatory and market challenges.	[35,45,107,161,170,228,258]
S. polycystum	Ag-NPs	Extracellular	100 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM	Antimicrobial	Ag-NPs derived from *S. polycystum* provide environmentally sustainable antimicrobial alternatives for food and dairy applications. At the laboratory scale, these Ag-NPs, characterized through UV–Vis spectroscopy, FTIR, and SEM, demonstrated inhibitory effects on pathogens such as *E. coli* (47% inhibition at a concentration of 16 µg/mL) and exhibited antioxidant activity (78.2% inhibition of DPPH), making them suitable for applications in packaging and preservation. Commercial obstacles encompass scalability, stability, and regulatory limitations regarding direct food applications, thereby confining uses to packaging films and equipment disinfection.	Future prospects include the development of intelligent packaging systems, the application of targeted antimicrobial agents, and the implementation of sustainable bioreactors, utilizing the plentiful resources of seaweed. Nonetheless, the issues of toxicity, the risk of antimicrobial resistance, and the environmental consequences associated with seaweed harvesting necessitate careful examination. Comprehensive safety studies and lifecycle evaluations are essential to address regulatory and consumer challenges, facilitating the scalable and sustainable integration of practices within the food and dairy sectors.	[35,50,161,170,228,258]

Turbinaria conoide	Au-NPs and Ag-NPs	Extracellular	2–17 nm 2–19 nm	FTIR, XRD, FESEM, EDX, and HRTEM analysis	Antimicrofouling	Au-NPs and Ag-NPs produced through the utilization of *T. conoides* present potential applications in the food and dairy sectors. At the laboratory scale, Ag-NPs demonstrated significant antimicrobial and antibiofilm properties against pathogens such as *E. coli*, facilitating their application in active packaging, food preservation, and coatings for dairy equipment. Au-NPs ranging from 2 to 19 nm were appropriate for applications in biosensing and nutrient encapsulation. Applications at a commercial scale encompassed nano-enhanced packaging and quality control sensors; however, challenges such as toxicity, regulatory obstacles, and issues related to scalability continue to exist.	Future developments include intelligent packaging systems, tailored nutritional solutions, and eco-friendly manufacturing processes utilizing seaweed byproducts. Progress in safety research and bioprocessing may facilitate worldwide market integration, corresponding with the increasing demand for environmentally sustainable solutions. The application of these NPs presents considerable opportunities for improving food safety and extending shelf life within the dairy sector.	[13,26,52,102,126,170,254, 255,259–261]
Stoechospermum marginatum	ZnO-NPs	Extracellular	80–126 nm	UV–Vis spectroscopy, HPLC, and FTIR	Antidengue	ZnO-NPs produced from *S. marginatum* provide environmentally sustainable alternatives for applications in the food and dairy sectors. In laboratory settings, the antimicrobial, UV-blocking, and zinc-enhancing characteristics contributed to food preservation, packaging, and nutritional enhancement, effectively inhibiting pathogens such as *E. coli* and strengthening dairy products. ZnO-NPs were utilized in commercial applications such as antimicrobial packaging for cheese and yogurt, nutrient fortification in milk, and coatings in dairy processing to mitigate biofouling. Challenges encompass scalability, financial implications, and regulatory obstacles necessitating toxicity assessments.	Future prospects encompass intelligent packaging integrated with nanosensors, targeted zinc delivery mechanisms, and eco-friendly wastewater management solutions. Innovations in synthetic biology and machine learning have the potential to enhance synthesis processes, whereas aquaculture plays a crucial role in maintaining a sustainable supply of seaweed. Comprehensive studies on long-term safety and environmental impact are essential for evaluating the benefits and risks, thereby establishing ZnO-NPs as a significant advancement in food safety and nutrition.	[36,126,170,200,262–264]

Red algae	*Acanthophora spicifera*	Au-NPs	Extracellular	20 nm	FTIR, XRD, PDI, and zeta potential	Antioxidant, antibacterial, and anticancer	Au-NPs produced from *A. spicifera* demonstrate potential utility in food and dairy applications. At the laboratory scale, their antimicrobial efficacy against pathogens such as *Vibrio harveyi*, along with their antioxidant properties, contributed to improved food safety and extended shelf life, making them appropriate for dairy products and packaging films. Identified as spherical with a diameter of less than 20 nm through XRD and TEM, these particles demonstrated biocompatibility. Au-NPs have the potential to enhance pathogen control in dairy processing, active packaging, and colorimetric sensors for contaminant detection. However, challenges related to reproducibility, stability, and regulatory compliance impede their scalability.	Future developments encompass intelligent packaging, biosensors, and functional dairy products, utilizing their environmentally sustainable synthesis. Progress in algal biorefineries and the establishment of regulatory frameworks may enhance sustainability and promote adoption, positioning AuNPs as novel solutions for food security and quality assurance, subject to additional toxicological investigations.	[30,102,170,233,255,265–267]
	Amphiroa spp.	Ag-NPs	Extracellular	56–250 nm	UV–Vis spectroscopy, FTIR, XRD, and SEM	Antioxidant, antimicrobial, and cytotoxic Activities	Ag-NPs produced by *Amphiroa* spp. present potential applications in the food and dairy sectors, attributed to their antimicrobial, antioxidant, and biocompatible characteristics. At the laboratory scale, Ag-NPs were synthesized in an environmentally friendly manner using algal extracts, demonstrating effectiveness against pathogens such as *E. coli* and *St. aureus* for applications in packaging and preservation. In commercial applications, they were investigated for use in active packaging and the stabilization of dairy products; however, challenges related to cost, stability, and regulatory compliance remain significant.	Future prospects encompass the sustainable large-scale production facilitated by bioreactors, the integration of synergistic nanomaterial combinations, and the implementation of smart packaging systems for real-time quality monitoring. The progression of regulations and the enhancement of consumer knowledge will facilitate increased adoption. Ag-NPs, possessing antiviral properties and applicable as edible coatings, have the potential to revolutionize food safety and sustainability. Their effectiveness hinges on advancements in scalability and public acceptance, positioning them as a significant innovation for the food and dairy sectors.	[40,43,84,165,170,228,268]

Galaxaura elongata	SnO_2-NPs	Extracellular	35 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM	Antimicrobial and cytotoxicity	Microbially synthesized SnO_2-NPs utilizing *G. elongata* demonstrate potential for applications in the food and dairy industries. At the laboratory scale, the antimicrobial activity demonstrated (inhibition zones: 16–24 mm), along with antioxidant properties, render them suitable for active packaging applications. This capability contributed to the extension of shelf life for dairy products such as cheese and yogurt, while also inhibiting lipid oxidation. Nanosensors incorporating SnO_2-NPs were capable of identifying spoilage or contaminants. The commercial scaling of antimicrobial films, stabilizers, or smart packaging encounters significant challenges related to reproducibility, safety, and regulatory compliance. The process of green synthesis promotes environmental sustainability; however, the migration of NPs and their cytotoxic effects, indicated by an IC_{50} value of 28.08 μg/mL, necessitates careful examination.	Future prospects encompass multifunctional packaging, sustainable production through bioreactors, and the establishment of regulatory frameworks to guarantee safety. The integration of SnO_2-NPs with biodegradable polymers and Internet of Things-enabled sensors has the potential to significantly enhance food safety and quality, contingent upon the consideration of consumer acceptance and environmental implications.	[107,170,269–274]

Gelidium amansii	Ag-NPs	Intracellular	27–54 nm	UV–Vis spectroscopy, FTIR, and SEM	Antimicrobial	Ag-NPs produced through the use of *G. amansii* present significant potential for applications within the food and dairy sectors, attributed to their antimicrobial and antioxidant characteristics. In laboratory settings, Ag-NPs demonstrated efficacy against pathogens such as *E. coli* and *St. aureus*, thereby prolonging the shelf life of dairy and food products via coatings or packaging applications. They were utilized in active packaging films to improve the preservation of seafood and dairy products; however, regulatory issues restricts their direct application in food. Scalable and environmentally sustainable synthesis utilizing algae facilitates economical production; however, it faces challenges related to toxicity, environmental repercussions, and consumer acceptance.	Future prospects include intelligent packaging, synergistic antimicrobial systems, and enhanced synthesis aimed at sustainability. Comprehensive long-term safety studies and the establishment of standardized protocols are essential to address regulatory challenges and realize the potential of Ag-NPs in enhancing food safety and extending shelf life.	[40,55,73,161,164,168,170,228,236,275]

Gracilaria crassa	SiO_2-NPs	Extracellular	20–50 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, Tg, and zeta potential	Antioxidant	Microbially synthesized SiO_2-NPs by *G. crassa* present potential applications within the food and dairy sectors. Applications at the laboratory scale encompassed antimicrobial packaging, enzyme immobilization for the hydrolysis of lactose, nutrient delivery systems, and biosensors designed for the detection of contaminants. In commercial applications, these SiO_2-NPs functioned as anti-caking agents, stabilizers, and integral components in intelligent packaging systems designed to prolong shelf life. The green synthesis approach utilizing *G. crassa* extracts is environmentally sustainable, employing algal BACs to facilitate the processing of silica precursors. Challenges encompass scalability, the necessity for regulatory approval owing to potential toxicity concerns, and considerations regarding cost-effectiveness.	Future prospects encompass the optimization of synthesis through machine learning, the implementation of sustainable packaging utilizing biopolymers, and the integration of a circular economy through waste valorization. The integration of SiO_2-NPs with additional biogenic NPs has the potential to improve antimicrobial efficacy. Comprehensive safety evaluations and consumer awareness are essential for market acceptance, establishing these SiO_2-NPs as revolutionary for food safety and preservation.	[102,170,216,218,219,276–278]
G. edulis	Ag-NPs	Extracellular	62 nm	UV–Vis spectroscopy, FTIR, XRD, and SEM	Antioxidant, antibacterial, and anticancer	The synthesis of Ag-NPs utilizing *G. edulis* present potential applications within the food and dairy sectors, attributed to their antimicrobial and antioxidant characteristics. Laboratory investigations validated their environmentally benign synthesis, demonstrating that 20–80 nm spherical NPs exhibit efficacy against pathogens such as *E. coli* and *St. aureus*, making them appropriate for applications in food packaging films and dairy preservation. The potential for commercial scalability exists due to the plentiful availability of seaweed; however, regulatory limitations and challenges related to standardization hinder widespread adoption.	Future prospects encompass intelligent packaging solutions, coatings for dairy processing equipment, and synergistic formulations incorporating natural antimicrobials to improve safety and effectiveness. Studies on encapsulation and toxicity are essential to comply with regulatory standards. Utilizing seaweed waste in conjunction with biorefinery methodologies has the potential to enhance sustainability. Ongoing investigation into the secure and standardized manufacturing processes will reveal the potential of Ag-NPs in prolonging shelf life and enhancing food safety.	[40,53,161,168,170,228,279]

Lemanea fluviatilis	Au-NPs	Intracellular	5–15 nm	UV–Vis spectroscopy, FTIR, XRD, DLS, and SEM	Antioxidant	Au-NPs produced through *L. fluviatilis* provide environmentally sustainable alternatives for applications in the food and dairy sectors. At the laboratory scale, these spherical Au-NPs, ranging from 5 to 15 nm, demonstrated antioxidant, antimicrobial, and fluorescent characteristics, making them suitable for biosensing contaminants or enhancing the shelf life of products such as yogurt. Challenges encompass low yield, issues with reproducibility, and the necessity for toxicity testing. Au-NPs have the potential to improve antimicrobial packaging, functional foods, and quality control sensors in commercial applications. However, challenges related to cost, scalability, and regulatory approval from organizations such as the FDA must be addressed.	Future prospects encompass intelligent packaging solutions, the nanoencapsulation of nutrients, and the sustainable production methods utilizing bioreactors or waste-to-value systems. Improvements in safety data, economical synthesis methods, and consumer acceptance are essential for realizing their potential in food safety, dairy processing, and veterinary applications, in accordance with trends in sustainable food technology.	[102,132,170,226,233,254,256,280,281]
Kappaphycus alvarezii	Ag-NPs	Extracellular	12 nm	UV–Vis spectroscopy, FTIR, XRD, TEM, FESEM-EDX, and zeta potential	-	The synthesis of Ag-NPs utilizing *K. alvarezii* demonstrates potential for applications in the food and dairy sectors, attributed to their antimicrobial characteristics and environmentally friendly nature. At the laboratory scale, these Ag-NPs revealed the ability to inhibit pathogens such as *E. coli* in edible coatings and packaging films, thereby prolonging the shelf life of dairy products. Ag-NPs were investigated for their applications in active packaging and equipment sanitization, utilizing the scalability of *K. alvarezii*. Challenges encompass regulatory obstacles, concerns regarding toxicity, and the need for standardization.	Future prospects encompass intelligent packaging systems, synergistic formulations incorporating natural antimicrobials, and sustainable manufacturing practices utilizing seaweed waste. The implementation of advanced synthesis techniques alongside AI optimization has the potential to significantly improve scalability. Although presenting considerable promise, thorough safety validation and assessments of environmental impact are essential.	[65,73,74,161,168,170,226,228]

Cyanobacteria	*Anabaena variabilis*	Ag-NPs	Extracellular	11–15 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM	Antibacterial and antifungal	Ag-NPs synthesized by *A. variabilis* offer promising applications in food and dairy products due to their eco-friendly, antimicrobial properties. At the laboratory scale, Ag-NPs inhibited pathogens like *E. coli* and *St. aureus*, enhanced food packaging, and purified water. Commercially, they were used in antimicrobial coatings for packaging and dairy equipment, extending shelf life and ensuring hygiene. Challenges include scalability, regulatory hurdles, and potential environmental risks.	Future prospects involve smart packaging, probiotic-enhanced dairy, and synergistic antimicrobial strategies. Comprehensive toxicological studies and standardized production are needed for regulatory approval. By optimizing minimal effective doses and developing biodegradable formulations, *A. variabilis* Ag-NPs could revolutionize food safety and sustainability, provided that consumer trust and environmental concerns are addressed through transparent research and localized production.	[50,55,168,170,228,282,283]
	Arthrospira platensis	ZnO-NPs	Extracellular	30–55 nm	UV–Vis spectroscopy, FTIR, EDX, XRD, and TEM	Antimicrobial and anticancer	ZnO-NPs produced through *A. platensis* present potential applications in the food and dairy sectors. In laboratory settings, green synthesis utilizing metabolites from *A. platensis* demonstrated antimicrobial properties against pathogens such as *E. coli* and *St. aureus*. These NPs are well-suited for applications in biodegradable packaging and nutritional enhancement. The potential for commercial scalability exists through the utilization of industrial bioreactors, taking advantage of the rapid growth of *A. platensis* and the use of food waste as a growth medium; however, challenges related to cost and NP uniformity persist. Applications encompass active packaging, antimicrobial coatings, and zinc-fortified dairy products.	Future prospects encompass precision synthesis, intelligent packaging solutions, and sustainable methodologies such as biomass recycling. Long-term safety studies are essential for obtaining regulatory approval and ensuring consumer acceptance. Interdisciplinary research will improve the role of ZnO-NPs in functional foods, probiotics, and plant-based dairy, effectively addressing nutritional and preservation requirements in a sustainable manner.	[1,21,70,95,106,125,126,129,170,182,263]

Cylindrospermum stagnale	CuO-NPs	Intracellular	12 nm	UV–Vis spectroscopy, FTIR, SEM, and TEM	Antimicrobial, anticancer, and larvicidal	CuO-NPs produced from *C. stagnale* exhibit potential for applications in the food and dairy sectors, attributed to their antimicrobial and antioxidant characteristics. At the laboratory scale, these CuO-NPs, measuring 12.21 nm, demonstrated inhibitory effects on pathogens such as *E. coli* and *C. albicans*, indicating potential applications in active packaging or preservation for dairy products, including cheese. They have the potential for commercial scalability in applications such as antimicrobial coatings or biodegradable films, which could improve shelf life. Nevertheless, high-dose toxicity, scalability expenses, and regulatory obstacles present significant challenges.	Future prospects encompass intelligent packaging, nanofertilizers for agricultural crops, and sustainable synthesis; however, they necessitate toxicological assessments and the establishment of consumer confidence. Achieving a balance between effectiveness and safety, while also considering environmental consequences, is essential. Ongoing investigation into food matrix interactions and regulatory partnerships will facilitate their integration within the food and dairy sectors.	[22,23,25,39,81,105,106,170,284,285]
Phormidium spp.	CuO-NPs	Extracellular	22 nm	UV–Vis spectroscopy, FTIR, XRD, SEM, TEM, and AFM	Antioxidant, antimicrobial, anti-inflammatory, and dye degradation	CuO-NPs produced by *Phormidium* spp. provide environmentally sustainable alternatives for applications in the food and dairy sectors. In laboratory settings, the antimicrobial and antioxidant properties observed (e.g., 94% bacterial inhibition and 90% radical scavenging) facilitate their application in active packaging and preservation, thereby prolonging the shelf life of products such as cheese. Challenges to commercial-scale adoption include low yield, toxicity issues, and stringent regulations; however, optimizing bioreactors and utilizing biocompatible coatings are suggested to improve viability.	Future prospects encompass intelligent packaging, hybrid NPs, and eco-friendly production utilizing agricultural waste materials. Long-term safety, regulatory approval, and consumer acceptance represent significant challenges. Advancements in scalability and toxicity studies indicate that CuO-NPs have the potential to transform food safety by minimizing spoilage and improving the quality of dairy products, thereby supporting global food security through innovative and environmentally friendly nanotechnology solutions.	[17,23,24,105,106,170,187,200,285,286]

Synechocystis spp.	Ag-NPs	Extracellular	10–35 nm	UV–Vis spectroscopy, FTIR, XRD, and TEM	Antimicrobial, antioxidative, anti-inflammatory, and diabetic	Ag-NPs produced by *Synechocystis* spp. present potential applications within the food and dairy sectors. In laboratory settings, these environmentally friendly Ag-NPs demonstrated significant antimicrobial efficacy against pathogens such as *E. coli* and *St. aureus*, making them appropriate for applications in food packaging and dairy preservation. Ag-NPs were produced through the reduction of silver ions mediated by nitrate reductase, which guarantees their biocompatibility. The application of commercial-scale active packaging and equipment coatings is currently limited, yet it remains feasible. However, challenges related to scalability, stability, and regulatory compliance must be addressed.	Future prospects encompass genetic engineering aimed at enhancing yields, the development of intelligent packaging solutions, and the creation of synergistic formulations incorporating natural preservatives. Solar-powered bioreactors with sustainable design may improve production efficiency. Nonetheless, challenges such as toxicity, expense, and consumer acceptance persist. Through enhanced synthesis and comprehensive safety evaluations, Ag-NPs derived from *Synechocystis* spp., have the potential to transform food safety and prolong shelf life.	[1,7,9,31,96,106,161,165,170,172,285,287]

4. Analytical Techniques for Confirming Microbially Synthesized Nanoparticles

The confirmation of NPs produced through microbial approaches depends on a range of complementary analytical techniques (Table 6), with each of them providing distinct information regarding their physicochemical properties.

Table 6. Comparative overview of analytical techniques for characterizing microbially synthesized nanoparticles.

Technique	Information Provided	Strengths	Weaknesses	Best Use Case
UV–Vis	SPR, preliminary size	Fast, cost-effective, non-destructive	Limited specificity, interference	Initial confirmation of NP synthesis
TEM	Size, shape, crystallinity	High resolution, direct visualization	Costly, complex preparation	Detailed morphological analysis
SEM	Surface morphology, elemental composition (with EDS)	Wide field of view, 3D imaging	Lower resolution, preparation artifacts	Surface and elemental studies
DLS	Hydrodynamic size, polydispersity	Non-invasive, rapid, solution-based	Interference, no morphological data	Size distribution in suspensions
XRD	Crystal structure, phase	Non-destructive, precise crystallinity data	Bulk analysis, no morphology	Crystallinity and phase confirmation
FTIR	Surface functional groups	Identifies capping agents, non-destructive	Qualitative, complex spectra	Surface chemistry and stabilization
EDS	Elemental composition	Specific, integrates with SEM/TEM	Limited sensitivity, no structural data	Compositional verification

Sources: [73,130,160,288–293].

UV–Vis spectroscopy is frequently the first technique utilized, identifying SPR peaks—generally observed at approximately 420–450 nm for Ag-NPs and 520–550 nm for Au-NPs [160,290]. This method offers a swift, economical, and non-invasive initial confirmation of NP formation [160,293]. Nonetheless, it exhibits a lack of specificity attributed to possible spectral overlap with microbial biomolecules and provides restricted insights regarding morphology or composition [160,290].

TEM provides high-resolution imaging that is essential for assessing NP size, shape, and crystallinity, frequently enhanced by selected area electron diffraction (SAED) [288,292]. This method is regarded as optimal for conducting detailed morphological analysis, such as confirming the presence of spherical AgNPs synthesized by *Bacillus* species [292,293]. Its limitations encompass elevated operational costs, complex sample preparation processes, and the analysis of limited sample areas, which may not adequately represent the overall heterogeneity of the sample [160].

SEM, often integrated with energy-dispersive X-ray spectroscopy (EDS), offers three-dimensional surface imaging alongside elemental composition analysis [291,292]. This method is especially effective for visualizing NP distribution on microbial cells or within biofilms [130]. SEM provides a wider field of view in comparison to TEM; however, it exhibits a reduced resolution for NPs that are smaller than 5–10 nm [160,291,292]. Furthermore, the necessity for sample coating could lead to the introduction of imaging artifacts.

Dynamic Light Scattering (DLS) evaluates the hydrodynamic size and polydispersity index (PDI) of NPs within colloidal suspension [160,290]. This method is a non-invasive and rapid approach that is appropriate for assessing the size distribution of NPs and their colloidal stability, specifically for Ag-NPs derived from *Escherichia coli* [73,290]. Nonetheless, DLS frequently presents an overestimation of particle size as a result of solvation shells and is prone to interference from leftover microbial debris.

XRD is utilized to ascertain the crystalline characteristics and phase composition of NPs, such as determining the face-centered cubic (FCC) structure of AgNPs [160,288,289]. This non-destructive technique provides comprehensive structural information; however, it necessitates larger sample quantities and demonstrates a reduced efficacy in characterizing amorphous NPs [288–290]. Morphological data are supplied.

FTIR serves as a method for identifying surface functional groups that play a role in the stabilization of NPs, including proteins or polysaccharides that cap AgNPs synthesized by *F. oxysporum* [73,160,289]. While qualitative in nature, FTIR provides insights into the mechanisms of capping and stabilization [160,290]. The interpretation of complex spectra resulting from microbial biomolecules can present significant challenges.

EDS, when combined with SEM or TEM, facilitates qualitative and semi-quantitative elemental analysis, confirming the existence of particular elements (e.g., silver in AgNPs) [130,160,292]. EDS delivers a high specificity; however, it exhibits a limited sensitivity for trace elements and does not provide insights into crystalline structure or morphology.

Therefore, a critical conclusion can be drawn regarding several aspects of these analytical techniques, including resolution and detail, cost and accessibility, sample preparation, and their complementary nature. TEM provides the highest resolution for morphological and crystallographic analysis, establishing it as the benchmark for NP characterization. SEM offers additional surface imaging capabilities; however, its effectiveness diminishes when analyzing very small NPs. DLS and UV–Vis spectroscopy provide less comprehensive information but are highly effective for swift, solution-based analysis. Regarding cost and accessibility, UV–Vis spectroscopy and DLS are the most economical and readily available options, making them suitable for routine monitoring. The utilization of TEM, SEM, and XRD is constrained by the necessity for costly equipment and specialized knowledge, thereby restricting their application to laboratories with substantial financial resources. Sample preparation for UV–Vis spectroscopy and DLS involves minimal steps, making it suitable for the analysis of NPs in microbial media. TEM and SEM require intricate preparation processes, which may introduce artifacts, whereas XRD and FTIR are non-destructive techniques that necessitate adequate sample quantities. In terms of complementary nature, no single technique offers complete characterization. TEM can ascertain size and morphology, XRD validates crystallinity, FTIR detects the presence of capping agents, and EDS establishes compositional elements. A variety of techniques are commonly utilized for thorough NP characterization, including UV–Vis spectroscopy for preliminary screening, TEM/SEM for imaging, XRD for assessing crystallinity, and FTIR/EDS for conducting chemical analysis.

5. Nanomaterial Applications in Food and Dairy Products

The integration of nanotechnology within the food and dairy industry represents a significant transformation in this domain. NPs are utilized in the processing of food and dairy products to yield high-quality and health-safe outcomes [6,7,15,17,23,24,229]. Table 7 delineates the various types of nanomaterials used, the microorganisms utilized in their synthesis, and their specific applications within food and dairy products. Furthermore, the characteristics of the active compounds present in dairy products may be altered as a result of the diminutive scale of NPs. Nonetheless, various issues have been highlighted regarding the possible risks associated with the application of nanotechnology in food and dairy products, underscoring the necessity of verifying the safety of these products prior to their commercialization [6,7,15,26,126,145,160].

Table 7. Applications of microbial-synthesized nanomaterials in enhancing food and dairy product quality, safety, and shelf life.

Application	Nanomaterial Type	Microorganism(s)	Specific Use in Food/Dairy	References
Food Packaging and Preservation	Ag-NPs	*Pseudomonas stutzeri*, *F. oxysporum*	Antimicrobial films for milk, cheese, and yogurt to extend shelf life by inhibiting pathogens like *E. coli* and *L. monocytogenes*.	[31,55,130,133]
	ZnO-NPs	*Aeromonas hydrophila*	Edible coatings for dairy products (e.g., butter, soft cheese) to reduce microbial counts and moisture loss.	[129,294]
	Au-NPs/Ag-NPs	*F. oxysporum*	Nanosensors in smart packaging for real-time spoilage detection in milk and yogurt (e.g., pH changes, microbial metabolites).	[22,31,32,233,255]
Nutrient Delivery and Fortification	Nanoliposomes/Nanoemulsions	*Lactobacillus* spp., *Brevibacterium casei*	Encapsulation of BACs (e.g., omega-3 PUFAs, vitamins) in fortified milk/yogurt for improved stability and bioavailability.	[2,13,130]
	Bacterial Nanocellulose	*Komagataeibacter xylinus*	Controlled release of probiotics/enzymes in fermented dairy (e.g., yogurt) for enhanced gut health.	[130,133]
	Various NPs	Various microbes	Electrospraying for encapsulating heat-sensitive antioxidants in dairy products at room temperature.	[2,13]
Food Safety and Pathogen Detection	Au-NPs	*F. oxysporum*	Biosensors for detecting pathogens (e.g., *Salmonella*, *listeria*) in dairy products like milk and cheese.	[22,26,32,102,233,254,284]
	ZnO-NPs /CuO-NPs	*Alcaligenes faecalis*, *Micrococcus yunnanensis*	Antimicrobial coatings on dairy processing equipment to prevent contamination during milk pasteurization or cheese production.	[130,290,295]
Quality Enhancement	Bacterial Nanocellulose	*K. xylinus*	Thickener/stabilizer in ice cream and yogurt to improve texture and prevent phase separation.	[26]
	Ag-NPs	*Ps. stutzeri*	Nanoencapsulation of essential oils in cheese packaging to maintain flavor and provide antimicrobial protection.	[13,31,294]

The improvement of food product and dairy functionality via the incorporation of functional food components has become a significant trend in the market [1,8,55,294,296]. The incorporation of these functional food components can serve to inhibit unwanted microbial proliferation, enhance the taste, color, and flavor of a product, and, most importantly, confer health-promoting benefits [8,55,294,296,297]. A significant proportion of these functional food components demonstrate incompatibility with food matrices as a result of their low solubility in water, restricted oral bioavailability, undesirable sensory characteristics, and vulnerability to chemical degradation [8,296–298].

The utilization of contemporary technologies, including nanocomposites and metal NPs, is essential to address the growing demand for food and dairy products in international markets [9,22,31,290,298,299]. These technologies encompass the enhancement of nutritional value [16], the facilitation of active ingredient delivery [2,13], the improvement of quality [128,298], the innovation of novel packaging technologies [25,172,284], the detection of harmful contaminants [132], the inhibition of detrimental bacteria [14,127,183], and the extension of product shelf life [171,294].

5.1. In Functional Foods

Functional foods are defined as those that, beyond their nutritional value, serve a specific physiological role within the body and may facilitate the delivery or transmission of various BACs, including phenols, short-chain fatty acids, bacteriocins, and other relevant substances [2,8,297,300–302]. Functional foods produced through nanotechnology have the capability to alter the sensory characteristics of food products [13]. For instance, they can decrease the volume of fat emulsion in ice cream, augment its surface area, improve the biological efficacy of the emulsification process, and consequently minimize the quantity of emulsifier incorporated into the ice cream mixture [13,298]. Furthermore, a nano-capsule was engineered to encapsulate phytosterols such as β-carotene and lycopene, serving as a substitute for detrimental cholesterol [13]. Additionally, the development of certain nano-plant oils aims to provide an alternative to cholesterol, thereby mitigating the absorption and accumulation of harmful cholesterol in the bloodstream and the associated health complications [19].

5.2. In Milk

Ag-NPs were synthesized using extracts from the following three species of red algae: *Caulerpa racemosa*, *Jania rubens*, and *Padina pavonica*. The application of these particles served to inhibit the growth of *Listeria monocytogenes* bacteria [303]. The findings demonstrated the significant effectiveness of Ag-NPS from *P. pavonica* extract. Following a storage period of 28 days, *L. monocytogenes* bacteria were entirely inactivated in dairy products, including cheese and whey [303]. The enzyme laccase derived from *Trametes versicolor* was utilized to synthesize NPs incorporating various metals and chitosan. The produced particles were employed to eliminate aflatoxin M1 from milk samples. The findings indicated that laccase-NPs exhibited the greatest adsorption efficiency in relation to M1. The synthesized Fe_3O_4/Cs/MoS_2/laccase NPs achieved the highest removal rate of M1 (68.5%) in milk samples after 1 h of treatment [299]. Selenium NPs (Se-NPs) were synthesized using *Lactaseibacillus paracasei* bacteria derived from human milk, with a particle diameter ranging from 3.0 to 50.0 nm. The particles demonstrated significant efficacy as an anti-*Candida* and *Fusarium* species, effectively targeting pathogenic fungi isolated from animal sources [304]. Nisin derived from *Lactococcus lactis* was utilized in conjunction with MgO ions for the synthesis of magnesium NPs (Mg-NPs). The particles demonstrated inhibitory effects on pathogenic bacteria found in milk, including *E. coli* and *Staphylococcus aureus* [11]. ZnO-NPs were synthesized using the *T. harzianum* mold and employed for antibacterial and antitumor applications [36,264]. The particles were utilized in soy milk as antimicrobial agents targeting a species of both Gram-positive and Gram-negative bacteria. The maximum inhibition observed was 14.3 mm for *Enterococcus faecalis* and 11.6 mm for *E. coli* [264].

5.3. In Yogurt

With the increasing awareness among consumers about the health-promoting attributes of their dietary selections, the idea of incorporating functional food elements into a range of food and dairy products has come to light [8,235,305]. Yogurt is considered a suitable medium for the integration of functional ingredients due to various factors [235,306]. Methodology for augmenting yogurt with functional components is firmly entrenched in the dairy industry. Nonetheless, the prospective uses of nano-scale functional ingredients in yogurt continue to be a subject of active research [7]. In total, 200 μg/mL of Fe-NPs, synthesized using *B. subtilis* ML6, was incorporated as a fortifying agent in yogurt. The incorporation of these particles enhanced the sensory characteristics of the resultant yogurt. The incorporation of 200–400 μg/mL of Fe-NPs was observed to enhance the shelf life of yogurt [5]. Nisin derived from *Lc. lactis* was utilized in the synthesis of NPs. A concentration of 0.125 mg/mL of nisin NPs exhibited significant antibacterial efficacy against methicillin-resistant *St. aureus* and *E. coli* O157:H7. Yogurt that was inoculated with nisin NPs exhibited an extended shelf life compared to yogurt produced without the incorporation of these NPs [12]. In another investigation, ZnO-NPs were synthesized utilizing *Lactobacillus gasseri*. The particles exhibited significant antibacterial efficacy. The incorporation of these particles into yogurt resulted in an enhanced total solids content, as well as improvements in its chemical, physical, and microbial characteristics. The sensory attributes exhibited greater consumer acceptability over a 28-day period of refrigerated storage [178].

5.4. In Cheese

The production of cheese represents a significant sector within the global dairy industry. All varieties of cheese produced exhibit elevated concentrations of solid constituents, encompassing proteins, fats, and carbohydrates [8,210]. Cheese serves as an appropriate substrate for the proliferation of diverse microorganisms [210,276,287]. Nanotechnology has been integrated into the cheese industry to inhibit microbial growth and enhance the shelf life of cheese. A significant number of investigations focus on the development of nano-coatings intended for the encapsulation of produced cheeses [13,210,307]. This research was conducted to investigate the inhibitory effects of both pure nisin derived from *Lc. lactis* and nisin NPs against *A. flavus* via inoculation in laboratory-produced Ras cheese. The nisin NPs employed in our investigation exhibited a remarkable biocompatibility and safety for applications in food preservation. Moreover, the sensory characteristics of the Ras cheese treated with nisin and nisin NPs demonstrated a significant degree of overall acceptability [196]. NPs were synthesized utilizing a yogurt starter culture comprising *Lb. delbrueckii* subsp. *bulgaricus*, *Streptococcus thermophilus*, and nickel oxide ions to enhance the preservation of Domiati cheese against enterotoxigenic *St. aureus*. The findings indicated that a concentration of 35 μg/mL of the particles effectively inhibited *St. aureus* for a duration of 21 days throughout the cheese ripening process [308]. The prior study aimed to assess the presence of *L. monocytogenes* during the maturation period at temperatures of 5, 10, and 20 °C for artisanal Canastra cheeses utilizing a packaging system based on Ag-NPs. The assessed packaging methodology did not influence the initial pH levels (approximately 5.0) or water activity (a_w) (approximately 0.95) during the entire storage period. As a result, the active packaging system being studied failed to demonstrate effectiveness in inactivating *L. monocytogenes* throughout the storage period of artisanal Canastra cheeses [287].

5.5. In Meat Production

Meat products of diverse varieties represent a significant proportion of food products prevalent in international markets, facing numerous challenges such as a limited shelf life and susceptibility to microbial contamination [309,310]. The application of nanotechnology in the production and preservation of meat represents a groundbreaking advancement [55,309,311]. The previous research focused on examining the impacts of dietary Zn-NPs in conjunction with *B. licheniformis* on the growth performance, carcass characteristics, blood metabolite levels, and population of specific cecal microorganisms in broiler chickens. In summary, the incorporation of Zn-NPs with *B. licheniformis* resulted in enhanced weights of broilers, improved carcass characteristics, and superior meat quality attributes, along with favorable alterations in certain blood indices and a reduction in cecal microbial load [311]. Minced beef exhibits a high rate of perishability attributed to its extensive surface area, which is susceptible to spoilage, coupled with elevated a_w levels. Nisin synthesized by *Lc. lactis* was utilized in conjunction with Zn ions to generate NPs. The microbial population decreased from approximately 2 to 4 log

CFU/cm^2 in packed minced beef during a storage period of 15 days at 4 °C [312]. This detailed analysis aimed to investigate the progress of films containing NPs designed to improve the preservation of meat products via advanced packaging techniques. Throughout the film development process, extensive research underscored the application of natural polymers, with a particular emphasis on chitosan. The literature predominantly examines polymeric NPs, with metallic NPs following in frequency, while chicken and beef emerge as the primary products of interest in these studies. The main analyses performed on these products focused on lipid oxidation and the evaluation of antimicrobial effectiveness. Most research findings demonstrate that these films significantly mitigate lipid oxidation, consequently prolonging the shelf life of meat products [309]. A bilayer membrane was developed consisting of chitosan/zein in conjunction with a layer of nisin produced by *Lc. lactis*, incorporating nano Zn ions for the preservation of carp fillets [230]. The coating procedure demonstrated a reduction of 1.8–2.3 log CFU/g following the tenth day of storage. Additionally, *Pseudomonas* bacteria represent the predominant fraction of bacterial contamination in the fillets, while the membranes played a role in inhibiting the proliferation of this bacterial species [230]. Synthetic NPs have been employed in conjunction with microorganisms as a facilitator in the production of various types of meat, including beef, poultry, and fish, to enhance preservation and extend shelf life through their roles as antimicrobial agents or antioxidants. The incorporation of these particles into meat products, their integration into biofilm manufacturing, and their application in packaging materials serve to enhance the shelf life of these products.

6. Potential Risks and Threats Associated with the Implementation of Nanotechnology

NPs are synthesized in substantial volumes and subsequently discharged into the ecosystem. During the stages of the manufacturing, processing, transportation, environmental remediation, and disposal of NPs, various potential risks may emerge [15,132,313–315]. These particles influence the health of the human body, as well as that of animals, impacting every organ system within the body [1,4,14,15,126]. Nonetheless, the ultimate outcome of NPs remains uncertain. To thoroughly assess the detrimental impacts of nanotechnology on public health, extensive scientific investigations concentrating on bioavailability, absorption, and in vivo accumulation are necessary [15,313].

Currently, the application of nanotechnology is more prevalent in food packaging than in food processing [31,105,255]. This trend is attributed to the favorable perception of employing nanotechnology in surface packaging, as it does not involve the introduction of NPs into the food system, thereby alleviating concerns associated with this technology [22,23,31,255]. Recent studies suggest that NPs may migrate from packaging materials into food, subsequently entering the bloodstream and accumulating within the body's systems, thereby presenting a potential risk to public health [15,255]. ZnO-NPs and TiO_2-NPs have been observed to induce genotoxic effects in intestinal epithelial cells [129,255,316]. The toxicity of NPs is influenced by various parameters such as the size of the NPs, the viscosity of the solution, the temperature at which they are stored, and the length of the storage period [17]. Furthermore, in fermented dairy products, particularly those that include probiotic bacteria, a detrimental impact of NPs on viable cells is noted, as the majority of these particles impede the growth of microorganisms, resulting in a reduction in the population of these bacteria and a decline in their metabolic byproducts [317].

Considering the numerous uncertainties associated with the applications of nanotechnology, it is essential to perform genotoxicity studies and precise risk assessments.

Researchers may identify novel approaches to assess and mitigate the risks associated with nanotechnology, thereby safeguarding both consumers and the environment, through the examination of the behavior, transport pathways, and potential long-term effects of NPs.

6.1. Regulatory Frameworks and Challenges

Microbially synthesized NPs such as Ag-NPs, ZnO-NPs, and TiO_2-NPs are being increasingly utilized in food and dairy applications, especially in the areas of packaging and preservation [31,55,284]. Regulatory frameworks worldwide are designed to ensure safety, although they vary in their scope and implementation methods. Within the European Union, the European Food Safety Authority (EFSA) offers directives regarding the safety evaluation of NPs utilized in food additives, contact materials, and novel foods, emphasizing the importance of physicochemical characterization [170,254,285,318]. Nevertheless, the standardization of testing methodologies for toxicity and migration is still constrained. The Food and Drug Administration (FDA) in the United States oversees NPs under general food safety regulations, lacking specific legislation for nanotechnology. This absence of targeted regulation leads to ambiguities concerning the long-term health implications of these materials [170,254,284]. Australia, via Food Standards Australia New Zealand (FSANZ), performs risk assessments for NPs, including TiO_2-NPs, although frameworks for compliance specific to nanotechnology are still in development [29,285]. Significant global challenges encompass the lack of standardized definitions for nanofoods, the inadequacy of methods for migration testing, and the scarcity of data regarding chronic toxicity, bioaccumulation, and genotoxicity [315,319]. To address these regulatory gaps, it is essential to establish harmonized protocols for safety, toxicity, and environmental risk assessments.

6.2. Consumer Perception

The perception of consumers regarding microbially synthesized NPs in food and dairy products is notably shaped by their awareness, perceived advantages, and concerns related to safety.

6.2.1. Benefits Driving Acceptance

Microbially synthesized NPs provide various functional benefits in food systems, particularly through their antimicrobial properties, which improve food safety, extend shelf life, and enhance overall product quality [161,172,184,254,284,298]. For example, Ag-NPs are being progressively integrated into packaging materials due to their effectiveness in inhibiting microbial growth [31]. In a similar vein, smart packaging technologies that incorporate nanosensors are capable of detecting spoilage and contamination in real time [161,192,233,320]. Consumers place significant importance on concrete advantages, including enhanced nutrition and safety, particularly within premium categories such as dairy products [284,315,320]. Studies demonstrate that acceptance tends to rise notably when the perceived advantages, particularly those associated with health, nutrition, and safety, are clearly greater than the potential risks involved [284].

6.2.2. Concerns and Mistrust

Despite their potential, consumer mistrust continues to pose a significant obstacle to the adoption of NP-based food technologies. A considerable segment of the population possesses a limited understanding of nanotechnology, frequently leading to widespread skepticism [15]. In addition to scientific risk data, numerous consumers take into account wider ethical, moral, and social implications when assessing the use of nanomaterials in food. Concerns encompass possible nanotoxicity effects, including oxidative stress, DNA damage, and bioaccumulation within organs. Regulatory actions in specific regions, including the prohibition of certain NPs in various parts of Europe, contribute to increased consumer apprehension [15,315]. The lack of clear and transparent labeling, along with inconsistencies in international regulatory frameworks, leads to a decline in public trust.

6.2.3. Strategies for Enhancing Acceptance

To promote public acceptance, it is crucial to adopt strategies that emphasize transparency and education. This encompasses engaging consumers in the product development process, ensuring the transparent and accurate labeling of NP content, and enhancing public awareness about both the advantages and potential risks [15]. Surveys carried out in nations such as Switzerland highlight the significance of collaboration among multiple stakeholders—including industry, regulators, and academia—to guarantee that NP applications meet consumer expectations and values.

6.3. Environmental Impacts

As an environmentally acceptable substitute for traditional chemical synthesis, NPs produced by microbes such as bacteria, fungus, or plant extracts are a viable option. According to Chavez-Hernandez et al. [321], these environmentally friendly synthesis techniques are in line with sustainability principles and lessen reliance on harmful chemicals. By producing less waste than conventional plastics made from petrochemicals, biodegradable nanocomposites like starch and polylactic acid (PLA) further improve environmental friendliness [75,284,321]. There have been encouraging results in the field of environmental remediation using certain NPs, such as carbon nanotubes (CNTs) and iron oxide (Fe_2O_3). Contributing to cleaner ecosystems and sustainable resource management, these materials efficiently adsorb heavy metals and remove microbiological contaminants from polluted water sources [284,321]. There is, nevertheless, cause for concern about the bioaccumulation and environmental persistence of NPs, even though they have advantages. Soil and water are possible entry points for NPs into the food chain. For example, as shown with copper oxide NPs (CuO-NPs), they can cause pollution and oxidative stress in plants as they degrade, because they release harmful ions such heavy metals [314]. In addition to potentially interfering with biological processes in exposed organisms, non-biodegradable NPs add to particle pollution. Researchers must immediately begin collecting data on the environmental impacts, distribution routes, and ultimate destinations of NPs produced by microbes. Environmental risks can only be fully understood by life cycle assessments (LCAs) and eco-toxicological testing with model organisms (such as plants, soil microorganisms, and aquatic species) [321,322]. Guaranteeing safe and sustainable deployment will need the development of strong regulatory frameworks, as well as standardized processes for NP disposal, monitoring, and risk assessment.

7. Future Perspectives and Directions

To enhance the synthesis of biogenic NPs utilizing bacteria, fungi, yeasts, and algae, researchers must explore novel approaches to address challenges related to purification, scalability, contamination, toxicity, and aggregation. Future directions should focus on utilizing synthetic biology to design microbes for accurate NP synthesis and self-purification. Additionally, the development of integrated bioreactor systems that combine synthesis and purification processes is essential. Employing artificial intelligence to enhance microbial selection and purification workflows is also recommended. The integration of nanotechnology, including lab-on-chip devices and nanostructured supports, has the potential to improve the precision of synthesis and the efficiency of purification processes. Utilizing waste-derived substrates and recyclable purification media represents a sustainable approach that is consistent with the principles of a circular economy. Standardized protocols, interdisciplinary collaboration, and the investigation of novel microbes, such as extremophiles and marine species, will facilitate scalability and foster innovation. Application-specific NP design, concentrating on biomedical or environmental requirements, guarantees customized solutions, underpinned by stringent regulatory frameworks to promote commercialization.

Recent advancements in nanotechnology have led to notable developments within the food and dairy sectors, facilitating the emergence of innovative solutions designed to enhance food safety, quality, and functionality. One of its notable applications includes the detection and analysis of mycotoxins, pesticide residues, and chemical contaminants within food matrices. Advanced nanoscale sensors and detection platforms enable rigorous quality control and adherence to regulatory standards, thereby ensuring consumer safety and confidence. Notwithstanding these developments, the extensive deployment of nanotechnology within food systems is still in its early phases, requiring additional investigation, risk evaluation, and technological enhancement for widespread application.

One of the most rapidly evolving domains of investigation is food packaging utilizing nanotechnology. The advancement of intelligent packaging systems, utilizing nano-membranes derived from biodegradable, carbon-neutral nanocomposites, and silica-based materials, presents significant potential. Nano-enabled coatings significantly enhance barrier properties, thereby reducing microbial contamination and prolonging product shelf life. Furthermore, the incorporation of nano-sensors into packaging materials facilitates the immediate identification of spoilage, contamination, or chemical alterations, thus reducing food waste and providing significant advantages to both producers and consumers.

The future indicates a trajectory towards the advancement of green nanotechnology, which prioritizes environmentally sustainable methodologies. The utilization of advantageous microorganisms, such as lactic acid bacteria and probiotic yeasts, for the synthesis of NPs presents a promising approach to address potential toxicity issues linked to traditional nanomaterials. These biological nanofactories are capable of synthesizing functional nanostructures that exhibit an enhanced biocompatibility, safety, and efficiency. These advancements are expected to significantly impact food preservation, especially in the realm of fermented dairy products.

Moreover, nanotechnology is anticipated to transform the manufacturing processes of functional foods and enhance precision in drug delivery systems. The application of probiotic bacteria as starter cultures, in conjunction with nanocarriers, will improve the delivery of BACs and probiotics in fermented dairy products. Furthermore, the integration of nanofibers and their customized interactions with food constituents offers significant opportunities for post-processing, enhancements in texture, and the precise release of nutrients and BACs.

The comprehensive modification and optimization of nanotechnology applications within the food sector is crucial to fully harness this potential. Addressing safety, environmental implications, regulatory structures, and consumer acceptance will be crucial. Should these challenges be addressed, nanotechnology is set to emerge as a significant influence in the food and dairy sectors, revolutionizing food processing, preservation, packaging, and the development of functional foods in the foreseeable future.

8. Conclusions

The utilization of green nanotechnology, which involves the microbial synthesis of NPs by various microorganisms such as bacteria, fungi, yeast, and algae, signifies a significant advancement in food and dairy systems. This approach provides sustainable and innovative solutions aimed at improving safety, quality, and functionality. This review highlights the diverse capabilities of microbially synthesized NPs, including Ag-NPs, ZnO-NPs, and TiO_2-NPs, which demonstrate significant antimicrobial, antioxidant, antifungal, and antiviral activities. The aforementioned attributes facilitate sophisticated applications such as antimicrobial packaging, nanoencapsulation to enhance the bioavailability of BACs, pathogen detection, and the extension of shelf life in dairy products (e.g., milk, yogurt, and cheese) and meat. The utilization of biological resources, such as agro-industrial byproducts from areas like West Asia, is consistent with the principles of a circular economy. This approach minimizes environmental consequences and lowers production expenses in comparison to traditional chemical and physical synthesis techniques.

Notwithstanding these advancements, considerable challenges remain, particularly concerning scalability and purification. Intricate purification methodologies, especially concerning intracellular NPs, along with the variability in NP dimensions and morphology, as well as challenges related to aggregation, hinder production at an industrial scale. The proposed solutions encompass the prioritization of extracellular synthesis, the application of advanced separation techniques such as magnetic separation and nanofiltration, and the optimization of bioreactors through the implementation of standardized protocols. Furthermore, potential hazards including the migration of NPs from packaging into food, bioaccumulation, and genotoxicity (for instance, ZnO-NPs and TiO_2-NPs causing damage to intestinal cells) require comprehensive safety evaluations. Global regulatory frameworks, such as those established by the EU's EFSA and the US FDA, exhibit a deficiency in specific guidelines pertaining to nanotechnology. This absence results in inconsistencies that obstruct the process of commercialization. The acceptance of consumers is additionally hindered by a lack of awareness and apprehensions regarding nanotoxicity, highlighting the necessity for clear labeling, public education initiatives, and collaboration among stakeholders.

The environmental implications of green NPs are twofold. Biodegradable nanocomposites and waste-derived substrates contribute to sustainability; however, issues regarding the persistence, bioaccumulation, and toxicity of NPs, such as CuO-NPs inducing oxidative stress in plants, necessitate thorough life cycle assessments and eco-toxicological investigations. Future research avenues encompass the utilization of synthetic biology for the accurate synthesis of nanoparticles, the incorporation of artificial intelligence for the selection of microbial strains, and the advancement of sustainable bioreactor systems. Advancements including intelligent packaging integrated with nanosensors, dairy products enhanced with probiotics, and strategies for waste valorization hold the potential to tackle challenges related to food security and nutritional requirements. Nonetheless, the realization of this potential is contingent upon the establishment of cohesive global regulations, the implementation of standardized testing protocols, and collaborative interdisciplinary initiatives aimed at ensuring safety, scalability, and consumer confidence.

In a nutshell, NPs synthesized through microbial processes present significant potential to transform food and dairy systems by improving safety, nutritional content, and sustainability. Addressing technical, regulatory, and societal obstacles through ongoing research and collaboration will establish green nanotechnology as a fundamental component of advanced food technologies, tackling worldwide issues related to food security and environmental sustainability.

Author Contributions: A.K.N., S.T.G.A.-S., D.K.V., S.S., and A.R.P. have conceptualized, interpreted, corrected, and compiled literature and technically sound final versions of the manuscript; A.K.N., M.T., S.S., and P.P. have compiled the tables for manuscripts; A.K.N., S.T.G.A.-S., D.K.V.,

P.P., M.T., S.S., and A.R.P. have read the manuscript and provided suggestions and corrections for the final submission. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable

Acknowledgments: The authors, A.K.N. and S.T.G.A.-S. would like to acknowledge the financial assistance of the Food and Dairy Lab., Department of Food Science, College of Agriculture, University of Basrah.

Conflicts of Interest: The authors state that there are no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACCases	Acetyl-CoA carboxylase
AFM	Atomic force microscopy
Ag_2O	Silver oxide
$AgNO_3$	Silver nitrate
Ag	Silver
AOT	Sodium bis-2-ethylhexyl-sulfosuccinate
Au	Gold
BACs	Bioactive compounds
CFU	Colony-forming units
CNTs	Carbon nanotubes
CuO	Copper oxide
CVD	Chemical vapor deposition
DLS	Dynamic light scattering
DNA	Deoxyribonucleic acid
DPPH	2,2-diphenyl-1-picrylhydrazyl
E551	Silicon dioxide
EDX	Energy dispersive X-ray
EFSA	European Food Safety Authority
EU	European Union
FCC	Face-centered cubic
Fe_2O_3	Iron oxide
Fe_3O_4/Cs/MoS_2/laccase-NPs	Iron oxide/Chitosan/Molybdenum disulfide/laccase nanoparticles
Fe	Iron
FESEM	Field emission scanning electron microscopy
FE–SEM–EDX	Field Emission Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy
FSANZ	Food Standards Australia New Zealand
FTIR	Fourier-transform infrared
GRAS	Generally Recognized as Safe
$H[AuCl_4]$	Chloroauric acid
H_2S	Hydrogen sulfide
HPLC	High-Performance Liquid Chromatography
HRTEM	High-resolution transmission electron microscopy
IC_{50}	Half-maximal inhibitory concentration
Lb.	*Lactobacillus*
Lc.	*Lactococcus*
LCAs	Life cycle assessments
Mg	Magnesium
MgO	Magnesium Oxide
NADH	Nicotinamide adenine dinucleotide
NADH-DNR	NADH-dependent nitrate reductase
NADPH	Nicotinamide adenine dinucleotide phosphate hydrogen
NC-AFM	Non-contact atomic force microscopy

NPs	Nanoparticles
Pb	Lead
PDI	Polydispersity index
Pd	Palladium
PdO	Palladium oxide
PECVD	Plasma-enhanced chemical vapor deposition
PL spectrometer	Photoluminescence spectroscopy
PLA	Polylactic acid
PLAL	Pulsed laser ablation in liquid
Ps.	*Pseudomonas*
PUFAs	Polyunsaturated fatty acid
PVD	Physical vapor deposition
PVP	Polyvinylpyrrolidone
RF Plasma	Radio Frequency Plasma
RNA	Ribonucleic acid
Sa.	*Saccharomyces*
SAED	Selected area electron diffraction
SEM	Scanning electron microscope
Se	Selenium
SnO_2	Tin oxide
SPR	Surface plasmon resonance
St.	*Staphylococcus*
TEM	Transmission electron microscopy
Tg	Glass transition temperature
TiO_2	Titanium dioxide
US FDA	United States Food and Drug Administration
UV–Vis spectroscopy	Ultraviolet–visible spectroscopy
XRD	X-ray diffraction
ZnO	Zinc oxide

References

1. Santillán-Urquiza, E.; Ruiz-Espinosa, H.; Angulo-Molina, A.; Ruiz, J.F.V.; Méndez-Rojas, M. A. Applications of nanomaterials in functional fortified dairy products: Benefits and implications for human health. In *Nutrient Delivery*; Academic Press: Cambridge, MA, USA, 2017; pp. 293–328.
2. Vélez, M.A.; Perotti, M.C.; Santiago, L.; Gennaro, A.M.; Hynes, E. Bioactive compounds delivery using nanotechnology: Design and applications in dairy food. In *Nutrient Delivery*; Academic Press: Cambridge, MA, USA, 2017; pp. 221–250.
3. Scott, N.R.; Chen, H.; Cui, H. Nanotechnology Applications and Implications of Agrochemicals toward Sustainable Agriculture and Food Systems. *J. Agric. Food Chem.* **2018**, *66*, 6451–6456.
4. Verma, D.K.; Goyal, M.R.; Suleria, H.A.R. *Nanotechnology and Nanomaterial Applications in Food, Health and Biomedical Sciences*; CRC Press: Boca Raton, FL, USA; Apple Academic Press: Burlington, CA, USA, 2020; ISBN 9781771887649. https://doi.org/10.1201/9780429425660.
5. El-Saadony, M.T.; Sitohy, M.Z.; Ramadan, M.F.; Saad, A.M. Green Nanotechnology for Preserving and Enriching Yogurt with Biologically Available Iron (II). *Innov. Food Sci. Emerg. Technol.* **2021**, *69*, 102645. https://doi.org/10.1016/j.ifset.2021.102645.
6. Ao, B.; Du, Q.; Liu, D.; Shi, X.; Tu, J.; Xia, X. A review on synthesis and antibacterial potential of bio-selenium nanoparticles in the food industry. *Front. Microbiol.* **2023**, *14*, 1229838.
7. Ramani, A.; Taherabbas, S.; Saji, R.; Bumbadiya, M.; Gandhi, K.; Seth, R. Nanotechnology: An Emerging Trend in the Dairy Industry-Applications and Future Challenges. *Food Humanit.* **2024**, *3*, 100409.
8. Verma, D.K.; Patel, A.R.; Tripathy, S.; Gupta, A.K.; Singh, S.; Shah, N.; Utama, G.L.; Chávez-González, M.L.; Zongo, K.; Banwo, K.; et al. Processing and formulation technology of nutritional and functional food products by utilizing cheese and/or paneer whey: A critical review. *J. King Saud Univ.-Sci.* **2024**, *36*, 103508. https://doi.org/10.1016/j.jksus.2024.103508.
9. Kaptan, B. Nanotechnological Applications in Current Innovative Approaches in Dairy Technology—A review. *J. Agric. Sci.* **2025**, *31*, 1–11.
10. Mirhosseini, M.; Firouzabadi, F.B. Reduction of Listeria monocytogenes and Bacillus cereus in milk by zinc oxide nanoparticles. *Iran. J. Pathol.* **2015**, *10*, 97.

11. Mirhosseini, M.; Afzali, M. Investigation into the Antibacterial Behavior of Suspensions of Magnesium Oxide Nanoparticles in Combination with Nisin and Heat against Escherichia Coli and Staphylococcus Aureus in Milk. *Food Control.* **2016**, *68*, 208–215. https://doi.org/10.1016/j.foodcont.2016.03.048.
12. Elsherif, W.M.; Hassanien, A.A.; Zayed, G.M.; Kamal, S.M. Natural Approach of Using Nisin and Its Nanoform as Food Bio-Preservatives against Methicillin Resistant Staphylococcus Aureus and *E. Coli* O157:H7 in Yoghurt. *BMC Vet. Res.* **2024**, *20*, 192. https://doi.org/10.1186/s12917-024-03985-1.
13. Tripathy, S.; Verma, D.K.; Gupta, A.K.; Srivastav, P.P.; Patel, A.R.; González, M.L.C.; Utama, G.L.; Aguilar, C.N. Nanoencapsulation of biofunctional components as a burgeoning nanotechnology-based approach for functional food development: A review. *Biocatal. Agric. Biotechnol.* **2023**, *53*, 102890. https://doi.org/10.1016/j.bcab.2023.102890.
14. Zorraquín-Peña, I.; Cueva, C.; Bartolomé, B.; Moreno-Arribas, M.V. Silver nanoparticles against foodborne bacteria. Effects at intestinal level and health limitations. *Microorganisms* **2020**, *8*, 132.
15. Rothen-Rutishauser, B.; Bogdanovich, M.; Harter, R.; Milosevic, A.; Petri-Fink, A. Use of nanoparticles in food industry: Current legislation, health risk discussions and public perception with a focus on Switzerland. *Toxicol. Environ. Chem.* **2021**, *103*, 423–437.
16. Karmous, I.; Tlahig, S.; Loumerem, M.; Lachiheb, B.; Bouhamda, T.; Mabrouk, M.; Debouba, M.; Chaoui, A. Assessment of the risks of copper-and zinc oxide-based nanoparticles used in Vigna radiata L. culture on food quality, human nutrition and health. *Environ. Geochem. Health* **2022**, *44*, 4045–4061.
17. Xuan, L.; Ju, Z.; Skonieczna, M.; Zhou, P.K.; Huang, R. Nanoparticles-Induced Potential Toxicity on Human Health: Applications, Toxicity Mechanisms, and Evaluation Models. *MedComm* **2023**, *4*, e327.
18. Khan, S.T.; Saleem, S.; Ahamed, M.; Ahmad, J. Survival of probiotic bacteria in the presence of food grade nanoparticles from chocolates: An in vitro and in vivo study. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 6689–6700.
19. Maurya, V.K.; Shakya, A.; Aggarwal, M.; Gothandam, K.M.; Bohn, T.; Pareek, S. Fate of B-carotene within Loaded Delivery Systems in Food: State of Knowledge. *Antioxidants* **2021**, *10*, 426.
20. Karmakar, P.; Ray, P.R.; Chatterjee, P.N.; Mahato, A.; Haldar, L. Potential of zinc oxide nanoparticle for dietary fortification in yoghurt: Physicochemical, microbiological, rheological and textural analysis. *Asian J. Dairy Food Res*. **2022**, *39*, 175–180.
21. Sari, P.E.; Abidin, Z.; Arief, I.I.; Budiman, C. Characteristics and antibacterial activity of zno nanoparticle-fortified probiotic yogurt. *Bul. Peternak.* **2024**, *48*, 284–291.
22. Primožič, M.; Knez, Ž.; Leitgeb, M. (Bio)Nanotechnology in Food Science—Food Packaging. *Nanomaterials* **2021**, *11*, 292.
23. de Sousa, M.S.; Schlogl, A.E.; Estanislau, F.R.; Souza, V.G.L.; dos Reis Coimbra, J.S.; Santos, I.J.B. Nanotechnology in Packaging for Food Industry: Past, Present, and Future. *Coatings* **2023**, *13*, 1411.
24. Eker, F.; Duman, H.; Akdaşçi, E.; Bolat, E.; Sarıtaş, S.; Karav, S.; Witkowska, A.M. A Comprehensive Review of Nanoparticles: From Classification to Application and Toxicity. *Molecules* **2024**, *29*, 3482.
25. Ghosh, S.; Mandal, R.K.; Mukherjee, A.; Roy, S. Nanotechnology in the manufacturing of sustainable food packaging: A review. *Discov. Nano* **2025**, *20*, 36.
26. Grasso, G.; Zane, D.; Dragone, R. Microbial nanotechnology: Challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. *Nanomaterials* **2019**, *10*, 11.
27. Behera, A.; Mohapatra, S.S.; Verma, D.K. Nanomaterials: Fundamental Principle and Applications. In *Nanotechnology and Nanomaterial Applications in Food, Health and Biomedical Sciences*; Verma, D.K., Goyal, M.R., Suleria, H.A.R., Eds.; CRC Press: Boca Raton, FL, USA; Apple Academic Press: Burlington, CA, USA, 2020; pp. 163–194.
28. Verma, D.K.; Srivastava, S.; Kumar, V.; Asthir, B.; Mohan, M.; Srivastav, P.P. Nano-Particle-Based Delivery Systems: Applications in Agriculture. In *Engineering Interventions in Agricultural Processing*; Goyal, M.R., Verma, D.K., Eds.; as part of book series on Innovations in Agricultural and Biological Engineering; CRC Press: Boca Raton, FL, USA; Apple Academic Press: Burlington, CA, USA, 2018; Volume 8, pp. 107–130.
29. Kumari, R.; Suman, K.; Karmakar, S.; Mishra, V.; Lakra, S.G.; Saurav, G.K.; Mahto, B.K. Regulation and safety measures for nanotechnology-based agri-products. *Front. Genome Ed.* **2023**, *5*, 1200987.
30. Nagda, G.; Rai, N.; Jaya Shakshi Bhalothia, C.; Singh, N.A. Nanoparticles Synthesis Using Extremophilic Microbes and their Potential Agricultural Applications. In *Extremophiles for Sustainable Agriculture and Soil Health Improvement*; Springer Nature: Cham, Switzerland, 2024; pp. 455–483.
31. Rao, M.M.; Mohammad, N.; Banerjee, S.; Khanna, P.K. Synthesis and food packaging application of silver nano-particles: A review. *Hybrid Adv.* **2024**, *6*, 100230. https://doi.org/10.1016/j.hybadv.2024.100230.

32. Rahmati, F.; Hosseini, S.S.; Mahuti Safai, S.; Asgari Lajayer, B.; Hatami, M. New insights into the role of nanotechnology in microbial food safety. *3 Biotech* **2020**, *10*, 425.
33. Barabadi, H.; Mobaraki, K.; Jounaki, K.; Sadeghian-Abadi, S.; Vahidi, H.; Jahani, R.; Noqani, H.; Hosseini, O.; Ashouri, F.; Amidi, S. Exploring the biological application of Penicillium fimorum-derived silver nanoparticles: In vitro physicochemical, antifungal, biofilm inhibitory, antioxidant, anticoagulant, and thrombolytic performance. *Heliyon* **2023**, *9*, e16853.
34. Liu, P.; Long, H.; Cheng, H.; Liang, M.; Liu, Z.; Han, Z.; Guo, Z.; Shi, H.; Sun, M.; He, S. Highly-efficient synthesis of biogenic selenium nanoparticles by Bacillus paramycoides and their antibacterial and antioxidant activities. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1227619.
35. Hamouda, R.A.; Aljohani, E.S. Assessment of silver nanoparticles derived from brown algae sargassum vulgare: Insight into antioxidants, anticancer, antibacterial and hepatoprotective effect. *Mar. Drugs* **2024**, *22*, 154. https://doi.org/10.3390/md22040154.
36. Sirelkhatim, A.; Mahmud, S.; Seeni, A.; Kaus, N.H.M.; Ann, L.C.; Bakhori, S.K.M.; Hasan, H.; Mohamad, D. Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. *Nano-Micro Lett.* **2015**, *7*, 219–242.
37. Bruna, T.; Maldonado-Bravo, F.; Jara, P.; Caro, N. Silver nanoparticles and their antibacterial applications. *Int. J. Mol. Sci.* **2021**, *22*, 7202.
38. Hamouda, R.A.; Alharbi, A.A.; Al-Tuwaijri, M.M.; Makharita, R.R. The Antibacterial Activities and Characterizations of Biosynthesized Zinc Oxide Nanoparticles, and Their Coated with Alginate Derived from Fucus Vesiculosus. *Polymers* **2023**, *15*, 2335. https://doi.org/10.3390/polym15102335.
39. Sonbol, H.; AlYahya, S.; Ameen, F.; Alsamhary, K.; Alwakeel, S.; Al-Otaibi, S.; Korany, S. Bioinspired Synthesize of CuO Nanoparticles Using Cylindrospermum Stagnale for Antibacterial, Anticancer and Larvicidal Applications. *Appl. Nanosci.* **2023**, *13*, 917–927. https://doi.org/10.1007/s13204-021-01940-2.
40. Gong, X.; Jadhav, N.D.; Lonikar, V.V.; Kulkarni, A.N.; Zhang, H.; Sankapal, B.R.; Ren, J.; Xu, B.B.; Pathan, H.M.; Ma, Y.; et al. An overview of green synthesized silver nanoparticles towards bioactive antibacterial, antimicrobial and antifungal applications. *Adv. Colloid Interface Sci.* **2024**, *323*, 103053.
41. Abdel-Maksoud, G.; Abdel-Nasser, M.; Hassan, S.E.D.; Eid, A.M.; Abdel-Nasser, A.; Fouda, A. Biosynthesis of Titanium Dioxide Nanoparticles Using Probiotic Bacterial Strain, Lactobacillus Rhamnosus, and Evaluate of Their Biocompatibility and Antifungal Activity. *Biomass Convers. Biorefinery* **2023**, *14*, 23961–23983. https://doi.org/10.1007/s13399-023-04587-x.
42. Gaber, S.E.; Hashem, A.H.; El-Sayyad, G.S.; Attia, M.S. Antifungal activity of myco-synthesized bimetallic ZnO-CuO nanoparticles against fungal plant pathogen Fusarium oxysporum. *Biomass Convers. Biorefinery* **2024**, *14*, 25395–25409. https://doi.org/10.1007/s13399-023-04550-w.
43. Pachaiappan, R.; Ponce, L.C.; Manavalan, K.; Awad, F.; Rajan, V.F. Nanoparticles as an exotic antibacterial, antifungal, and antiviral agents. In *Advances in Nanotechnology for Marine Antifouling*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 231–270. https://doi.org/10.1016/B978-0-323-91762-9.00005-8.
44. Mohammed, E.J.; Abdelaziz, A.E.; Mekky, A.E.; Mahmoud, N.N.; Sharaf, M.; Al-Habibi, M.M.; Khairy, N.M.; Al-Askar, A.A.; Youssef, F.S.; Gaber, M.A.; et al. Biomedical promise of Aspergillus flavus-biosynthesized selenium nanoparticles: A green synthesis approach to antiviral, anticancer, anti-biofilm, and antibacterial applications. *Pharmaceuticals* **2024**, *17*, 915.
45. Balaraman, P.; Balasubramanian, B.; Kaliannan, D.; Durai, M.; Kamyab, H.; Park, S.; Chelliapan, S.; Lee, C.T.; Maluventhen, V.; Maruthupandian, A. Phyco-Synthesis of Silver Nanoparticles Mediated from Marine Algae Sargassum Myriocystum and Its Potential Biological and Environmental Applications. *Waste Biomass Valorization* **2020**, *11*, 5255–5271. https://doi.org/10.1007/s12649-020-01083-5.
46. Annamalai, J.; Ummalyma, S.B.; Pandey, A.; Bhaskar, T. Recent trends in microbial nanoparticle synthesis and potential application in environmental technology: A comprehensive review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 49362–49382.
47. Alsafran, M.; Razavi, M.M.; Rizwan, M.; Usman, K. A review on synthesis and characterization of selenium nanoparticles from plant extracts for applications in agriculture, biomedicine, and environment. *Green Chem. Lett. Rev.* **2025**, *18*, 2488237.
48. Khan, M.A.; Masood, A.; Ali, K.; Farid, N.; Bashir, A.; Dar, M.S. Green synthesis of silver, starch, and zinc oxide mediated nanoparticles with probiotics and plant extracts, their characterization and anti-bacterial activity. *Microb. Pathog.* **2024**, *196*, 107012.
49. Chaudhary, R.; Nawaz, K.; Khan, A.K.; Hano, C.; Abbasi, B.H.; Anjum, S. An Overview of the Algae-mediated Biosynthesis of Nanoparticles and Their Biomedical Applications. *Biomolecules* **2020**, *10*, 1498.
50. Xu, L.; Wang, Y.Y.; Huang, J.; Chen, C.Y.; Wang, Z.X.; Xie, H. Silver nanoparticles: Synthesis, medical applications and biosafety. *Theranostics* **2020**, *10*, 8996. https://doi.org/10.7150/thno.45413.

51. Bisht, N.; Phalswal, P.; Khanna, P.K. Selenium nanoparticles: A review on synthesis and biomedical applications. *Mater. Adv.* **2022**, *3*, 1415–1431.
52. Pasparakis, G. Recent developments in the use of gold and silver nanoparticles in biomedicine. *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnology*, **2022**, *14*, e1817. https://doi.org/10.1002/wnan.1817.
53. Mohanta, Y.K.; Mishra, A.K.; Panda, J.; Chakrabartty, I.; Sarma, B.; Panda, S.K.; Chopra, H.; Zengin, G.; Moloney, M.G.; Sharifi-Rad, M. Promising applications of phyto-fabricated silver nanoparticles: Recent trends in biomedicine. *Biochem. Biophys. Res. Commun.* **2023**, *688*, 149126.
54. Salman, M.; Ismail, M.; Ullah, B.; Khan, M.M.; Hussein, M.; Khan, J.U.; Ahmad, B.; Bashar, N.U.; Baseer, A.; Munir, S. The Role of Bacillus Species in the Synthesis of Metal and Metal Oxide Nanoparticles and Their Biomedical Applications: A Mini Review. *Nanomed. J.* **2023**, *10*, 85–95.
55. Kalairaj, A.; Rajendran, S.; Karthikeyan, R.; Panda, R.C.; Senthilvelan, T. A Comprehensive Review on Preparation of Silver Nanoparticles from a Bacteriocin for the Natural Preservation of Food Products. *Appl. Biochem. Biotechnol.* **2024**, *197*, 1419–1452.
56. Chauhan, R.; Reddy, A.; Abraham, J. Biosynthesis of Silver and Zinc Oxide Nanoparticles Using Pichia Fermentans JA2 and Their Antimicrobial Property. *Appl. Nanosci.* **2015**, *5*, 63–71. https://doi.org/10.1007/s13204-014-0292-7.
57. Agressott, E.V.; de Moura, T.A.; Marinho, N.L.; Vasconcelos, T.D.L.; Cunha, F.A.; Fechine, P.B.A.; de Souza Filho, A.G.; Paschoal, A.R. Tip-Enhanced Raman spectroscopy investigations of core-shell Ag-proteins nanoparticles synthesized by Rhodotorula mucilaginosa and Rhodotorula glutinis fungi. *Vib. Spectrosc.* **2020**, *110*, 103104.
58. Bachheti, R.K.; Abate, L.; Bachheti, A.; Madhusudhan, A.; Husen, A. Algae-, fungi-, and yeast-mediated biological synthesis of nanoparticles and their various biomedical applications. In *Handbook of Greener Synthesis of Nanomaterials and Compounds*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 701–734.
59. Salem, S.S. Bio-fabrication of selenium nanoparticles using Baker's yeast extract and its antimicrobial efficacy on food borne pathogens. *Appl. Biochem. Biotechnol.* **2022**, *194*, 1898–1910.
60. Fath-Alla, A.A.; Khalil, N.M.; Mohamed, A.S.; Abd El-Ghany, M.N. Antiradical and Anti-Inflammatory Activity of Saccharomyces Cerevisiae-Mediated Selenium Nanoparticles. *Egypt. J. Bot.* **2024**, *64*, 773–787. https://doi.org/10.21608/ejbo.2024.267306.2692.
61. Gharieb, M.M.; Soliman, A.M.; Omara, M.S. Biosynthesis of Selenium Nanoparticles by Potential Endophytic Fungi Penicillium Citrinum and Rhizopus Arrhizus: Characterization and Maximization. *Biomass Convers. Biorefinery* **2023**, *15*, 2319–2328. https://doi.org/10.1007/s13399-023-05084-x.
62. Venkatesan, J.; Kim, S.K.; Shim, M.S. Antimicrobial, Antioxidant, and Anticancer Activities of Biosynthesized Silver Nanoparticles Using Marine Algae Ecklonia Cava. *Nanomaterials* **2016**, *6*, 235. https://doi.org/10.3390/nano6120235.
63. Dahoumane, S.A.; Mechouet, M.; Wijesekera, K.; Filipe, C.D.; Sicard, C.; Bazylinski, D.A.; Jeffryes, C. Algae-mediated biosynthesis of inorganic nanomaterials as a promising route in nanobiotechnology—A review. *Green Chem.* **2017**, *19*, 552–587.
64. Chaturvedi, M.; Yadav, T.; Masih, S.C. Biogenic synthesis of nanoparticles from algae and its various applications. In *Algae and Sustainable Technologies*; CRC Press: Boca Raton, FL, USA, 2020; pp. 185–200.
65. Khan, M.S.; Ranjani, S.; Hemalatha, S. Synthesis and characterization of Kappaphycus alvarezii derived silver nanoparticles and determination of antibacterial activity. *Mater. Chem. Phys.* **2022**, *282*, 125985. https://doi.org/10.1016/j.matchemphys.2022.125985.
66. Rajeshkumar, S.; Bharath, L.V. Mechanism of plant-mediated synthesis of silver nanoparticles–a review on biomolecules involved, characterisation and antibacterial activity. *Chem.-Biol. Interact.* **2017**, *273*, 219–227.
67. Jadoun, S.; Arif, R.; Jangid, N.K.; Meena, R.K. Green Synthesis of Nanoparticles Using Plant Extracts: A Review. *Environ. Chem. Lett.* **2021**, *19*, 355–374.
68. Mohammadidargah, M.; Pedram, P.; Cabrera-Barjas, G.; Delattre, C.; Nesic, A.; Santagata, G.; Cerruti, P.; Moeini, A. Biomimetic synthesis of nanoparticles: A comprehensive review on green synthesis of nanoparticles with a focus on Prosopis farcta plant extracts and biomedical applications. *Adv. Colloid Interface Sci.* **2024**, *332*, 103277. https://doi.org/10.1016/j.cis.2024.103277.
69. Doan, L.; Lam, N.N.; Tran, K.; Huynh, K.G. Fruit Derived Silver Nanoparticles Synthesis for Beginners—A Review. *Nanocomposites* **2025**, *11*, 20–51.
70. Vasyliev, G.; Vorobyova, V. Valorization of Food Waste to Produce Eco-Friendly Means of Corrosion Protection and "Green" Synthesis of Nanoparticles. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 6615118.

71. Abdul Razak, N.A.; Othman, N.H.; Mat Shayuti, M.S.; Jumahat, A.; Sapiai, N.; Lau, W.J. Agricultural and Industrial Waste-Derived Mesoporous Silica Nanoparticles: A Review on Chemical Synthesis Route. *J. Environ. Chem. Eng.* **2022**, *10*, 107322.
72. Suriyaraj, S.P.; Verma, D.K.; Bakrudeen, H.B.; Prabhu, Y.A.; Vaidevi, S.; Ramiya, B.; Monika, V.; Kartik, J.P.M.; Chandraraj, K. Characterization Techniques for Nanomaterials: Research and Opportunities for Potential Biomedical Applications. In *Nanotechnology and Nanomaterial Applications in Food, Health and Biomedical Sciences*; Verma, D.K., Goyal, M.R., Suleria, H.A.R., Eds.; CRC Press: Boca Raton, FL, USA; Apple Academic Press: Burlington, CA, USA, 2020; pp. 195–229.
73. Gudikandula, K.; Charya Maringanti, S. Synthesis of silver nanoparticles by chemical and biological methods and their antimicrobial properties. *J. Exp. Nanosci.* **2016**, *11*, 714–721.
74. Faried, M.; Shameli, K.; Miyake, M.; Hajalilou, A.; Kalantari, K.; Zakaria, Z.; Hara, H.; Khairudin, N.B.A. Synthesis of Silver Nanoparticles via Green Method Using Ultrasound Irradiation in Seaweed Kappaphycus Alvarezii Media. *Res. Chem. Intermed.* **2016**, *42*, 7991–8004. https://doi.org/10.1007/s11164-016-2574-z.
75. Ali, Z.A.; Niamah, A.K.; Hannosh, W.S. Isolation, Preparation and Characterization of Polylactic Acid Film Reinforced with Nano Silica. *J. Phys. Conf. Ser.* **2021**, *2063*, 012028.
76. Al-Masoodi, A.H.H.; Al-Masoodi, A.H.; Goh, B.T.; Abd Majid, W.H.B. Plasma-assisted growth of nanomaterials. In *Energy From Plasma*; Woodhead Publishing: Cambridge, UK, 2025; pp. 243–269.
77. Carlsson, J.O.; Martin, P.M. Chemical vapor deposition. In *Handbook of Deposition Technologies for Films and Coatings*; William Andrew Publishing: Kansas City, MO, USA, 2010; pp. 314–363.
78. Johns, C.; Islam, M.S.; Groza, J.R. Physical and Chemical Vapor Deposition Processes. In *Materials Processing Handbook*; CRC Press: Boca Raton, FL, USA, 2007; pp. 143–168.
79. Awan, T.I.; Afsheen, S.; Kausar, S. Advanced Deposition Techniques. In *Thin Film Deposition Techniques: Thin Film Deposition Techniques and Its Applications in Different Fields*; Springer Nature: Singapore, 2025; pp. 161–187.
80. Kustov, L.; Vikanova, K. Synthesis of metal nanoparticles under microwave irradiation: Get much with less energy. *Metals* **2023**, *13*, 1714.
81. Guisbiers, G.; Lara, H.H.; Mendoza-Cruz, R.; Naranjo, G.; Vincent, B.A.; Peralta, X.G.; Nash, K.L. Inhibition of Candida albicans biofilm by pure selenium nanoparticles synthesized by pulsed laser ablation in liquids. *Nanomed. : Nanotechnol. Biol. Med.* **2017**, *13*, 1095–1103.
82. Yu, Y.; Theerthagiri, J.; Lee, S.J.; Muthusamy, G.; Ashokkumar, M.; Choi, M.Y. Integrated technique of pulsed laser irradiation and sonochemical processes for the production of highly surface-active NiPd spheres. *Chem. Eng. J.* **2021**, *411*, 128486.
83. Xu, H.; Zeiger, B.W.; Suslick, K.S. Sonochemical synthesis of nanomaterials. *Chem. Soc. Rev.* **2013**, *42*, 2555–2567.
84. Calderón-Jiménez, B.; Montoro Bustos, A.R.; Pereira Reyes, R.; Paniagua, S.A.; Vega-Baudrit, J.R. Novel pathway for the sonochemical synthesis of silver nanoparticles with near-spherical shape and high stability in aqueous media. *Sci. Rep.* **2022**, *12*, 882. https://doi.org/10.1038/s41598-022-04921-9.
85. IAEA. *Gamma Irradiators for Radiation Processing*; International Atomic Energy Agency, Industrial Applications and Chemistry Section: Vienna, Austria, 2006. Available online: https://inis.iaea.org/records/517fx-exh85 (accessed on 12 April 2025).
86. Flores-Rojas, G.G.; López-Saucedo, F.; Bucio, E. Gamma-irradiation applied in the synthesis of metallic and organic nanoparticles: A short review. *Radiat. Phys. Chem.* **2020**, *169*, 107962.
87. Ouaras, K.; Lombardi, G.; Hassouni, K. Nanoparticles synthesis in microwave plasmas: Peculiarities and comprehensive insight. *Sci. Rep.* **2024**, *14*, 4653.
88. Pierson, H.O. *Handbook of Chemical Vapor Deposition: Principles, Technology and Applications*; William Andrew: Norwich, NY, USA, 1999.
89. Obaidullah, M.; Bahadur, N.M.; Furusawa, T.; Sato, M.; Sakuma, H.; Suzuki, N. Microwave assisted rapid synthesis of Fe_2O_3@ SiO_2 core-shell nanocomposite for the persistence of magnetic property at high temperature. *Colloids Surf. A Physicochem. Eng. Asp.* **2019**, *572*, 138–146.
90. Ratti, M.; Naddeo, J.J.; Griepenburg, J.C.; O'Malley, S.M.; Bubb, D.M.; Klein, E.A. Production of metal nanoparticles by pulsed laser-ablation in liquids: A tool for studying the antibacterial properties of nanoparticles. *J. Vis. Exp. JoVE* **2017**, *124*, 55416.
91. Ye, F.; Musselman, K.P. Synthesis of low dimensional nanomaterials by pulsed laser ablation in liquid. *APL Mater.* **2024**, *12*, 050602.
92. Rodriguez-Sanchez, L.; Blanco, M.C.; López-Quintela, M.A. Electrochemical synthesis of silver nanoparticles. *J. Phys. Chem. B* **2000**, *104*, 9683–9688.

93. Saleh, H.M.; Hassan, A.I. Synthesis and characterization of nanomaterials for application in cost-effective electrochemical devices. *Sustainability* **2023**, *15*, 10891.
94. Abdo, A.M.; Fouda, A.; Eid, A.M.; Fahmy, N.M.; Elsayed, A.M.; Khalil, A.M.A.; Alzahrani, O.M.; Ahmed, A.F.; Soliman, A.M. Green Synthesis of Zinc Oxide Nanoparticles (ZnO-NPs) by Pseudomonas Aeruginosa and Their Activity against Pathogenic Microbes and Common House Mosquito, Culex Pipiens. *Materials* **2021**, *14*, 6983. https://doi.org/10.3390/ma14226983.
95. El-Belely, E.F.; Farag, M.M.S.; Said, H.A.; Amin, A.S.; Azab, E.; Gobouri, A.A.; Fouda, A. Green Synthesis of Zinc Oxide Nanoparticles (ZnO-NPs) Using Arthrospira Platensis (Class: Cyanophyceae) and Evaluation of Their Biomedical Activities. *Nanomaterials* **2021**, *11*, 95. https://doi.org/10.3390/nano11010095.
96. Younis, N.S.; Mohamed, M.E.; El Semary, N.A. Green Synthesis of Silver Nanoparticles by the Cyanobacteria Synechocystis Sp.: Characterization, Antimicrobial and Diabetic Wound-Healing Actions. *Mar. Drugs* **2022**, *20*, 56. https://doi.org/10.3390/md20010056.
97. Haris, M.; Fatima, N.; Iqbal, J.; Chalgham, W.; Mumtaz, A.S.; El-Sheikh, M.A.; Tavafoghi, M. Oscillatoria Limnetica Mediated Green Synthesis of Iron Oxide (Fe2O3) Nanoparticles and Their Diverse In Vitro Bioactivities. *Molecules* **2023**, *28*, 2091. https://doi.org/10.3390/molecules28052091.
98. Chowdhury, S.; Basu, A.; Kundu, S. Green Synthesis of Protein Capped Silver Nanoparticles from Phytopathogenic Fungus Macrophomina Phaseolina (Tassi) Goid with Antimicrobial Properties against Multidrug-Resistant Bacteria. *Nanoscale Res. Lett.* **2014**, *9*, 365. https://doi.org/10.1186/1556-276X-9-365.
99. Elgorban, A.M.; Al-Rahmah, A.N.; Sayed, S.R.; Hirad, A.; Mostafa, A.A.F.; Bahkali, A.H. Antimicrobial Activity and Green Synthesis of Silver Nanoparticles Using Trichoderma Viride. *Biotechnol. Biotechnol. Equip.* **2016**, *30*, 299–304. https://doi.org/10.1080/13102818.2015.1133255.
100. Zhu, Y.; Hu, X.; Qiao, M.; Zhao, L.; Dong, C. Penicillium Polonicum-Mediated Green Synthesis of Silver Nanoparticles: Unveiling Antimicrobial and Seed Germination Advancements. *Heliyon* **2024**, *10*, e28971. https://doi.org/10.1016/j.heliyon.2024.e28971.
101. Bafghi, M.H.; Darroudi, M.; Zargar, M.; Zarrinfar, H.; Nazari, R. Biosynthesis of Selenium Nanoparticles by Aspergillus Flavus and Candida Albicans for Antifungal Applications. *Micro. Nano Lett.* **2021**, *16*, 656–669. https://doi.org/10.1049/mna2.12096.
102. Pechyen, C.; Tangnorawich, B.; Toommee, S.; Marks, R.; Parcharoen, Y. Green Synthesis of Metal Nanoparticles, Characterization, and Biosensing Applications. *Sens. Int.* **2024**, *5*, 100287.
103. Hosseingholian, A.; Gohari, S.D.; Feirahi, F.; Moammeri, F.; Mesbahian, G.; Moghaddam, Z.S.; Ren, Q. Recent advances in green synthesized nanoparticles: From production to application. *Mater. Today Sustain.* **2023**, *24*, 100500.
104. Ghosh, P.R.; Fawcett, D.; Sharma, S.B.; JPoinern, G.E. Production of High-Value Nanoparticles via Biogenic Processes Using Aquacultural and Horticultural Food Waste. *Materials* **2017**, *10*, 852. https://doi.org/10.3390/ma10080852.
105. Baraketi, S.; Khwaldia, K. Nanoparticles from Agri-Food by-Products: Green Technology Synthesis and Application in Food Packaging. *Curr. Opin. Green Sustain. Chem.* **2024**, *49*, 100953.
106. Dejene, B.K. Eco-friendly synthesis of metallic nanoparticles from agri-food waste extracts: Applications in food packaging and healthcare–A critical review. *Mater. Today Chem.* **2025**, *45*, 102619.
107. Kour, D.; Khan, S.S.; Kumari, S.; Singh, S.; Khan, R.T.; Kumari, C.; Kumari, S.; Dasila, H.; Kour, H.; Kaur, M.; et al. Microbial nanotechnology for agriculture, food, and environmental sustainability: Current status and future perspective. *Folia Microbiol.* **2024**, *69*, 491–520. https://doi.org/10.1007/s12223-024-01147-2.
108. Abd El-Ghany, M.N.; Hamdi, S.A.; Korany, S.M.; Elbaz, R.M.; Emam, A.N.; Farahat, M.G. Biogenic Silver Nanoparticles Produced by Soil Rare Actinomycetes and Their Significant Effect on Aspergillus-Derived Mycotoxins. *Microorganisms* **2023**, *11*, 1006. https://doi.org/10.3390/microorganisms11041006.
109. Seshan, K. *Handbook of Thin Film Deposition*; Elsevier: Amsterdam, The Netherlands, 2012.
110. Lieberman, M.A.; Lichtenberg, A.J. *Principles of Plasma Discharges and Materials Processing*; Wiley: Hoboken, NJ, USA, 2005.
111. Chu, P.K.; Li, L. Characterization of Plasma-enhanced CVD processes. *Mater. Chem. Phys.* **2006**, *96*, 253–277.
112. Tsuji, M.; Hashimoto, M.; Nishizawa, Y.; Kubokawa, M.; Tsuji, T. Microwave-assisted synthesis of metallic nanostructures in solution. *Chem.–A Eur. J.* **2005**, *11*, 440–452.
113. Bilecka, I.; Niederberger, M. Microwave chemistry for inorganic nanomaterials synthesis. *Nanoscale* **2010**, *2*, 1358–1374.
114. Suslick, K.S.; Price, G.J. Applications of ultrasound to materials chemistry. *Annu. Rev. Mater. Sci.* **1999**, *29*, 295–326.
115. Brust, M.; Kiely, C.J. Some recent advances in nanostructure preparation from gold and silver particles: A short topical review. *Colloids Surf. A Physicochem. Eng. Asp.* **2002**, *202*, 175–186.

116. Pol, V.G.; Srivastava, D.N.; Palchik, O.; Palchik, V.; Slifkin, M.A.; Weiss, A.M.; Gedanken, A. Sonochemical deposition of silver nanoparticles on silica spheres. *Langmuir* **2002**, *18*, 3352–3357.
117. Pol, V.G.; Gedanken, A.; Calderon-Moreno, J. Deposition of gold nanoparticles on silica spheres: A sonochemical approach. *Chem. Mater.* **2003**, *15*, 1111–1118.
118. Capek, I. Preparation of metal nanoparticles in water-in-oil (w/o) microemulsions. *Adv. Colloid Interface Sci.* **2004**, *110*, 49–74.
119. Eastoe, J.; Hollamby, M.J.; Hudson, L. Recent advances in nanoparticle synthesis with reversed micelles. *Adv. Colloid Interface science*, **2006**, *128*, 5–15.
120. Rao, C.N.R.; Müller, A.; Cheetham, A.K. (Eds.). *The Chemistry of Nanomaterials: Synthesis, Properties and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2006.
121. Niederberger, M. Nonaqueous sol–gel routes to metal oxide nanoparticles. *Acc. Chem. Res.* **2007**, *40*, 793–800.
122. Banerjee, A.; Bandopadhyay, R. Use of Dextran Nanoparticle: A Paradigm Shift in Bacterial Exopolysaccharide Based Biomedical Applications. *Int. J. Biol. Macromol.* **2016**, *87*, 295–301. https://doi.org/10.1016/j.ijbiomac.2016.02.059.
123. Du, P.; Xu, Y.; Shi, Y.; Xu, Q.; Xu, Y. Amino Modified Cellulose Fibers Loaded Zinc Oxide Nanoparticles via Paper-Making Wet-Forming for Antibacterial Materials. *Int. J. Biol. Macromol.* **2023**, *227*, 795–804. https://doi.org/10.1016/j.ijbiomac.2022.12.145.
124. Ashour, M.A.; Abd-Elhalim, B.T. Biosynthesis and biocompatibility evaluation of zinc oxide nanoparticles prepared using Priestia megaterium bacteria. *Sci. Rep.* **2024**, *14*, 4147.
125. Akbar, A.; Sadiq, M.B.; Ali, I.; Muhammad, N.; Rehman, Z.; Khan, M.N.; Muhammad, J.; Khan, S.A.; Rehman, F.U.; Anal, A.K. Synthesis and antimicrobial activity of zinc oxide nanoparticles against foodborne pathogens Salmonella typhimurium and Staphylococcus aureus. *Biocatal. Agric. Biotechnol.* **2019**, *17*, 36–42.
126. Mohd Yusof, H.; Mohamad, R.; Zaidan, U.H.; Abdul Rahman, N.A. Microbial synthesis of zinc oxide nanoparticles and their potential application as an antimicrobial agent and a feed supplement in animal industry: A review. *J. Anim. Sci. Biotechnol.* **2019**, *10*, 57. https://doi.org/10.1186/s40104-019-0368-z.
127. Fouda, A.; Abdel-Rahman, M.A.; Eid, A.M.; Selim, S.; Ejaz, H.; Alruwaili, M.; Manni, E.; Almuhayawi, M.S.; Al Jaouni, S.K.; Hassan, S.E.D. Investigating the Potential of Green-Fabricated Zinc Oxide Nanoparticles to Inhibit the Foodborne Pathogenic Bacteria Isolated from Spoiled Fruits. *Catalysts* **2024**, *14*, 427.
128. Gökmen, G.G.; Mirsafi, F.S.; Leißner, T.; Akan, T.; Mishra, Y.K.; Kışla, D. Zinc oxide nanomaterials: Safeguarding food quality and sustainability. *Compr. Rev. Food Sci. Food Saf.* **2024**, *23*, e70051.
129. Espitia, P.J.P.; Otoni, C.G.; Soares, N.F.F. Zinc oxide nanoparticles for food packaging applications. In *Antimicrobial Food Packaging*; Academic Press: Cambridge, MA, USA, 2025; pp. 603–610.
130. Li, X.; Xu, H.; Chen, Z.S.; Chen, G. Biosynthesis of nanoparticles by microorganisms and their applications. *J. Nanomater.* **2011**, *2011*, 270974.
131. Cunha, F.A.; Cunha Mda, C.S.O.; da Frota, S.M.; Mallmann, E.J.J.; Freire, T.M.; Costa, L.S.; Paula, A.J.; Menezes, E.A.; Fechine, P.B.A. Biogenic Synthesis of Multifunctional Silver Nanoparticles from Rhodotorula Glutinis and Rhodotorula Mucilaginosa: Antifungal, Catalytic and Cytotoxicity Activities. *World J. Microbiol. Biotechnol.* **2018**, *34*, 127. https://doi.org/10.1007/s11274-018-2514-8.
132. Kapoor, R.T.; Salvadori, M.R.; Rafatullah, M.; Siddiqui, M.R.; Khan, M.A.; Alshareef, S.A. Exploration of microbial factories for synthesis of nanoparticles–a sustainable approach for bioremediation of environmental contaminants. *Front. Microbiol.* **2021**, *12*, 658294.
133. Ghosh, S.; Ahmad, R.; Zeyaullah, M.; Khare, S.K. Microbial nano-factories: Synthesis and biomedical applications. *Front. Chem.* **2021**, *9*, 626834.
134. El-Sheekh, M.M.; El-Kassas, H.Y.; Ali, S.S. Microalgae-based bioremediation of refractory pollutants: An approach towards environmental sustainability. *Microb. Cell Factories* **2025**, *24*, 19.
135. Lee, J.H.; Kim, Y.G.; Cho, M.H.; Lee, J. ZnO nanoparticles inhibit Pseudomonas aeruginosa biofilm formation and virulence factor production. *Microbiol. Res.* **2014**, *169*, 888–896.
136. Pasha, A.; Kumbhakar, D.V.; Sana, S.S.; Ravinder, D.; Lakshmi, B.V.; Kalangi, S.K.; Pawar, S.C. Role of Biosynthesized Ag-NPs Using Aspergillus Niger (MK503444.1) in Antimicrobial, Anti-Cancer and Anti-Angiogenic Activities. *Front. Pharmacol.* **2022**, *12*, 812474. https://doi.org/10.3389/fphar.2021.812474.
137. Koul, B.; Poonia, A.K.; Yadav, D.; Jin, J.O. Microbe-mediated biosynthesis of nanoparticles: Applications and future prospects. *Biomolecules* **2021**, *11*, 886.

138. Sharma, B.K.; Dakshinamoorthi, B.M.; Jagadeesan, M.; Sekaran, S.; Somasundaram, A.; Jagadeeswari, S.; Ramasamy, P. Current state and future prospects of microbiologically produced nanoparticles: A narrative review. *Process Biochem.* **2024**, *147*, 554–568.
139. Gehrke, I.; Geiser, A.; Somborn-Schulz, A. Innovations in nanotechnology for water treatment. *Nanotechnol. Sci. Appl.* **2015**, *8*, 1–17.
140. Kulkarni, D.; Sherkar, R.; Shirsathe, C.; Sonwane, R.; Varpe, N.; Shelke, S.; More, M.P.; Pardeshi, S.R.; Dhaneshwar, G.; Junnuthula, V.; et al. Biofabrication of nanoparticles: Sources, synthesis, and biomedical applications. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1159193.
141. Herrmann, I.K. How nanotechnology-enabled concepts could contribute to the prevention, diagnosis and therapy of bacterial infections. *Crit. Care* **2015**, *19*, 239.
142. Ajith, M.P.; Aswathi, M.; Priyadarshini, E.; Rajamani, P. Recent innovations of nanotechnology in water treatment: A comprehensive review. *Bioresour. Technol.* **2021**, *342*, 126000.
143. Abady, M.M.; Mohammed, D.M.; Soliman, T.N.; Shalaby, R.A.; Sakr, F.A. Sustainable synthesis of nanomaterials using different renewable sources. *Bull. Natl. Res. Cent.* **2025**, *49*, 24.
144. Dorobantu, L.S.; Fallone, C.; Noble, A.J.; Veinot, J.; Ma, G.; Goss, G.G.; Burrell, R.E. Toxicity of silver nanoparticles against bacteria, yeast, and algae. *J. Nanoparticle Res.* **2015**, *17*, 172.
145. Ajith, M.P.; Rajamani, P. Nanotechnology for water purification–current trends and challenges. *J. Nanotechnol. Nanomater.* **2021**, *2*, 88–91.
146. Zaki, M.; Khalil H.P.S, A.; Sabaruddin, F.A.; Bairwan, R.D.; Oyekanmi, A.A.; Alfatah, T.; Danish, M.; Mistar, E.M.; Abdullah, C.K. Microbial treatment for nanocellulose extraction from marine algae and its applications as sustainable functional material. *Bioresour. Technol. Rep.* **2021**, *16*, 100811.
147. Fabris, M.; Abbriano, R.M.; Pernice, M.; Sutherland, D.L.; Commault, A.S.; Hall, C.C.; Labeeuw, L.; McCauley, J.I.; Kuzhiuparambil, U.; Ray, P.; et al. Emerging technologies in algal biotechnology: Toward the establishment of a sustainable, algae-based bioeconomy. *Front. Plant Sci.* **2020**, *11*, 279.
148. Varsha, V.S.; Boreda, T.; Pailla, S.R.; Kambhampati, Y.; Gourav, T.; Yadavalli, R.; Vijaya Laxmi, G.; Nadimpalli, S.; Nagendranatha Reddy, C. Nanotechnology and Microbes: Revolutionizing Water Management. In *Nano-Microbiology for Sustainable Development*; Springer Nature: Cham, Switzerland, 2025; pp. 293–329.
149. Kaczmarek, M.; Białkowska, A.M. Enzymatic functionalization of bacterial nanocellulose: Current approaches and future prospects. *J. Nanobiotechnology* **2025**, *23*, 82.
150. Mekuye, B.; Abera, B. Nanomaterials: An overview of synthesis, classification, characterization, and applications. *Nano Sel.* **2023**, *4*, 486–501.
151. Saravanan, A.; Kumar, P.S.; Varjani, S.; Jeevanantham, S.; Yaashikaa, P.R.; Thamarai, P.; Abirami, B.; George, C.S. A review on algal-bacterial symbiotic system for effective treatment of wastewater. *Chemosphere* **2021**, *271*, 129540.
152. Kumar, A.; Nighojkar, A.; Varma, P.; Prakash, N.J.; Kandasubramanian, B.; Zimmermann, K.; Dixit, F. Algal mediated intervention for the retrieval of emerging pollutants from aqueous media. *J. Hazard. Mater.* **2023**, *455*, 131568.
153. Elayaraja, S.; Liu, G.; Zagorsek, K.; Mabrok, M.; Ji, M.; Ye, Z.; Zhu, S.; Rodkhum, C. TEMPO-oxidized biodegradable bacterial cellulose (BBC) membrane coated with biologically-synthesized silver nanoparticles (AgNPs) as a potential antimicrobial agent in aquaculture (In vitro). *Aquaculture* **2021**, *530*, 735746.
154. Ahmad, F.; Salem-Bekhit, M.M.; Khan, F.; Alshehri, S.; Khan, A.; Ghoneim, M.M.; Wu, H.F.; Taha, E.I.; Elbagory, I. Unique properties of surface-functionalized nanoparticles for bio-application: Functionalization mechanisms and importance in application. *Nanomaterials* **2022**, *12*, 1333.
155. Ovais, M.; Khalil, A.T.; Ayaz, M.; Ahmad, I.; Nethi, S.K.; Mukherjee, S. Biosynthesis of metal nanoparticles via microbial enzymes: A mechanistic approach. *Int. J. Mol. Sci.* **2018**, *19*, 4100.
156. Mohiuddin, O.; Harvey, A.; Ledesma, M.T.O.; Velasquez-Orta, S. Bioremediation of waste by yeast strains. *Electron. J. Biotechnol.* **2024**, *69*, 30–42.
157. Shivaji, S.; Madhu, S.; Singh, S. Extracellular Synthesis of Antibacterial Silver Nanoparticles Using Psychrophilic Bacteria. *Process Biochem.* **2011**, *46*, 1800–1807. https://doi.org/10.1016/j.procbio.2011.06.008.
158. Shah, A.H.; Rather, M.A. Intracellular and extracellular microbial enzymes and their role in nanoparticle synthesis. In *Microbial Nanotechnology: Green Synthesis and Applications*; Springer: Singapore, 2021; pp. 41–59.
159. Ali, J.; Ali, N.; Wang, L.; Waseem, H.; Pan, G. Revisiting the mechanistic pathways for bacterial mediated synthesis of noble metal nanoparticles. *J. Microbiol. Methods* **2019**, *159*, 18–25.

160. Altammar, K.A. A review on nanoparticles: Characteristics, synthesis, applications, and challenges. *Front. Microbiol.* **2023**, *14*, 1155622.
161. Kumar, S.; Basumatary, I.B.; Sudhani, H.P.; Bajpai, V.K.; Chen, L.; Shukla, S.; Mukherjee, A. Plant extract mediated silver nanoparticles and their applications as antimicrobials and in sustainable food packaging: A state-of-the-art review. *Trends Food Sci. Technol.* **2021**, *112*, 651–666. https://doi.org/10.1016/j.tifs.2021.04.031.
162. Sheershwal, A.; Singh, A.; Sharma, V.; Trivedi, B. Microbial synthesis of nanoparticles for sustainable agricultural advancements: A comprehensive review. *Nanotechnol. Environ. Eng.* **2025**, *10*, 16.
163. Abada, E.; Galal, T.; Ismail, I. Biosynthesis of silver nanoparticles by Nocardiopsis sp.-MW279108 and its antimicrobial activity. *J. Basic Microbiol.* **2021**, *61*, 993–1001.
164. Dawadi, S.; Katuwal, S.; Gupta, A.; Lamichhane, U.; Thapa, R.; Jaisi, S.; Lamichhane, G.; Bhattarai, D.P.; Parajuli, N. Current research on silver nanoparticles: Synthesis, characterization, and applications. *J. Nanomater.* **2021**, *2021*, 6687290.
165. Abbas, R.; Luo, J.; Qi, X.; Naz, A.; Khan, I.A.; Liu, H.; Yu, S.; Wei, J. Silver nanoparticles: Synthesis, structure, properties and applications. *Nanomaterials* **2024**, *14*, 1425.
166. Pal, V.K.; Bandyopadhyay, P.; Singh, A. Hydrogen Sulfide in Physiology and Pathogenesis of Bacteria and Viruses. *IUBMB Life* **2018**, *70*, 393–410.
167. Wang, Z.; Li, N.; Zhou, X.; Wei, S.; Zhu, Y.; Li, M.; Gong, J.; He, Y.; Dong, X.; Gao, C.; et al. Optimization of fermentation parameters to improve the biosynthesis of selenium nanoparticles by Bacillus licheniformis F1 and its comprehensive application. *BMC Microbiol.* **2024**, *24*, 271.
168. Rodrigues, A.S.; Batista, J.G.; Rodrigues, M.Á.; Thipe, V.C.; Minarini, L.A.; Lopes, P.S.; Lugão, A.B. Advances in silver nanoparticles: A comprehensive review on their potential as antimicrobial agents and their mechanisms of action elucidated by proteomics. *Front. Microbiol.* **2024**, *15*, 1440065.
169. Jayaseelan, C.; Rahuman, A.A.; Kirthi, A.V.; Marimuthu, S.; Santhoshkumar, T.; Bagavan, A.; Gaurav, K.; Karthik, L.; Rao, K.V.B. Novel Microbial Route to Synthesize ZnO Nanoparticles Using Aeromonas Hydrophila and Their Activity against Pathogenic Bacteria and Fungi. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2012**, *90*, 78–84. https://doi.org/10.1016/j.saa.2012.01.006.
170. Tarhan, Ö. Safety and regulatory issues of nanomaterials in foods. In *Handbook of Food Nanotechnology*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 655–703.
171. Kumawat, G.; Rajpurohit, D.; Vyas, D.; Bhojiya, A.A.; Upadhyay, S.K.; Jain, D. Characterization of green-synthesized zinc oxide nanoparticles and its influence on post-harvest shelf-life of garlic against black mold disease caused by Aspergillus niger. *Front. Microbiol.* **2025**, *16*, 1532593.
172. Ligaj, M.; Tichoniuk, M.; Cierpiszewski, R.; Foltynowicz, Z. Efficiency of novel antimicrobial coating based on iron nanoparticles for dairy products' packaging. *Coatings*, **2020**, *10*, 156.
173. Al-Maliki, Q.A.; Taj-Aldeen, W.R. Antibacterial and Antibiofilm Activity of Bacteria Mediated Synthesized Fe3O4 nanoparticles Using Bacillus Coagulans. *J. Nanostructures* **2021**, *11*, 782–789.
174. Daramola, O.B.; Torimiro, N.; George, R.C. Colorimetric-Based Detection of Enteric Bacterial Pathogens Using Chromogens-Functionalized Iron Oxide-Gold Nanocomposites Biosynthesized by Bacillus Subtilis. *Discov. Biotechnol.* **2025**, *2*, 1. https://doi.org/10.1007/s44340-025-00008-z.
175. Fonseca, B.B.; Silva, P.L.A.P.A.; Silva, A.C.A.; Dantas, N.O.; De Paula, A.T.; Olivieri, O.C.L.; Beletti, M.E.; Rossi, D.A.; Goulart, L.R. Nanocomposite of Ag-Doped ZnO and AgO nanocrystals as a preventive measure to control biofilm formation in eggshell and salmonella spp. Entry into eggs. *Front. Microbiol.* **2019**, *10*, 217.
176. Dharmaraj, D.; Krishnamoorthy, M.; Rajendran, K.; Karuppiah, K.; Annamalai, J.; Durairaj, K.R.; Santhiyagu, P.; Ethiraj, K. Antibacterial and Cytotoxicity Activities of Biosynthesized Silver Oxide (Ag_2O) Nanoparticles Using Bacillus Paramycoides. *J. Drug Deliv. Sci. Technol.* **2021**, *61*, 102111. https://doi.org/10.1016/j.jddst.2020.102111.
177. Ibrahem, K.H.; Ali, F.A.; Abdulla Surchee, S.M. Biosynthesis and Characterization with Antimicrobial Activity of TiO2 Nanoparticles Using Probiotic Bifidobacterium Bifidum. *Cell. Mol. Biol.* **2020**, *66*, 112–118. https://doi.org/10.14715/cmb/2020.66.7.17.
178. El-Sayed, H.S.; El-Sayed, S.M.; Youssef, A.M. Novel Approach for Biosynthesizing of Zinc Oxide Nanoparticles Using Lactobacillus Gasseri and Their Influence on Microbiological, Chemical, Sensory Properties of Integrated Yogurt. *Food Chem.* **2021**, *365*, 130513. https://doi.org/10.1016/j.foodchem.2021.130513.
179. Qiao, L.; Dou, X.; Song, X.; Xu, C. Green synthesis of nanoparticles by probiotics and their application. *Adv. Appl. Microbiol.* **2022**, *119*, 83–128.

180. Nasiri Poroj, S.; Larypoor, M.; Fazeli, M.R.; Shariatmadari, F. The synergistic effect of titanium dioxide nanoparticles and yeast isolated from fermented foods in reduction of aflatoxin B1. *Food Sci. Nutr.* **2023**, *11*, 7109–7119.
181. Abdel-Nasser, A.; Fathy, H.M.; Badr, A.N.; Barakat, O.S.; Hathout, A.S. Chitosan nanoparticles loaded with Lactobacillus rhamnosus bioactive metabolites: Preparation, characterization, and antifungal activity. *Heliyon* **2025**, *11*, e41875.
182. Al-Nabulsi, A.; Osaili, T.; Sawalha, A.; Olaimat, A.N.; Albiss, B.A.; Mehyar, G.; Ayyash, M.; Holley, R. Antimicrobial activity of chitosan coating containing ZnO nanoparticles against E. coli O157: H7 on the surface of white brined cheese. *Int. J. Food Microbiol.* **2020**, *334*, 108838.
183. Krishnamoorthy, R.; Athinarayanan, J.; Periyasamy, V.S.; Alshuniaber, M.A.; Alshammari, G.; Hakeem, M.J.; Ahmed, M.A.; Alshatwi, A.A. Antibacterial mechanisms of zinc oxide nanoparticle against bacterial food pathogens resistant to beta-lactam antibiotics. *Molecules* **2022**, *27*, 2489.
184. Manivasagan, P.; Venkatesan, J.; Senthilkumar, K.; Sivakumar, K.; Kim, S.K. Biosynthesis, antimicrobial and cytotoxic effect of silver nanoparticles using a novel Nocardiopsis sp. MBRC-1. *BioMed Res. Int.* **2013**, *2013*, 287638.
185. Dhanaraj, S.; Thirunavukkarasu, S.; John, H.A.; Pandian, S.; Salmen, S.H.; Chinnathambi, A.; Alharbi, S.A. Novel marine Nocardiopsis dassonvillei-DS013 mediated silver nanoparticles characterization and its bactericidal potential against clinical isolates. *Saudi J. Biol. Sci.* **2020**, *27*, 991–995.
186. Khalil, M.A.; El-Shanshoury, A.E.R.R.; Alghamdi, M.A.; Alsalmi, F.A.; Mohamed, S.F.; Sun, J.; Ali, S.S. Biosynthesis of Silver Nanoparticles by Marine Actinobacterium Nocardiopsis Dassonvillei and Exploring Their Therapeutic Potentials. *Front. Microbiol.* **2022**, *12*, 705673. https://doi.org/10.3389/fmicb.2021.705673.
187. Arserim-Uçar, D.K.; Çabuk, B. Emerging antibacterial and antifungal applications of nanomaterials on food products. In *Nanotoxicity*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 415–453.
188. Akbar, M.; Ali, N.; Imran, M.; Hussain, A.; Hassan, S.W.; Haroon, U.; Kamal, A.; Chaudhary, H.J.; Munis, M.F.H. Spherical Fe_2O_3 nanoparticles inhibit the production of aflatoxins (B1 and B2) and regulate total soluble solids and titratable acidity of peach fruit. *Int. J. Food Microbiol.* **2024**, *410*, 110508.
189. Bhattacharjee, G.; Gohil, J.; Gohil, N.; Chaudhari, H.; Gangapuram, B.; Khambhati, K.; Maurya, R.; Alzahrani, K.J.; Ramakrishna, S.; Singh, V. Biosynthesis and Characterization of Serratia Marcescens Derived Silver Nanoparticles: Investigating Its Antibacterial, Anti-Biofilm Potency and Molecular Docking Analysis with Biofilm-Associated Proteins. *J. Mol. Liq.* **2022**, *365*, 120094. https://doi.org/10.1016/j.molliq.2022.120094.
190. Baráti-Deák, B.; Da Costa Arruda, G.C.; Perjéssy, J.; Klupács, A.; Zalán, Z.; Mohácsi-Farkas, C.; Belák, Á. Inhibition of foodborne pathogenic bacteria by excreted metabolites of Serratia marcescens strains isolated from a dairy-producing environment. *Microorganisms* **2023**, *11*, 403.
191. Cherednichenko, Y.; Batasheva, S.; Akhatova, F.; Fakhrullin, R.; Rozhina, E. Antibiofilm activity of silver nanoparticles-halloysite nanocomposite in Serratia marcescens. *J. Nanoparticle Res.* **2024**, *26*, 71.
192. Baygar, T.; Ugur, A. In vitro evaluation of antimicrobial and antibiofilm potentials of silver nanoparticles biosynthesised by Streptomyces griseorubens. *IET Nanobiotechnol.* **2017**, *11*, 677–681.
193. Fouda, A.; Hassan, S.E.D.; Abdo, A.M.; El-Gamal, M.S. Antimicrobial, Antioxidant and Larvicidal Activities of Spherical Silver Nanoparticles Synthesized by *Endophytic streptomyces* spp. *Biol. Trace Elem. Res.* **2020**, *195*, 707–724. https://doi.org/10.1007/s12011-019-01883-4.
194. Hoeksma, J.; Misset, T.; Wever, C.; Kemmink, J.; Kruijtzer, J.; Versluis, K.; Liskamp, R.M.J.; Boons, G.J.; Heck, A.J.R.; Boekhout, T.; et al. A New Perspective on Fungal Metabolites: Identification of Bioactive Compounds from Fungi Using Zebrafish Embryogenesis as Read-Out. *Sci. Rep.* **2019**, *9*, 17546. https://doi.org/10.1038/s41598-019-54127-9.
195. Yaraki, M.T.; Zahed Nasab, S.; Zare, I.; Dahri, M.; Moein Sadeghi, M.; Koohi, M.; Tan, Y.N. Biomimetic Metallic Nanostructures for Biomedical Applications, Catalysis, and Beyond. *Ind. Eng. Chem. Res.* **2022**, *61*, 7547–7593.
196. Abd-Elhamed, E.Y.; El-Bassiony, T.A.E.R.; Elsherif, W.M.; Shaker, E.M. Enhancing Ras Cheese Safety: Antifungal Effects of Nisin and Its Nanoparticles against Aspergillus Flavus. *BMC Vet. Res.* **2024**, *20*, 493. https://doi.org/10.1186/s12917-024-04323-1.
197. Eissa, E.S.H.; Bazina, W.K.; Abd El-Aziz, Y.M.; Abd Elghany, N.A.; Tawfik, W.A.; Mossa, M.I.; Abd El Megeed, O.H.; Abd El-Hamed, N.N.; El-Saeed, A.F.; El-Haroun, E.; et al. Nano-selenium impacts on growth performance, digestive enzymes, antioxidant, immune resistance and histopathological scores of Nile tilapia, Oreochromis niloticus against Aspergillus flavus infection. *Aquac. Int.* **2024**, *32*, 1587–1611.
198. Ghareib, M.; Abdallah, W.; Tahon, M.; Tallima, A. Biosynthesis of copper oxide nanoparticles using the preformed biomass of Aspergillus fumigatus and their antibacterial and photocatalytic activities. *Dig. J. Nanomater. Biostructures (DJNB)* **2019**, *14*, 291–303.

199. Shahzad, A.; Saeed, H.; Iqtedar, M.; Hussain, S.Z.; Kaleem, A.; Abdullah, R.; Sharif, S.; Naz, S.; Saleem, F.; Aihetasham, A.; et al. Size-Controlled Production of Silver Nanoparticles by Aspergillus Fumigatus BTCB10: Likely Antibacterial and Cytotoxic Effects. *J. Nanomater.* **2019**, *2019*, 5168698. https://doi.org/10.1155/2019/5168698.
200. Kalpana, V.N.; Kataru, B.A.S.; Sravani, N.; Vigneshwari, T.; Panneerselvam, A.; Rajeswari, V.D. Biosynthesis of zinc oxide nanoparticles using culture filtrates of Aspergillus niger: Antimicrobial textiles and dye degradation studies. *OpenNano* **2018**, *3*, 48–55. https://doi.org/10.1016/j.onano.2018.06.001.
201. Hassan, S.A.; Hanif, E.; Khan, U.H.; Tanoli, A.K. Antifungal activity of silver nanoparticles from Aspergillus niger. *Pak. J. Pharm. Sci*. **2019**, *32*, 1163–1166.
202. Awad, M.A.; Eid, A.M.; Elsheikh, T.M.; Al-Faifi, Z.E.; Saad, N.; Sultan, M.H.; Selim, S.; Al-Khalaf, A.A.; Fouda, A. Mycosynthesis, characterization, and mosquitocidal activity of silver nanoparticles fabricated by Aspergillus niger strain. *J. Fungi* **2022**, *8*, 396.
203. Soliman, M.K.Y.; Abu-Elghait, M.; Salem, S.S.; Azab, M.S. Multifunctional Properties of Silver and Gold Nanoparticles Synthesis by Fusarium Pseudonygamai. *Biomass Convers. Biorefinery* **2022**, *14*, 28253–28270. https://doi.org/10.1007/s13399-022-03507-9.
204. Shah, S.H.; Shan, X.; Baig, S.; Zhao, H.; Ismail, B.; Shahzadi, I.; Majeed, Z.; Nawazish, S.; Siddique, M.; Baig, A. First Identification of Potato Tuber Rot Caused by Penicillium Solitum, Its Silver Nanoparticles Synthesis, Characterization and Use against Harmful Pathogens. *Front. Plant Sci.* **2023**, *14*, 1255480. https://doi.org/10.3389/fpls.2023.1255480.
205. Adebayo-Tayo, B.C.; Ogunleye, G.E.; Ogbole, O. Biomedical application of greenly synthesized silver nanoparticles using the filtrate of Trichoderma viride: Anticancer and immunomodulatory potentials. *Polym. Med.* **2019**, *49*, 57–62.
206. Garza-García, J.J.; Hernández-Díaz, J.A.; Zamudio-Ojeda, A.; León-Morales, J.M.; Guerrero-Guzmán, A.; Sánchez-Chiprés, D.R.; López-Velázquez, J.C.; García-Morales, S. The role of selenium nanoparticles in agriculture and food technology. *Biol. Trace Elem. Res.* **2022**, *200*, 2528–2548.
207. Hussain, A.; Lakhan, M.N.; Hanan, A.; Soomro, I.A.; Ahmed, M.; Bibi, F.; Zehra, I. Recent progress on green synthesis of selenium nanoparticles—A review. *Mater. Today Sustain.* **2023**, *23*, 100420.
208. Kantorová, V.; Krausová, G.; Hyršlová, I.; Loula, M.; Mestek, O.; Kaňa, A. Determination of selenium nanoparticles in fermented dairy products. *Spectrochim. Acta Part B At. Spectrosc.* **2023**, *199*, 106592.
209. Jain, D.; Shivani Bhojiya, A.A.; Singh, H.; Daima, H.K.; Singh, M.; Mohanty, S.R.; Stephen, B.J.; Singh, A. Microbial fabrication of zinc oxide nanoparticles and evaluation of their antimicrobial and photocatalytic properties. *Front. Chem.* **2020**, *8*, 778.
210. Dinika, I.; Verma, D.K.; Balia, R.; Utama, G.L.; Patel, A.R. Potential of cheese whey bioactive proteins and peptides in the development of antimicrobial edible film composite: A review of recent trends. *Trends Food Sci. Technol.* **2020**, *103*, 57–67. https://doi.org/10.1016/j.tifs.2020.06.017.
211. Maruthupandy, M.; Muneeswaran, T.; Rajivgandhi, G.; Quero, F.; Anand, M.; Song, J.-M. Biologically synthesized copper and zinc oxide nanoparticles for important biomolecules detection and antimicrobial applications. *Mater. Today Commun.* **2020**, *22*, 100766.
212. Mansoor, S.; Zahoor, I.; Baba, T.R.; Padder, S.A.; Bhat, Z.A.; Koul, A.M.; Jiang, L. Fabrication of silver nanoparticles against fungal pathogens. *Front. Nanotechnol.* **2021**, *3*, 679358.
213. Islam, S.N.; Naqvi, S.M.A.; Raza, A.; Jaiswal, A.; Singh, A.K.; Dixit, M.; Barnwal, A.; Gambhir, S.; Ahmad, A. Mycosynthesis of Highly Fluorescent Selenium Nanoparticles from Fusarium Oxysporum, Their Antifungal Activity against Black Fungus Aspergillus Niger, and in-Vivo Biodistribution Studies. *3 Biotech* **2022**, *12*, 309. https://doi.org/10.1007/s13205-022-03383-0.
214. Reddy, B.; Bandi, R. Synthesis of selenium nanoparticles by using microorganisms and agri-based products. In *Agri-Waste and Microbes for Production of Sustainable Nanomaterials*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 655–683.
215. Zhang, T.; Qi, M.; Wu, Q.; Xiang, P.; Tang, D.; Li, Q. Recent research progress on the synthesis and biological effects of selenium nanoparticles. *Front. Nutr.* **2023**, *10*, 1183487.
216. Winkler, H.C.; Suter, M.; Naegeli, H. Critical review of the safety assessment of nano-structured silica additives in food. *J. Nanobiotechnol.* **2016**, *14*, 44.
217. Rose, G.K.; Soni, R.; Rishi, P.; Soni, S.K. Optimization of the biological synthesis of silver nanoparticles using Penicillium oxalicum GRS-1 and their antimicrobial effects against common food-borne pathogens. *Green Process. Synth.* **2019**, *8*, 144–156.
218. Pulikkalparambil, H.; Phothisarattana, D.; Promhuad, K.; Harnkarnsujarit, N. Effect of silicon dioxide nanoparticle on microstructure, mechanical and barrier properties of biodegradable PBAT/PBS food packaging. *Food Biosci.* **2023**, *55*, 103023.
219. Zhang, W.; Ahari, H.; Zhang, Z.; Jafari, S.M. Role of silica (SiO_2) nano/micro-particles in the functionality of degradable packaging films/coatings and their application in food preservation. *Trends Food Sci. Technol.* **2023**, *133*, 75–86.

220. Kaabo, H.E.; Saied, E.; Hassan, S.E.D.; Mahdy, H.M.; Sultan, M.H. Penicillium Oxalicum-Mediated the Green Synthesis of Silica Nanoparticles: Characterization and Environmental Applications. *Biomass Convers. Biorefinery* **2024**, *15*, 5229–5246. https://doi.org/10.1007/s13399-024-05350-6.
221. Neethu, S.; Midhun, S.J.; Sunil, M.A.; Soumya, S.; Radhakrishnan, E.K.; Jyothis, M. Efficient visible light induced synthesis of silver nanoparticles by Penicillium polonicum ARA 10 isolated from Chetomorpha antennina and its antibacterial efficacy against Salmonella enterica serovar Typhimurium. *J. Photochem. Photobiol. B Biol.* **2018**, *180*, 175–185.
222. Rudrappa, M.; Kumar, R.S.; Nagaraja, S.K.; Hiremath, H.; Gunagambhire, P.V.; Almansour, A.I.; Perumal, K.; Nayaka, S. Myco-nanofabrication of silver nanoparticles by Penicillium brasilianum NP5 and their antimicrobial, photoprotective and anticancer effect on MDA-MB-231 breast cancer cell line. *Antibiotics* **2023**, *12*, 567.
223. Rani, S.; Kumar, P.; Dahiya, P.; Dang, A.S.; Suneja, P. Biogenic synthesis of zinc nanoparticles, their applications, and toxicity prospects. *Front. Microbiol.* **2022**, *13*, 824427.
224. Murali, M.; Gowtham, H.G.; Shilpa, N.; Singh, S.B.; Aiyaz, M.; Sayyed, R.Z.; Shivamallu, C.; Achar, R.R.; Silina, E.; Stupin, V.; et al. Zinc oxide nanoparticles prepared through microbial mediated synthesis for therapeutic applications: A possible alternative for plants. *Front. Microbiol.* **2023**, *14*, 1227951.
225. Shobha, B.; Ashwini, B.S.; Ghazwani, M.; Hani, U.; Atwah, B.; Alhumaidi, M.S.; Basavaraju, S.; Chowdappa, S.; Ravikiran, T.; Wahab, S.; et al. Trichoderma-Mediated ZnO Nanoparticles and Their Antibiofilm and Antibacterial Activities. *J. Fungi* **2023**, *9*, 133. https://doi.org/10.3390/jof9020133.
226. Balakumaran, M.D.; Ramachandran, R.; Balashanmugam, P.; Mukeshkumar, D.J.; Kalaichelvan, P.T. Mycosynthesis of silver and gold nanoparticles: Optimization, characterization and antimicrobial activity against human pathogens. *Microbiol. Res.* **2016**, *182*, 8–20.
227. Elamawi, R.M.; Al-Harbi, R.E.; Hendi, A.A. Biosynthesis and characterization of silver nanoparticles using Trichoderma longibrachiatum and their effect on phytopathogenic fungi. *Egypt. J. Biol. Pest Control.* **2018**, *28*, 28.
228. Bamal, D.; Singh, A.; Chaudhary, G.; Kumar, M.; Singh, M.; Rani, N.; Mundlia, P.; Sehrawat, A.R. Silver nanoparticles biosynthesis, characterization, antimicrobial activities, applications, cytotoxicity and safety issues: An updated review. *Nanomaterials* **2021**, *11*, 2086. https://doi.org/10.3390/nano11082086.
229. Thipe, V.C.; Lima, C.S.; Nogueira, K.M.; Batista, J.G.; Ferreira, A.H.; Katti, K.V.; Lugão, A.B. Silver nanoparticles applications and ecotoxicology for controlling mycotoxins. In *Silver Nanomaterials for Agri-Food Applications*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 549–575.
230. Zhang, L.; Yu, D.; Xu, Y.; Jiang, Q.; Xia, W.; Yu, D. Changes in Quality and Microbial Diversity of Refrigerated Carp Fillets Treated by Chitosan/Zein Bilayer Film with Curcumin/Nisin-Loaded Pectin Nanoparticles. *Food Biosci.* **2023**, *54*, 102941. https://doi.org/10.1016/j.fbio.2023.102941.
231. EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA); Turck, D.; Castenmiller, J.; De Henauw, S.; Hirsch-Ernst, K.I.; Kearney, J.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; et al. Safety of selenium-enriched biomass of Yarrowia lipolytica as a novel food pursuant to Regulation (EU) 2015/2283. *EFSA J.* **2020**, *18*, 5992.
232. Lashani, E.; Moghimi, H.; Turner, R.J.; Amoozegar, M.A. Characterization and Biological Activity of Selenium Nanoparticles Biosynthesized by Yarrowia Lipolytica. *Microb. Biotechnol.* **2024**, *17*, e70013. https://doi.org/10.1111/1751-7915.70013.
233. Karnwal, A.; Kumar Sachan, R.S.; Devgon, I.; Devgon, J.; Pant, G.; Panchpuri, M.; Ahmad, A.; Alshammari, M.B.; Hossain, K.; Kumar, G. Gold nanoparticles in nanobiotechnology: From synthesis to biosensing applications. *ACS Omega* **2024**, *9*, 29966–29982. https://doi.org/10.1021/acsomega.3c10352.
234. Stałanowska, K.; Railean, V.; Pomastowski, P.; Pszczółkowska, A.; Okorski, A.; Lahuta, L.B. Seeds Priming with Bio-Silver Nanoparticles Protects Pea (*Pisum sativum* L.) Seedlings Against Selected Fungal Pathogens. *Int. J. Mol. Sci.* **2024**, *25*, 11402. https://doi.org/10.3390/ijms252111402.
235. Niamah, A.K.; Al-fekaiki, D.F.; Thyab Gddoa Al-Sahlany, S.; Verma, D.K.; Patel, A.R.; Singh, S. Investigating the Effect of Addition of Probiotic Microorganisms (Bacteria or Yeast) to Yoghurt on the Viability and Volatile Aromatic Profiles. *J. Food Meas. Charact.* **2023**, *17*, 5463–5473. https://doi.org/10.1007/s11694-023-02056-7.
236. Sati, A.; Ranade, T.N.; Mali, S.N.; Ahmad Yasin, H.K.; Pratap, A. Silver Nanoparticles (AgNPs): Comprehensive Insights into Bio/Synthesis, Key Influencing Factors, Multifaceted Applications, and Toxicity—A 2024 Update. *ACS Omega* **2025**, *10*, 7549–7582. https://doi.org/10.1021/acsomega.4c11045.
237. Kthiri, A.; Hamimed, S.; Othmani, A.; Landoulsi, A.; O'Sullivan, S.; Sheehan, D. Novel Static Magnetic Field Effects on Green Chemistry Biosynthesis of Silver Nanoparticles in Saccharomyces Cerevisiae. *Sci. Rep.* **2021**, *11*, 20078. https://doi.org/10.1038/s41598-021-99487-3.

238. Jiang, Z.; Wang, T.; Sun, Y.; Nong, Y.; Tang, L.; Gu, T.; Wang, S.; Li, Z. Application of Pb(II) to Probe the Physiological Responses of Fungal Intracellular Vesicles. *Ecotoxicol. Environ. Saf.* **2020**, *194*, 110441. https://doi.org/10.1016/j.ecoenv.2020.110441.
239. Khanna, P.; Kaur, A.; Goyal, D. Algae-based metallic nanoparticles: Synthesis, characterization and applications. *J. Microbiol. Methods,* **2019**, *163*, 105656.
240. Dananjaya, S.H.S.; Thu Thao, N.T.; Wijerathna, H.M.S.M.; Lee, J.; Edussuriya, M.; Choi, D.; Saravana Kumar, R. In Vitro and in Vivo Anticandidal Efficacy of Green Synthesized Gold Nanoparticles Using Spirulina Maxima Polysaccharide. *Process Biochem.* **2020**, *92*, 138–148. https://doi.org/10.1016/j.procbio.2020.03.003.
241. AlFadhly, N.K.; Alhelfi, N.; Altemimi, A.B.; Verma, D.K.; Cacciola, F. Tendencies affecting the growth and cultivation of genus Spirulina: An investigative review on current trends. *Plants* **2022**, *11*, 3063. https://doi.org/10.3390/plants11223063.
242. AlFadhly, N.K.; Alhelfi, N.; Altemimi, A.B.; Verma, D.K.; Cacciola, F.; Narayanankutty, A. Trends and technological advancements in the possible food applications of Spirulina and their health benefits: A Review. *Molecules* **2022**, *27*, 5584. https://doi.org/10.3390/molecules27175584.
243. Ayele, A.; Suresh, A.; Benor, S. Phycoremediation of heavy metals, factors involved and mechanisms related to functional groups in the algae cell surface—A review. In *Strategies and Tools for Pollutant Mitigation: Avenues to a Cleaner Environment*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 269–289.
244. Irfan, M.; Sana, A.; Maryam, A.; Naveed, M. Exploring How Microbial Extracellular Metabolites Drive Nanoparticle Synthesis: A Bioinformatics Approach. *BioNanoScience* **2025**, *15*, 310.
245. Parial, D.; Patra, H.K.; Dasgupta, A.K.R.; Pal, R. Screening of Different Algae for Green Synthesis of Gold Nanoparticles. *Eur. J. Phycol.* **2012**, *47*, 22–29. https://doi.org/10.1080/09670262.2011.653406.
246. Hamouda, R.A.; Abd El Maksoud, A.I.; Wageed, M.; Alotaibi, A.S.; Elebeedy, D.; Khalil, H.; Hassan, A.; Abdella, A. Characterization and Anticancer Activity of Biosynthesized Au/Cellulose Nanocomposite from Chlorella Vulgaris. *Polymers* **2021**, *13*, 3340. https://doi.org/10.3390/polym13193340.
247. Anuluxan, S.; Thavaranjit, A.C.; Prabagar, S.; De Silva, R.C.L.; Prabagar, J. Synthesis of Silver Nanoparticles from Turbinaria Ornata and Its Antibacterial Activity against Water Contaminating Bacteria. *Chem. Pap.* **2022**, *76*, 2365–2374. https://doi.org/10.1007/s11696-021-02033-8.
248. Al-Gebory, L.; Mengüç, M.P. The Effect of PH on Particle Agglomeration and Optical Properties of Nanoparticle Suspensions. *J. Quant. Spectrosc. Radiat. Transf.* **2018**, *219*, 46–60. https://doi.org/10.1016/j.jqsrt.2018.07.020.
249. Godymchuk, A.; Papina, I.; Karepina, E.; Kuznetsov, D.; Lapin, I.; Svetlichnyi, V. Agglomeration of Iron Oxide Nanoparticles: PH Effect Is Stronger than Amino Acid Acidity. *J. Nanoparticle Res.* **2019**, *21*, 208. https://doi.org/10.1007/s11051-019-4634-y.
250. Yazdani, A.; Sayadi, M.; Heidari, A. Green biosynthesis of palladium oxide nanoparticles using dictyota indica seaweed and its application for adsorption. *J. Water Environ. Nanotechnol.* **2018**, *3*, 337–347. https://doi.org/10.22090/jwent.2018.04.006.
251. Alaqarbeh, M.; Adil, S.F.; Ghrear, T.; Khan, M.; Bouachrine, M.; Al-Warthan, A. Recent progress in the application of palladium nanoparticles: A review. *Catalysts* **2023**, *13*, 1343.
252. Maryška, L.; Jindřichová, B.; Siegel, J.; Záruba, K.; Burketová; L. Impact of palladium nanoparticles on plant and its fungal pathogen. A case study: Brassica napus–Plenodomus lingam. *AoB Plants* **2023**, *15*, plad004.
253. Senthilkumar, P.; Surendran, L.; Sudhagar, B.; Ranjith Santhosh Kumar, D.S. Facile Green Synthesis of Gold Nanoparticles from Marine Algae Gelidiella Acerosa and Evaluation of Its Biological Potential. *SN Appl. Sci.* **2019**, *1*, 284. https://doi.org/10.1007/s42452-019-0284-z.
254. Chen, H.; Zhou, K.; Zhao, G. Gold nanoparticles: From synthesis, properties to their potential application as colorimetric sensors in food safety screening. *Trends Food Sci. Technol.* **2018**, *78*, 83–94. https://doi.org/10.1016/j.tifs.2018.05.027.
255. Paidari, S.; Ibrahim, S. A. Potential application of gold nanoparticles in food packaging: A mini review. *Gold Bull.* **2021**, *54*, 31–36. https://doi.org/10.1007/s13404-021-00290-9.
256. Mikhailova, E.O. Gold Nanoparticles: Biosynthesis and Potential of Biomedical Application. *J. Funct. Biomater.* **2021**, *12*, 70. https://doi.org/10.3390/jfb12040070.
257. Subbulakshmi, A.; Durgadevi, S.; Anitha, S.; Govarthanan, M.; Biruntha, M.; Rameshthangam, P.; Kumar, P. Biogenic gold nanoparticles from Gelidiella acerosa: Bactericidal and photocatalytic degradation of two commercial dyes. *Appl. Nanosci.* **2023**, *13*, 4033–4042.
258. Thiurunavukkarau, R.; Shanmugam, S.; Subramanian, K.; Pandi, P.; Muralitharan, G.; Arokiarajan, M.; Kasinathan, K.; Sivaraj, A.; Kalyanasundaram, R.; AlOmar, S.Y.; et al. Silver nanoparticles synthesized from the seaweed Sargassum polycystum and screening for their biological potential. *Sci. Rep.* **2022**, *12*, 14757. https://doi.org/10.1038/s41598-022-18379-2.

259. Vijayan, S.R.; Santhiyagu, P.; Singamuthu, M.; Kumari Ahila, N.; Jayaraman, R.; Ethiraj, K. Synthesis and Characterization of Silver and Gold Nanoparticles Using Aqueous Extract of Seaweed, Turbinaria Conoides, and Their Antimicrofouling Activity. *Sci. World J.* **2014**, *2014*, 938272. https://doi.org/10.1155/2014/938272.
260. Heinemann, M.G.; Rosa, C.H.; Rosa, G.R.; Dias, D. Biogenic synthesis of gold and silver nanoparticles used in environmental applications: A review. *Trends Environ. Anal. Chem.* **2021**, *30*, e00129. https://doi.org/10.1016/j.teac.2021.e00129.
261. Bhandari, M.; Raj, S.; Kumar, A.; Kaur, D.P. Bibliometric analysis on exploitation of biogenic gold and silver nanoparticles in breast, ovarian and cervical cancer therapy. *Front. Pharmacol.* **2022**, *13*, 1035769. https://doi.org/10.3389/fphar.2022.1035769.
262. Kothai, R.; Arul, B.; Anbazhagan, V. Anti-Dengue Activity of ZnO Nanoparticles of Crude Fucoidan from Brown Seaweed *S. Marginatum*. *Appl. Biochem. Biotechnol.* **2023**, *195*, 3747–3763. https://doi.org/10.1007/s12010-022-03966-w.
263. Acharya, R.; Tettey, F.; Gupta, A.; Sharma, K.R.; Parajuli, N.; Bhattarai, N. Bioinspired synthesis and characterization of zinc oxide nanoparticles and assessment of their cytotoxicity and antimicrobial efficacy. *Discov. Appl. Sci.* **2024**, *6*, 85. https://doi.org/10.1007/s42452-024-05719-2.
264. Helmy, E.A.M.; Amin, B.H.; Alqhtani, A.H.; Pokoo-Aikins, A.; Yosri, M. Estimation of the Antibacterial and Anti-Tumor Impacts of Soy Milk and Ecofriendly Myco-Manufactured Zinc Oxide Nanomaterials. In Vitro Appraisal. *Pol. J. Environ. Stud.* **2024**, *33*, 2093–2102. https://doi.org/10.15244/pjoes/174792.
265. Babu, B.; Palanisamy, S.; Vinosha, M.; Anjali, R.; Kumar, P.; Pandi, B.; Tabarsa, M.; You, S.; Prabhu, N.M. Bioengineered gold nanoparticles from marine seaweed Acanthophora spicifera for pharmaceutical uses: Antioxidant, antibacterial, and anticancer activities. *Bioprocess Biosyst. Eng.* **2020**, *43*, 2231–2242. https://doi.org/10.1007/s00449-020-02408-3.
266. Botteon, C.E.A.; Silva, L.B.; Ccana-Ccapatinta, G.V.; Silva, T.S.; Ambrosio, S.R.; Veneziani, R.C.S.; Bastos, J.K.; Marcato, P.D. Biosynthesis and characterization of gold nanoparticles using Brazilian red propolis and evaluation of its antimicrobial and anticancer activities. *Sci. Rep.* **2021**, *11*, 1974. https://doi.org/10.1038/s41598-021-81281-w.
267. Nisha Sachan, R.S.K.; Singh, A.; Karnwal, A.; Shidiki, A.; Kumar, G. Plant-mediated gold nanoparticles in cancer therapy: Exploring anti-cancer mechanisms, drug delivery applications, and future prospects. *Front. Nanotechnol.* **2024**, *6*, 1490980. https://doi.org/10.3389/fnano.2024.1490980.
268. Logeswari, V.; Yamini, S.; Pavithra, P.; Papitha, A.S.; Lakshmi, D. Study of Antioxidant, Antimicrobial and Cytotoxic Activities of Ag-Co Bimetallic Nanoparticles Biosynthesized from Red Alga (*Amphiroa* sp.). *Indian J. Sci. Technol.* **2024**, *17*, 2013–2023. https://doi.org/10.17485/IJST/v17i19.861.
269. Gebreslassie, Y.T.; Gebretnsae, H.G. Green and cost-effective synthesis of tin oxide nanoparticles: A review on the synthesis methodologies, mechanism of formation, and their potential applications. *Nanoscale Res. Lett.* **2021**, *16*, 97. https://doi.org/10.1186/s11671-021-03555-6.
270. Dheyab, M.A.; Aziz, A.A.; Jameel, M.S.; Oladzadabbasabadi, N. Recent advances in synthesis, modification, and potential application of tin oxide nanoparticles. *Surf. Interfaces* **2022**, *28*, 101677. https://doi.org/10.1016/j.surfin.2021.101677.
271. Al-Enazi, N.M.; Ameen, F.; Alsamhary, K.; Dawoud, T.; Al-Khattaf, F.; AlNadhari, S. Tin Oxide Nanoparticles (SnO_2-NPs) Synthesis Using Galaxaura Elongata and Its Anti-Microbial and Cytotoxicity Study: A Greenery Approach. *Appl. Nanosci.* **2023**, *13*, 519–527. https://doi.org/10.1007/s13204-021-01828-1.
272. Kharbanda, J.; Priya, R. Synthesis and applications of tin oxide nanoparticles: An overview. *Mater. Today Proc.* **2022**, *68*, 916–921. https://doi.org/10.1016/j.matpr.2022.07.131.
273. Bastardo-Fernández, I.; Chekri, R.; Oster, C.; Thoury, V.; Fisicaro, P.; Jitaru, P.; Noireaux, J. Assessment of TiO_2 (nano) particles migration from food packaging materials to food simulants by single particle ICP-MS/MS using a high efficiency sample introduction system. *NanoImpact* **2024**, *34*, 100503. https://doi.org/10.1016/j.impact.2024.100503.
274. Ghareeb, A.; Fouda, A.; Kishk, R.M.; El Kazzaz, W.M. Unlocking the potential of titanium dioxide nanoparticles: An insight into green synthesis, optimizations, characterizations, and multifunctional applications. *Microb. Cell Factories* **2024**, *23*, 341. https://doi.org/10.1186/s12934-024-02609-5.
275. Pugazhendhi, A.; Prabakar, D.; Jacob, J.M.; Karuppusamy, I.; Saratale, R.G. Synthesis and Characterization of Silver Nanoparticles Using Gelidium Amansii and Its Antimicrobial Property against Various Pathogenic Bacteria. *Microb. Pathog.* **2018**, *114*, 41–45. https://doi.org/10.1016/j.micpath.2017.11.013.
276. Beniwal, A.; Saini, P.; Kokkiligadda, A.; Vij, S. Use of silicon dioxide nanoparticles for β-galactosidase immobilization and modulated ethanol production by co-immobilized K. marxianus and S. cerevisiae in deproteinized cheese whey. *LWT* **2018**, *87*, 553–561. https://doi.org/10.1016/j.lwt.2017.09.028.

277. Mahawar, L.; Ramasamy, K.P.; Suhel, M.; Prasad, S.M.; Živčák, M.; Brestic, M.; Rastogi, A.; Skalický, M. Silicon nanoparticles: Comprehensive review on biogenic synthesis and applications in agriculture. *Environ. Res.* **2023**, *232*, 116292. https://doi.org/10.1016/j.envres.2023.116292.
278. Palanimuthu, V.; Periakaruppan, R.; Romanovski, V.; Bharathi, A.; Vijai Selvaraj, K.S.; Anukeerthana, S.; Nishanthi, R.; Vanajadevi, G. Synthesis and Structural Characterization of SiO_2 Nanoparticles Using Extract of Gracilaria Crassa Via Green Chemistry Approach. *ChemistryOpen* **2024**, *14*, e202400356. https://doi.org/10.1002/open.202400356.
279. Mohanta, Y.K.; Mishra, A.K.; Nayak, D.; Patra, B.; Bratovcic, A.; Avula, S.K.; Mohanta, T.K.; Murugan, K.; Saravanan, M. Exploring Dose-Dependent Cytotoxicity Profile of Gracilaria Edulis-Mediated Green Synthesized Silver Nanoparticles against MDA-MB-231 Breast Carcinoma. *Oxid. Med. Cell Longev.* **2022**, *2022*, 3863138. https://doi.org/10.1155/2022/3863138.
280. Sharma, B.; Purkayastha, D.D.; Hazra, S.; Thajamanbi, M.; Bhattacharjee, C.R.; Ghosh, N.N.; Rout, J. Biosynthesis of Fluorescent Gold Nanoparticles Using an Edible Freshwater Red Alga, *Lemanea fluviatilis* (L.) C.Ag. and Antioxidant Activity of Biomatrix Loaded Nanoparticles. *Bioprocess Biosyst. Eng.* **2014**, *37*, 2559–2565. https://doi.org/10.1007/s00449-014-1233-2.
281. Hammami, I.; Alabdallah, N.M.; Al Jomaa, A.; Kamoun, M. Gold Nanoparticles: Synthesis Properties and Applications. *J. King Saud. Univ. Sci.* **2021**, *33*, 101560.
282. Ahamad, I.; Aziz, N.; Zaki, A.; Fatma, T. Synthesis and characterization of silver nanoparticles using Anabaena variabilis as a potential antimicrobial agent. *J. Appl. Phycol.* **2021**, *33*, 829–841. https://doi.org/10.1007/s10811-020-02323-w.
283. Ismail, G.A.; Allam, N.G.; El-Gemizy, W.M.; Salem, M.A. The role of silver nanoparticles biosynthesized by Anabaena variabilis and Spirulina platensis cyanobacteria for malachite green removal from wastewater. *Environ. Technol.* **2021**, *42*, 4475–4489. https://doi.org/10.1080/09593330.2020.1766576.
284. Onyeaka, H.; Passaretti, P.; Miri, T.; Al-Sharify, Z.T. The safety of nanomaterials in food production and packaging. *Curr. Res. Food Sci.* **2022**, *5*, 763–774.
285. Schoonjans, R.; Castenmiller, J.; Chaudhry, Q.; Cubadda, F.; Daskaleros, T.; Franz, R.; Gott, D.; Mast, J.; Mortensen, A.; Oomen, A.G.; et al. Regulatory safety assessment of nanoparticles for the food chain in Europe. *Trends Food Sci. Technol.* **2023**, *134*, 98–111.
286. Asif, N.; Ahmad, R.; Fatima, S.; Shehzadi, S.; Siddiqui, T.; Zaki, A.; Fatma, T. Toxicological Assessment of Phormidium Sp. Derived Copper Oxide Nanoparticles for Its Biomedical and Environmental Applications. *Sci. Rep.* **2023**, *13*, 6246. https://doi.org/10.1038/s41598-023-33360-3.
287. Ramos, G.L.P.A.; Bovo, F.; Baptista, R.C.; Kamimura, B.A.; Magnani, M.; Sant'Ana, A.S. Impact of Silver Nanoparticles Active Packaging on the Behavior of Listeria Monocytogenes and Other Microbial Groups during Ripening and Storage of Canastra Cheeses. *Food Control* **2024**, *166*, 110742. https://doi.org/10.1016/j.foodcont.2024.110742.
288. Arshad, A. *Bacterial Synthesis and Applications of Nanoparticles*; Scholars' Press: London, UK, 2018.
289. Singh, J.; Dutta, T.; Kim, K.H.; Rawat, M.; Samddar, P.; Kumar, P. 'Green'synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *J. Nanobiotechnol.* **2018**, *16*, 84.
290. Bahrulolum, H.; Nooraei, S.; Javanshir, N.; Tarrahimofrad, H.; Mirbagheri, V.S.; Easton, A.J.; Ahmadian, G. Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *J. Nanobiotechnol.* **2021**, *19*, 86.
291. Lahiri, D.; Nag, M.; Sheikh, H.I.; Sarkar, T.; Edinur, H.A.; Pati, S.; Ray, R.R. Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade. *Front. Microbiol.* **2021**, *12*, 636588.
292. Singh, S.S.; Salem, D.R.; Sani, R.K. Spectroscopy, microscopy, and other techniques for characterization of bacterial nanocellulose and comparison with plant-derived nanocellulose. In *Microbial and Natural Macromolecules*; Academic Press: Cambridge, MA, USA, 2021; pp. 419–454.
293. Sandhu, A.; Goel, A. Biosynthesis of Nanoparticles by Micro-organisms and its Applications. *J. Young Pharm.* **2023**, *15*, 430–440.
294. Manikandan, V.; Min, S.C. Roles of polysaccharides-based nanomaterials in food preservation and extension of shelf-life of food products: A review. *Int. J. Biol. Macromol.* **2023**, *252*, 126381.
295. Shende, S.S.; Rajput, V.D.; Gorovtsov, A.V.; Minkina, T.M.; Sushkova, S.N. (Eds.). *Microbial Synthesis of Nanomaterials*; Nova Science Publishers: Hauppauge, NY, USA, 2021.
296. Banwo, K.; Olojede, A.O.; Adesulu-Dahunsi, A.T.; Verma, D.K.; Thakur, M.; Tripathy, S.; Singh, S.; Patel, A.R.; Gupta, A.K.; Aguilar, C.N.; et al. Functional importance of bioactive compounds of foods with Potential Health Benefits: A review on recent trends. *Food Biosci.* **2021**, *43*, 101320. https://doi.org/10.1016/j.fbio.2021.101320.
297. Tripathy, S.; Verma, D.K.; Thakur, M.; Patel, A.R.; Srivastav, P.P.; Singh, S.; Gupta, A.K.; Chavez-Gonzalez, M.L.; Aguilar, C.N.; Chakravorty, N.; et al. Curcumin extraction, isolation, quantification and its application in functional foods: A review

with a focus on immune enhancement activities and COVID-19. *Front. Nutr.* **2021**, *8*, 747956. https://doi.org/10.3389/fnut.2021.747956.

298. Pandhi, S.; Mahato, D.K.; Kumar, A. Overview of Green Nanofabrication Technologies for Food Quality and Safety Applications. *Food Rev. Int.* **2023**, *39*, 240–260. https://doi.org/10.1080/87559129.2021.1904254.
299. Rezagholizade-shirvan, A.; Ghasemi, A.; Mazaheri, Y.; Shokri, S.; Fallahizadeh, S.; Alizadeh Sani, M.; Mohtashami, M.; Mahmoudzadeh, M.; Sarafraz, M.; Darroudi, M.; et al. Removal of Aflatoxin M1 in Milk Using Magnetic Laccase/MoS2/Chitosan Nanocomposite as an Efficient Sorbent. *Chemosphere* **2024**, *365*, 143334. https://doi.org/10.1016/j.chemosphere.2024.143334.
300. Patel, A.; Shah, N.; Verma, D.K. Lactic Acid Bacteria (Lab) Bacteriocins: An Ecologicaland Sustainable Biopreservativeapproach to Improve the Safety and Shelf Life of Foods. In *Microorganisms in Sustainable Agriculture, Food, and the Environment*; Apple Academic Press: Cambridge, MA, USA, 2017; pp. 197–257.
301. Verma, D.K.; Thakur, M.; Singh, S.; Tripathy, S.; Gupta, A.K.; Baranwal, D.; Patel, A.R.; Shah, N.; Utama, G.L.; Niamah, A.K.; et al. Bacteriocins as antimicrobial and preservative agents in food: Biosynthesis, separation and application. *Food Biosci.* **2022**, *46*, 101594. https://doi.org/10.1016/j.fbio.2022.101594.
302. Niamah, A.K.; Al-Sahlany, S.T.G.; Verma, D.K.; Shukla, R.M.; Patel, A.R.; Tripathy, S.; Singh, S.; Baranwal, D.; Singh, A.K.; Utama, G.L.; et al. Emerging lactic acid bacteria bacteriocins as anti-cancer and anti-tumor agents for human health. *Heliyon* 2024a, *10*, e37054. https://doi.org/10.1016/j.heliyon.2024.e37054.
303. El-Zamkan, M.A.; Hendy, B.A.; Diab, H.M.; Marraiki, N.; Batiha, G.E.S.; Saber, H.; Younis, W.; Thangamani, S.; Alzahrani, K.J.; Ahmed, A.S. Control of Virulent Listeria Monocytogenes Originating from Dairy Products and Cattle Environment Using Marine Algal Extracts, Silver Nanoparticles Thereof, and Quaternary Disinfectants. *Infect. Drug Resist.* **2021**, *14*, 2721–2739. https://doi.org/10.2147/IDR.S300593.
304. El-Saadony, M.T.; Saad, A.M.; Taha, T.F.; Najjar, A.A.; Zabermawi, N.M.; Nader, M.M.; AbuQamar, S.F.; El-Tarabily, K.A.; Salama, A. Selenium Nanoparticles from Lactobacillus Paracasei HM1 Capable of Antagonizing Animal Pathogenic Fungi as a New Source from Human Breast Milk. *Saudi. J. Biol. Sci.* **2021**, *28*, 6782–6794. https://doi.org/10.1016/j.sjbs.2021.07.059.
305. Al-Sahlany, S.T.G.; Al-Kaabi, W.J.; Al-Manhel, A.J.A.; Niamah, A.K.; Altemimi, A.B.; Al-Wafi, H.; Cacciola, F. Effects of β-Glucan Extracted from Saccharomyces Cerevisiae on the Quality of Bio-Yoghurts: In Vitro and in Vivo Evaluation. *J. Food Meas. Charact.* **2022**, *16*, 3607–3617. https://doi.org/10.1007/s11694-022-01468-1.
306. Al-Sahlany, S.T.G.; Khassaf, W.H.; Niamah, A.K.; Al-Manhel, A.J. Date Juice Addition to Bio-Yogurt: The Effects on Physicochemical and Microbiological Properties during Storage, as Well as Blood Parameters in Vivo. *J. Saudi Soc. Agric. Sci.* **2022**, *22*, 71–77. https://doi.org/10.1016/j.jssas.2022.06.005.
307. Fang, M.; Wang, J.; Fang, S.; Zuo, X. Fabrication of Carboxymethyl Chitosan Films for Cheese Packaging Containing Gliadin-Carboxymethyl Chitosan Nanoparticles Co-Encapsulating Natamycin and Theaflavins. *Int. J. Biol. Macromol.* **2023**, *246*, 125685. https://doi.org/10.1016/j.ijbiomac.2023.125685.
308. Ahmed, A.A.H.; Maharik, N.; Valero, A.; Elsherif, W.; Kamal, S.M. Effect of Yoghourt Starter Culture and Nickel Oxide Nanoparticles on the Activity of Enterotoxigenic Staphylococcus Aureus in Domiati Cheese. *Appl. Sci.* **2023**, *13*, 3935. https://doi.org/10.3390/app13063935.
309. Machado, É.F.; Favarin, F.R.; Ourique, A.F. The Use of Nanostructured Films in the Development of Packaging for Meat and Meat Products: A Brief Review of the Literature. *Food Chemistry Advances* **2022**, *1*, 100050.
310. Niamah, A.K.; Al-Sahlany, S.T.G.; Verma, D.K.; Singh, S.; Tripathy, S.; Thakur, M.; Patel, A.R.; González, M.L.C.; Aguilar, C.N.; Srivastav, P.P. Enzymes for meat and meat processing industry: Current trends, technological development, and future prospects. In *Enzymatic Processes for Food Valorization*; Academic Press: Cambridge, MA, USA, 2024; pp. 23–36. https://doi.org/10.1016/B978-0-323-95996-4.00002-2.
311. Abd El-Hack, M.E.; Alaidaroos, B.A.; Farsi, R.M.; Abou-Kassem, D.E.; El-Saadony, M.T.; Saad, A.M.; Shafi, M.E.; Albaqami, N.M.; Taha, A.E.; Ashour, E.A. Impacts of Supplementing Broiler Diets with Biological Curcumin, Zinc Nanoparticles and Bacillus Licheniformis on Growth, Carcass Traits, Blood Indices, Meat Quality and Cecal Microbial Load. *Animals* **2021**, *11*, 1878. https://doi.org/10.3390/ani11071878.
312. Morsy, M.K.; Elsabagh, R.; Trinetta, V. Evaluation of Novel Synergistic Antimicrobial Activity of Nisin, Lysozyme, EDTA Nanoparticles, and/or ZnO Nanoparticles to Control Foodborne Pathogens on Minced Beef. *Food Control* **2018**, *92*, 249–254. https://doi.org/10.1016/j.foodcont.2018.04.061.

313. Wang, L.; Wu, W.M.; Bolan, N.S.; Tsang, D.C.W.; Li, Y.; Qin, M.; Hou, D. Environmental Fate, Toxicity and Risk Management Strategies of Nanoplastics in the Environment: Current Status and Future Perspectives. *J. Hazard Mater.* **2021**, *401*, 123415. https://doi.org/10.1016/j.jhazmat.2020.123415.
314. Gulati, S.; Kumar, S.; Jain, S.; Radhika Sharma, N.; Batra, K. Toxicological perspectives and environmental risks of consumer nanoproducts. In *Handbook of Consumer Nanoproducts*; Springer Nature: Singapore, 2022; pp. 1253–1275.
315. FOODGRADS. Consumer Mistrust in Food Nanoparticles: Benefits, Risks & the Future. Available online: https://foodgrads.com/2025/02/09/consumer-mistrust-in-food-nanoparticles-benefits-risks-the-future/ (accessed on 4 May 2025).
316. Zijno, A.; De Angelis, I.; De Berardis, B.; Andreoli, C.; Russo, M.T.; Pietraforte, D.; Scorza, G.; Degan, P.; Ponti, J.; Rossi, F.; et al. Different Mechanisms Are Involved in Oxidative DNA Damage and Genotoxicity Induction by ZnO and TiO2 Nanoparticles in Human Colon Carcinoma Cells. *Toxicol. Vitr.* **2015**, *29*, 1503–1512. https://doi.org/10.1016/j.tiv.2015.06.009.
317. Mikiciuk, J.; Mikiciuk, E.; Wrońska, A.; Szterk, A. Antimicrobial Potential of Commercial Silver Nanoparticles and the Characterization of Their Physical Properties toward Probiotic Bacteria Isolated from Fermented Milk Products. *J. Environ. Sci. Health B* **2016**, *51*, 222–229. https://doi.org/10.1080/03601234.2015.1120614.
318. Rasmussen, K.; Rauscher, H.; Gottardo, S.; Hoekstra, E.; Schoonjans, R.; Peters, R.; Aschberger, K. Regulatory status of nanotechnologies in food in the EU. In *Nanomaterials for Food Applications*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 381–410.
319. FSA (Food Standards Agency). Potential use of Nanomaterials as Food Additives or Food Ingredients in Relation to Consumer Safety and Regulatory Controls. Available online: https://www.food.gov.uk/research/chemical-hazards-in-food-and-feed/potential-use-of-nanomaterials-as-food-additives-or-food-ingredients-in-relation-to-consumer-safety-and-regulatory-controls (accessed on 4 May 2025).
320. Kuzma, J.; Grieger, K.; Cimadori, I.; Cummings, C.L.; Loschin, N.; Wei, W. Parameters, practices, and preferences for regulatory review of emerging biotechnology products in food and agriculture. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1256388.
321. Chavez-Hernandez, J.A.; Velarde-Salcedo, A.J.; Navarro-Tovar, G.; Gonzalez, C. Safe nanomaterials: From their use, application and disposal to regulations. *Nanoscale Adv.* **2024**, *6*, 1583–1610.
322. Jiang, Z.; Wang, Z.; Zhao, Y.; Peng, M. Unveiling the vital role of soil microorganisms in selenium cycling: A review. *Front. Microbiol.* **2024**, *15*, 1448539.