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**A. ROYANI [1,2,*], C. VERMA [3], M. HANAFI [4],
V.S. AIGBODION [5,6], and A. MANAF [2,**]**

[1] Research Centre for Metallurgy,
National Research and Innovation Agency (BRIN),
15314 South Tangerang, Indonesia
[2] Postgraduate Program of Materials Science Study,
Department of Physics, Faculty of Mathematics and Natural Sciences,
Universitas Indonesia,
16424 Depok, Indonesia
[3] Interdisciplinary Research Centre for Advanced Materials,
King Fahd University of Petroleum and Minerals,
31261 Dhahran, Saudi Arabia
[4] Research Centre for Pharmaceutical Ingredients and Traditional Medicine,
National Research and Innovation Agency (BRIN),
15314 South Tangerang, Indonesia
[5] Department of Metallurgy and Materials Engineering,
University of Nigeria,
410001 Nsukka, Nigeria
[6] Faculty of Engineering and Built Environment,
University of Johannesburg,
2006 Johannesburg, South Africa

* ahmad.royani@brin.go.id, ** azwar@sci.ui.ac.id

GREEN SYNTHESIZED PLANT-BASED METALLIC NANOPARTICLES FOR ANTIMICROBIAL AND ANTICORROSION APPLICATIONS

Metal nanoparticles (MNPs) developed through green synthesis with various plant extracts have piqued the scientific community due to their antimicrobial and anticorrosion properties. Several synthesis methods and characteristics have been suc-

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cessfully implemented and developed to evaluate the pharmacological properties and performance of these MNPs. This article discusses the synthesis and characteristics of plant-based metallic nanoparticles, the different types of plant-based metallic nanoparticles, and their prospective applications. This short review intends to understand, what is commonly reported in scientific papers about MNPs as antimicrobial and anticorrosion agents, as well as highlight the essential parameters and procedures, which affect the antimicrobial and anticorrosion investigation of plant-based MNPs. However, despite the many antibacterial and anticorrosion approaches reported in the literature, very few platforms have achieved large scale. The difficulty in attaining large-scale success could be due, in part, to the complexity of the problem and the various parameters. Therefore, systematic research will be required to establish a standardized, widely accepted validation methodology for synthesizing and characterizing plant-based metallic nanoparticles.

Keywords: anticorrosion agent, antimicrobial agent, green synthesis, plant extracts, nanotechnology, metal nanoparticles.

1. Introduction

Nanotechnology is an interdisciplinary field of study that is rapidly evolving. It has a wide range of potential applications in the fields of science and technology [1]. This field combines essential concepts from various disciples, such as physics, engineering, biology, and chemistry, to develop new materials for synthesizing and manufacturing metallic nanoparticles (MNPs). These nanoparticles have a size range of 1–100 nm in at least one dimension. Nanotechnology is focused on the synthesizing, characterization, and implementation of various nanoparticles. Noble metals and ceramics, such as gold, silver, palladium, and zirconium, are commonly used in the chemical and physical synthesis of NPs; however, this process is not environmentally friendly [2]. The development of eco-friendly and safety to environmental of NPs processing technologies is essential. In recent years, several eco-friendly, cost-effective, easy, safe, scalable, and reproducible green synthesis approaches to produce metal nanoparticles (MNPs) have been developed, motivated by safety design concepts. Consequently, various biological synthesis methods (with a microorganism such as fungi, bacteria, and plant extracts) are currently widely used in metal nanoparticle fabrication approaches [3, 4]. Synthesis of plant-based metal nanoparticles is now considered the goal approach among green biological synthesis because of its ease of use and plant diversity sources [5, 6].

The use of plant extracts and other biomass for the synthesis of metallic nanoparticles (MNPs) is a fast and straightforward, cost-effective, sustainable, and environmentally friendly process [6–8]. The synthesis of plant-mediated nanoparticles is also easily adaptable for clinical use and industrial manufacturing [9]. Surprisingly, secondary metabolites in plant extracts like alkaloids, terpenoids, tannins, polyphenols, and flavonoids usually function as reducing or capping agents [10, 11]. MNPs from some plants can exhibit increased antibacterial activity, anticorrosion, and antibiofilm based on their physical properties and morphology, as well as their composition, making it a very prospective way to against antimicrobial resistance [12–14].

The study of various plants as potential biogenic for MNPs has attracted extensive interest, as evidenced by the annual increase in their research reports. Unfortunately, the methods applied to assess the antibacterial, antibiofilm, and anticorrosion activity and efficiency of MNPs do not appear to have been fully explained in terms of the test procedure in those studies. As a result, this review briefly describes the conventional and green synthetic methods used in synthesizing nanoparticles as antimicrobial and anticorrosion materials to provide readers with a useful reference. This review highlights current knowledge about the ability of plant materials to biosynthesis MNPs. It presents a database on which future researchers can base their work on synthesizing green metallic oxides from plant sources. We also discuss the benefits and drawbacks of conventional and green synthesis methods and the applications discovered in the results. Thus, this review assists researchers by pointing them toward the best experimental setup for evaluating MNPs, and it serves as a resource for future research.

2. Plant-Based Metallic Nanoparticles

Recently, the concept of ‘green chemistry’ for sustainable development has been widely investigated [15–18]. The goal of sustainable development was defined as development that follows current demands and is capable of harmonizing future generations to meet people’s needs [19]. Environmentally friendly sustainable development is particularly significant for stakeholders in numerous industrial sectors because they are concerned for the environment from pollution and uncontrolled use of natural resources, as well as the threat of environmental impacts [20, 21]. The three most significant aspects required for the green synthesis of MNPs include using non-toxic reducing agents, eco-friendly solvents, and safe stabilizers [4].

2.1. Plant-Based Metallic Nanoparticles: Synthesis and Characterization

Metallic nanoparticles (MNPs) have been widely produced by synthesis methods, including physical, chemical, or biosynthetic pathways. Generally, there are two approaches to MNPs synthesis: ‘bottom-up’ and ‘top-down’. Both synthesis techniques could be carried out in liquid states using solvents such as hexane, ethanol, and water or in solid conditions, gas, vacuum, and supercritical liquid conditions [22, 23]. The bulk material is gradually destroyed to produce nanoparticles in top-down methods [24]. Physical top-down approaches include mechanical grinding, sputtering, and lithography, whereas top-down chemical approaches include chemical etching and electroblasting [25]. On the other hand, bottom-up methods use atoms or molecules to produce nanoparticle materials. This category of methods consists of a wide range of physical and chemical syntheses. Spinning, molecular beam epitaxy, and physical vapour deposition are physical methods [26]. Chemical methods include laser pyrolysis, sol-gel processes, vapour deposition, plasma spraying, supercritical fluid technology, aerosol, and condensation atomic or molecular [26, 27]. The environmentally friendly synthesis of MNPs falls into bottom-up approaches, with reduction or oxidation serving as the main chemical reaction [28]. Another study indicated no significant difference in the extent or grade of mineralization obtained by utilizing either top-down technique or bottom-up one in thick. On the other hand, the mechanisms in traditional top-down and non-traditional bottom-up mineralization methods are different [29]. Figure 1 summarizes nanoparticle synthesis methods and green synthesis of plant-based metallic nanoparticles (MNPs).

Several metallic nanoparticles were synthesized using different plant parts such as stem or bark [30], flower [31], root [32], seed [33], and leave [5, 34, 35]. Metallic biosynthesis was applied by a straightforward and simple protocol with different plants [6, 36]. Material of plant parts such as leaves and or stems was obtained from various sources and cleaned with tap water to remove dust or other unwanted particles. The plant part was dried, then ground, and powdered. The plant parts were cut into small pieces or ground and then dissolved in a suitable solvent at a specific temperature to obtain plant extracts [37, 38]. Furthermore, metal salts were added to the extract solution to promote bioreduction and produce MNPs [39, 23].

Characterization or testing of these MNPs must be comprehensive and exhaustive to ensure repeatability in manufacture, biological activity, and safety. Various physicochemical techniques were utilized to characterize the synthesized MNPs. Several analytical approaches are necessary to characterize the product of MNPs, such as thermogravimetric analysis (TGA), which was utilized to evaluate the thermal nanoparticles, thermal decomposition, and phase transition [40–43]. X-ray diffraction (XRD) was used to evaluate the overall oxidation state of the particles, atomic positions, phases, and nanoparticle structures [44–46]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are general morphological and surface characterization methods. SEM could provide submicron morphological information and micron non-elemental information; however, TEM has a much higher resolution than SEM. As a result, TEM is better suited for analysing the

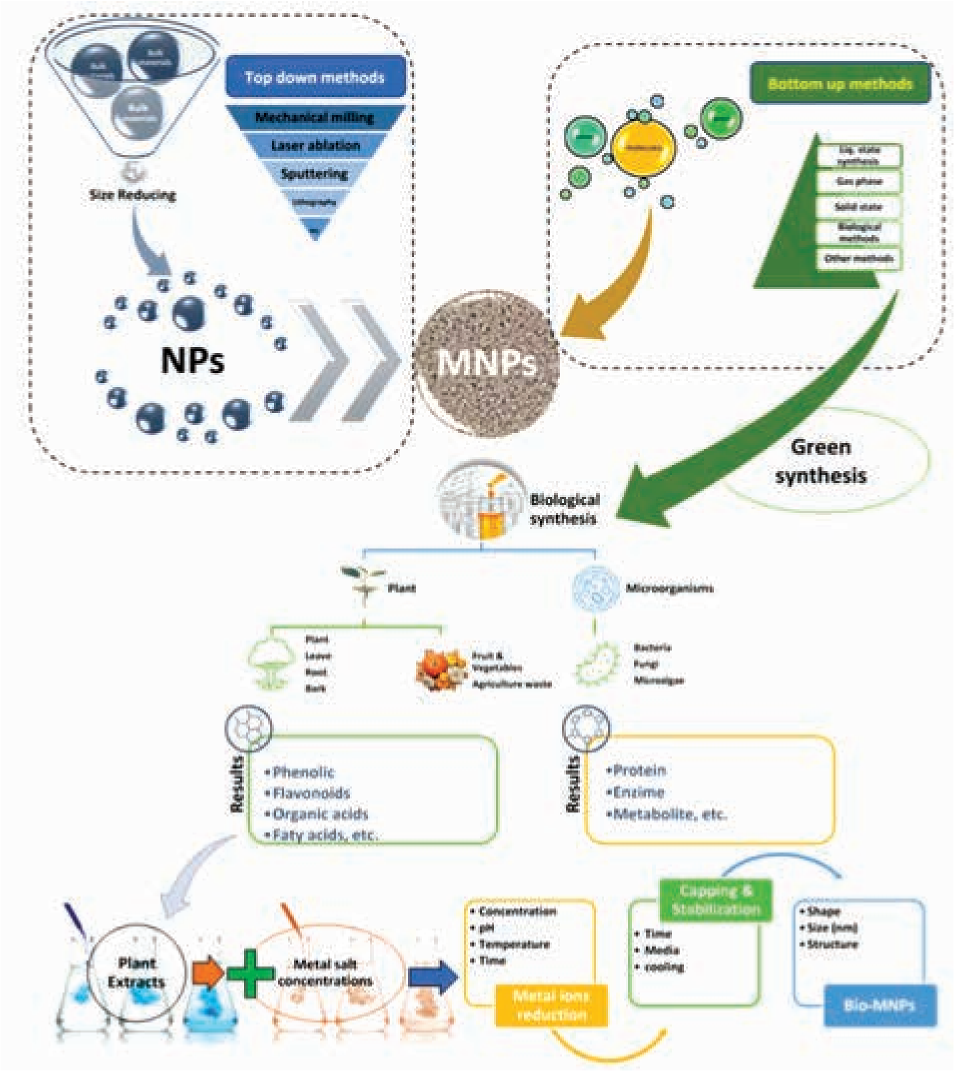

Fig. 1. The nanoparticle and plant-based metallic nanoparticles (plant-MNPs) synthesis methods

surface morphology of nanoparticle samples in the shape and size of nanoparticles [47, 48].

Dynamic light scattering (DLS) is a method used to analyse the distribution of nanoparticle size and surface charge, as well as the quality of nanoparticles [49]. It could also be used to determine the polydispersity index of prepared nanoparticles. Energy dispersion spectroscopy (EDS) could be utilized to analyse the elemental composition of metallic nanoparticles, and this analysis can provide sample elements in MNPs [50]. By evaluating organic functional groups on the surface of nanoparticles, Fourier transforms infrared spectroscopy (FTIR) can characterize surface chemistry [51, 52]. Surface chemical properties could be evaluated using x-ray photoelectron spectroscopy (XPS) [53]. Nanoparticles could be characterized at the atomic scale using atomic force microscopy (AFM) [54]. Nuclear magnetic resonance (NMR) is another distinctive technique for identifying compounds in the plant during the green synthesis of plant-mediated MNPs [55].

2.2. Greenness of Plant-Based Metallic Nanoparticles: Advantages and Drawbacks

Biological synthesis pathways based on plant sources are an appealing alternative to chemical and physical methods involving expensive toxic chemicals [56]. It is one of the best nanoparticle synthesis platforms because it is free of toxic chemicals and contains herbal and natural capping agents to stabilize MNPs [57]. The use of plants and other biomass as precursor materials for the synthesis of metallic nanoparticles (MNPs) is a fast, simple, sustainable, not expensive, and eco-friendly process [33, 58, 59]. Plant-mediated nanoparticle synthesis can also be used in clinical adaptation and is easily adapted for large-scale production in the industry [60]. Furthermore, secondary metabolites found in the plant extracts, like alkaloids, terpenoids, polyphenols, tannins, and flavonoids, have been indicated to function as capping or reducing agents [61, 62]. Depending on their morphology, physical characteristics, and composition, MNPs from various plants can exhibit increased antibacterial and anticorrosion activity, causing them excellent potential against bacteria [63] and corrosion by microbe [64].

The development of green synthesis, which uses plant extracts as a substitute for industrial chemicals to reduce metal ions, has gained considerable interest. In addition to its advantages, the green synthesis of plant extracts based on metallic nanoparticles must also be evaluated for its disadvantages. The main findings reveal data on the geographical and seasonal distribution of plants and their compositions, that synthesis is limited by location and time of production and low for purity and yield [65]. Another potential disadvantage of nanotechnology is the loss of jobs in traditional storm and manufacturing industries. Today, nanotechnology is so expensive that developing it is prohibitively costly. Manufacturing is also complex, which may increase the price of the synthesis of nanoproducts [66]. Furthermore, nanotechnology could cause pollution, which is known as nanopollution. This pollution is highly hazardous to living things, especially the content of various metals.

2.3. Greenness of Plant-Based Metallic Nanoparticles: Types of Plant-Based MNPs

Gold nanoparticles are plant-based metal nanoparticles that have gained the most attention. Due to their simple surface functionalization and ease of production [67], gold nanoparticles (AuNPs) are frequently used. They have unique properties, such as their high potential for use in the medical field [68], excellent biocompatibility, and low toxicity [69]. Various bioactive components of the complex biogenic function were utilized as reducing agents in synthesizing gold nanoparticles and reducing gold metal ions and nanoparticle granules [70]. Several studies have demonstrated that phytochemicals, such as proteins, phenols, flavonoids, and other active compounds, have an essential role in reducing metal ions and can be employed as coverings for gold nanoparticles in the manufacture of MNPs with plant extracts [71–73].

Silver nanoparticles are frequently synthesized as the second type of plant-based metal nanoparticles (AgNPs). The production of silver nanoparticles (AgNPs) from plants is one of the most straightforward [46]. A solution of silver metal ion and biological reducing agents were required for the eco-friendly synthesis of silver nanoparticles. The easiest and cheapest method to produce AgNPs is reducing and stabilizing Ag ions using a combination of phytochemical bioactive compounds from plant extracts, like phenolics, polysaccharides, amino acids, vitamins, proteins, biosurfactants, terpenes, saponins, and alkaloids [74]. Almost every plant has the potential to be used for the synthesis of AgNPs [75–77]. The existence of silver nanoparticles in plant extracts obtained from silver nitrate solutions shows that biologically synthesized silver nanoparticles are more efficient against numerous pathogens that cause disease [78].

Furthermore, zinc oxide nanoparticles (ZnONPs) have been intensively synthesized in recent years because of their various prospective applications, especially in the aesthetic and biomedical industries [45, 48]. Several studies on the biosynthesis of ZnONPs with plant extracts and other biomass, as well as the application of zinc nanoparticles, have been widely reported [79, 80]. Many developments have been focused on improving the performance of its low-cost, safe, simple synthesis, and eco-friendly [81]. ZnNPs can be synthesized from various plant parts, including flowers, leaves, fruits, seeds, and roots [45, 82]. Also, ZnONPs synthesis was reported from *Pelargonium odoratissimum* aqueous leaf extracts for antioxidant, antibacterial, and antiinflammatory activities [79].

The type of plant parts was also used to produce zirconium for various nanoparticle applications [47, 83, 84]. Aqueous leaf extracts of *Laurus nobilis* (bay leaf) were used to prepare zirconium oxide NPs in a recent study, and the average size of the prepared NPs was found to be of 20–100 nm [13]. Similarly, *Sphagenicola trilobata* leaf extract produced zirconium nanoparticles (ZrNPs). The synthesized ZrNPs demonstrated potential antifungal activity, antimalarial activity, and moderate antitubercular [41]. The biogenic production of zirconium dioxide nanoparticles using *Curcuma longa* has been successfully implemented with XRD and FTIR for structural and size investigation [59]. Likewise, zirconia nanoparticles based on *Punica granatum* peel extracts were reported due to the adaptability of Zr, so these nanoparticles are possible candidates for use in coatings as antibacterial agents in orthopaedics (as metallic implants). Additionally, the green ZrNP that was generated would support excellent antibacterial activity on the surface of medical equipment [83]. In another study, a plant extract of *Euclea natalensis* was synthesized for producing nanoparticles. The adsorptive properties of the nanoparticles were further tested against tetracycline antibiotics, and the nanoparticles were characterized using TEM. At the same time, the synthetic material had a crystal size of at least 5.25 nm [84].

Copper (Cu) is a relatively inexpensive metal that is less expensive than gold (Au) and silver (Ag), and CuNPs have been synthesized by reducing aqueous Cu ions with various plant extracts [48]. *Chromolaena odorata* leaf extract was successfully used as a stabilizer to synthesize copper nanoparticles with rod-shaped results with an average diameter of 30 nm [85]. However, there are numerous concerns about the biosafety of copper metal [53]. Other metals reported in the literature include nickel (Ni) [86] and Chromium (Cr) [87]. It should be noted that several different metals, such as titanium (Ti), palladium (Pd), selenium (Se) [51], and platinum (Pt) [33], have recently been used to develop bio-NPs by different methods and applications in several industrial sectors.

2.4. Methods of Antibacterial and Anticorrosion Testing

The properties and performance of the green synthesis MNPs against bacteria and corrosion by microbes are required to obtain antibacterial activity. These antibacterial characteristics can be assessed using various physical and analytical evaluation methods [88]. Physical testing techniques such as fluorescence spectroscopy, atomic force microscopy (AFM), transmission electron microscopy (TEM), and plasma mass spectroscopy have been widely used and implemented to obtain discrete information about interactions between MNPs and microorganisms [41–43]. These physical testing (biological assays) also provide information on microbial growth and the mechanism of death by biogenic MNPs [40].

The colony forming unit (CFU) test, the on-off staining test, the disc diffusion test, and the minimum inhibitory concentration (MIC) assay are some of the most commonly used analytical methods for determining the antimicrobial activity of MNPs [88]. The main analytical techniques for evaluating MNPs antimicrobial activity are diffusion and dilution susceptibility testing [48, 89]. The disc diffusion assay is a diffusion susceptibility testing method that uses green synthetic MNPs inseminated in discs that are then propagated across an agar medium containing bacteria and surrounding the discs. The diffusion (spread) of plant-metallic nanoparticles inhibits the growth of fungi and bacteria in the region surrounding the disc [90]. The diameter of this inhibitory concentration zone was evaluated by measuring the distance that an inhibitory concentration of green-synthesized MNPs could reach until reaching a specific bacterial density [13]. However, this method is ineffective in estimating the MIC, which is the minimal concentration of bio-fabricated MNPs that prevents the development of observable bacteria after a predetermined amount of time incubated at a predetermined temperature [91].

The dilution method is widely used to investigate the MIC. The dilution susceptibility testing method (dilution methods) can evaluate the antimicrobial activity of green MNPs using agar culture media or liquid culture medium [56]. The dilution method is preferable to the diffusion method for determining MIC because it provides a more quantitative estimate of MNPs antibacterial [92]. The agar dilution technique includes adding nanoparticle solutions of varying concentrations into a liquid medium. A standardized bacterial or microbe suspension was injected into the agar medium with multiple strokes after pouring and hardening the mixture to a specific agar depth in a Petri dish with a flat surface [93, 94]. The agar plates are placed and subsequently incubated at a predetermined temperature according to verified process or organism practice guidelines.

Testing the diameter of the inhibition zone or the minimum inhibitory concentration (MIC) and modifying the antibacterial or other microorganism activity of MNPs was influenced by the following factors [56, 95, 96]: (a) diversity of strains within the bacteria or microorganism, (b) type and species of bacteria or microorganisms, (c) pH and composition of the culture medium, (d) the density of the inoculum, (e) the incubation time and temperature, (f) the time of disc application, (g) the depth of the agar medium, (h) the shape, size, and zeta potential of nanoparticles, and (i) the synergistic and the additive effects of antibacterial nanoparticles when used with conventional or nonconventional antibiotics.

While the anticorrosion testing technique for MNPs performance can use weight loss (gravimetry) and electrochemical methods [97], the weight loss method is typically accomplished by exposing coupons to the test solution with and without MNPs for a specific time [63]. Coupons are collected, cleaned, and weighed to determine the weight change after a certain exposure time [98, 99]. Furthermore, the corrosion rate (CR, mpy) and percentage of inhibition efficiency (IE), were determined [100]. The electrochemical testing method utilizes three electrodes (a counter electrode, a working electrode, and a reference electrode) arranged in an electrochemical cell [33, 64]. Electrochemical corrosion testing technique can be carried out using polarization resistance (ASTM G5 and G59), electrochemical impedance spectroscopy (EISO ISO 16773), cyclic potentiodynamic polarization measuring for medical devices (ASTM F2129), pitting and crevice corrosion resistance measurement (ASTM G5 and G150), and potential corrosion measurements (ASTM G69).

The corrosion rate and effectiveness of MNPs can be affected by the following variables: the type and concentration of MNPs, the temperature and exposure time, the concentration and type of solution medium used, the distance between electrodes, the roughness of the specimen or coupon, and the chemical composition of the specimen and solution medium used.

2.5. Greenness of Plant-Based Metallic Nanoparticles: Potential Applications

Recently, the development of plant-based metal nanoparticles has been a growing interest for commercial use due to its various potential industrial applications, including electronics, oil and gas, energy, environmental, and biomedical applications. MNPs from Au and Ag salt metal concentrations have been extensively studied and are of great interest for applications as antimicrobial and anticorrosion agents [97]. According to the study of various literature, it has great application potential for various fields, including but not limited to: (i) energy, oil, and gas industry as a corrosion inhibitor and biocide, catalyst, and additive in coatings [101, 102], (ii) nanomedicine and human health protection are used as antimicrobial, antiparasitic, anticancer, antipathogen [48, 78, 103], antioxidant, and antiinflammatory activity [79], (iii) in the agriculture, it is designated as precision agriculture with controlled agricultural chemicals, delivery of target-specific biomolecules, detection and treatment of plant diseases, and enhanced nutrient absorption, (iv) in the field of food science and technology for processing, packaging, and storing, (v) in biological and environmental engineering fields, MNPs used as biocatalysts, photocatalysts, and biosensors [39, 45, 104]. Figure 2 provides results of the potential applications of MNPs in various fields.

Other prospective applications, such as photocatalytic and absorption potential applications [42, 43], and water treatment [105, 106], are

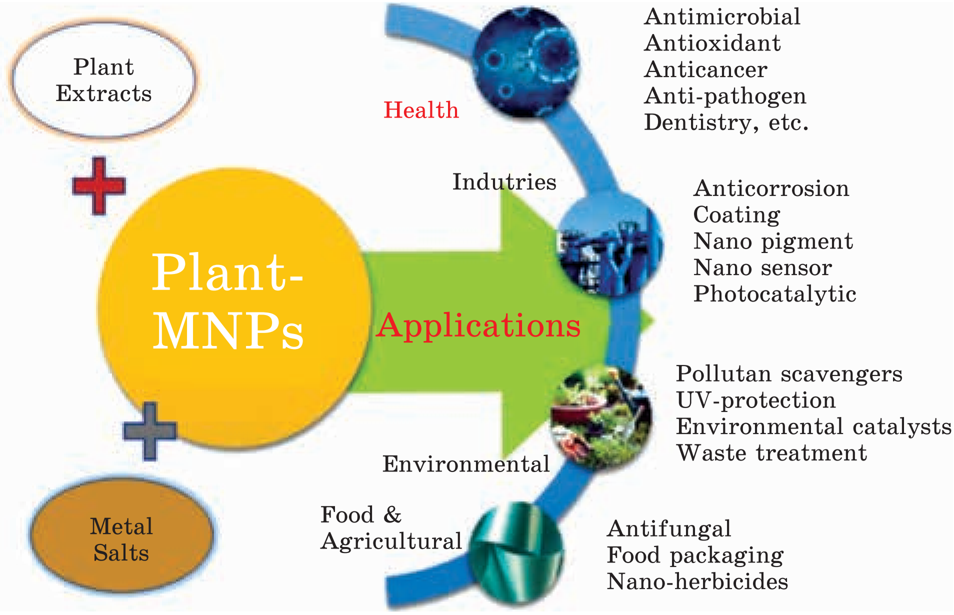

Fig. 2. The potential application of plant-based metallic nanoparticles in several fields

documented in the literature, as shown in Fig. 2. Using ginger extract to synthesize silver, copper, and nickel nanoparticles is an easy, safe, and not expensive method for water decontamination and environmental applications [106]. Green synthesis of AgNPs using *Ustilago maydis* was applied to reduce and stabilize agents [74].

3. Literature Survey

3.1. Plant-Based Metallic Nanoparticles for Antibacterial Activities

The results of a literature survey on plant-based metallic nanoparticles (MNPs) for antibacterial activities in various applications are summarized in Table 1.

3.2. Plant-Based Metallic Nanoparticles for Anticorrosive Activities

Numerous plant-based metallic nanoparticles were used for anticorrosion or biocide to control corrosion by microbe can be found in Table 2.

4. Conclusions and Prospects

In recent years, plant-based nanotechnology has developed rapidly, becoming one of the most popular and studied disciplines because of its

Table 1. **Literature data on MNPs for antibacterial agents in various fields**

Plant type	Synthesis conditions	NP characteristics	Methods
Punica granatum (pomegranate)	Incubated at 37 °C for 1 h and centrifugation	Zr NPs (20–60 nm)	Dilution in aqueous extracts
The root of *Eucleanatalensis*	Sol–gel methods for 3 h and dried at 105 °C	Zr NPs (5.90–8.54 nm) with TEM	Dilution in aqueous extracts
Myristica fragrans	Bioaugmentation with aqueous fruit extracts at room temperature	ZnO NPs (41.23 nm by XRD)	Bioaugmentation
Sphagneticola trilobata	Mix. zirconyl nitrate in plant extract (1:1) for 20 minutes at 400 rpm	Zr NPs (20–100 nm by TEM)	Reduction of aqueous zirconyl nitrate in leaf extract
Guettarda spciosa	At 85 °C, dried at 100 °C for 3 h, and calcined at 500 °C for 2 h	ZrO_2 NPs (4–9 nm with HR-TEM), spherical particles	Dilution in aqueous extracts
Moringa oleifera	Zinc acetate in M. oleifera extract + NaOH at 24 °C for 1 h	ZnO (52 nm by XRD), hexagonal	Precipitation
Lemon & Peel	ZrCl dissolved in filtrate extracts (juice & peel)	Zr NPs (peak at 457 & 478 nm for peel, 217 & 270 nm for lemon)	Dilution in aqueous extracts
Azadirachta indica	$AgNO_3$ in water extracts at room temperature	Ag NPs (absorbance peak: 420–450 nm)	Bio-reduction
Laurus nobilis (bay leaf)	Dilution of $ZrOCl_2{\cdot}8H_2O$ in leaf extract at 80 °C for 2 h and stirred	ZrO_2 NPs (20–100 nm, SEM)	Dilution in aqueous extracts (biological synthesis)
Eleutherine americana	Synthesis by $AgNO_3$ and ethanolic extract to a colour change at room temperature for 24 h	Ag NPs (≈1 μm by TEM), amorphous	Bioreduction
Ustilago maydis	Mixing of 0.01 N $AgNO_3$ with Ustilago maydis aqueous extract with a source of light	Ag NPs (100 to 5000 nm)	Sol-gel

Bacteria tested	MIC or IE	Remarks	Ref.
Gram-positive (B. subtilis & S. aureus), gram-negative (*E. coli* & *K. pneumoniae*), and fungi (*A. niger*)	Max. concentration 200 µg/mL	Antibacterial for various bacteria, agar well diffusion	[83]
—	—	Optimal conditions for adsorptive properties	[84]
E. coli, *K. pneumonia*, *P. aeruginosa*, *S. aureus*	Zone inhibition: *E. coli* (15 mm), *K. pneumoniae* (27 mm), *P. aeruginosa* (17 mm), *S. aureus* (21 mm)	Antimicrobial, antioxidant, biocompatible	[45]
Candida albicans, *Aspergillus niger*, *plasmodium vivax*	*Candida albicans* (12 mm), *Aspergillus niger* (14 mm), *Plasmodium vivax* (13 mm)	Antifungal & antimalaria	[41]
E. coli, *B. subtilis*, *S. typhi*, *P. aeruginosa*	ZrO_2NPs are not comparable with antibiotics	Natural reducing agent, disc diffusion	[47]
B. subtilis, E. coli	*B. subtilis* (3.5 cm), *E. coli* (3.3 cm)	Photocatalytic, antibacterial	[43]
MCF-7 cell	IE: 92.52% (NPs + lemon), 95.16% (NPs + peel)	Antioxidant, anticancer	[22]
E. coli, gram-positive	22 mm at 100 µL	Antimicrobial	[12]
Gram-positive, gram-negative	13–15 mm (zone inhibition)	Biomedical applications	[13]
Free radicals	64.5% (160 ppm)	Antioxidant	[46]
—	—	Ustilago maydis reduce not only $AgNO_3$ but also a stabilizer AgNPS	[74]

Plant type	Synthesis conditions	NP characteristics	Methods
Cannabis sativa	Synthesized by the cortex and core part of the stem	C–Au NPs (12–18 nm) & C–Ag NPs (20–40 nm), crystalline	Dilution in aqueous extracts
Tridax procumbens	Heated at 60 °C and 95 °C	55 nm	Dilution in aqueous extracts
Coriander sativum	At 40 °C for 45 min.	Tri-metallic oxide (Ni/Cr/Cu)	Dilution in aqueous extracts
Different spices	0.5 M $CuSO_4$ added to spice extract (ratio 1:1) and kept in the dark at 37 °C for 24 h	Cu NPs (150–200 nm)	Phytosynthesis
Acacia cyanophylla	Optimum aqueous extract conditions: 35 °C for 48 h	Ag NPs (88.11 nm)	Bioreduction

properties and potential relevance in controlling or inhibiting microorganisms. Most published data on nanoparticle synthesis and characterization is intended for biotechnology and medicine applications. At the same time, it is still limited to industrial applications, especially anticorrosion agents. Plant-based metallic nanoparticles (MNPs) provide straightforward, non-toxic, relatively inexpensive and green synthesis methods. Nanotechnology enables improved developmental activities to generate and analyse new formulations based on metal nanoparticles with promising applications in various fields. This review has discussed various plant-based MNPs and their potential applications. Because of the growing threat NPs approach to the environment and human health, research was conducted to characterize the toxicity, advantages, and drawbacks of plant-based metallic nanoparticles and their future applications. Using plant-based metallic nanoparticles with added value has become a significant and efficient effort to improve synthesis efficiency.

In this review, we also identified the main parameters to consider when testing antimicrobial and antibacterial activity to maximize their effectiveness and broaden their wide applications. The strategy for selecting the test method, which aims to deliver the correct dose in the right time frame, will ultimately determine the efficiency level with which it can be used. The application and implementation of technological approaches for commercial enhancement and adoption in different fields should be enforced in the future. The spread of nanotechno-

The End of Table 1.

	Bacteria tested	MIC or IE	Remarks	Ref.
	P. aeruginosa, *E. coli*	MIC: 6.25 & 5 µg/mL; and MBC: 12.5 & 25 µg/mL for *P. aeruginosa* & *E. coli*	Antibiofilms	[107]
	Several microorganisms	Zone of inhibtion <10 mm	antipathogens	[78]
	E. coli, *S. aureus*	Zone inhibition (random)	antimicrobial	[44]
	S. aureus	High antibacterial activity (1.33 cm ZOI)	Antibacterial	[108]
	E. coli	MIC: 3.125–12.5 µg/mL	Reduction agents, high antibacterial activity	[56]

logy in the coming years will help to replace existing harmful tools by removing harmful contaminants from the soil and preserving the sanctity of the environment. Improvements made possible by embedding nanotechnology have demonstrated tremendous potential for lowering total costs and processing time. The long-term effects of nanoparticle use are still being studied, as proper evaluation is required before proceeding with large-scale implementations to mitigate potential environmental impacts.

This review also investigates the antibacterial and quality processes that affect MNPs assessment and anticorrosion and addresses what is often stated in the scientific literature on the antimicrobial and anticorrosion properties of plant-based metallic nanoparticles. Because of minimum information about the chemical, biological, and laboratory equipment, it is not easy to collect accurate and reproducible data and acquire deep insights into comparative investigations. Moreover, there is a lack of standardization of experimental techniques and laboratory settings, as well as a lack of information and word count restrictions enforced by many journals, making this situation even more complicated.

Although many antibacterial and anticorrosion approaches have been reported in the literature, very few platforms have achieved large scale until now. The difficulty of achieving success on a broad scale can be partially due to the problem complexity and the complexity of its parameters. In addition, the existing *in vitro* methods for assessing an-

Table 2. **Literature on MNPs for anticorrosive agents in various fields**

Plant type	Synthesis conditions	NP characteristics	Methods
Tangerine peels	Dilution extract to deionized water and mixed with $AgNO_3$	TPE-Ag NPs (38.4–47.6, 40–50, & 36.9–56.1 nm for XRD, TEM, & DLS)	Bio-reduction
Allium cepa peels	Dilution extract to deionized water and mixed with $AgNO_3$	Ag NPs by UV–Vis, TEM & DLS (42.5 nm by TEM)	Bio-reduction
Punica granatum (pomegranate)	Zinc salt solution was added to Pomegranate extract at 60 °C for 2 h	ZnO NPs (400 nm)	Dilution in aqueous extracts
Nutshell	$AgNO_3$ added to extract solutions	Ag NPs (30 nm with TEM)	Dilution in aqueous extracts
Olive	A mix of 1 M $TiCl_4$ & 20 mL Olive extract at room temperature for 1 h	TiO NPs (70–74 nm)	Bioreduction
Red onion peels	Mix. of $AgNO_3$ & aqueous extract at room temperature	Ag NPs (45 nm)	Bioreduction
Pandanus amaryllifolius	Mix. of $Zn(NO_3)_{2.6}H_2O$ & aqueous extract at various temperature (60, 70 & 80 °C)	ZnO NPs	Bioreduction
Sida acuta	Mixing until colour changes	Ag NPs (14.9 nm)	Biosynthesis
Cannabis sativa	At room temperature for 1 h	Cr_2O_3 NPs (85–90 nm)	Bioreduction
Lonchocarpus laxiflorus	The mixture of $AgNO_3$ & extract at 25 °C for 48 h	Ag NPs (2.3 nm)	Bioreduction

tibacterial agents do not accommodate actual *in vivo* field conditions. Also omitted was the study of bioactive compounds, which play a crucial role in antibacterial and anticorrosion prevention. Structured and consistent research will be required to establish widely accepted standardized validation methods for generating and characterizing plant-based metal nanoparticles. Addressing this significant challenge will necessitate the collaborative efforts of researchers from various disciplines to deliver fundamental advances in bionanotechnology and other in-

	Bacteria tested	MIC or IE	Remarks	Ref.
	Desulfovibio sp.	93.9% and 90.3% at 303 and 333 K for 1 g/l TPE-Ag NPs	Corrosion inhibition by adsorption	[64]
	SRB (*Desulfovibio sp.*)	MIC: 2.07 mg/L; IE: 30.8% for carbonate scale; 55.9% for biocorrosion.	Anticorrosion & antiscale	[63]
	Gram-negative, gram-positive	IE: 99.9% by coating with ZnO NPs (298–328 K)	Anticorrosion & antimicrobial	[33]
	—	IE: 90.81% at 0.4 mg/L	Anticorrosion & anticancer	[109]
	—	IE: 94.3% at 30 °C & 85.5% at 60 °C	Anticorrosion	[110]
	—	IE: 94.5% at 30 °C & 86.7% at 60 °C	Corrosion inhibitor for pickling and acid wash operations	[111]
	—	IE: 79% at 60 °C	Corrosion inhibitor	[112]
	E. coli, *S. aureus*, *S. faecalis*	Max. zone (13 mm) & IE: 88%	Antimicrobial & anticorrosion	[113]
	HepG2 cell	IE: 89% at 303 K	Anticancer & anticorrosion	[87]
	—	The activation energy (E_a): 80 KJ/mol	Anticorrosion	[114]

dustries. However, it must also provide numerous opportunities for innovation.

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REFERENCES

1. P. Mulvaney, *ACS Nano*, **9**, No. 3: 2215–2217 (2015); https://doi.org/10.1021/acsnano.5b01418
2. S. Bayda, M. Adeel, T. Tuccinardi, M. Cordani, F. Rizzolio, and A. Baeza, *Molecules*, **25**, No. 112: 1–15 (2020); https://doi.org/10.3390/molecules25010112
3. N. Pantidos, *J. Nanomed. Nanotechnol.*, **05**, No. 05: 1–10 (2014); https://doi.org/10.4172/2157-7439.1000233
4. M. Shah, D. Fawcett, S. Sharma, S.K. Tripathy, and G.E.J. Poinern, *Materials*, **8**, No. 11: 7278–7308 (2015); https://doi.org/10.3390/ma8115377
5. A.M. El Shafey, *Green Process. Synth.*, **9**, No. 1: 304–339 (2020).
6. J.A. Aboyewa, N.R.S. Sibuyi, M. Meyer, and O.O. Oguntibeju, *Plants*, **10**, No. 1929: 1–24 (2021); https://doi.org/10.3390/plants10091929
7. H. Kumar, K. Bhardwaj, D.S. Dhanjal, E. Nepovimova, F. Șen, H. Regassa, R. Singh, R. Verma, V. Kumar, D. Kumar, S.K. Bhatia, and K. Kuca, *Int. J. Mol. Sci.*, **21**, No. 22: 1–18 (2020); https://doi.org/10.3390/ijms21228458
8. S. Ahmed, Saifullah, M. Ahmad, B. L. Swami, and S. Ikram, *J. Radiat. Res. Appl. Sci.*, **9**, No. 1: 1–7 (2016); https://doi.org/10.1016/j.jrras.2015.06.006
9. M.S. Akhtar, J. Panwar, and Y.S. Yun, *ACS Sustain. Chem. Eng.*, **1**, No. 6: 591–602 (2013); https://doi.org/10.1021/sc300118u
10. N.S. Al-Radadi and S.I.Y. Adam, *Arab. J. Chem.*, **13**, No. 2: 4386–4403 (2020); https://doi.org/10.1016/j.arabjc.2019.08.008
11. G. Marslin, K. Siram, Q. Maqbool, R.K. Selvakesavan, D. Kruszka, P. Kachlicki, and G. Franklin, *Materials*, **11**, No. 6: 940 (2018); https://doi.org/10.3390/ma11060940
12. P. Roy, B. Das, A. Mohanty, and S. Mohapatra, *Appl. Nanosci.*, **7**, No. 8: 843–850 (2017); https://doi.org/10.1007/s13204-017-0621-8
13. T.P. Chau, S. Kandasamy, A. Chinnathambi, T.A. Alahmadi, and K. Brindhadevi, *Appl. Nanosci.* (2021); https://doi.org/10.1007/s13204-021-02041-w
14. M.M. Luzala, C.K. Muanga, J. Kyana, J.B. Safari, E.N. Zola, G.V. Mbusa, Y.B. Nuapia, J.M.I. Liesse, C.I. Nkanga, R.W.M. Krause, A. Balciunaitien, and P.B. Memvanga, *Nanomaterials*, **12**, No. 11: 1–99 (2022); https://doi.org/10.3390/nano12111841
15. S.H. Alrefaee, K.Y. Rhee, C. Verma, M.A. Quraishi, and E.E. Ebenso, *J. Mol. Liq.*, **321**, No. 114666: 1–14 (2021); https://doi.org/10.1016/j.molliq.2020.114666
16. C. Verma, E.E. Ebenso, I. Bahadur, and M.A. Quraishi, *J. Mol. Liq.*, **266**: 577–590 (2018); https://doi.org/10.1016/j.molliq.2018.06.110
17. H. Chopra, S. Bibi, I. Singh, M.M. Hasan, M.S. Khan, Q. Yousafi, A.A. Baig, M.M. Rahman, F. Islam, T. Bin Emran, and S. Cavalu, *Front. Bioeng. Biotechnol.*, **10**: 874742 (2022); https://doi.org/10.3389/fbioe.2022.874742

18. M. Naghdi, M. Taheran, S.K. Brar, M. Verma, R.Y. Surampalli, and J.R. Valero, *Beilstein J. Nanotechnol.*, **6**, No. 1: 2354–2376 (2015); https://doi.org/10.3762/bjnano.6.243
19. F. Pacheco-Torgal and J.A. Labrincha, *Constr. Build. Mater.*, **40**: 729–737 (2013); https://doi.org/10.1016/j.conbuildmat.2012.11.007
20. Q. Liu, Y. Zhu, W. Yang, and X. Wang, *Sustainability*, **14**, No. 1714: 1–23 (2022); https://doi.org/10.3390/su14031714
21. S.S.C. Tay, C.C. Lee, and L.X. Yi, *Global megatrends: Implications for the ASEAN Economic Community*, (China: 2017), p. 98–122.
22. R.H. Salih, S.H. Ahmed, R.S. Hameed, and I.H.T. Al-karkhi, *Med. Leg. Updat.*, **21**, No. 2: 977–981 (2021); https://doi.org/10.37506/mlu.v21i2.2810
23. A.K. Shukla and S. Iravani, *Environ. Chem. Lett.*, **15**, No. 2: 223–231 (2017); https://doi.org/10.1007/s10311-017-0618-2
24. H. Alfarisi, S. Sa'diah, B. Juliandi, and T. Wresdiyati, *Molekul*, **17**, No. 1: 68–75 (2022); https://doi.org/10.20884/1.jm.2022.17.1.5601
25. S. Aryal, H. Park, J.F. Leary, and J. Key, *Int. J. Nanomedicine*, **14**: 6631–6644 (2019); https://doi.org/10.2147/IJN.S212037
26. S. Kumar, P. Bhushan, and S. Bhattacharya, *Energy, Environment, and Sustainability*, (Eds. A. Bhattacharya, S. Agarwal, A. Chanda, N. Pandey, and A. Sen) (Singapore: Springer Singapore: 2018), p. 167–198.
27. P.G. Jamkhande, N.W. Ghule, A.H. Bamer, and M.G. Kalaskar, *J. Drug Deliv. Sci. Technol.*, **53**: 101174 (2019); https://doi.org/10.1016/j.jddst.2019.101174
28. G. Suriati, M. Mariatti, and A. Azizan, *Int. J. Automot. Mech. Eng.*, **10**, No. 1: 1920–1927 (2014); https://doi.org/10.15282/ijame.10.2014.9.0160
29. Y. Liu, S. Mai, N. Li, C.K.Y. Yiu, J. Mao, D.H. Pashley, and F.R. Tay, *Acta Biomater*, **7**, No. 4: 1742–1751 (2011); https://doi.org/10.1016/j.actbio.2010.11.028
30. E. Burlacu, C. Tanase, N.A. Coman, and L. Berta, *Molecules*, **24**, No. 23: 4354 (2019); https://doi.org/10.3390/molecules24234354
31. H. Kumar, K. Bhardwaj, K. Kuča, A. Kalia, E. Nepovimova, R. Verma, and D. Kumar, *Nanomaterials*, **10**, No. 4: 766 (2020); https://doi.org/10.3390/nano10040766
32. L.N. Khanal, K.R. Sharma, H. Paudyal, K. Parajuli, B. Dahal, G.C. Ganga, Y.R. Pokharel, and S.K. Kalauni, *J. Nanomater.*, **2022**: 1–11 (2022); https://doi.org/10.1155/2022/1832587
33. E.A. Ibadi, H.R.A.K. Al-Hetty, M.A.W. Alwardi, R.S. Alazragi, H.A. Almashhadani, and M.M. Kadhim, *J. Corros. Scale Inhib.*, **11**, No. 4: 1569–1582 (2022); https://doi.org/10.17675/2305-6894-2022-11-4-9
34. S.P. Patil and P.M. Rane, *Beni-Suef Univ. J. Basic Appl. Sci.*, **9**, No. 60: 1–7 (2020); https://doi.org/10.1186/s43088-020-00088-2
35. O.A. Olaseinde and O. Oluwafemi, *J. Multidiscip. Eng. Sci. Stud.*, **5**, No. 2: 2509–2517 (2019).
36. S.S. Salem and A. Fouda, *Biol. Trace Elem. Res.*, **199**, No. 1: 344–370 (2021); https://doi.org/10.1007/s12011-020-02138-3

37. P. Kurhade, S. Kodape, and R. Choudhury, *Chem. Pap.*, **75**, No. 10: 5187–5222 (2021);
https://doi.org/10.1007/s11696-021-01693-w
38. A. Royani, M. Hanafi, and A. Manaf, *Int. J. Corros. Scale Inhib.*, **11**, No. 3: 862–888 (2022);
https://doi.org/10.17675/2305-6894-2022-11-3-1
39. R.Z. Maarebia, A. Wahid Wahab, and P. Taba, *J. Akta Kim. Indones. (Indonesia Chim. Acta)*, **12**, No. 1: 29 (2019);
https://doi.org/10.20956/ica.v12i1.5881
40. S.J.P. Begum, S. Pratibha, J.M. Rawat, D. Venugopal, P. Sahu, A. Gowda, K.A. Qureshi, and M. Jaremko, *Pharmaceuticals*, **15**, No. 455: 1–20 (2022);
https://doi.org/10.3390/ph15040455
41. S. Kazi, S. Nirwan, S. Kunde, S. Jadhav, M. Rai, D. Kamble, S. Sayyed, and P. Chavan, *Bionanoscience*, **12**, No. 3: 731–740 (2022);
https://doi.org/10.1007/s12668-022-01006-9
42. S. Yasmin, S. Nouren, H.N. Bhatti, D.N. Iqbal, S. Iftikhar, J. Majeed, R. Mustafa, N. Nisar, J. Nisar, A. Nazir, M. Iqbal, and H. Rizvi, *Green Process. Synth.*, **9**, No. 1: 87–96 (2020),
https://doi.org/10.1515/gps-2020-0010
43. S. Pal, S. Mondal, J. Maity, and R. Mukherjee, *Int. J. Nanosci. Nanotechnol.*, **14**, No. 2: 111–119 (2018).
44. K. Sathish Kumar, G.R. Venkatakrishnan, R. Rengaraj, P.K. Gayathri, G. Lavanya, and D. Hemapriya, *J. Niger. Soc. Phys. Sci.*, **3**, No. 3: 144–147 (2021);
https://doi.org/10.46481/jnsps.2021.237
45. S. Faisal, H. Jan, S.A. Shah, S. Shah, A. Khan, M.T. Akbar, M. Rizwan, F. Jan, Wajidullah, N. Akhtar, A. Khattak, and S. Syed, *ACS Omega*, **6**, No. 14: 9709–9722 (2021);
https://doi.org/10.1021/acsomega.1c00310
46. J.R. Manullang, R.A. Nugroho, M. Rohmah, R. Rudianto, and A. Qorysuchi, *Nusant. Biosci.*, **13**, No. 2: 247–254 (2021);
https://doi.org/10.13057/nusbiosci/n130216
47. N. Muthulakshmi, A. Kathirvel, R. Subramanian, and M. Senthil, *Biointerface Res. Appl. Chem.*, **13**, No. 2: 1–12 (2023);
https://doi.org/10.33263/BRIAC132.190
48. M. Gholami-Shabani, F. Sotoodehnejadnematalahi, M. Shams-Ghahfarokhi, A. Eslamifar, and M. Razzaghi-Abyaneh, *IET Nanobiotechnology*, **16**, No. 1: 1–13 (2022);
https://doi.org/10.1049/nbt2.12070
49. N.K. Sharma, J. Vishwakarma, S. Rai, T.S. Alomar, N. Almasoud, and A. Bhattarai, *ACS Omega*, **7**: 27004–27020 (2022);
https://doi.org/10.1021/acsomega.2c01400
50. B.S. Тъзън, J. Hohmann, and B. Kivcak, *Green Process. Synth.*, **7**, No. 4: 372–379 (2018);
https://doi.org/10.1515/gps-2017-0027
51. A.A. Kamnev, Y.A. Dyatlova, O.A. Kenzhegulov, A.A. Vladimirova, P.V. Mamchenkova, and A.V. Tugarova, *Molecules*, **26**, No. 1146: 1–14 (2021);
https://doi.org/10.3390/molecules26041146
52. M.A. Huq, *Int. J. Mol. Sci.*, **21**, No. 1510: 1–14 (2020);
https://doi.org/10.3390/ijms21041510
53. N. Karikalan, *Rasayan J. Chem.*, **11**, No. 4: 1451–1457 (2018);
https://doi.org/10.31788/RJC.2018.1143068

54. Y. Gu, Hong. Xie, J. Gao, D. Liu, C.T. Williams, C.J. Murphy, and H.J. Ploehn, *Langmuir*, **21**, No. 7: 3122–3131 (2005); https://doi.org/10.1021/la047843e
55. A.A. Ahmed and P. Dutta, *Int. J. Chem. Stud.*, **8**, No. 2: 1162–1165 (2020); https://doi.org/10.22271/chemi.2020.v8.i2r.8926
56. J. Jalab, W. Abdelwahed, A. Kitaz, and R. Al-Kayali, *Heliyon*, **7**, No. 9: 1–9 (2021); https://doi.org/10.1016/j.heliyon.2021.e08033
57. S. Arora, M. Latwal, K.D. Bahukhandi, D. Kumar, T. Vemulapalli, S. Egutoori, and N.A. Siddiqui, *Nat. Environ. Pollut. Technol.*, **20**, No. 2: 481–490 (2021); https://doi.org/10.46488/NEPT.2021.v20i02.004
58. J. Pulit, M. Banach, and Z. Kowalski, *J. Comput. Theor. Nanosci.*, **10**, No. 2: 1–9 (2013); https://doi.org/10.1166/jctn.2013.2691
59. M. Bishwokarma, A. Bhujel, M. Baskota, and R. Pandit, *J. Nepal Chem. Soc.*, **42**, No. 1: 45–50 (2021); https://doi.org/10.3126/jncs.v42i1.35328
60. H. Barabadi, M. Najafi, H. Samadian, A. Azarnezhad, H. Vahidi, M.A. Mahjoub, M. Koohiyan, and A. Ahmadi, *Med.*, **55**, No. 8: 439 (2019); https://doi.org/10.3390/medicina55080439
61. S.H. Mohammed, A.M. Rheima, F.M.D. Aljaafari, M.F. Al Marjani, and Z.S. Abbas, *Egypt. J. Chem.*, **65**, No. 4: 377–382 (2022); https://doi.org/10.21608/EJCHEM.2021.91747.4355
62. S. Amaliyah, D.P. Pangesti, M. Masruri, A. Sabarudin, and S.B. Sumitro, *Heliyon*, **6**, No. 8: 1–12 (2020); https://doi.org/10.1016/j.heliyon.2020.e04636
63. E. Ituen, L. Yuanhua, C. Verma, A. Alfantazi, O. Akaranta, and E.E. Ebenso, *JCIS Open*, **3**, No. 100012: 1–10 (2021); https://doi.org/10.1016/j.jciso.2021.100012
64. E. Ituen, E. Ekemini, L. Yuanhua, and A. Singh, *J. Mol. Struct.*, **1207**, No. 127819: 1–11 (2020); https://doi.org/10.1016/j.molstruc.2020.127819
65. S. Ying, Z. Guan, P.C. Ofoegbu, P. Clubb, C. Rico, F. He, and J. Hong, *Environ. Technol. Innov.*, **26**, No. 102336: 1–20 (2022); https://doi.org/10.1016/j.eti.2022.102336
66. K. Parveen, V. Banse, and L. Ledwani, *AIP Conf. Proc.*, 1724: 2016; https://doi.org/10.1063/1.4945168
67. X. Hu, Y. Zhang, T. Ding, J. Liu, and H. Zhao, *Front. Bioeng. Biotechnol.*, **8**, No. 990: 1–17 (2020); https://doi.org/10.3389/fbioe.2020.00990
68. H. Daraee, A. Eatemadi, E. Abbasi, S.F. Aval, M. Kouhi, and A. Akbarzadeh, *Artif. Cells, Nanomedicine Biotechnol.*, **44**, No. 1: 410–422 (2016); https://doi.org/10.3109/21691401.2014.955107
69. E. Rodríguez-Leyn, B.E. Rodríguez-Vбzquez, A. Martнnez-Higuera, C. Rodríguez-Beas, E. Larios-Rodríguez, R.E. Navarro, R. Lypez-Esparza, and R.A. Iciguez-Palomares, *Nanoscale Res. Lett.*, **14**, No. 334: 1–16 (2019); https://doi.org/10.1186/s11671-019-3158-9
70. P. Anbu, S.C.B. Gopinath, and S. Jayanthi, *Nanomater. Nanotechnol.*, **10**: 1–9 (2020); https://doi.org/10.1177/1847980420961697
71. K. Xin Lee, K. Shameli, M. Miyake, N. Kuwano, N.B. Bt A. Khairudin, S.E. Bt Mohamad, and Y.P. Yew, *J. Nanomater.*, **2016**, No. 8489094: 1–7 (2016);

https://doi.org/10.1155/2016/8489094

72. P. Elia, R. Zach, S. Hazan, S. Kolusheva, Z. Porat, and Y. Zeiri, *Int. J. Nanomedicine*, **9**: 4007–4021 (2014).
73. A. Sobczak-Kupiec, D. Malina, M. Zimowska, and Z. Wzorek, *Dig. J. Nanomater. Biostructures*, **6**, No. 2: 803–808 (2011).
74. S. Cortйs-Camargo, A. Jimйnez-Rosales, and P.E. Acuсa-Avila, *J. Nanotechnol.*, **2022**: 1–7 (2022); https://doi.org/10.1155/2022/2494882
75. M. Tariq, K.N. Mohammad, B. Ahmed, M.A. Siddiqui, and J. Lee, *Molecules*, **27**, No. 4754: 1–27 (2022); https://doi.org/10.3390/molecules27154754
76. N.M. Alabdallah and M.M. Hasan, *Saudi J. Biol. Sci.*, **28**, No. 10: 5631–5639 (2021); https://doi.org/10.1016/j.sjbs.2021.05.081
77. M.S. Sadak, *Bull. Natl. Res. Cent.*, **43**, No. 38: 1–6 (2019); https://doi.org/10.1186/s42269-019-0077-y
78. T. Dhanalakshmia and S. Rajendran, *Arch. Appl. Sci. Res.*, **4**, No. 3: 1289–1293 (2012).
79. A.S. Abdelbaky, T.A. Abd El-Mageed, A.O. Babalghith, S. Selim, and A.M.H.A. Mohamed, *Antioxidants*, **11**, No. 1444: 1–25 (2022); https://doi.org/10.3390/antiox11081444
80. M.G. Demissie, F.K. Sabir, G.D. Edossa, and B.A. Gonfa, *J. Chem.*, **2020**, No. 7459042: 1–9 (2020); https://doi.org/10.1155/2020/7459042
81. A. Jayachandran, A. TR, and A.S. Nair, *Biochem. Biophys. Reports*, **26**: 100995 (2021); https://doi.org/10.1016/j.bbrep.2021.100995
82. G.M. Al-Senani, (2020); https://doi.org/10.3390/ma13040890
83. T.P. Chau, G.R. Veeraragavan, M. Narayanan, A. Chinnathambi, S.A. Alharbi, B. Subramani, K. Brindhadevi, T. Pimpimon, and S. Pikulkaew, *Environ. Res.*, **209**, No. 112771: 1–8 (2022); https://doi.org/10.1016/j.envres.2022.112771
84. A.F.V. da Silva, A.P. Fagundes, D.L.P. Macuvele, E.F.U. de Carvalho, M. Durazzo, N. Padoin, C. Soares, and H.G. Riella, *Colloids Surfaces A Physicochem. Eng. Asp.*, **583**, No. 123915: 1–10 (2019); https://doi.org/10.1016/j.colsurfa.2019.123915
85. S. Suprapto, C.A.H. Handoyo, P.A. Senja, V.B. Ramadhan, and Y.L. Ni'mah, *IJCA (Indonesian J. Chem. Anal.*, **3**, No. 1: 9–16 (2020); https://doi.org/10.20885/ijca.vol3.iss1.art2
86. M. Bhaumik, A. Maity, and H.G. Brink, *J. Colloid Interface Sci.*, **611**: 408–420 (2022); https://doi.org/10.1016/j.jcis.2021.11.181
87. U.R. Sharma and N. Sharma, *Biointerface Res. Appl. Chem.*, **11**, No. 1: 8402–8412 (2021); https://doi.org/10.33263/BRIAC111.84028412
88. M. Benkova, O. Soukup, and J. Marek, *J. Appl. Microbiol.*, **129**, No. 4: 806–822 (2020); https://doi.org/10.1111/jam.14704
89. R. Temmerman, K. Goethals, A. Garmyn, G. Vanantwerpen, M. Vanrobaeys, F. Haesebrouck, G. Antonissen, and M. Devreese, *Front. Microbiol.*, **11**,

No. 570975: 1–8 (2020);
https://doi.org/10.3389/fmicb.2020.570975

90. M. Naseer, U. Aslam, B. Khalid, and B. Chen, *Sci. Rep.*, **10**, No. 9055: 1–10 (2020);
https://doi.org/10.1038/s41598-020-65949-3
91. U.S. Patil, *OIE Terr. Man.*, 1–11 (2012);
https://www.woah.org/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/GUIDE_2.1_ANTIMICROBIAL.pdf
92. A. Rautela, J. Rani, and M. Debnath (Das), *J. Anal. Sci. Technol.*, **10**, No. 5: 1–10 (2019);
https://doi.org/10.1186/s40543-018-0163-z
93. Y.Y. Loo, Y. Rukayadi, M.Ab.R. Nor-Khaizura, C.H. Kuan, B.W. Chieng, M. Nishibuchi, and S. Radu, *Front. Microbiol.*, **9**, No. 1555: 1–7 (2018);
https://doi.org/10.3389/fmicb.2018.01555
94. A. Royani, M. Hanafi, H. Julistiono, and A. Manaf, *Mater. Today: Proc.*, 72, Pt. 6: 2796–2802;
https://doi.org/10.1016/j.matpr.2022.06.466
95. E. Van de Vel, I. Samper, and K. Raes, *Crit. Rev. Food Sci. Nutr.*, **59**, No. 3: 357–378 (2019);
https://doi.org/http10.1080/10408398.2017.1371112
96. J. Li, S. Xie, S. Ahmed, F. Wang, Y. Gu, C. Zhang, X. Chai, Y. Wu, J. Cai, and G. Cheng, *Front. Pharmacol.*, **8**, No. 364: 1–11 (2017);
https://doi.org/10.3389/fphar.2017.00364
97. A.M. Atta, G.A. El-Mahdy, H.A. Al-Lohedan, and A.O. Ezzat, *Molecules*, **19**: 6246–6262 (2014);
https://doi.org/10.3390/molecules19056246
98. S. Prifiharni, A. Royani, J. Triwardono, G. Priyotomo, and Sundjono, *AIP Conf. Proc.*, **2232**, No. 1: 020007 (2020);
https://doi.org/10.1063/5.0006768H.
99. A. Royani, S. Prifiharni, G. Priyotomo, J. Triwardono, and Sundjono, *IOP Conf. Ser.: Earth Environ. Sci.*, **399**: 012089;
https://doi.org/10.1088/1755-1315/399/1/012089
100. A. Fetouh, B. Abd-El-Nabey, Y.M. Goher, and M.S. Karam, *J. Electrochem.*, **24**, No. 1: 89–100 (2018);
https://doi.org/10.13208/j.electrochem.160427
101. A. Mathiazhagan and R. Joseph, *Int. J. Chem. Eng. Appl.*, **2**, No. 4: 225–237 (2011).
102. P.A. Rasheed, K.A. Jabbar, H.R. Mackey, and K.A. Mahmoud, *Curr. Opin. Chem. Eng.*, **25**: 35–42 (2019);
https://doi.org/10.1016/j.coche.2019.06.003
103. D. Zhang, X.L. Ma, Y. Gu, H. Huang, and G.W. Zhang, *Front. Chem.*, **8**: 1–18 (2020);
https://doi.org/10.3389/fchem.2020.00799
104. G.Z. Gayda, O.M. Demkiv, N.Y. Stasyuk, R.Y. Serkiz, M.D. Lootsik, A. Errachid, M.V. Gonchar, and M. Nisnevitch, *Appl. Sci.*, **9**, No. 4: 720 (2019);
https://doi.org/10.3390/app9040720
105. H. Tabassum and I.Z. Ahmad, *Lett. Appl. Microbiol.*, **75**, No. 4: 731–743 (2022);
https://doi.org/10.1111/lam.13588
106. A. Kamal, S. Zaki, H. Shokry, and D. Abd-El-haleem, *J. Pure Appl. Microbiol.*, **14**, No. 2: 1227–1236 (2020);

https://doi.org/10.22207/JPAM.14.2.17

107. P. Singh, S. Pandir, J. Garnaes, S. Tujic, V.R. Mokkapati, A. Sultan, A. Thygesen, A. Mackevica, R.V. Mateiu, A.E. Daugaard, A. Baun, and I. Mijakovic, *Int. J. Nanomedicine*, **13**: 3571–3591 (2018); https://doi.org/10.2147/IJN.S157958
108. G. Vijayakumar, H. Kesavan, A. Kannan, D. Arulanandam, J.H. Kim, K.J. Kim, H.J. Song, H.J. Kim, and S.K. Rangarajulu, *Processes*, **9**, No. 1341: 1–18 (2021); https://doi.org/10.3390/pr9081341
109. L.V. Hublikar, S.V. Ganachari, N. Raghavendra, N.R. Banapurmath, V.B. Patil, T.M.Y. Khan, and I.A. Badruddin, *Coatings*, **11**, No. 1215: 1–19 (2021); https://doi.org/10.3390/coatings11101215
110. E.A. Essien, D. Kavaz, E.B. Ituen, and S.A. Umoren, *J. Adhes. Sci. Technol.*, 1–20 (2018); https://doi.org/10.1080/01694243.2018.1445800
111. E. Ituen, A. Singh, L. Yuanhua, and O. Akaranta, *Clean. Eng. Technol.*, **3**, No. 100119: 1–13 (2021); https://doi.org/10.1016/j.clet.2021.100119
112. R.Md. Akhir, M.H. Norashikin, M.M. Mahat, and N.N. Bonnia, *Int. J. Eng. Technol.*, **7**, No. 4.14: 488492 (2018); https://doi.org/10.14419/ijet.v7i4.14.27775
113. M. Idrees, S. Batool, T. Kalsoom, S. Raina, H.M.A. Sharif, and S. Yasmeen, *Environ. Technol.*, **40**, No. 8: 1071–1078 (2019); https://doi.org/10.1080/09593330.2018.1435738
114. G.A. Ijuo, S. Nguamo, and J.O. Igoli, *Prog. Chem. Biochem. Res.*, **5**, No. 2: 133–146 (2022); https://doi.org/10.22034/pcbr.2022.324366.1208

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А. Рояні[1,2]*, К. Верма*[3]*, М. Ханафі*[4]*, В.С. Айгбодіон*[5,6]*, А. Манаф*[2]
[1] Науково-дослідний центр металурґії,
Національне аґентство досліджень та інновацій (BRIN),
15314 Південний Танґеранґ, Індонезія
[2] Програма післядипломної освіти з вивчення матеріалів,
Кафедра фізики, факультет математики та природничих наук,
Університет Індонезії,
16424 Депок, Індонезія
[3] Міждисциплінарний науково-дослідний центр передових матеріалів,
Університет нафти та мінералів імені Короля Фахда,
31261 Дахран, Саудівська Аравія
[4] Науково-дослідний центр фармацевтичних інґредієнтів і традиційної медицини,
Національне аґентство досліджень та інновацій (BRIN),
15314 Південний Танґеранґ, Індонезія
[5] Кафедра металурґії та матеріалознавства,
Університет Нігерії,
410001 Нсукка, Нігерія
[6] Факультет інженерії та антропогенного середовища,
Університет Йоганнесбурга,
2006 Йоганнесбург, Південна Африка

«ЗЕЛЕНІ» СИНТЕЗОВАНІ МЕТАЛЕВІ НАНОЧАСТИНКИ НА РОСЛИННІЙ ОСНОВІ ДЛЯ ПРОТИМІКРОБНИХ ТА АНТИКОРОЗІЙНИХ ЗАСТОСУВАНЬ

Металеві наночастинки (МНЧ), розроблені шляхом «зеленого» синтезу з різними рослинними екстрактами, привернули увагу наукової спільноти завдяки своїм протимікробним і антикорозійним властивостям. Кілька методів синтезу і характеристик було успішно реалізовано та розроблено задля оцінки фармакологічних властивостей і ефективности цих МНЧ. У цій статті обговорюються синтез та характеризація металевих наночастинок рослинного походження, різні типи металевих наночастинок рослинного походження та їхнє перспективне застосування. Цей огляд має сприяти розумінню того, що в наукових статтях зазвичай стверджується про МНЧ як протимікробні та антикорозійні засоби, а також висвітлити основні параметри та процедури, які впливають на протимікробні й антикорозійні дослідження МНЧ рослинного походження. Одначе, незважаючи на численні антибактеріальні й антикорозійні підходи, описані в літературі, зовсім небагато основоположень досягли великого масштабу. Труднощі в досягненні широкомасштабного успіху частково можуть бути пов'язані зі складністю проблеми та різними параметрами. Таким чином, будуть потрібні систематичні дослідження, щоб створити стандартизовану, широко прийняту методологію валідації для синтезу та характеризації металевих наночастинок рослинного походження.

Ключові слова: антикорозійний засіб, протимікробний засіб, «зелений» синтез, рослинні екстракти, нанотехнології, наночастинки металів.