GIDA
THE JOURNAL OF FOOD
E-ISSN 1309-6273, ISSN 1300-3070

Review / Derleme
GIDA (2026) 51 (1) 187-205
doi:10.15237/gida.GD25053

GREEN SYNTHESIZED METALLIC NANOPARTICLES BY PLANT-BASED EXTRACTS AND THEIR FOOD APPLICATIONS: A REVIEW

Meliha ARSLANTURK[1], Basak Ebru ÖZCAN[2], Ayse KARADAĞ[1]

[1]Yıldız Technical University Faculty of Chemical and Metallurgical Engineering, Department of Food Engineering, İstanbul, Türkiye
[2]Kırklareli University Faculty of Engineering, Department of Food Engineering, Kırklareli, Türkiye

Received / Geliş: 15.04.2025; *Accepted* / Kabul: 21.11.2025; *Published online* /Online baskı: 31.12.2025

ABSTRACT

Studies using plant-based extracts as reducing agents contribute to the synthesis of non-toxic, environmentally friendly, and economically viable metallic nanoparticles (MNPs) as an alternative to traditional chemical reduction procedures. While the synthesized nanostructures stand out with unique features depending on the metal type, they commonly share properties such as antimicrobial activity. This review presents a comprehensive overview of recent advances in green-synthesized MNPs using plant extracts. It highlights the latest research on their applications in food packaging, as food additives, and as antimicrobial agents targeting pathogens. Furthermore, this paper discusses the toxicological aspects, safety concerns, and limitations of green-synthesized MNPs. Most studies indicate that these on biosynthesized nanomaterials are safe for use as novel food ingredients; however, further in vitro and in vivo investigations are still required to fully establish their safety and efficacy.
Keywords: Nanotechnology, silver nanoparticles, titanium dioxide, nanosensors, smart packaging

BİTKİSEL EKSTRAKTLAR İLE YEŞİL SENTEZLENEN METALİK NANOPARTİKÜLLER VE BUNLARIN GIDA UYGULAMALARI: BİR DERLEME

ÖZ

Bitki bazlı ekstraktları indirgeyici ajan olarak kullanan çalışmalar, geleneksel kimyasal indirgeme prosedürlerine alternatif olarak toksik olmayan, çevre dostu ve ekonomik olarak uygulanabilir metalik nanopartiküllerin (MNP'ler) sentezlenmesine önemli anlamda katkı sağlamaktadır. Sentezlenen bu nanoyapılar, metal türüne bağlı olarak, genellikle antimikrobiyal ajanlar olarak görev yapma gibi ortak özelliğe sahiptirler. Bu derlemede, bitki bazlı ekstraktlar kullanılarak yeşil sentezlenen MNP'ler hakkında güncel çalışmalar kapsamlı bir şekilde açıklanmaktadır. Özellikle bu nanopartiküllerin gıda ambalajında ve patojenlere karşı gıda katkı maddesi ve antimikrobiyal ajan olarak kullanımıyla ilgili son çalışmalar derlenmiştir. Ayrıca, yeşil sentezlenmiş MNP'lerin toksikolojisi, güvenilirliği ve kullanımlarındaki sınırlamalar da tartışılmıştır. Biyosentezlenmiş MNP'ler üzerine yapılan çalışmaların önemli bir çoğunluğu, bu nanomalzemelerin yeni bir gıda bileşeni olarak kullanımının güvenilir olduğunu göstermekte olsa da bu nanopartiküllerin güvenli ve etkili kullanımları için daha fazla in vitro ve in vivo çalışmaya ihtiyaç duyulmaktadır.
Anahtar kelimeler: Nanoteknoloji, gümüş nanopartiküller, titanyum dioksit, nanosensörler, akıllı ambalaj

Yazışmalardan sorumlu yazar / Corresponding author: Başak Ebru ÖZCAN
ORCID No: 0000-0001-6059-7388 **E-posta:** basakebruozcan@klu.edu.tr

INTRODUCTION

Nanotechnology is a specialized field of scientific research focused on the fabrication, manipulation, and characterization of matter at the nanoscale, typically ranging from 1 to 100 nm, to generate innovative materials with remarkable properties (Alharbi et al., 2022; Bayda et al., 2020). Nanoscale metals, due to their smaller size and larger surface area compared to their bulk counterparts, exhibit unique characteristics driven by surface and interface effects, as well as quantum effects. These nanoscale metals find broad applications in diverse fields such as biology, medicine, and food technology (Ying et al., 2022; Zhao et al., 2016).

Two fundamental approaches, top-down and bottom-up, are used to synthesize nanomaterials with the desired size, shape, and functionality (Singh et al., 2018). The bottom-up approach involves biological techniques employing plants, microorganisms, and other biological agents to build nanostructures from atoms or smaller entities (Alharbi et al., 2022). Conversely, the top-down method relies on physical processes such as mechanical pressure, evaporation, electrical, and radiation energy to breakdown of bulk materials into nano-sized particles (Aboyewa et al., 2021).

Green synthesis of nanoparticles (NPs) through living cells and biological pathways has emerged as a highly effective technique, producing greater quantities compared to conventional methods (Aboyewa et al., 2021). This evolving and straightforward method attracts researchers due to its advantages including low toxicity, environmental friendliness, and cost-effectiveness compared to traditional physical methods that are expensive, time-consuming, and energy-intensive (Alharbi et al., 2022), as well as chemical methods that often use toxic reagents (Zhang et al., 2016). Common metallic nanoparticles (MNPs) synthesized by green materials include Silver (Ag), iron (Fe), copper (Cu), platinum (Pt), gold (Au), palladium (Pd), copper oxide (CuO), iron oxide (FeO), zinc oxide (ZnO), silicon dioxide (SiO_2) and titanium dioxide (TiO_2) (Aboyewa et al., 2021).

Recently, extracts from different plant parts such as roots, seeds, leaves, flowers, and fruits have become increasingly popular for MNP synthesis (Figure 1). Alongside plant extracts, various biological organisms have been explored in green synthesis (Figure 2), including fungi (Guilger-Casagrande and Lima, 2019), yeast (Skalickova et al., 2017), bacteria (Saravanan et al., 2018), and microalgae (Mukherjee et al., 2021). While microbes offer advantages over plants and other physical or chemical methods, their use required controlled isolation, culturing, skilled personnel, and often longer processing and response times (Jeevanandam et al., 2022). Plants, being abundant and diverse in nature, are generally easier to access and thus are frequently featured in research (Alharbi et al., 2022).

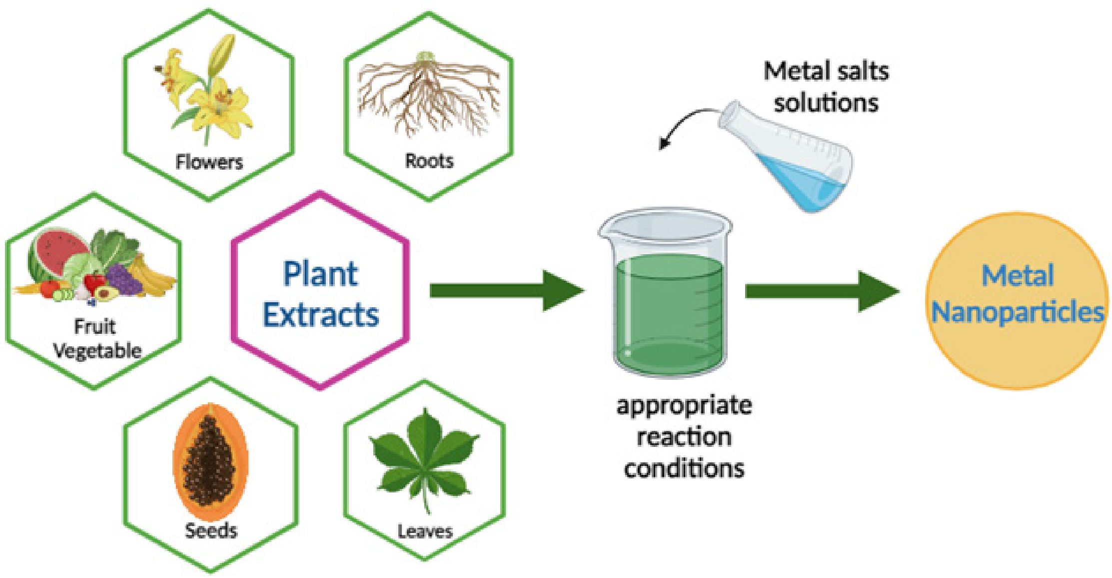

Figure 1. Schematic of the synthesis of metal nanoparticles using plant extracts

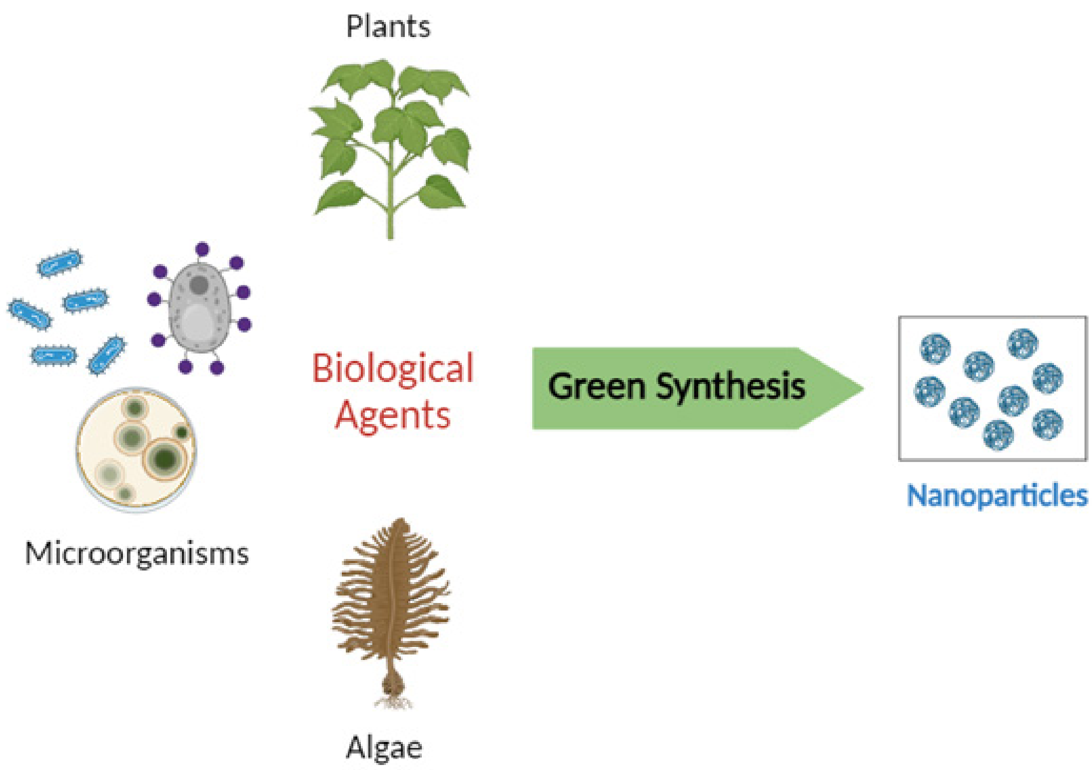

Figure 2. The green synthesis of nanoparticles using biological agents

Addressing human health and environmental sustainability is a global priority. Green synthesized MNPs hold immense promise for tackling environmental challenges while protecting human health. Some metallic NPs play vital roles in water purification, waste reduction, and environmental remediation, while some others are employed in therapeutics, medical diagnostics, and drug delivery. In the food sector, MNPs, specifically Au, Pd, Pt, Cu, Ag, Fe, CuO, FeO, ZnO, SiO_2, and TiO are utilized as food additives, and in food packaging and storage to enhance properties like antimicrobial activity, and gas barrier capabilities (Hebbar et al., 2020). Silver nanoparticles are the most widely used due to their well-documented antimicrobial effects. Magnesium (Mg) is common in dietary supplements, while silicon dioxide and titanium dioxide are applied as protective coatings and in environmental treatment agents for air and water purification. Additionally, a wide variety of nanomaterials such as Ag, Ca, and Au has also applications in health supplements (Vance et al., 2015).

Recent studies have successfully synthesized MNPs using plant-based extracts, including black currant pomace (AgNPs), Croton sparsiflorus leaf (AuNPs), Camellia sinensis leaf (PdNPs), Moringa oleifera fruit (FeNPs), Peganum harmala seed (PtNPs) and Millettia pinnata leaf (ZnONPs) (Boomi et al., 2020; Fahmy et al., 2021; Jegadeesan et al., 2019; Lebaschi et al., 2017; Sandhya et al., 2023; Vorobyova et al., 2020).

This study presents a comprehensive review of recent developments in the green synthesis of MNPs using plant-based extracts. It further discusses the toxicological aspects, safety considerations and food-related limitations of these green-synthesized MNPs. Moreover, the latest research on their applications in food packaging, as food additives, and as antimicrobial agents against foodborne pathogens is comprehensively examined.

PRODUCTION OF MNPs USING PLANT-BASED EXTRACTS

The standard green synthesis of MNPs involves the reduction of metal ions by reducing agents derived from plant-based bioproduct extracts. These extracts, sourced from both edible and inedible waste parts of plants, contain various biomolecules such as proteins, pigments, and other organic compounds that serve as capping agents, playing a crucial role in the stabilizing the nanoparticles (Abdel-Shafy and Mansour, 2018). Phenolic compounds, known for their free radical scavenging ability and antioxidant properties, act as reducing agents, enable the formation of MNPs and potentially replacing synthetic materials (Aswathi et al., 2023; Vijayaram et al., 2024). Comprehensive phytochemical characterization studies are required to identify bioactive compounds responsible for nanoparticle synthesis and to better understand their reducing capabilities within the plant extracts. For example, Saha et al. (2023) reported that the majority of the organic compounds present on the surface of MNPs originated from green coffee bean extract and coupled with nanoparticles during the reduction process. Similarly, Mali et al. (2020) demonstrated that copper nanoparticles were stabilized with flavonoids and other phenolic compounds of Celastrus paniculatus leaf extracts. Moreover, the reducing strength of plant-based extracts is linked to their antioxidant activities, where a higher concentration of antioxidant content indicates a greater reductive potential of the extract (Vorobyova et al., 2020).

A wide range of metallic nanostructures has been green-synthesized using extracts from various plant-based products. The key properties and application of commonly studied metal and metal oxide NPs commonly are briefly discussed in Table 1.

Table 1. Green synthesized MNPs by plant-based extracts

Nanoparticles	Plant-based sources	Shape	Size (nm)	References
Ag	*Myrsine africana* leaf	Spherical, oval	28	(Sarwer et al., 2022)
Ag	*Allium Sativum* flower	Spherical	20-35	(Velsankar et al., 2020)
Ag	*Justica wynaadensis* leaves	Crystalline	30-50	(Lava et al., 2020)
Ag	*Morus alba L.* mulberry fruit	Spherical	80-150	(Razavi et al., 2020)
Ag	Ginger root extract	Hexagonal, spherical	15	(Yadi et al., 2022)
Ag	*Allium ampeloprasum* leaf	Spherical	12-47	(F. Zhang et al., 2023)
Ag	*Berberis asiatica* root	Spherical	10	(Dangi et al., 2020)
Ag	*Gymnema sylvestre* leaf	Spherical	20-30	(Gomathi et al., 2020)
Au	*Croton sparsiflorus* leaf	Spherical	16-200	(Boomi et al., 2020)
Au	*Croton Caudatus Geisel* leaf	Spherical	20-50	(Vijaya Kumar et al., 2019)
Au	Cinnamon bark	Spherical	35	(ElMitwalli et al., 2020)
Pt	*Peganum harmala* seed	Spherical	20	(Fahmy et al., 2021)
Pd	*Camellia sinensis* leaf	Spherical	5-8	(Lebaschi et al., 2017)
Pd	*Lithodora hispidula (Sm.)* Griseb leaf	Rod	22	(Turunc et al., 2017)
Pd	*Peganum harmala* seed	Spherical	23	(Fahmy et al., 2021)
ZnO	*Azadirachta indica* leaf	Crystallite	52	(Iqbal et al., 2021)
ZnO	*Citrus microcarpa*	Quasi-spherical	20-65	(Villegas-Fuentes et al., 2023)
Fe	*Terminalia bellirica*	Spherical	21	(Jegadeesan et al., 2019)
Fe	*Moringa oleifera fruit*	Irregular	45	(Jegadeesan et al., 2019)
CuO	*Eucalyptus Globoulus* leaf	Quasi-spherical	85	(Alhalili, 2022)
CuO	*Ephedra Alata*	Spherical	10-16	(Atri et al., 2023)
Cu	*Celastrus paniculatus Willd* leaf,	Spherical	2-10	(Mali et al., 2020)

Table 1. Continued

Cu	*Millettia pinnata* flower	Spherical	13-35	(Thiruvengadam et al., 2019)
ZnO	*Millettia Pinnata* leaf	Spherical, crystalline	17	(Sandhya et al., 2023)
ZnO	Tanner's Cassia flower	Spherical	60	(Padmasree et al., 2023)
SiO_2	*Rhus coriaria* L.	Amorphous	55	(Rahimzadeh et al., 2022)
TiO_2	*Tinospora cordifolia*	Crystalline	15	(Saini and Kumar, 2023)

Ag: silver; Fe: iron; Cu: copper; Pt: platinum; Pd: palladium; Au: gold; ZnO: zinc oxide; CuO: copper oxide; SiO_2: silicon dioxide; TiO_2: titanium dioxide

Silver nanoparticles (AgNPs)

AgNPs are among the most extensively researched MNPs due to their broad applications in food industry and biomedicine. Their biological activities include antimicrobial effects against bacteria, viruses, and fungi, as well as anti-inflammatory, antioxidant, anticancer, and anti-diabetic properties. (Lava et al., 2020; Velsankar et al., 2020). Although the detailed mechanisms of AgNPs's antibacterial activities are not fully elucidated, it is suggested that AgNPs may adhere to bacterial cell walls, impairing membrane permeability and, eventually, cell respiration. This interaction influenced by the negatively charged bacterial cell surface, leads to protein denaturation and ultimately cell death (Chung et al., 2016; Kanchi and Ahmed, 2018).

The synthesis of AgNPs generally involves mixing plant extract with a silver ion solution, where the formation of AgNPs is indicated by a color change from yellow to various shades of brown (Widatalla et al., 2022). Numerous studies document the green synthesis of AgNPs from different plant sources and their corresponding characteristics (Kanchi and Ahmed, 2018). Velsankar et al. (2020) reported that *Allium sativum* flower extract produced spherical, crystalline AgNPs sized 20-35 nm, characterized by multiple instrumental techniques. AgNPs with extract of black currant pomaces effectively inhibited pathogenic organisms such as Gram-negative bacteria *Escherichia coli* (Vorobyova et al., 2020). Firdhouse and Lalitha (2016) demonstrated that the biosynthesized AgNPs from various plants disclosed excellent antibacterial effects against *E. coli, Salmonella paratyphi, Staphylococcus aureus,* and *Bacillus subtilis*. Similarly, AgNPs produced with Forsythia suspensa fruit water extract showed antibacterial activity against several food-borne pathogens (Du et al., 2019). Additionally, AgNPs synthesized from *Mentha crispa* L. leaf extract have been successfully applied in the treatment of dye-contaminated wastewater, yielding positive outcomes (Dinh et al., 2023).

Regarding antidiabetic potential, AgNPs synthesized using *Tephrosia tinctoria* root extract inhibited carbohydrate digesting enzymes (α-glucosidase and α-amylase) and enhanced glucose uptake in cells more effectively than the root extract alone. However, their antioxidant effect was lower than that of extract by itself (Rajaram et al., 2015). Furthermore, AgNPs derived from *Allium cepa* (onion) displayed significantly greater α -amylase inhibition activity than the acarbose, a standard antidiabetic drug, in all the tested concentration (Jini and Sharmila, 2020). AgNPs synthesized from aqueous leaf extract of *Ocimum americanum* (Hoary Basil) also demonstrating promising in vitro antibacterial, antioxidant, anticancer, and photocatalytic reduction activities (Manikandan et al., 2021).

Gold nanoparticles (AuNPs)

Plant-based extracts have long been employed as reducing and stabilizing agents in the green synthesis of gold nanoparticles (AuNPs). This process typically involves of mixing gold ion solutions with plant extracts, resulting in characteristics color change to reddish, indicating the formation of AuNPs (Arunachalam and Annamalai, 2013). The creation of AuNPs occurs rapidly through bioaccumulation, where metal ions are quickly reduced immediately of metal absorption and localization processes that are significantly faster than many alternative methods (Kanchi and Ahmed, 2018).

AuNPs have received significant attention among all MNPs due to their high potential for use in medicine and biology (Jain et al., 2006), attributed to their strong scattering and absorption properties, biocompatibility, controlled cytotoxicity (Babu et al., 2011; ElMitwalli et al., 2020), low toxicity, and muscle relaxant effects (Jadoun et al., 2021). In the food industry, AuNPs are utilized in packaging and storage to inhibit foodborne pathogens through their antibacterial, antifungal, and antioxidant activities. Additionally, they enhance packaging characteristics such as mechanical strength, water vapor permeability, freshness indicators, and antibacterial protection (A. Kumar et al., 2021).

Islam et al. (2019) synthesized AuNPs using Salix alba L. leaf extract and examined their under different pH and sodium chloride concentrations, and elevated temperatures. They reported that phytochemical coating on AuNPs influence their stability across different environments, demonstrating high stability in acidic media but reduced stability as the pH increases.

Mycotoxins, toxic secondary metabolites produced by fungi such as *Aspergillus, Fusarium,* and *Penicillium species* (Goyal et al., 2016) contaminate oilseeds, grains, nuts, spices, and coffee (Negash, 2018). Bhardwaj et al. (2020) leveraged AuNPs to anchor signal amplification and generate plasmonic resonant coupling between nanoparticles and chip surfaces, developing a surface plasmon resonance-based nanosensor for detecting aflatoxin in wheat. The AuNP-modified chip effectively detected Aflatoxin B1 at an impressive limit of 0.003 nM, significantly surpassing the bare self-assembled Au chip's detection limit of 0.19 nM. Moreover, AuNPs synthesized using leaf extracts from *Croton Caudatus Geisel* (Vijaya Kumar et al., 2019), Salix alba L. (Islam et al., 2019) and Croton sparsiflorus (Boomi et al., 2020) have demonstrated varied biological activities, including antinociceptive and muscle relaxant effects, cytotoxicity, and anticancer properties.

Copper (CuNPs) and copper oxide nanoparticles (CuONPs)
Copper (Cu) and its compounds have long been utilized for disinfecting human tissues, liquids, and solids. Copper is widely applied as an antibiotic, antifouling, fungicide, algaecide, and water purifier (Perelshtein et al., 2009).

Several plant extracts have been employed in the biosynthesize of CuNPs, such as the stem latex of Euphorbia nivulia plant (Valodkar et al., 2011), Eucalyptus sp. leaf (Kolekar et al., 2015), and Cymbopogon citratus (Brumbaugh et al., 2014). Recently, Atri et al. (2023) synthesized CuONPs using an aqueous extract of *Ephedra Alata* as a reducing agent. Their results showed that these biosynthesized CuO-NPs are effective in eradicating pathogenic bacteria such as *B. subtilis* and *S. aureus*, degrading dyes, and acting as antifungal agent against *Candida albicans*. Additionally, CuNPs synthesized with ethanolic extract of *Kigelia africana* fruit displayed promising antibacterial and antifungal activities (Alao et al., 2022).

Palladium nanoparticles (PdNPs) and platinum nanoparticles (PtNPs) Pd and Pt are valuable, high density metals that can efficiently catalyze numerous chemical processes and frequently employed in medical diagnostics, catalysts, and biosensors. The production of PdNPs and PtNPs using herbal extracts has been extensively studied due to their unique properties, such as ligand-free catalysis. These NPs exhibit antibacterial activity against both Gram-negative and Gram-positive microorganisms (Siddiqi and Husen, 2016).

There are many studies on plant-based extracts regarding the successful production of PdNPs, *Cinnamomum Camphora* leaf (Yang et al., 2010), *Stachys lavandulifolia* tea (Veisi et al., 2015), *Hippophae rhamnoides Linn* leaf (Nasrollahzadeh et al., 2015), *Euphorbia granulate* leaf (Nasrollahzadeh and Mohammad Sajadi, 2016), Rosa canina fruit (Veisi et al., 2016), *Camellia sinensis* black tea leaves (Lebaschi et al., 2017). For the green synthesis of PtNPs, various extracts have been used, such as *Prunus yedoensis* tree gum (Velmurugan et al., 2016), and Al-Madina dates (Al-Radadi, 2019).

Although Pt-group metal complexes are commonly used as anticancer drugs, they can be toxic to normal cells. In contrast, biosynthesized Pd and Pt NPs are non-toxic due to the presence of capping and stabilizing phytochemicals. Several studies have reported the effectiveness of these functionalized NPs in cancer treatment and their potential as nano-drugs (Al-Radadi, 2019; Fahmy et al., 2021; Sonbol et al., 2021). Considered a new and promising alternative to overcome drug resistance, the unique nanospecific properties of PtNPs and PdNPs may offer new possibilities for clinical therapy. Sonbol et al. (2021) synthesized PdNPs using a one-step, cost-effective, and eco-friendly green approach with extract from Padina boryana, a brown algae. They highlighted the potential role of biosynthesized PdNPs in the effective clinical management of multi-drug resistant pathogens and breast cancer cells.

Iron (FeNPs) and iron oxide nanoparticles (FeONPs)
Iron nanoparticles (FeNPs) and iron oxide nanoparticles (FeONPs) differ from conventional iron and iron oxides in several physical and chemical properties that infleuce their absorption, biodistribution, and elimination (Paunovic et al., 2020). In recent years, FeNPs have attracted significant attraction due to their strong magnetic properties, exceptional responsiveness to magnetic fields, catalytic activity, and unique features such as stability and biocompatibility (Tan et al., 2023).

Many plant-based extracts have been used for the biosynthesis of FeNPs. For example, *Terminalia chebula* fruit extract served as as both a reducing and capping agent in green synthesis of FeNPs, offering an alternative to chemical methods requiring hazardous agents, and toxic organic solvents (Mohan Kumar et al., 2013). Naseem and Farrukh (2015) used leaf extracts from *Lawsonia inermis* and *Gardenia jasminoides* for synthesizing of FeNPs, which showed strong inhibition of *S. aureus* and *E. coli*, indicating their potential for medical and pharmacological use. Another study employed *Trigonella foenum-graecum* seed extract for FeNPs synthesis applied in photocatalytic degradation of methyl orange dye and antibacterial activity (Radini et al., 2018). Machado et al. (2015) explored 26 plant species including avocado, apple, apricot, cherry, eucalyptus, kiwi, lemon, medlar, mandarin, mulberry, olive, orange, oak, passion fruit, pear, plum, pine, peach, pomegranate, quince, raspberry, strawberry, tea-green, tea-black, vine, and walnut for zero-valent FeNPs synthesis. Among these, pomegranate and mulberry leaf extracts produced the smallest NPs (5-10 nm), while apple, pine, and plum leaf extracts yielded the largest NPs (~100 nm). Additionally, Jegadeesan et al. (2019) synthesized FeNPs using fruit and leaf extracts from *Terminalia bellirica* and *Moringa oleifera*.

FeNPs fall into three main categories: FeO, FeO hydroxides, and nanoscale zero-valent Fe. They are widely used for removing chemical substances such as pesticides, dyes, pharmaceutical wastes, and heavy metal ions like nickel, lead, and chromium, owing to their high reactivity and surface-to-volume ratio (Mahto et al., 2018). Mohamed et al. (2023) synthesized green FeONPs using clove and green coffee extracts to remove heavy metals (Cd^{2+} and Ni^{2+}) from water. These FeONPs also demonstrated antibacterial activity against both *S. aureus* and E. coli, alongside effective heavy metal adsorption. Devatha et al. (2016) produced FeNPs for domestic wastewater treatment using leaf extracts from *Magnolia champaca, Murraya Koenigii, Mangifera indica,* and *Azadiracta indica*. Green synthesized zero-valent FeNPs derived from grape seed extract demonstrated promising low-cost, eco-friendly applications with and high decolorization efficiency (Gao et al., 2016).

Titanium dioxide nanoparticles (TiO_2NPs)

Titanium dioxide (TiO_2), also known as “titanium white”, with particles sizes ranging from 0.1 to 1.0 µm, was once considered safe for the human body due to its low solubility in water and lack of absorption in the gastrointestinal tract (Gmoshinski et al., 2019). TiO_2NP have been extensively studied as disinfectants and were previously used as food additives. TiO_2NPs (E171) were commonly incorporated into bioactive materials as anti-caking agents, food colorings, and flavor enhancers, and were often added to foods such as gum, puddings, and candy (He et al., 2019). However, in 2021, the European Commission banned TiO_2 as a food additive (Younes et al., 2021). In contrast, many other countries have not imposed restrictions on its use.

Saini and Kumar (2023) synthesized TiO_2NP using a cost-effective, and eco-friendly green method with an extract from *Tinospora cordifolia*. They indicated the successful enhancement of photocatalytic activity and excellent antibacterial effects of the biosynthesized nanoparticles. Another study by Almaimani (2023) reported that Pluronic F-127-coated TiO_2NP obtained from extracts of *Atractylodes macrocephala* leaf exhibited antioxidant, antimicrobial, and anticancer properties.

Besides antibacterial properties to the active film, TiO_2 also acts as a crosslinking agent, enhancing the film's mechanical strength, barrier performance, and other chemical and physical characteristics. TiO_2 gives the active film ethylene scavenging capacity, which is essential for extending the shelf life of food (Siripatrawan and Kaewklin, 2018). Due to its minimal TiO_2 migration, the composite film is considered suitable for food packaging applications. This property has been further improved through various studies (Lian et al., 2016; Lin et al., 2014).

Zinc oxide nanoparticles (ZnONPs)

ZnONPs have drawn considerable attention in the biomedical field such as antidiabetic, antibacterial (Iqbal et al., 2021), anticancer, and antifungal activities (Sandhya et al., 2023). Numerous studies have reported the green synthesis of ZnO nanoparticles using plants, microorganisms, and other sources, similar to other metallic nanoparticles (Jadoun et al., 2021).

Padmasree et al. (2023) described the green synthesis of ZnONPs using *Tanner's Cassia* flower extract and demonstrated their antibacterial activity against *E. coli* using the disc diffusion method. Similarly, ZnONPs biosynthesized with M*illettia Pinnata* leaves extract showed strong antibacterial activity against *Bacillus globigii* and *E. coli,* as well as antifungal activity *Aspergillus niger*. These nanoparticles also exhibited anticancer properties (Sandhya et al., 2023). Moreover, chitosan composite films incorporated with varying amounts of ZnONPs were prepared to improve the mechanical properties of chitosan, as well as its antibacterial activity. The addition of ZnONPs enhanced the chitosan films' tensile strength and elongation at break while reducing light transmission. During a 15-day preservation period, chitosan films containing 0.6% ZnONPs successfully inhibited cherry tomato respiration and displayed strong antibacterial activity against E. coli and S. aureus, common foodborne pathogens (Li et al., 2021).

Silicon dioxide nanoparticles (SiO_2NPs)

SiO_2NPs have been utilized across various sectors due to their excellent and tunable chemical, physical, and mechanical properties, as well as their low toxicity, biocompatibility, high porosity, large specific surface area, and ease of modification (P. Sharma et al., 2022).

In terms of stability, thermal characteristics, and surface area, a study comparing green synthesis and chemical methods found that SiO_2NPs synthesized Rhus coriaria L. extract outperformed chemically produced SiO_2NPs. This improvement is attributed to the green synthesis approach enhances stability, improves thermal properties, and increases surface area (Rahimzadeh et al., 2022).

TOXICOLOGY AND SAFETY OF BIOSYNTHESIZED MNPS

The biosynthesis of MNPs has emerged as a viable and environmentally friendly alternative to conventional chemical methods. Using biological systems such as microorganisms, algae, and plants to synthesize MNPs has several advantages, particularly from a toxicological safety perspective (Ahmed et al., 2022). This biosynthesis approach typically involves simple, cost-effective, and eco-sustainable techniques. The employment of biological agents in the reduction and stabilization processes eliminates the need for energy-intensive and ecologically hazardous operations common in conventional methods. Such sustainable production is consistent with global initiatives to mitigate the environmental impact of nanomaterial production (A. Saravanan et al., 2021).

Biosynthesized MNPs exhibit reduced toxicity and improved compatibility with biological tissues, making them suitable for various biomedical applications where biocompatibility is critical, such as drug delivery, imaging, and treatments (Kanchi and Ahmed, 2018).

Ensuring the safety of food additives is a top priority in the food industry. Biosynthesized MNPs perform better than their conventionally manufactured counterparts due to their lower toxicity. Their environmentally friendly synthesis pathways, frequently using plant extracts, reduce reliance on toxic chemicals, meeting both customer expectations for safer food products and regulatory requirements (Hebbar et al., 2020). Moreover, biosynthesized MNPs possess unique antibacterial and antioxidant properties, offering the potential to enhance food quality and extend shelf life. These green NPs effectively combat harmful microorganisms, reducing the dependence on chemical preservatives, supporting the development of more natural and safer food products (S. Sharma et al., 2019).

LIMITATIONS OF MNPs

Nanotechnology has steadily made their way into the agriculture and food sectors, offering various benefits throughout the food chain. However, the use of nanoparticles raises concerns about potential adverse effects on consumer health related to their physicochemical properties and toxicological impacts (Das et al., 2009).

The reliability of MNPs is crucial in food-related applications such as food additives, antimicrobial agents against foodborne pathogens, and food packaging enhancements. Consequently, biosynthesized MNPs, particularly those derived from plant extracts are non-toxic and environmentally benign, have attracted widespread attention. Various biosynthesized MNPs with anti-microbial (Alao et al., 2022; Sonbol et al., 2021), antioxidant (Lava et al., 2020; Thiruvengadam et al., 2019), anticancer (Boomi et al., 2020; Sonbol et al., 2021), anti-diabetic (Velsankar et al., 2020), and anti-inflammatory (Lava et al., 2020) characteristics have been demonstrated in researches. Despite these advantages, the direct effect of these nanoscale particles on living organisms have been investigated through in vivo and in vitro studies, leading to regulations in various countries (Schoonjans et al., 2023).

Some studies have reported that TiO2NPs can cause DNA damage (Jugan et al., 2012; Song et al., 2016). Kanchi and Ahmed (2018) highlighted that AgNPs hold excellent prospects for different applications in various sectors like biomedicine, including cell imaging, drug delivery, and implants. However, they emphasized the need for further research o analyze the in vivo toxicity of AgNPs and their precise effects on humans and animals.

Regulatory bodies such as EFSA (European Food Safety Authority) and FDA (Food and Drug Administration) provide important guidelines for the use of metal nanoparticles in foods. In 2021, the European Commission banned TiO2 (E171) as a food additive (Younes et al., 2021). Conversely, the FDA permits the use of TiO_2 as a food colorant, provided its content does not exceed a specified percentage by weight (FDA-CFR - Code of Federal Regulations Title 21, 2023). The EFSA Panel on Food Additives and Nutrient Sources also reassessed the safety of FeO (E172) and hydroxides used as food additives, but concluded that a comprehensive safety assessment could not be carried out due to insufficient biological and toxicological data (EFSA, 2015).

Based on current studies and regulatory information, the use of many NPs at certain doses in food processes is generally considered safe. However, concerns remain regarding direct consumption at specific levels, long-term exposure and potential bioaccumulation in the human body. Therefore, extensive large-scale in vivo toxicological studies are necessary to better assess the safety of biosynthesized MNPs.

FOOD APPLICATIONS OF MNPs

Nanomaterials offer a fresh viewpoint on food systems since their distinct physiochemical and biological characteristics compared to their bulk counterparts. This advancement is transforming the food processing industry, where nanotechnology is increasingly applied in areas such as emulsion preparation, encapsulation, and targeted delivery.

Particularly green-produced MNPs have received considerable interest for their roles in food additives, food-packaging development, and control of foodborne pathogenic microorganisms (Adeyemi and Fawole, 2023; Pathakoti et al., 2017). Several studies show that incorporating MNPs in food can extend shelf life, increase the bioavailability of essential nutrients, create new smart packaging solutions, and promote food traceability for better monitoring during storage and transportation (S. Sharma et al., 2019). Table 2 shows selected research on the use of MNPs in food applications.

Food additives

NPs can be employed in food processing to improve nutritional quality, texture, flavor, color, and stability, as well as to extend shelf life and protect beneficial components such as aroma compounds, vitamins, and antimicrobials (Gómez and Madrid, 2019). Although the usage of MNPs was previously limited, recent research has expanded their application through green synthesis techniques employing biological extracts regarded non-toxic, thereby contributing to their utilization in food processing (Adeyemi and Fawole, 2023).

Table 2. The use of MNPs in food applications

Nanoparticles	Other components	Applications	Applied on food products	Results / Effects	References
Ag	Polyetherimid (PEI)	Gas nanosensor for intelligent packaging	Salmon, Chicken, Turkey, Beef	Color change was observed in AgNPs-PEI films after 20 hours for salmon, chicken, and turkey, and after 60 hours for beef.	(Ryspayeva et al., 2018)
Ag	Carboxymethyl cellulose (CMC), Guar gum	Film for preserving aroma volatile components	Kinnow fruit (*Citrus reticulata*)	Fruit aroma and sensory quality of kinnow coated with films containing CMC and guar gum-based AgNPs were preserved for 120 days at 4°C.	(Shah et al., 2016)

Table 2. Continued

Ag	Sodium carboxymethyl cellulose (Na-CMC)	Film for preservation against mold growth	Banana	While no mold growth was observed in banana blocks coated with Na-CMC-AgNPs based film during the 5-day storage period, molds appeared on the third day in samples coated with AgNPs-free films.	(Goh et al., 2023)
SiO_2	Schiff's reagent	Colorimetric nanosensors for monitoring food quality	Milk	Milk spoilage occurred at 32, 60, and 84 h at 19, 15, and 13 °C, respectively, and could be detected colorimetrically.	(Ziyaina et al., 2019)
Au	-	Biosensor for Aflatoxin B1 detection	Wheat	The AuNPs modified Au chip was successfully utilized for Aflatoxin B1 detection ranging from 0.01 to 50 nM with a limit of detection of 0.003 nM.	(Bhardwaj et al., 2020)
ZnO	Chitosan	Film for food preservation	Cherry tomatoes	The chitosan-ZnONPs composite film showed antibacterial activity against *Alicyclobacillus acidoterrestris, Staphylococcus aureus, Escherichia coli,* and *Salmonella.*	(Li et al., 2021)

Metal oxide-based NPs such as SiO2NPs (E551), are commonly employed in bioactive materials as anti-caking agents and food flavor carriers. Additionally, CuO nanoparticles can be used as nutritional dietary supplements at concentrations below 2% by weight of the food (He et al., 2019). Phue et al. (2022) studied the effect of the common food additive TiO_2NPs on the allergenicity of milk proteins, including casein and β-lactoglobulin, as well as skim milk. The results revealed that interaction between TiO_2NPs and milk proteins in skim milk led to an increased allergenicity.

Food packaging

Packaging plays a crucial role in the food industry by extending shelf life, improving handling and protecting from physical and chemical damage during storage or transport. As customers' awareness of healthy and safe foods grows, researchers are focusing on advanced packaging materials that maintain the quality and sensory attributes. Nanomaterials-based sensors have become a prominent trend in active and smart packaging applications, enabling real-time monitoring of food quality (He et al., 2019).

Compared to traditional materials, nanomaterials designed for food packaging offer enhanced antimicrobial and barrier features. These materials can act as barriers to gases and moisture, distribute flavors, colors, enzymes, antioxidants, and antibrowning agents, ultimately prolonging the shelf life even after packaging is opened (Sekhon, 2010). Antimicrobial packaging, which leverages nanotechnology, plays a major role in increasing microbiological safety and extending product shelf life (Duncan, 2011). Nanosensors detect both internal conditions (like microbial growth or chemical change) and external environmental factors (such as temperature and humidity), helping monitor food quality throughout the production, transportation, and final sale (Neethirajan and Jayas, 2011).

An optical sensor based on polyetherimide and AgNPs was created to monitor color changes in meat (beef, turkey, chicken, and salmon). The polyetherimide/AgNPs films changed color after exposure to gaseous spoilage products within 20 to 60 hours, indicating freshness (Ryspayeva et al., 2018). N. Kumar et al. (2014) developed a simple and sensitive colorimetric method for the detection of melamine in milk using AuNPs. Melamine was hypothesized to be capable of causing AuNPs aggregation and the consequent color shift from red to blue/violet, detectable by the naked eye. Jayakumar et al. (2019) reported that pH-sensing polyvinyl alcohol (PVA)-starch films, fabricated with phytochemicals and ZnONPs, show promising potential for food packaging applications. Biosynthesized AgNPs from Moringa oleifera leaf extract coated on low-density polyethylene films offer enhanced food safety by preventing microbial contamination (Chougule et al., 2021). Similarly, AgNPs synthesized using Nymphae odorata extract incorporated into sodium alginate films inhibited S. aureus and E. coli at very low concentrations (Gudimalla et al., 2021). Edible films based on carboxymethyl cellulose (CMC) and guar gum containing AgNPs extend the shelf-life and retain the quality of kinnow mandarin during 120 days of storage at 4 °C (Shah et al., 2016). The addition of AgNPs to Na-CMC-coated banana blocks prevented mold growth during 5 days of storage, demonstrating enhanced storage stability compared to Na-CMC alone (Goh et al., 2023). CuNPs produced using Ocimum sanctum leaf extract were incorporated into cellulose-based film matrix, exhibiting strong antibacterial activity against *E. coli*. These biodegradable composite films are suitable for food packaging and medical applications (Sadanand et al., 2016).

Antimicrobial agents against foodborne pathogens

Nanotechnology has significantly advanced the detection and control of foodborne pathogens, addressing limitations of traditional methods that are often labor-intensive, time-consuming, and require specialized equipment and expertise. Nanotechnology applications facilitate the rapid detection of harmful substances, controlled release of preservatives to extend shelf life, and the development of innovative food packaging solutions that improve safety.

For example, Lotha et al. (2018) demonstrated that AgNPs synthesized from purified plant extracts effectively inhibited biofilm formation by various foodborne pathogens such as *Enterococcus faecalis, B. subtilis, S. aureus, E. coli, Salmonella typhi, Pseudomonas aeruginosa*, and *Enterobacter cloacae*. Similarly, AuNPs produced using extracts from medicinal plants *Cucurbita pepo* and *Malva crispa* exhibited inhibitory effects against Gram-negative *E. coli* and Gram-positive *Listeria monocytogenes* (Chandran et al., 2019).

CONCLUSION

Green synthesis techniques using plant-mediated biological extracts have become highly significant due to their non-toxic, environmentally friendly, and cost-effective nature. Biosynthesized MNPs produced by these methods have attracted substantial attention because they bypass the use of hazardous chemicals typically involved in conventional synthesis. Research demonstrates that these nanoparticles possess diverse bioactivities=including antibacterial, antioxidant, anticancer, antidiabetic, and anti-inflammatory properties=as well as environmental applications such as wastewater purification.

The advantageous features of MNPs have facilitated their application in the food business, and various studies are now underway in this area. MNPs are used as antibacterial agents against foodborne and other pathogenic microbes, as additives to enhance shelf life, flavor, and other quality attributes in food processing, and as advanced components in food packaging by providing antibacterial and barrier properties that preserve food and extend shelf life. Recent packaging innovations incorporating biosynthesized MNPs have enabled smart, active packaging solutions that better monitor and protect food from spoilage.

Despite demonstrated benefits, fewer studies have focused explicitly on green-synthesized MNPs in food applications compared to those produced by conventional routes. However, the available evidence suggests that green-synthesized MNPs offer distinct advantages such as reduced toxicity, eco-friendliness, and economic feasibility, making them safer alternatives for broader application in the food sector. This emerging research area holds great promise for advancing safer, more sustainable food technologies.

This review supports fostering further investigation into biosynthesized MNPs' safe and effective use in food systems, aiming to validate their advantages and promote their integration into commercial food products and packaging.

AUTHORSHIP CONTRIBUTIONS

Meliha Arslanturk: Writing-original draft, Writing-review, Conceptualization, Visualization. Basak Ebru Ozcan: Writing-original draft, Writing-review, Editing, Conceptualization, Supervision, Visualization. Ayse Karadag: Writing-review, Conceptualization, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

No data was used for the research described in the article.

REFERENCES

AbdelShafy, H. I., Mansour, M. S. (2018). Green synthesis of metallic nanoparticles from natural resources and food waste and their environmental application. Green metal nanoparticles: Synthesis, characterization and their applications, 321-385. https://doi.org/10.1002/9781119418900.ch11

Aboyewa, J. A., Sibuyi, N. R., Meyer, M., Oguntibeju, O. O. (2021). Green synthesis of metallic nanoparticles using some selected medicinal plants from southern africa and their biological applications. *Plants,* 10(9), 1929. https://doi.org/10.3390/plants10091929

Adeyemi, J. O., Fawole, O. A. (2023). Metal-based nanoparticles in food packaging and coating technologies: a review. *Biomolecules,* 13 (7), 1092. https://doi.org/10.3390/biom13071092

Ahmed, S. F., Mofijur, M., Rafa, N., Chowdhury, A. T., Chowdhury, S., Nahrin, M., Islam, A. B. M. S., Ong, H. C. (2022). Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environmental Research,* 204, 111967. https://doi.org/10.1016/j.envres.2021.111967

Alao, I. I., Peter Oyekunle, I., Iwuozor, K. O., Emenike, E. C. (2022). Green synthesis of Copper Nanoparticles and Investigation of its Antimicrobial Properties. Advanced Journal of Chemistry-Section B, B, 4(1), 39-52. https://doi.org/10.22034/ajcb.2022.323779.1106

Alhalili, Z. (2022). Green synthesis of copper oxide nanoparticles CuO NPs from Eucalyptus Globoulus leaf extract: Adsorption and design of experiments. *Arabian Journal of Chemistry,* 15(5). https://doi.org/10.1016/j.arabjc.2022.103739

Alharbi, N. S., Alsubhi, N. S., Felimban, A. I. (2022). Green synthesis of silver nanoparticles using medicinal plants: Characterization and application. *Journal of Radiation Research and Applied Sciences*, 15(3), 109–124. https://doi.org/10.1016/j.jrras.2022.06.012

Almaimani, R. A. (2023). Synthesis and characterization of Pluronic F-127-coated titanium dioxide nanoparticles synthesized from extracts of Atractylodes macrocephala leaf for antioxidant, antimicrobial, and anticancer properties. *Green Processing and Synthesis,* 12(1). https://doi.org/10.1515/gps-2023-0100

Al-Radadi, N. S. (2019). Green synthesis of platinum nanoparticles using Saudi's Dates extract and their usage on the cancer cell treatment. *Arabian Journal of Chemistry,* 12(3), 330–349. https://doi.org/10.1016/ j.arabjc.2018.05.008

Arunachalam, K. D., Annamalai, S. K. (2013). Chrysopogon zizanioides aqueous extract mediated synthesis, characterization of crystalline silver and gold nanoparticles for biomedical applications. *International Journal of Nanomedicine,* 8, 2375–2384. https://doi.org/10.2147/ IJN.S44076

Aswathi, V. P., Meera, S., Maria, C. G. A., Nidhin, M. (2023). Green synthesis of nanoparticles from biodegradable waste extracts and their applications: a critical review. Nanotechnology for *Environmental Engineering,* 8(2), 377-397. https://doi.org/10.1007/s41204-022-00276-8

Atri, A., Echabaane, M., Bouzidi, A., Harabi, I., Soucase, B. M., Ben Chaâbane, R. (2023). Green synthesis of copper oxide nanoparticles using Ephedra Alata plant extract and a study of their antifungal, antibacterial activity and photocatalytic performance under sunlight. *Heliyon,* 9(2). https://doi.org/10.1016/ j.heliyon.2023.e13484

Babu, P. J., Sharma, P., Kalita, M. C., Bora, U. (2011). Green synthesis of biocompatible gold nanoparticles using Fagopyrum esculentum leaf extract. *Frontiers of Materials Science,* 5(4), 379–387. https://doi.org/10.1007/s11706-011-0153-1

Bayda, S., Adeel, M., Tuccinardi, T., Cordani, M., Rizzolio, F. (2020). The history of nanoscience and nanotechnology: From chemical-physical applications to nanomedicine. *Molecules,* 25(1), 112. https://doi.org/10.3390/ molecules25010112

Bhardwaj, H., Sumana, G., Marquette, C. A. (2020). A label-free ultrasensitive microfluidic surface Plasmon resonance biosensor for Aflatoxin B1 detection using nanoparticles integrated gold chip. *Food Chemistry,* 307, 125530. https://doi.org/10.1016/j. foodchem.2019.125530

Boomi, P., Poorani, G. P., Selvam, S., Palanisamy, S., Jegatheeswaran, S., Anand, K., Balakumar, C., Premkumar, K., Prabu, H. G. (2020). Green biosynthesis of gold nanoparticles using Croton sparsiflorus leaves extract and evaluation of UV protection, antibacterial and anticancer applications. *Applied Organometallic Chemistry,* 34(5). https://doi.org/10.1002/ aoc.5574

Brumbaugh, A. D., Cohen, K. A., St. Angelo, S. K. (2014). Ultrasmall copper nanoparticles synthesized with a plant tea reducing agent. A*CS Sustainable Chemistry and Engineering,* 2(8), 1933–1939. https://doi.org/10.1021/sc500393t

Chandran, K., Song, S., Yun, S. Il. (2019). Effect of size and shape controlled biogenic synthesis of gold nanoparticles and their mode of interactions against food borne bacterial pathogens. *Arabian Journal of Chemistry,* 12(8), 1994–2006. https://doi.org/10.1016/j.arabjc.2014.11.041

Chougule, S. S., Gurme, S. T., Jadhav, J. P., Dongale, T. D., Tiwari, A. P. (2021). Low density polyethylene films incorporated with Biosynthesised silver nanoparticles using Moringa oleifera plant extract for antimicrobial, food packaging, and photocatalytic degradation applications. *Journal of Plant Biochemistry and Biotechnology,* 30(1), 208–214. https://doi.org/ 10.1007/ s13562-020-00584-7

Chung, I. M., Park, I., Seung-Hyun, K., Thiruvengadam, M., Rajakumar, G. (2016). Plant-Mediated Synthesis of Silver Nanoparticles: Their Characteristic Properties and Therapeutic Applications. Nanoscale Research Letters, 11, 1-14. https:// doi.org/10.1186/s11671-016-1257-4

Dangi, S., Gupta, A., Gupta, D. K., Singh, S., Parajuli, N. (2020). Green synthesis of silver nanoparticles using aqueous root extract of Berberis asiatica and evaluation of their antibacterial activity. *Chemical Data Collections,* 28. https:// doi.org/10.1016/j.cdc.2020.100411

Das, M., Saxena, N., Dwivedi, P. D. (2009). Emerging trends of nanoparticles application in food technology: Safety paradigms. *Nanotoxicology,* 3(1), 10–18. https://doi.org/10.1080/ 17435390802504237

Devatha, C. P., Thalla, A. K., Katte, S. Y. (2016). Green synthesis of iron nanoparticles using different leaf extracts for treatment of domestic wastewater. *Journal of Cleaner Production,* 139, 1425–1435. https://doi.org/10.1016/ j.jclepro.2016.09.019

Dinh, T. M., Tran, K. K., Le, A. T., Nguyen, T. M. N., Do, T. H., Liau, I. (2023). Green synthesis of silver nanoparticles using Mentha crispa L. leaf extract for treatment of dye wastewater. *Vietnam Journal of Science, Technology and Engineering,* 65(3), 14–20. https://doi.org/10.31276/ VJSTE.65(3).14-20

Du, J., Hu, Z., Yu, Z., Li, H., Pan, J., Zhao, D., Bai, Y. (2019). Antibacterial activity of a novel Forsythia suspensa fruit mediated green silver nanoparticles against food-borne pathogens and mechanisms investigation. M*aterials Science and Engineering* C, 102, 247–253. https://doi.org/ 10.1016/j. msec.2019.04.031

Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of Colloid and Interface Science*, 363(1), 1–24. https://doi.org/10.1016/j.jcis.2011.07.017

ElMitwalli, O. S., Barakat, O. A., Daoud, R. M., Akhtar, S., Henari, F. Z. (2020). Green synthesis of gold nanoparticles using cinnamon bark extract, characterization, and fluorescence activity in Au/eosin Y assemblies. *Journal of Nanoparticle Research,* 22, 1-9. https://doi.org/10.1007/ s11051-020-04983-8

Fahmy, S. A., Fawzy, I. M., Saleh, B. M., Issa, M. Y., Bakowsky, U., Azzazy, H. M. E. S. (2021). Green synthesis of platinum and palladium nanoparticles using Peganum harmala L. Seed alkaloids: Biological and computational studies. *Nanomaterials*, 11(4). https://doi.org/10.3390/ nano11040965

FDA-CFR - Code of Federal Regulations Title 21. (2023)

Firdhouse, M. J., Lalitha, P. (2016). Biogenic silver nanoparticles – Synthesis, characterization and its potential against cancer inducing bacteria. *Journal of Molecular Liquids,* 222, 1041–1050. https://doi.org/10.1016/j.molliq.2016.07.141

Gao, J. F., Li, H. Y., Pan, K. L., Si, C. Y. (2016). Green synthesis of nanoscale zero-valent iron using a grape seed extract as a stabilizing agent and the application for quick decolorization of azo and anthraquinone dyes. R*SC Advances*, 6(27), 22526–22537. https://doi.org/10.1039/ c5ra26668h

Gmoshinski, I. V., Bagryantseva, O. V., Khotimchenko, S. A. (2019). Toxicological and hygienic assessment of titanium dioxide nanoparticles as a component of E171 food additive (review of the literature and metahanalysis). *Health Risk Analysis,* 2, 145–163. https://doi.org/10.21668/health.risk/2019.2.17.eng

Goh, H. T., Cheok, C. Y., Yeap, S. P. (2023). Green synthesis of silver nanoparticles using banana peel extract and application on banana preservation. *Food Frontiers,* 4(1), 283–288. https://doi.org/10.1002/fft2.206

Gomathi, M., Prakasam, A., Rajkumar, P. V., Rajeshkumar, S., Chandrasekaran, R., Anbarasan, P. M. (2020). Green synthesis of silver nanoparticles using Gymnema sylvestre leaf extract and evaluation of its antibacterial activity. S*outh African Journal of Chemical Engineering,* 32, 1–4. https://doi.org/10.1016/j.sajce.2019.11.005

Gómez, B. G., Madrid, Y. (2019). Nanotechnology in the Food Field: Application of Metal-Based Nanoparticles. *In Advances in the Determination of Xenobiotics in Foods* (pp. 88-128).

Goyal, S., Ramawat, K. G., Mérillon, J. M. (2016). Different shades of fungal metabolites: an overview. Fungal metabolites, 1-29. https://doi.org/ 10.1007/978-3-319-19456-1_34-1

Gudimalla, A., Jose, J., Varghese, R. J., Thomas, S. (2021). Green Synthesis of Silver Nanoparticles Using Nymphae odorata Extract Incorporated Films and Antimicrobial Activity. *Journal of Polymers and the Environment,* 29(5), 1412–1423. https://doi.org/10.1007/s10924-020-01959-6

Guilger-Casagrande, M., Lima, R. de. (2019). Synthesis of silver nanoparticles mediated by fungi: a review. *Frontiers in bioengineering and biotechnology,* 7, 287. https://doi.org/10.3389/ fbioe.2019.00287

He, X., Deng, H., Hwang, H. min. (2019). The current application of nanotechnology in food and agriculture. *Journal of Food and Drug Analysis,* 27(1), 1-21. https://doi.org/10.1016/ j.jfda.2018.12.002

Hebbar, U., Ranjan, S., Dasgupta, N., Mishra, R. K. (Eds.) 2020. Nano-food Engineering. *Springer*.

Iqbal, Y., Raouf Malik, A., Iqbal, T., Hammad Aziz, M., Ahmed, F., Abolaban, F. A., Mansoor Ali, S., Ullah, H. (2021). Green synthesis of ZnO and Ag-doped ZnO nanoparticles using Azadirachta indica leaves: Characterization and their potential antibacterial, antidiabetic, and wound-healing activities. *Materials Letters*, 305. https://doi.org/10.1016/j.matlet.2021.130671

Islam, N. U., Jalil, K., Shahid, M., Rauf, A., Muhammad, N., Khan, A., Shah, M. R., Khan, M. A. (2019). Green synthesis and biological activities of gold nanoparticles functionalized with Salix alba. *Arabian Journal of Chemistry,* 12(8), 2914–2925. https://doi.org/10.1016/ j.arabjc.2015.06.025

Jadoun, S., Arif, R., Jangid, N. K., Meena, R. K. (2021). Green synthesis of nanoparticles using plant extracts: A review. *Environmental Chemistry Letters,* 19(1), 355-374. https://doi. org/ 10.1007/s10311-020-01074-x

Jain, P. K., Lee, K. S., El-Sayed, I. H., El-Sayed, M. A. (2006). Calculated absorption and scattering properties of gold nanoparticles of different size, shape, and composition: Applications in biological imaging and biomedicine. Jo*urnal of Physical Chemistry* B, 110(14), 7238–7248. https://doi.org/10.1021/ jp057170o

Jayakumar, A., K.V., H., T.S., S., Joseph, M., Mathew, S., G., P., Nair, I. C., E.K., R. (2019). Starch-PVA composite films with zinc-oxide nanoparticles and phytochemicals as intelligent pH sensing wraps for food packaging application. *International Journal of Biological Macromolecules,* 136, 395–403. https://doi.org/10.1016/ j.ijbiomac.2019.06.018

Jeevanandam, J., Kiew, S. F., Boakye-Ansah, S., Lau, S. Y., Barhoum, A., Danquah, M. K., Rodrigues, J. (2022). Green approaches for the synthesis of metal and metal oxide nanoparticles using microbial and plant extracts. *Nanoscale,* 14(7), 2534–2571. https://doi.org/10.1039/ d1nr08144f

Jegadeesan, G. B., Srimathi, K., Santosh Srinivas, N., Manishkanna, S., Vignesh, D. (2019). Green synthesis of iron oxide nanoparticles using Terminalia bellirica and Moringa oleifera fruit and leaf extracts: Antioxidant, antibacterial and thermoacoustic properties. *Biocatalysis and Agricultural Biotechnology,* 21. https://doi.org/ 10.1016/j.bcab.2019.101354

Jini, D., Sharmila, S. (2020). Green synthesis of silver nanoparticles from Allium cepa and its in vitro antidiabetic activity. Materials Today: *Proceedings,* 22, 432–438. https:// doi.org/ 10.1016/j.matpr.2019.07.672

Jugan, M. L., Barillet, S., Simon-Deckers, A., Herlin-Boime, N., Sauvaigo, S., Douki, T., Carriere, M. (2012). Titanium dioxide nanoparticles exhibit genotoxicity and impair DNA repair activity in A549 cells. *Nanotoxicology,* 6(5), 501–513. https:// doi.org/10.3109/ 17435390.2011.587903

Kanchi, S., Ahmed, S. (Eds.) (2018). Green metal nanoparticles: synthesis, characterization and their applications. John Wiley & Sons.

Kolekar, R., Bhade, S., Kumar, R. A. J. I. V., Reddy, P. R. I. Y. A. N. K. A., Singh, R. A. J. V. I. R., Pradeepkumar, K. (2015). Biosynthesis of copper nanoparticles using aqueous extract of Eucalyptus sp. plant leaves. *Current Science*, 109(2), 255-257.

Kumar, A., Choudhary, A., Kaur, H., Mehta, S., Husen, A. (2021). Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. Journal of Nanobiotechnology, 19(1), 256. https://doi.org/10.1186/s12951-021-00996-0

Kumar, N., Seth, R., Kumar, H. (2014). Colorimetric detection of melamine in milk by citrate-stabilized gold nanoparticles. Analytical Biochemistry, 456(1), 43–49. https://doi.org/ 10.1016/j.ab.2014.04.002

Lava, M. B., Muddapur, U. M., Basavegowda, N., More, S. S., More, V. S. (2020). Characterization, anticancer, antibacterial, anti-diabetic and anti-inflammatory activities of green synthesized silver nanoparticles using Justica wynaadensis leaves extract. *Materials Today: Proceedings*, 46, 5942–5947. https://doi.org/10.1016/j.matpr.2020.10.048

Lebaschi, S., Hekmati, M., Veisi, H. (2017). Green synthesis of palladium nanoparticles mediated by black tea leaves (Camellia sinensis) extract: Catalytic activity in the reduction of 4-nitrophenol and Suzuki-Miyaura coupling reaction under ligand-free conditions. *Journal of Colloid and Interface Science,* 485, 223–231. https://doi.org/ 10.1016/j.jcis.2016.09.027

Li, Y., Zhou, Y., Wang, Z., Cai, R., Yue, T., Cui, L. (2021). Preparation and characterization of chitosan–nano-zno composite films for preservation of cherry tomatoes. F*oods,* 10(12). https://doi.org/10.3390/foods10123135

Lian, Z., Zhang, Y., Zhao, Y. (2016). Nano-TiO2 particles and high hydrostatic pressure treatment for improving functionality of polyvinyl alcohol and chitosan composite films and nano-TiO_2 migration from film matrix in food simulants. Innovative F*ood Science and Emerging Technologies,* 33, 145–153. https://doi.org/10.1016/ j.ifset.2015.10.008

Lin, Q. B., Li, H., Zhong, H. N., Zhao, Q., Xiao, D. H., Wang, Z. W. (2014). Migration of Ti from nano-TiO_2-polyethylene composite packaging into food simulants. *Food Additives and Contaminants*- Part A, 31(7), 1284–1290. https://doi.org/10.1080/19440049.2014.907505

Lotha, R., Sundaramoorthy, N. S., Shamprasad, B. R., Nagarajan, S., Sivasubramanian, A. (2018). Plant nutraceuticals (Quercetrin and Afzelin) capped silver nanoparticles exert potent antibiofilm effect against food borne pathogen Salmonella enterica serovar typhimurium and curtail planktonic growth in zebrafish infection model. *Microbial Pathogenesis*, 120, 109–118. https://doi.org/10.1016/j.micpath.2018.04.044

Machado, S., Pacheco, J. G., Nouws, H. P. A., Albergaria, J. T., Delerue-Matos, C. (2015). Characterization of green zero-valent iron nanoparticles produced with tree leaf extracts. *Science of the Total Environment,* 533, 76–81. https://doi.org/10.1016/j.scitotenv.2015.06.091

Mahto, A., Kumar, A., Chaudhary, J. P., Bhatt, M., Sharma, A. K., Paul, P., Nataraj, S. K., Meena, R. (2018). Solvent-free production of nano-FeS anchored graphene from Ulva fasciata: A scalable synthesis of super-adsorbent for lead, chromium and dyes. *Journal of Hazardous Materials*, 353, 190–203. https://doi.org/10.1016/ j.jhazmat.2018.03.054

Mali, S. C., Dhaka, A., Githala, C. K., Trivedi, R. (2020). Green synthesis of copper nanoparticles using Celastrus paniculatus Willd. leaf extract and their photocatalytic and antifungal properties. *Biotechnology Reports,* 27. https://doi.org/ 10.1016/j.btre.2020.e00518

Manikandan, D. B., Sridhar, A., Krishnasamy Sekar, R., Perumalsamy, B., Veeran, S., Arumugam, M., Karuppaiah, P., Ramasamy, T. (2021). Green fabrication, characterization of silver nanoparticles using aqueous leaf extract of Ocimum americanum (Hoary Basil) and investigation of its in vitro antibacterial, antioxidant, anticancer and photocatalytic reduction. *Journal of Environmental Chemical Engineering*, 9(1). https://doi.org/10.1016/ j.jece.2020.104845

Mohamed, A., Atta, R. R., Kotp, A. A., Abo El-Ela, F. I., Abd El-Raheem, H., Farghali, A., Alkhalifah, D. H. M., Hozzein, W. N., Mahmoud, R. (2023). Green synthesis and characterization of iron oxide nanoparticles for the removal of heavy metals (Cd^{2+} and Ni^{2+}) from aqueous solutions with Antimicrobial Investigation. *Scientific Reports*, 13(1). https://doi.org/10.1038/s41598-023-31704-7

Mohan Kumar, K., Mandal, B. K., Siva Kumar, K., Sreedhara Reddy, P., Sreedhar, B. (2013). Biobased green method to synthesise palladium and iron nanoparticles using Terminalia chebula aqueous extract. Spectrochimica Acta- Part A: *Molecular and Biomolecular Spectroscopy*, 102, 128–133. https://doi.org/10.1016/j.saa.2012.10.015

Mukherjee, A., Sarkar, D., Sasmal, S. (2021). A review of green synthesis of metal nanoparticles using algae. *Frontiers in Microbiology,* 12, 693899. https://doi.org/10.3389/fmicb.2021.693899

Naseem, T., Farrukh, M. A. (2015). Antibacterial activity of green synthesis of iron nanoparticles using lawsonia inermis and gardenia jasminoides leaves extract. J*ournal of Chemistry,* 2015. https://doi.org/10.1155/2015/912342

Nasrollahzadeh, M., Mohammad Sajadi, S. (2016). Pd nanoparticles synthesized in situ with the use of Euphorbia granulate leaf extract: Catalytic properties of the resulting particles. *Journal of Colloid and Interface Science,* 462, 243–251. https://doi.org/10.1016/j.jcis.2015.09.065

Nasrollahzadeh, M., Sajadi, S. M., Maham, M. (2015). Green synthesis of palladium nanoparticles using Hippophae rhamnoides Linn leaf extract and their catalytic activity for the Suzuki-Miyaura coupling in water. *Journal of Molecular Catalysis A: Chemical*, 396, 297–303. https://doi.org/10.1016/j.molcata.2014.10.019

Neethirajan, S., Jayas, D. S. (2011). Nanotechnology for the food and bioprocessing industries. F*ood and bioprocess technology*, 4, 39-47. https://doi.org/10.1007/s11947-010-0328-2

Negash, D. (2018). A review of aflatoxin: occurrence, prevention, and gaps in both food and feed safety. *Journal of Nutritional Health & Food Engineering,* 8(2). https://doi.org/10.15406/jnhfe.2018.08.00268

Padmasree, G., Anuradha, K., Arun Kumar, A., Pragadeeswari, G. (2023). Studies on antibacterial efficacy of ZnO nanoparticles using Tanner's Cassia flower extract from green synthesis. Materials Today: *Proceedings,* 92, 658–661. https://doi.org/10.1016/j.matpr.2023.04.149
8

Pathakoti, K., Manubolu, M., Hwang, H. M. (2017). Nanostructures: Current uses and future applications in food science. *Journal of food and drug analysis,* 25(2), 245-253. https://doi.org/ 10.1016/j.jfda.2017.02.004

Paunovic, J., Vucevic, D., Radosavljevic, T., Mandić-Rajčević, S., Pantic, I. (2020). Iron-based nanoparticles and their potential toxicity: Focus on oxidative stress and apoptosis. *Chemico-biological interactions,* 316, 108935. https://doi.org/10.1016/j.cbi.2019.108935

Perelshtein, I., Applerot, G., Perkas, N., Wehrschuetz-Sigl, E., Hasmann, A., Guebitz, G., Gedanken, A. (2009). CuO-cotton nanocomposite: Formation, morphology, and antibacterial activity. *Surface and Coatings Technology,* 204(1–2), 54–57. https://doi.org/10.1016/ j.surfcoat.2009.06.028

Phue, W. H., Xu, K., George, S. (2022). Inorganic food additive nanomaterials alter the allergenicity of milk proteins. *Food* and Chemical Toxicology, 162. https://doi.org/10.1016/j. fct.2022.112874

Radini, I. A., Hasan, N., Malik, M. A., Khan, Z. (2018). Biosynthesis of iron nanoparticles using Trigonella foenum-graecum seed extract for photocatalytic methyl orange dye degradation and antibacterial applications. *Journal of Photochemistry and Photobiology B: Biology,* 183, 154–163. https://doi.org/10.1016/j.jphotobiol.2018.04.014

Rahimzadeh, C. Y., Barzinjy, A. A., Mohammed, A. S., Hamad, S. M. (2022). Green synthesis of SiO2 nanoparticles from Rhus coriaria L. extract: Comparison with chemically synthesized SiO2 nanoparticles. *PLoS ONE*, 17(8 August). https://doi.org/10.1371/journal.pone.0268184

Rajaram, K., Aiswarya, D. C., Sureshkumar, P. (2015). Green synthesis of silver nanoparticle using Tephrosia tinctoria and its antidiabetic activity. *Materials Letters,* 138, 251–254. https://doi.org/10.1016/j.matlet.2014.10.017

Razavi, R., Molaei, R., Moradi, M., Tajik, H., Ezati, P., Shafipour

Yordshahi, A. (2020). Biosynthesis of metallic nanoparticles using mulberry fruit (Morus alba L.) extract for the preparation of antimicrobial nanocellulose film. *Applied Nanoscience (Switzerland),* 10(2), 465–476. https://doi.org/10.1007/s13204-019-01137-8

Ryspayeva, A., Jones, T. D. A., Hughes, P. A., Nekouie Esfahani, M., Shuttleworth, M. P., Harris, R. A., Kay, R. W., Desmulliez, M. P. Y., Marques-Hueso, J. (2018). PEI/Ag as an optical gas nano-sensor for intelligent food packaging. In 2018 IEEE 18th international conference on nanotechnology (IEEE-NANO) (pp. 1-4). IEEE.

Sadanand, V., Rajini, N., Varada Rajulu, A., Satyanarayana, B. (2016). Preparation of cellulose composites with in situ generated copper nanoparticles using leaf extract and their properties. *Carbohydrate Polymers,* 150, 32–39. https://doi.org/10.1016/j.carbpol.2016.04.121

Saha, P., Habib, M. A., Islam, A. B. M. N., Karim, K. M. R., Mahiuddin, M. (2023). Green synthesis of bismuth nanoparticles using green coffee beans extract. *Discover Materials ,* 3(1). https://doi.org/ 10.1007/s43939-023-00044-8

Saini, R., Kumar, P. (2023). Green synthesis of TiO_2 nanoparticles using Tinospora cordifolia plant extract & its potential application for photocatalysis and antibacterial activity. *Inorganic Chemistry Communications*, 156. https://doi.org/10.1016/j.inoche.2023.111221

Sandhya, P., Prasad, M. S. N. A., Reddy Prasad, P., Supriya, G., Nagendra Kumar, P. V. (2023). Millettia Pinnata leaves extract mediated ZnO nanoparticles and their antimicrobial, cytotoxicity study. Materials Today: *Proceedings*, 92, 662–666. https://doi.org/10.1016/j.matpr.2023.04.150

Saravanan, A., Kumar, P. S., Karishma, S., Vo, D. V. N., Jeevanantham, S., Yaashikaa, P. R., George, C. S. (2021). A review on biosynthesis of metal nanoparticles and its environmental applications. *Chemosphere,* 264. https://doi.org/10.1016/j.chemosphere.2020.128580

Saravanan, M., Barik, S. K., MubarakAli, D., Prakash, P., Pugazhendhi, A. (2018). Synthesis of silver nanoparticles from Bacillus brevis (NCIM 2533) and their antibacterial activity against pathogenic bacteria. *Microbial Pathogenesis,* 116, 221–226. https://doi.org/10.1016/ j.micpath.2018.01.038

Sarwer, Q., Amjad, M. S., Mehmood, A., Binish, Z., Mustafa, G., Farooq, A., Qaseem, M. F., Abasi, F., Pérez de la Lastra, J. M. (2022). Green Synthesis and Characterization of Silver Nanoparticles Using Myrsine africana Leaf Extract for Their Antibacterial, Antioxidant and Phytotoxic Activities. *Molecules,* 27(21). https://doi.org/10.3390/molecules27217612

Schoonjans, R., Castenmiller, J., Chaudhry, Q., Cubadda, F., Daskaleros, T., Franz, R., Gott, D., Mast, J., Mortensen, A., Oomen, A. G., Rauscher, H., Weigel, S., Astuto, M. C., Cattaneo, I., Barthelemy, E., Rincon, A., Tarazona, J. (2023).

Regulatory safety assessment of nanoparticles for the food chain in Europe. *Trends in Food Science & Technology,* 134, 98-111. https://doi.org/10.1016/j.tifs.2023.01.017

Scientific Opinion on the re-evaluation of iron oxides and hydroxides (E 172) as food additives. (2015). *EFSA Journal,* 13(12). https://doi.org/10.2903/j.efsa.2015.4317

Sekhon, B. S. (2010). Food nanotechnology-an overview. *Nanotechnology, Science and Applications,* 1–15. https://doi.org/10.2147/nsa.s12187498

Shah, S. W. A., Qaisar, M., Jahangir, M., Abbasi, K. S., Khan, S. U., Ali, N., Liaquat, M. (2016). Influence of CMC- and guar gum-based silver nanoparticle coatings combined with low temperature on major aroma volatile components and the sensory quality of kinnow (Citrus reticulata). International *Journal of Food Science and Technology,* 51(11), 2345–2352. https://doi.org/ 10.1111/ijfs.13213

Sharma, P., Prakash, J., Kaushal, R. (2022). An insight into the green synthesis of SiO2 nanostructures as a novel adsorbent for removal of toxic water pollutants. *Environmental Research,* 212. https://doi.org/10.1016/ j.envres.2022.113328

Sharma, S., Jaiswal, S., Duffy, B., Jaiswal, A. K. (2019). Nanostructured Materials for Food Applications: Spectroscopy, Microscopy and Physical Properties. In Bioengineering (Vol. 6, Issue 1). https://doi.org/10.3390/ bioengineering6010026

Siddiqi, K. S., Husen, A. (2016). Green synthesis, characterization and uses of palladium/platinum nanoparticles. N*anoscale research letters,* 11, 1-13. https://doi.org/10.1186/s11671-016-1695-z

Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., Kumar, P. (2018). Green'synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *Journal of nanobiotechnology,* 16, 1-24. https://doi.org/10.1186/s12951-018-0408-4

Siripatrawan, U., Kaewklin, P. (2018). Fabrication and characterization of chitosan-titanium dioxide nanocomposite film as ethylene scavenging and antimicrobial active food packaging. *Food Hydrocolloids*, 84, 125–134. https://doi.org/10.1016/j.foodhyd.2018.04.049

Skalickova, S., Baron, M., Sochor, J. (2017). Nanoparticles Biosynthesized by Yeast: A Review of their application. Kvasny Prumysl, 63(6), 290–292. https://doi.org/10.18832/kp201727

Sonbol, H., Ameen, F., AlYahya, S., Almansob, A., Alwakeel, S. (2021). Padina boryana mediated green synthesis of crystalline palladium nanoparticles as potential nanodrug against multidrug resistant bacteria and cancer cells. *Scientific Reports*, 11(1), 5444. https://doi.org/ 10.1038/s41598-021-84794-6

Song, B., Zhang, Y. L., Liu, J., Feng, X. L., Zhou, T., Shao, L. Q. (2016). Is neurotoxicity of metallic nanoparticles the cascades of oxidative stress?. *Nanoscale research letters,* 11, 1-11. https://doi.org/10.1186/s11671-016-1508-4

Tan, H. L., Lim, Y. C., Ng, L. Y., Lim, Y. P. (2023). Plant-mediated synthesis of iron nanoparticles for environmental application: Mini review. Materials Today: *Proceedings*, 87, 64–69. https://doi.org/10.1016/j.matpr.2023.02.101

Thiruvengadam, M., Chung, I. M., Gomathi, T., Ansari, M. A., Gopiesh Khanna, V., Babu, V., Rajakumar, G. (2019). Synthesis, characterization and pharmacological potential of green synthesized copper nanoparticles. *Bioprocess and Biosystems Engineering,* 42(11), 1769–1777. https://doi.org/10.1007/s00449-019-02173-y

Turunc, E., Binzet, R., Gumus, I., Binzet, G., Arslan, H. (2017). Green synthesis of silver and palladium nanoparticles using Lithodora hispidula (Sm.) Griseb. (Boraginaceae) and application to the electrocatalytic reduction of hydrogen peroxide. *Materials Chemistry and Physics,* 202, 310–319. https://doi.org/10.1016/ j.matchemphys.2017.09.032

Valodkar, M., Jadeja, R. N., Thounaojam, M. C., Devkar, R. V., Thakore, S. (2011). Biocompatible synthesis of peptide capped copper nanoparticles and their biological effect on tumor cells. *Materials Chemistry and Physics,* 128(1–2), 83–89. https://doi.org/10.1016/j.matchemphys.2011.02.039

Vance, M. E., Kuiken, T., Vejerano, E. P., McGinnis, S. P., Hochella, M. F., Hull, D. R. (2015). Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory. *Beilstein Journal of Nanotechnology,* 6(1), 1769–1780. https://doi.org/ 10.3762/bjnano.6.181

Veisi, H., Ghorbani-Vaghei, R., Hemmati, S., Haji Aliani, M., Ozturk, T. (2015). Green and effective route for the synthesis of monodispersed palladium nanoparticles using herbal tea extract (Stachys lavandulifolia) as reductant, stabilizer and capping agent, and their application as homogeneous and reusable catalyst in Suzuki coupling reactions in water. *Applied Organometallic Chemistry,* 29(1), 26–32. https://doi.org/10.1002/ aoc.3243

Veisi, H., Rashtiani, A., Barjasteh, V. (2016). Biosynthesis of palladium nanoparticles using Rosa canina fruit extract and their use as a heterogeneous and recyclable catalyst for Suzuki-Miyaura coupling reactions in water. *Applied Organometallic Chemistry,* 30(4), 231–235. https://doi.org/10.1002/aoc.3421

Velmurugan, P., Shim, J., Kim, K., Oh, B. T. (2016). Prunus × yedoensis tree gum mediated synthesis of platinum nanoparticles with antifungal activity against phytopathogens. *Materials Letters,* 174, 61–65. https://doi.org/ 10.1016/j.matlet.2016.03.069

Velsankar, K., Preethi, R., Ram, P. S. J., Ramesh, M., Sudhahar, S. (2020). Evaluations of biosynthesized Ag nanoparticles via Allium Sativum flower extract in biological applications. *Applied Nanoscience (Switzerland),* 10(9), 3675–3691. https://doi.org/10.1007/s13204-020-01463-2

Vijaya Kumar, P., Mary Jelastin Kala, S., Prakash, K. S. (2019). Green synthesis of gold nanoparticles using Croton Caudatus Geisel leaf extract and their biological studies. *Materials Letters,* 236, 19–22. https://doi.org/10.1016/ j.matlet.2018.10.025

Vijayaram, S., Razafindralambo, H., Sun, Y. Z., Vasantharaj, S., Ghafarifarsani, H., Hoseinifar, S. H., Raeeszadeh, M. (2024). Applications of Green Synthesized Metal Nanoparticles — a Review. *Biological Trace Element Research,* 202(1), 360-386. https://doi.org/10.1007/s12011-023-03645-9

Villegas-Fuentes, A., Garrafa-Gálvez, H. E., Quevedo-Robles, R. V., Luque-Morales, M., Vilchis-Nestor, A. R., Luque, P. A. (2023). Synthesis of semiconductor ZnO nanoparticles using

Citrus microcarpa extract and the influence of concentration on their optical properties. *Journal of Molecular Structure,* 1281. https://doi.org/10.1016/j.molstruc.2023.135067

Vorobyova, V., Vasyliev, G., Skiba, M. (2020). Eco-friendly "green" synthesis of silver nanoparticles with the black currant pomace extract and its antibacterial, electrochemical, and antioxidant activity. *Applied Nanoscience (Switzerland),* 10(12), 4523–4534. https://doi.org/ 10.1007/s13204-020-01369-z

Widatalla, H. A., Yassin, L. F., Alrasheid, A. A., Rahman Ahmed, S. A., Widdatallah, M. O., Eltilib, S. H., Mohamed, A. A. (2022). Green synthesis of silver nanoparticles using green tea leaf extract, characterization and evaluation of antimicrobial activity. *Nanoscale Advances,* 4(3), 911–915. https://doi.org/10.1039/ d1na00509j

Yadi, M., Azizi, M., Dianat-Moghadam, H., Akbarzadeh, A., Abyadeh, M., Milani, M. (2022). Antibacterial activity of green gold and silver nanoparticles using ginger root extract. *Bioprocess and Biosystems Engineering,* 45(12), 1905–1917. https://doi.org/10.1007/s00449-022-02780-2

Yang, X., Li, Q., Wang, H., Huang, J., Lin, L., Wang, W., Sun, D., Su, Y., Opiyo, J. B., Hong, L., Wang, Y., He, N., Jia, L. (2010). Green synthesis of palladium nanoparticles using broth of Cinnamomum camphora leaf. *Journal of Nanoparticle Research,* 12(5), 1589–1598. https://doi.org/10.1007/ s11051-009-9675-1

Ying, S., Guan, Z., Ofoegbu, P. C., Clubb, P., Rico, C., He, F., Hong, J. (2022). Green synthesis of nanoparticles: Current developments and limitations. *Environmental Technology and Innovation* 26, 102336. https://doi.org/10.1016/ j.eti.2022.102336

Younes, M., Aquilina, G., Castle, L., Engel, K. H., Fowler, P., Frutos Fernandez, M. J., Fürst, P., Gundert-Remy, U., Gürtler, R., Husøy, T., Manco, M., Mennes, W., Moldeus, P., Passamonti, S., Shah, R., Waalkens-Berendsen, I., Wölfle, D., Corsini, E., Cubadda, F., Wright, M. (2021). Safety assessment of titanium dioxide (E171) as a food additive. *EFSA Journal,* 19(5). https://doi.org/10.2903/j.efsa.2021.6585

Zhang, F., Jia, J., Yao, X. (2023). Allium ampeloprasum leaf aqueous extract green-formulated Ag nanoparticles: Determination of anti-human lung cancer and antioxidant effects. *Journal of Engineering Research (Kuwait),* 11(3), 28–33. https://doi.org/10.1016/J.JER.2023.100091

Zhang, X. F., Liu, Z. G., Shen, W., Gurunathan, S. (2016). Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches. *International journal of molecular sciences,* 17(9), 1534. https://doi.org/ 10.3390/ ijms17091534

Zhao, X., Liu, W., Cai, Z., Han, B., Qian, T., Zhao, D. (2016). An overview of preparation and applications of stabilized zero-valent iron nanoparticles for soil and groundwater remediation. *Water research,* 100, 245-266. https://doi.org/10.1016/j. watres.2016.05.019

Ziyaina, M., Rasco, B., Coffey, T., Ünlü, G., Sablani, S. S. (2019). Colorimetric detection of volatile organic compounds for shelf-life monitoring of milk. *Food Control,* 100, 220–226. https:// doi. org/10.1016/j.foodcont.2019.01.018

Cite this article as:
Arslantürk, M., Ozcan, B. E., Karadag, A. (2026). Green synthesized metallic nanoparticles by plant-based extracts and their food applications: A review. GIDA (2026) 51 (1) 187-205 doi: 10.15237/ gida.GD25053

Nasıl Atıf Yapılır?:
Arslantürk, M., Ozcan, B. E., Karadag, A. (2026). Bitkisel ekstraktlar ile yeşil sentezlenen metalik nanopartiküller ve bunların gıda uygulamaları: Bir derleme. GIDA (2026) 51 (1) 187-205 doi: 10.15237/ gida.GD25053