EXPLORING MEDICINAL PLANTS

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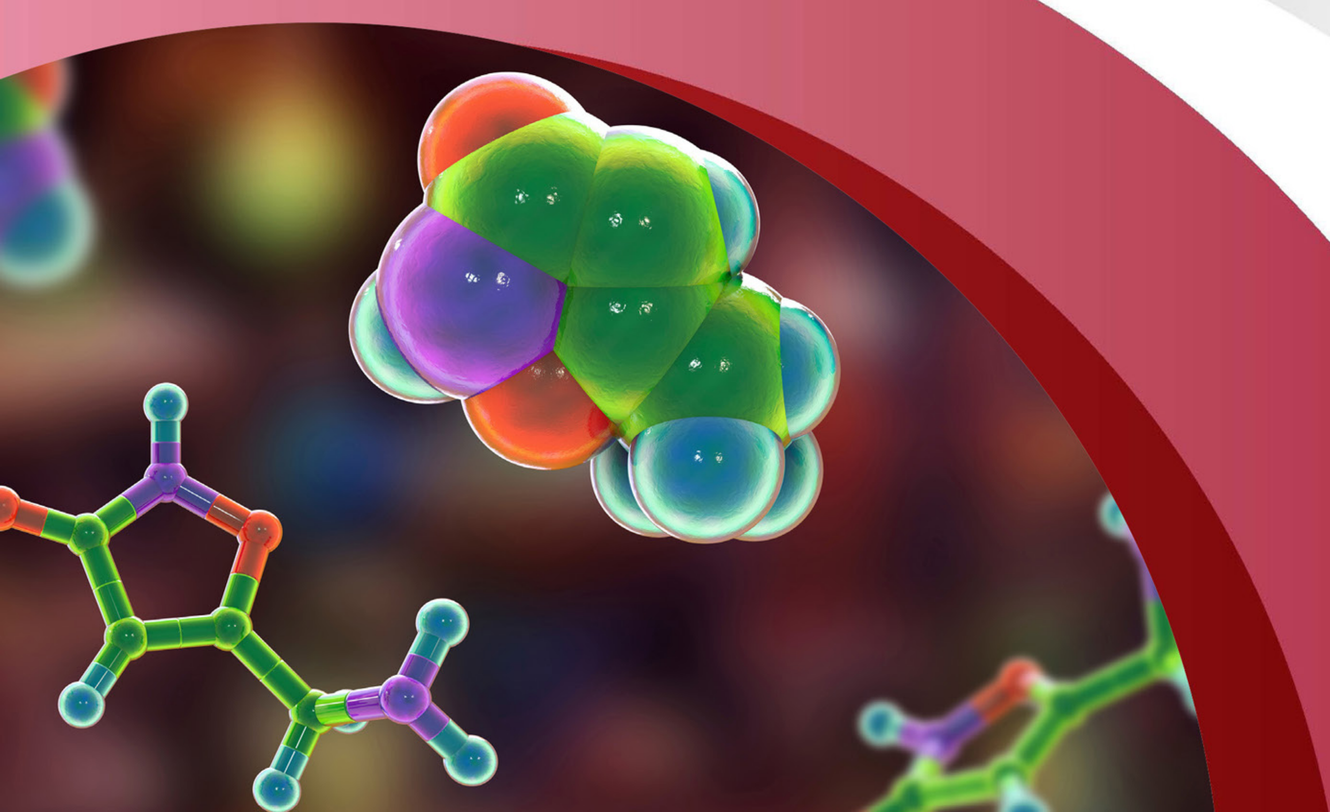
# SECONDARY METABOLITES FROM MEDICINAL PLANTS

## Nanoparticles Synthesis and their Applications

Edited by
Rakesh Kumar Bachheti
Archana Bachheti



# Secondary Metabolites from Medicinal Plants

Medicinal plant-based synthesis of nanoparticles from various extracts is easy, safe, and eco-friendly. Medicinal and herbal plants are the natural source of medicines, mainly due to the presence of secondary metabolites, and have been used as medicine since ancient times. *Secondary Metabolites from Medicinal Plants: Nanoparticles Synthesis and their Applications* provides an overview on medicinal plant-based secondary metabolites and their use in the synthesis of different types of nanoparticles. It explores trends in the growth, characterization, properties, and applications of nanoparticles from secondary metabolites including terpenoids, alkaloids, flavonoids, and phenolic compounds. It also explains the opportunities and future challenges of secondary metabolites in nanoparticle synthesis.

Nanotechnology is a burgeoning research field, and due to its widespread application in almost every branch of science and technology, it creates many new opportunities. As part of the *Exploring Medicinal Plants* series, this book will be of huge benefit to plant scientists and researchers as well as graduates, postgraduates, researchers, and consultants working in the field of nanoparticles.

# Exploring Medicinal Plants

**Series Editor**
*Azamal Husen*
*Wolaita Sodo University, Ethiopia*

Medicinal plants render a rich source of bioactive compounds used in drug formulation and development; they play a key role in traditional or indigenous health systems. As the demand for herbal medicines increases worldwide, supply is declining as most of the harvest is derived from naturally growing vegetation. Considering global interests and covering several important aspects associated with medicinal plants, the Exploring Medicinal Plants series comprises volumes valuable to academia, practitioners, and researchers interested in medicinal plants. Topics provide information on a range of subjects including diversity, conservation, propagation, cultivation, physiology, molecular biology, growth response under extreme environment, handling, storage, bioactive compounds, secondary metabolites, extraction, therapeutics, mode of action, and healthcare practices.

Led by Azamal Husen, PhD, this series is directed to a broad range of researchers and professionals consisting of topical books exploring information related to medicinal plants. It includes edited volumes, references, and textbooks available for individual print and electronic purchases.

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**Secondary Metabolites from Medicinal Plants: Nanoparticles Synthesis and their Applications**, *Rakesh Kumar Bachheti* and *Archana Bachheti*

# Secondary Metabolites from Medicinal Plants

## Nanoparticles Synthesis and their Applications

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# Preface

Nanotechnology is a promising interdisciplinary research field. Because of its widespread application in almost every branch of science and technology, it creates new opportunities in a variety of fields. Medicinal plant-based syntheses of nanoparticles from various extracts are easy, safe, and eco-friendly. Medicinal and herbal plants are the natural source of medicines, mainly due to the presence of secondary metabolites, and have been used as medicine since ancient times. In addition to serving as competitive weapons against other bacteria, fungi, amoebas, plants, insects, and large animals, secondary metabolites also act as metal transporters, symbiotic agents between microbes and plants, nematodes, insects, and higher animals. Medicinal and herbal plants can produce a vast and diverse group of secondary metabolites. Most of the time, pure isolated bioactive compounds are more biologically active, hence researchers and scientists are focusing their research on the synthesis of nanoparticles using a particular class of secondary metabolites such as terpenoids, alkaloids, and phenolic compounds such as flavonoids.

This book consists of 16 chapters highlighting specifically medicinal and herbal plant-based secondary metabolites in synthesizing different types of nanoparticles and their potential applications. These chapters discuss the role of a variety of molecules, including proteins and different low-molecular-weight substances like terpenoids, alkaloids, amino acids, alcoholic substances, and polyphenols in nanoparticle synthesis.

We are grateful not only to those colleagues who kindly agreed to contribute chapters to this volume but also to those who assisted us in reviewing these contributions. We also thank the reviewer who provided specific assistance in vetting and finalizing the manuscripts. We are grateful to Prof. Azamal Husen, the Series Editor for his tireless overall help at every step in preparing this book.

**Rakesh Kumar Bachheti**
**Archana Bachheti**

# Editors

**Rakesh Kumar Bachheti** graduated from the Hemwati Nandan Bahuguna Garhwal University (a Central university), India, in 1996. He completed his MSc in Organic Chemistry from Hemwati Nandan Bahuguna Garhwal University, India, in 1998. He completed a one-year Post Graduate Diploma in Pulp and Paper Technology from Forest Research Institute, India, in 2001. He obtained his Ph.D. in Organic Chemistry from Kumaun University, India, in 2007. He is presently working as an Associate Professor of Organic Chemistry in the Department of Industrial Chemistry at the Addis Ababa Science and Technology University (AASTU) of Ethiopia, where he teaches Ph.D., graduate, and undergraduate students. Before joining AASTU, Rakesh worked as Dean Project (Assistant) at Graphic Era University (A grade university by NACC), India. Rakesh also presented papers at international (Malaysia, Thailand, and India) and national conferences. He was also a member of important committees such as the Internal Quality Assurance Cell (IQAC), Anti-ragging Committee. His major research interests include natural products for industrial applications, biofuel and bioenergy, green synthesis of nanoparticles and their application, and pulp and paper technology. He retains a fundamental love for natural products, which permeates all of his research. He has also successfully advised 30 MSc and three Ph.D. students to completion, and countless undergraduates have researched in his laboratory. Dr Bachheti is actively involved in curriculum development for BSc/MSc/Ph.D. programmes. He has over 75 publications dealing with various aspects of natural product chemistry and nanotechnology and has 18 book chapters published by Springer, Elsevier, and Nova Publishing. Presently, he is supervising three Ph.D. students, three Master's students, and is also working on two research projects funded by AASTU.

**Archana (Joshi) Bachheti** earned a BSc in 1997 and MSc in 1999 from H.N.B. Garhwal University, India. She received her Ph.D. from Forest Research Institute, India, in 2006. She has carried out research projects and consultancy work in the areas of eco-restoration/development of wasteland, physico-chemical properties of *Jatropha curcus* seed oil and its relation to altitudinal variation and has been a Consultant Ecologist to a project funded by a government agency. Dr Joshi is currently a Professor at Graphic Era University, India. She has also served in many capacities in academia within India and provided expertise internationally for more than 15 years where she taught Ecology and Environment, Environmental Science, Freshwater Ecology, Disaster Management, and Bryophytes and Pteridophytes. Her major research interests encompass the broad, interdisciplinary field of plant ecology, with a focus on eco-restoration, green chemistry, especially the synthesis of nanomaterial, and medicinal properties of plants. The breadth of her research spans from the ecological amelioration of degraded land and the physical and chemical properties of plant oils, to plant-based nanomaterial. She has guided one PhD student and is presently supervising three scholars as well as guiding graduate and undergraduate students in their research projects. While it was the fascination with forest biodiversity that captured her interest, it has been her love for the exploration of values of biodiversity and social upliftment that has maintained that passion. Dr Joshi has published more than 50 research articles in international and national journals along with 10 book chapters. She has organized several national seminars/conferences at Graphic Era University, India.

# 1 Medicinal Plant-Based Metabolites in Nanoparticles Synthesis and Their Cutting-Edge Applications

## *An Overview*

*Yakob Godebo Godeto, Abate Ayele, Ibrahim Nasser Ahmed, Azamal Husen, and Rakesh Kumar Bachheti*

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## 1.1 INTRODUCTION

As a rapidly emerging technology and new research area in applied sciences and engineering, nanotechnology lays a strong foundation for a technological revolution and transformation in various sectors. Nanotechnology is a popular area of contemporary research and provides significant contributions to the industrial, agricultural, information technology, energy, environmental, food, and health sectors by producing nanomaterials from nanosized particles (particles with diameters of less than 100 nm) with novel properties and functions (Bachheti et al. 2021; 2021a). These and other promising benefits of nanoparticles, from domestic to industrial sectors, are likely due to their unique and novel properties such as particle size, surface area, reactivity, surface charge, and shape compared to their bulk counterparts (Bundschuh et al. 2018). The size and surface properties determine the solubility, absorption, emission, conductivity, reactivity, and optical behaviour of synthesized nanoparticles. These properties can be manipulated by altering the initial size of the source material (Koul et al. 2018; Bachheti et al. 2020). Nanoparticles with various outstanding properties and functions have been synthesized physically, chemically, and biogenically following two major approaches (i.e., bottom-up and top-down approaches) (Rafique et al. 2017; Khan et al. 2019; Ijaz et al. 2020; Jadoun et al. 2021).

In the bottom-up synthesis approach (such as vapour deposition, sol-gel, aerosol, chemical vapour deposition (CVD), laser pyrolysis, and the biological synthesis process), materials are built up from atom to cluster and then to nanoparticles. In contrast, in the top-down synthesis approach, crushing, splitting, and milling are used as size reduction techniques to reduce suitable materials to nanosized units (Rafique et al. 2017; Khan et al. 2019; Jadoun et al. 2021). Nanoparticles' physical, chemical, and biological synthesis processes are categorized under these two approaches. Nanoparticles with different sizes, shapes, and surface properties have been synthesized physically through CVD, the plasma method, microwave irradiation, pulsed laser ablation, ball milling, spray pyrolysis, and gamma radiation; chemically through chemical reduction, photochemical, polyol, microemulsion, thermal decomposition, electrochemical, pyrolysis, solvothermal, and coprecipitation; and biologically by using plants, microorganisms, and biomolecules (Kuppusamy et al. 2016; Rafique et al. 2017; Sharma et al. 2019; Cele 2020).

Currently, the interest of many researchers is shifting from conventional techniques (chemical and physical pathways) to biogenic synthesis as a greener approach. This is mainly because the biological process is known to be energy efficient, economical, environmentally benign, and results in a safe product, unlike with the physical and chemical techniques using toxic synthetic chemicals, high energy, and highly concentrated reducing and stabilizing agents that are harmful to the environment and human health (Kuppusamy et al. 2016; Marslin et al. 2018; Ijaz et al. 2020). Nowadays, nanoparticles of different sizes, shapes, and surface properties are synthesized employing various biological components such as reducing, capping, and stabilizing agents to overcome the drawbacks of conventional methods.

The application of green chemistry to synthesize nanoparticles using extracts and/or components of living and dead plant biomass (Jadoun et al. 2021), bacteria (Mukherjee and Nethi 2019), fungi (Neethu et al. 2019), microalgae (Jacob et al. 2021), yeasts (Skalickova et al. 2017), proteins, and enzymes (Hong et al. 2020; Arib et al. 2021) is gaining popularity due to their sufficient availability, low cost, biocompatibility, biodegradability, and lower environmental and health toxicity. Of the aforementioned biological entities, plants are abundantly available natural resources with varieties of diversity. They are rich in natural compounds such as flavonoids, alkaloids, saponins, tannins, steroids, and other nutritional compounds. These natural metabolites are derived directly or indirectly from various parts of plants such as roots, stems, barks, leaves, shoots, flowers, seeds, and nuts. These parts of plants participate in nanoparticle synthesis intracellularly, extracellularly, or reduction comprising their individual phytoconstituent isolates (Dauthal and Mukhopadhyay 2016) as indicated in Figure 1.1

Unlike the microbial route, which involves a multi-step process including the isolation of potential microbes, maintenance of culture, specific culture preparation, and subculturing, biological synthesis of nanoparticles using a medicinal plant is easy to scale up for large-scale production

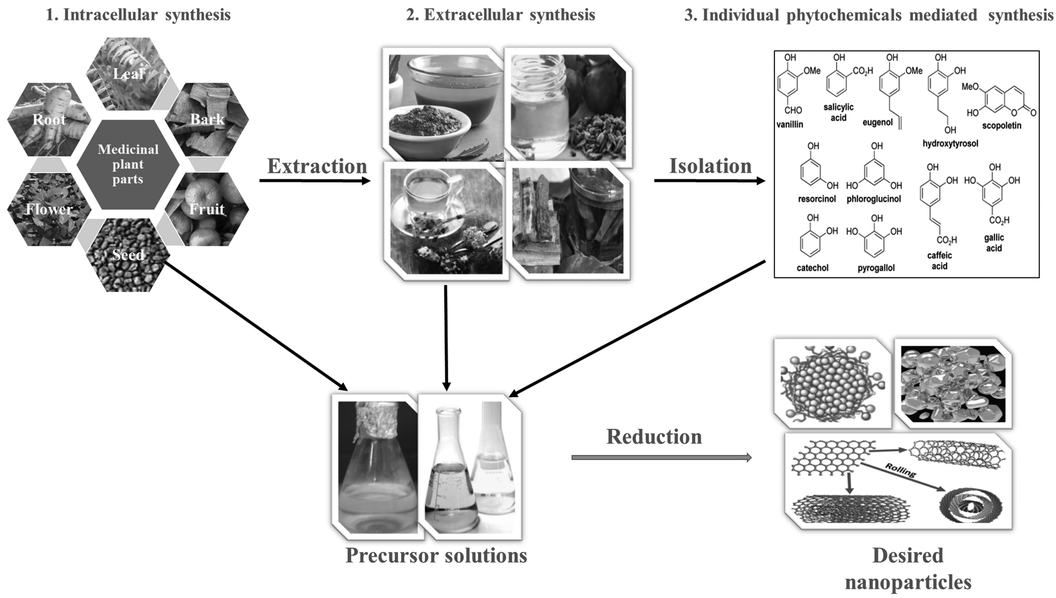


**FIGURE 1.1** Medicinal plant-mediated synthesis of nanoparticles (intracellularly, extracellularly, or using individual phytoconstituents).

and does not require any complex methodologies (Husen 2019; Bachheti 2019a; Chandra et al. 2020). The major role of utilizing various parts of medicinal plants (roots, stems, barks, leaves, shoots, flowers, seeds, and nuts) in nanoparticles synthesis is the use of their primary and secondary metabolites as reducing as well as capping and stabilizing agents (Ovais et al. 2018; Aritonang et al. 2019; Bachheti et al. 2020a, 2020b; Chandra et al. 2020). Plants possess thousands of small to more complex organic molecules used in traditional, folk, and modern medicine for healing different ailments either directly or indirectly. They possess carbohydrates, proteins, and lipids as a primary metabolite (Zaynab et al. 2019) and phenolics, alkaloids, polyphenols, quinones, tannins, flavonoids, terpenes, coumarins, lectins, and polypeptides, saponins, etc. as secondary metabolites (Alamgir 2017; Anand et al.2019).

Currently, numerous nanomaterials and nanocomposites such as metal and metal oxide (Küünal et al. 2018; Yadi et al. 2018; Bachheti et al. 2020), carbon-based (Zare et al. 2020), polymeric (Roy et al. 2014; Tripathi et al. 2019), lipid-based (Fernandes et al. 2021), and other nanomaterials have been synthesized biologically using medicinal plant extracts for domestic, environmental, industrial, biomedicinal, and other applications. These metabolites have been extracted from different parts of the plant by applying various traditional and modern methodologies to synthesize nanoparticles, a major building block of nanomaterials. Hence, this review work provides an overview of medicinal plant metabolites, their role in synthesizing various nanoparticles, and their cutting-edge applications of resulting nanomaterials, especially in the case of human health and environmental protection.

## 1.2 MEDICINAL PLANTS AND THEIR METABOLITES

### 1.2.1 Medicinal Value of Plants

From the initial hunter-gather stage to several adaptation stages, plants have played incredible roles in human livelihoods. Almost all of the world relies on them, particularly for shelter, food, and medicines (Beshah et al. 2020; Godeto et al. 2021; Abate et al. 2022; Asfaw et al. 2022). Medicinal plants as a source of treatment for ailments can be dated back to the earliest civilizations in China, India, and the Near East. Plant-based ingredients provide a wide range of medicinal properties. Herbal medicine is used by 60–80% of people worldwide for their primary healthcare needs (Wanjohi et al. 2020). Long before pharmaceutical development, communities relied on their traditional knowledge, skills, and customary practices to prevent, diagnose, and cure health problems, utilizing various natural resources (Barata et al. 2016). Herbalism is a type of traditional or folk medicine that relies on plants and plant extracts (Pan et al. 2014). All plants that traditional and official medicine considered curative or were used for that purpose are called medicinal plants. Medicinal plants have traditionally been a valuable source of both curative and preventive medicinal therapeutic preparations for humans and a source of important bioactive components for extraction. Nearly 80% of the world's population, particularly in developing countries, depends on traditional medicine and products for its healthcare needs (Mbuni et al. 2020; Abate et al. 2021). Many individuals suffering from diseases in developing regions combine conventional medicine with traditional ones. Their application begins in the distant past because treatment with plants is as old as humanity itself. Humans needed food to survive and as they used plants in their diet they discovered their medicinal properties (Šantić et al. 2017). Many pharmaceutical medications are derived from plants that were originally used in traditional medicine systems; according to the World Health Organization (WHO), approximately 25% of these medicines are derived from plants used in traditional medicine systems (Barata et al. 2016).

### 1.2.2 Classes of Plant Metabolites and Their Medicinal Values

The intermediates and products of metabolism are known as metabolites (Tiwari and Rana 2015). Plants are naturally capable of producing a wide range of metabolites, and the number of metabolites in the plant kingdom is estimated to be around 1,000,000 (Yonekura-Sakakibara et al. 2019). The role of phytochemicals in plant metabolism determines whether they are categorized as primary or secondary constituents. They are naturally synthesized in all parts of the plant body, including the bark, leaves, stems, roots, flowers, fruits, seeds, and so on; in other words, active components can be found in any part of the plant (Jyothiprabha and Venkatachalam 2016). Carbohydrates, proteins, nucleic acids, purines and pyrimidines, chlorophyll, etc., are primary metabolites. While terpenes, flavonoids, alkaloids, lignans, curcumin, saponins, plant steroids, phenolic, flavonoids, glycosides, etc., are examples of secondary constituents (Saxena et al. 2013; Alzandi et al. 2021). Secondary metabolites are important sources of medicines and play a vital role in plant adaptation to their environment (Tumbde et al. 2021). Plant extracts have been used in phytomedicines since the dawn of humanity. This can be driven by bark, leaves, flowers, roots, fruits, and seeds (Yadav and Agarwala 2011).

#### 1.2.2.1 Phenolics

Phenols are aromatic chemical compounds with weakly acidic properties that are distinguished by a hydroxyl (OH) group linked directly to an aromatic ring (Okigbo et al. 2009; Dai and Mumper 2010). It was discovered that, in addition to their primary antioxidant activity, this group of chemicals has a wide range of biological roles, the majority of which are associated with carcinogenesis modulation (Dai and Mumper 2010).

#### 1.2.2.2 Alkaloids

Alkaloids, which are biosynthesized from amino acids like tyrosine, are poisonous chemicals that protect plants against diseases and are commercially utilized as medicine (Ebenezer et al. 2019). Initially, alkaloids are pharmacologically active, nitrogen-containing basic compounds derived from plants. They can also cause hallucinations, loss of coordination, seizures, vomiting, and death by blocking ion channels, inhibiting enzymes, or interfering with neurotransmission (Tiwari and Rana 2015). They have valuable pharmacological properties such as antimalarial (quinine), anti-asthmatic (ephedrine), anticancer (homoharringtonine), vasodilatory (vincamine), antiarrhythmic (quinidine), analgesic (morphine), antibacterial (chelerythrine), and antihyperglycemic (e.g., piperine) (Umashankar 2020).

#### 1.2.2.3 Saponins

Saponins are naturally occurring surface-active glycosides produced primarily by plants, some bacteria, and lower marine animals. The antidiabetic properties of saponins enabled physicians to discover new medications that are beneficial in treating diabetes mellitus (Marrelli et al. 2016). Saponins are amphiphilic compounds with carbohydrate, triterpenoid, or steroid aglycone moieties. Fungicidal, antibacterial, antiviral, anti-inflammatory, anticancer, antioxidant, and immunomodulatory properties are among their biological activities (Alzandi et al. 2021).

#### 1.2.2.4 Terpenes

Terpenes, also known as isoprenoids, are the most copious and diverse group of naturally occurring compounds. They are chiefly found in plants, but larger classes of terpenes, such as sterols and squalene are also common in animals. The natural aroma, flavour, and pigment of plants are all due to this group of compounds. Among various therapeutic applications, they are known for antiplasmodial activity, which is remarkable because their mode of action is analogous to that of the widely used antimalarial medication chloroquine (Cox-Georgian et al. 2019).

#### 1.2.2.5 Carotenoids

Plants, algae, fungi, and bacteria all contain carotenoids, which are a type of tetraterpenoid molecule. They are phytonutrients that promote health and contribute to the prevention of cardiovascular disease (such as heart disease, cancer, and diabetes), Alzheimer's disease, and other age-related diseases (Pott et al. 2019).

#### 1.2.2.6 Tannins

Tannins are a type of polyphenol that can be divided into two categories: (1) condensed tannins (*syn*. proanthocyanidins), which are made up of flavan-3-of polymer subunits linked by 4–6 and 4–8 interflavan bonds, and (2) hydrolysable tannins, which are gallic acid esters with a central polyol, usually -D-glucopyranose (Pott et al. 2019). Tannins have a wide range of effects, from decreasing protein and other nutrient availability, such as amino acids and minerals, to protecting ruminants from bloat, improving rumen bypass protein, improving meat quality, and reducing helminth infestation (Makkar et al. 2009). Plant extracts containing tannins are employed as astringent, diuretic, anti-inflammatory, antiseptic, antioxidant, and haemostatic medicines and against stomach and duodenal tumours (Saxena et al. 2013).

#### 1.2.2.7 Flavonoids

Flavonoids are a type of secondary metabolite found in plants made up of polyphenolic compounds. They have antioxidative, anti-inflammatory, anticarcinogenic, and antimutagenic properties. As a result, they are a key ingredient in the pharmaceutical, nutraceutical, and cosmetics industries (Karak 2019; Umashankar 2020).

#### 1.2.2.8 Carbohydrates and Related Compounds

Carbohydrates and related chemicals derived from plants include fibres, cellulose and its derivatives, starch and its derivatives, mucilages (uronic acid-containing polymers), dextrins, fructans, pectins, and gums. They have been reported to have immune-modulatory, antitumour, hypoglycaemic, anticoagulant (e.g., heparin), and antiviral properties and their application as bulking agents in the pharmaceutical industry (Mustafa et al. 2017). Glycosides are secondary plant metabolites made up of two constituents (i.e., glycone (a carbohydrate component) and aglycone (a non-carbohydrate component)). The glycone component is typically composed of one or more glucose units, and the aglycone component may be any one of the plant's secondary metabolites from alkaloids, phenolics, or terpenoids (Mustafa et al. 2017).

#### 1.2.2.9 Lipids

Lipids are large classes of macromolecules including, but not limited to, fixed oils, waxes, essential oils, sterols, fat-soluble vitamins (such as vitamins A, D, E, and K), phospholipids, and other naturally occurring compounds. They accomplish decisive biological tasks in the body as major structural components of all biological membranes, energy reservoirs, and fuel for cellular processes (Hussein and El-Anssary 2019).

Plants are naturally enriched with various biological compounds for self-protection, growth, and reproduction (Pang et al. 2021). Different parts of plants possess varied quantities and types of phytoconstituents. Naturally existing phytochemicals in various plant parts have participated in healing several ailments in humans and other animals directly or indirectly from the start of the human era (Asaduzzaman and Asao 2018, Godeto et al. 2021). Major medicinal properties as a promising biological function of some commonly used medicinal plants and their metabolites are given in Table 1.1. They are used in medicine individually or in combination with other compatible substances to this day.

## 1.3 ROLES OF PLANT METABOLITES IN NANOPARTICLES SYNTHESIS

Amongst repeatedly reported green synthesis pathways, plant-mediated synthesis of nanoparticles is the current research interest of many scientists due to their abundance, flexibility to choose any parts (leaves, stems, barks, roots, shoots, fruits, seeds, flowers, etc.); they are easy to scale up and do not require additional processes such as isolation, culturing and sub-culturing, commonly used steps in microbial-based synthesis. Extracts from different plant parts possess several compounds with hydroxides, carbonyls, methoxy, amines, amides, thiols, carboxyls, phosphates, and other functional groups that play a decisive role in reacting with precursor compounds to form nanoparticles (Küünal et al. 2018; Bachheti et al. 2019; Painuli et al. 2020). For instance, the –OH functional groups in eugenol of clove extract for the synthesis of aqueous colloidal solutions of silver nanoparticles (AgNPs) act as a reducing agent and other terpenoids that are believed to be the surface-active molecules stabilize the synthesized nanoparticle (Parlinska-Wojtan et al. 2018).

On the other hand, terpenoid compounds in the aqueous flower extract of chamomile medicinal plant (*Matricaria chamomilla*) are involved in reducing the metal ion ($Ag^+$) to its reduced form ($Ag^0$) and also act as a capping agent of synthesized AgNPs (Parlinska-Wojtan et al. 2016). Moreover, Alanazi et al. (2016) reported that protein molecules in the leaf extract of *Calendula officinalis*, popular herbal and cosmetic plants are crucial in reducing, capping, and stabilizing activities in the biosynthesis of AgNPs. This implies that the existence of phytochemicals such as flavonoids, alkaloids, phenolic acids, carotenoids, saponins, terpenoids, proteins, lipids, and carbohydrates in medicinal plants are the major driving force for exploiting plant extracts in nanoparticles synthesis. Thus, metabolites of medicinal plants, especially secondary metabolites, participate extensively in reducing the starting precursor compounds to the desired nanoparticles and preventing the particles from undesired agglomerations by capping and stabilizing.

### 1.3.1 Roles of Flavonoids in Nanoparticles Synthesis

Flavonoids, encompassing various polyphenolic functional groups have participated in reducing several nanoparticles. For instance, quercetin and other flavonoid compounds are involved reducing silver nitrate precursor to AgNPs in an alkaline medium and the resulting nanoparticle has been used as antimicrobial, antioxidant, and anti-inflammatory agents (Hussain et al. 2019). The key is that flavonoids, polyphenolic phytochemicals comprising flavanones, flavones, isoflavones, and poly-methoxylated flavones contribute to the synthesis of wide verities of nanoparticles (Mondal

**TABLE 1.1**
**Some Commonly Used Medicinal Plants and Their Therapeutic Effects**

| S.N. | Medicinal plants | Parts used | Major metabolites (dominant compounds) | Therapeutic effects | References |
|---|---|---|---|---|---|
| 1 | Chamomile (*Matricaria chamomilla* L.) | Flowers, Leaves, Stems, Roots | Sesquiterpenes, flavonoids, coumarins, and polyacetylenes | Analgesic, anticancer, anti-inflammatory, antimicrobial, antioxidant, antiallergic, and activities | Singh et al. (2011); Roby et al. (2013) |
| 2 | *Bauhinia variegate* L. | Bark | Tannins, alkaloids, and saponins | Antibacterial activity | Parekh et al. (2006) |
| 3 | *Amaranthus spinosus* and *Boerhaavia erecta* | Stems | Tannins, alkaloids, saponins, polyuronides, betalains, amines, and amino acids | Antimalarial activities | Hilou et al. (2006) |
| 4 | *Allium sativum* | Bulbs | Cardiac glycosides, saponins, and terpenoids | Antibacterial activities | Pathmanathan et al. (2010) |
| 5 | *Eucalyptus citriodora* | Leaves | Tannins, alkaloids, cardiac glycosides, saponins, and terpenoid | | |
| 6 | *Ocimum sanctum* | Leaves | Cardiac glycosides and tannins | | |
| 7 | *Tribulus terrestris* | Leaves | Flavonoids, glycosides, alkaloids, saponin, and phenols | Antibacterial and antioxidant activities | Rehman et al. (2021) |
| 8 | *Vaccinium macrocarpon* | Leaves | Flavonoids, alkaloids, and phenols | | |
| 9 | *Cuminum cyminum* | Leaves | Flavonoids, glycosides, alkaloids, saponin, phenols, and tannins | | |
| 10 | *Rheum emodi* | Leaves | Flavonoids, alkaloids, phenols, and tannins | | |
| 11 | *Piper cubeba* | Leaves | Flavonoids, glycosides, and phenols | | |
| 12 | *Azadirachta indica* | Leaves | Saponin, phenols, flavonoids, and terpenoids | Antibacterial and antioxidant activities | Tiwari et al. (2021) |
| 13 | *Urtica parviflora* | Leaves | Phenols, flavonoids, and terpenoids | | |
| 14 | *Cassia fistula* | Leaves | Saponin, phenols, flavonoids, and terpenoids | | |
| 15 | *Crinum amoenum* | Leaves | Saponin and flavonoids | | |
| 16 | *Aleuritopteris bicolor* | Leaves | Saponin, phenols, flavonoids, and terpenoids | | |
| 17 | *Rosa indica* L. | Roots, Stems, Leaves | Flavonoids, tannin, alkaloids, and carbohydrates | Antifungal activities | Begum et al. (2021) |
| 18 | *Prunnus amygdalus L* | | Flavonoids and tannin, oil, and fats | | |
| 19 | *Prunus armeniaca* L. | | | | |
| 20 | *Momordica charantia* | Fruits | Flavonoid, flavonols, and phenolic | Kidney function | Mardani et al. (2014) |
| 21 | *Azadirachta indica* | Leaves | Coumarins, alkaloids, glycosides, proteins, and saponin | Antimicrobial activities | Nurudeen and Falana (2021) |
| 22 | *Calotropis procera* | Leaves | Alkaloid, flavonoid, proteins, saponin, and terpenoid | | |

(*Continued*)

**TABLE 1.1 (CONTINUED)**
**Some Commonly Used Medicinal Plants and Their Therapeutic Effects**

| S.N. | Medicinal plants | Parts used | Major metabolites (dominant compounds) | Therapeutic effects | References |
|---|---|---|---|---|---|
| 23 | *Carica papaya* | Leaves | Anthraquinone, alkaloids, flavonoid, glycosides, and saponin | | |
| 24 | *Vernonia amygdalina* | Leaves | Anthraquinone, alkaloids, coumarin, saponin, tannin, and terpenoid | | |
| 25 | *Myrtus communis* L.. | Leaves | Flavonoid, alkaloids, and terpenoid | Antibacterial activities | Sharara et al. (2021) |
| 26 | *Artemisia annua* | Leaves | Polyphenols, catechins, and terpenes | Antimicrobial activities | Golbarg et al. (2021) |
| 27 | *Oxalis corniculata* | Leaves | | | |
| 28 | *Solenostemma argel* | Aerial parts | Proteins | Antibacterial and antioxidant activities | El-Zayat et al. (2021) |
| 29 | *Teucrium polium* | Aerial parts | Crude fats and total carbohydrates | | |
| 30 | *Achillea fragrantissima* | Aerial parts | Proteins | | |
| 31 | *Peganum harmala* | Aerial parts | Crude fats and total carbohydrates | | |
| 32 | *Solanum virginianum* | Leaves | Phenols, flavonoids, saponins, terpenoids, steroids, and glycosides | Antibacterial activities | Gagare et al., 2021 |
| 33 | *Physalis angulata* | Leaves | | | |
| 34 | *Mesembryanthemum crystallinum*, *Mesembryanthemum forsskaolii Hochst.* Ex. *Boiss*, and *Mesembryanthemum nodiflorum* | Aerial parts | Phenolics, flavonoids, tannins, alkaloids, glycosides, steroids, and terpenoids | Antibacterial activities | El-Amier et al. (2021) |
| 35 | *Myrsine africana* | Leaves, Fruits | Terpenoids, steroids, flavonoids, carbohydrates, tannins, and saponins | Antitumour, antimicrobial and antioxidant activities | Laraib et al. (2021) |
| 36 | *Hibiscus rosa sinensis* | Leaves | Phenols, alkaloids, tannins, flavonoids, carbohydrates/ reducing sugars, terpenoids, phlobatanin, cardiac glycoside, and saponins | Antimicrobial activity | Priya and Sharma (2021) |
| 37 | *Chassalia kolly* | Leaves | Glycosides, alkaloids, flavonoids, anthocynes, reducing compound, mucilages, and saponosids | Anti-inflammatory and antioxidant activities | Alain et al. (2021) |
| 38 | *Pogostemon bengalensis* | Leaves | Flavonoids, phenols, alkaloids, saponins, tannins, and glycosides | Red blood cells haemolysis assay, antibacterial and antioxidant activities | Pimpliskar et al. (2021) |
| 39 | *Eryngium pyramidale Boiss*. and *Hausskn* | Aerial parts | Flavonoids, steroids, terpenoids, glycosides, and phenols | Antibacterial activity | Nejati et al. (2021) |
| 40 | *Gentiana cruciata* L. | Flowers | Polyphenols and tannins | Antibacterial and antifungal activity | Budniak et al. (2021) |

and Rahaman 2020). The hydroxide (–OH), carbonyl (–C=O), aldehyde (–CHO), ethoxy (–C–O–C), and carboxylic acid (–COOH) functional groups in the skeleton of flavonoid compounds are present in the reduction and stabilization of flavonoid-based nanoparticles (Khatamiet al. 2015; Hussain et al. 2019). The existence of the aforementioned and other functional groups in flavonoids enables the active chelation of the precursor ions and allows the desired nanoparticle formation (El-Seedi et al. 2019).

### 1.3.2 Roles of Terpenoids in Nanoparticles Synthesis

Terpenoids are a large class of naturally occurring compounds derived from the five-carbon compound isoprene, and isoprene polymers called terpenes (Perveen 2021). They are important phytochemicals for the biosynthesis of various nanoparticles. Plant terpenoids including monoterpenes, sesquiterpenes, diterpenes, sesquiterpenes, and triterpenes have found beneficial uses in medicine and their existence in plant biomass form a good platform for green synthesis of nanomaterials (Bergman et al. 2019). Medicinal plant terpenoids attached to the surface of nanoparticles during controlled synthesis are important molecules in reducing the precursor ions to required zerovalent forms and act as capping and stabilizing agents. According to Khan et al. (2016), terpenoids as major chemical constituents of various plant essential oils involved in the biosynthesis of AgNPs and their derivatives may play a crucial role as the surface-active molecule that may participate in reducing $Ag^+$ to $Ag^0$ and stabilizing the nanoparticles. Parlinska-Wojtan et al. (2016), on the other hand, justified that terpenoids present in the leaf extracts of chamomile are major reductants in the green synthesis of aqueous colloidal solutions of AgNPs, and also act as a capping and stabilizing agent to prevent undesired agglomerations and aggregations of the particles. In the other work, Kavitha et al. (2017) isolated terpenoid compounds from medicinal plant leaf extracts of *Andrographis paniculate* and participated in reducing the divalent ($Zn^{+2}$) to zerovalent ($Zn^0$) form by anchoring to the surface of zinc oxide nanoparticles (ZnONPs) via –C=O functional groups

### 1.3.3 Roles of Proteins in Nanoparticles Synthesis

Proteins, the primary plant metabolites, are macromolecules consisting of one or more long-chain amino acid units linked together by peptide bondage (Godeto et al. 2021). Recently, the reports revealed that biosynthesized protein nanoparticles are widely active in nanomedicines, mainly in drug delivery. This is mainly because the protein molecules have added advantages over other biomolecules, such as biocompatibility, biodegradability, ease of availability and preparation, high drug loading efficiencies, they are non-immunogenic, increase cellular uptake, and a high number of functional groups can be modified for targeting (Jain et al. 2018; Kianfar 2021; Reddy and Rapisarda 2021). In their study, Ahmad et al. (2013) depicted the presence of different –C=O groups attached to the surface of biosynthesized nanoparticles by Fourier-transform infrared spectroscopy (FT-IR) spectrophotometer, and the –C=O groups of amino acid residues tend to act as capping ligands for nanoparticles, thereby stabilizing the particles in aqueous solution by preventing unexpected agglomerations. It was sufficiently documented that the different functional groups such as thiols (SH), carbonyls (–C=O), hydroxyls (–OH), amines (–NH2), and amides (–C=ONH2) in amino acid residues of protein molecules are extensively useful components in the biosynthesis of various nanoparticles.

Protein molecules containing a disulphide bridge (S–S) as of in cysteine–cysteine linkage and thiol surface (S–H) in cysteine and methionine amino acids forms a catalytic site for the reduction of nanoparticles and act as reducing and capping agents (Durán et al. 2015). When they come into contact with the nanoparticles' surfaces, protein molecules can bind immediately to their surfaces (Elechiguerra et al. 2005). They can also facilitate the transportation of drug or generic materials into human cells (Hu et al. 2011). Moreover, the uptake and retention of nanoparticles inside human cells increase when proteins are used as natural capping agents (Rodriguez et al. 2013). Therefore there is no need for a separate capping step when peptides are present in nanoparticles as both reducing and capping agents, which is very significant for most therapeutic applications of nanoparticles (Chowdhury et al. 2014).

### 1.3.4 Roles of Phenolic Acids in Nanoparticles Synthesis

Phenolic acids are a class of polyphenolic compounds abundant in various medicinal plant sources. They refer to prominent bioactive secondary metabolites with –COOH functional groups with two subcategories, hydroxybenzoic acids and hydroxycinnamic acids, based on the attachment of –COOH to the benzene ring (Kumar and Goel 2019; Al Mamari 2021). The –OH and –COOH functional groups in phenolic acids, especially those of caffeic acid, gallic acid, ellagic acid, and protocatechuic acid are bioreductants of metal nanoparticles (Dauthal and Mukhopadhyay 2016; Amini and Akbari 2019). Natural phenolic acids present their reducing potentials by chelating to metal surfaces via –OH and –COOH groups. They facilitate the nucleation of nanoparticles by providing an electron ($e^-$) to the apparent metal ions and mediate the growth through oxidized phenolic acid anchored to the nanoparticles' surface (Amini and Akbari 2019). According to Kim and Han (2016), the catechol functional group in caffeic acid (3,4-dihydroxycinnamic acid) allows its strong chelation to the metal or metal oxides, thereby reducing the metal/metal oxide ions to corresponding nanoparticles.

## 1.4 PLANT METABOLITES-BASED SYNTHESIS PATHWAYS

As discussed in the sections above, metabolites sourced from different parts a of plant actively participate in the biosynthesis of various nanoparticles. In addition to reducing the precursor compound to corresponding nanoparticles and stabilizing them, biomolecules from plants also functionalize the surface of the nanoparticles (Küünal et al. 2018), which allows further modification to nanoparticle surfaces and induces synergetic effect for multiple applications.

### 1.4.1 Medicinal Plant Metabolites in Metal and Metal Oxide Nanoparticles Synthesis

Green synthesis of nanoparticles using metallic precursors was extensively studied through intracellular and extracellular reduction with the help of biomolecules from different microorganisms (bacteria, fungi, algae, yeast, etc.) and plant sources. Metallic nanoparticles are submicron scale entities with a metal/metal oxide core usually covered with a shell made up of organic or inorganic material or metal oxide (Khan 2020). Their extensive engagement in synthesizing various nanomaterials is due to their conspicuous properties such as good electrical and optical properties, antibacterial activity, chemical properties, and biocompatibility (Jamkhande et al. 2019; Wijesinghe et al. 2020). In addition, the flexibility to prepare particles with varied shapes, sizes, and morphology and the possibility for further modification of the surface broaden their application in different fields.

Primary and secondary metabolites of several medicinal plants have been widely consumed for metal and metal oxide nanoparticles synthesis through green chemistry approaches. Metallic nanoparticles synthesis involves the addition of prepared plant extracts to metal salt solutions at optimized reaction conditions (such as temperature, pH, reaction time, precursor, and extract dose, etc.) and observing a colour change that represents the first signal for metal nanoparticle formation (Dikshit et al. 2021). The general route for the formation of metal and metal oxide nanoparticles with the help of medicinal plant metabolites is presented in Figure 1.2. The phytochemicals in the extracts of medicinal plants are responsible for reducing metal ions to the corresponding nanoparticles. The progress of formation can be monitored with the help of UV-visible spectroscopy (Anandalakshmi et al. 2016). Heavy metals such as silver (Ag), gold (Au), zinc (Zn), palladium (Pd), lead (Pb), copper (Cu), iron (Fe), nickel (Ni), aluminium (Al), cobalt (Co), platinum (Pt) and metallic oxides like iron oxide ($Fe_3O_4$), zinc oxide (ZnO), titanium dioxide ($TiO_2$), copper oxide (CuO),

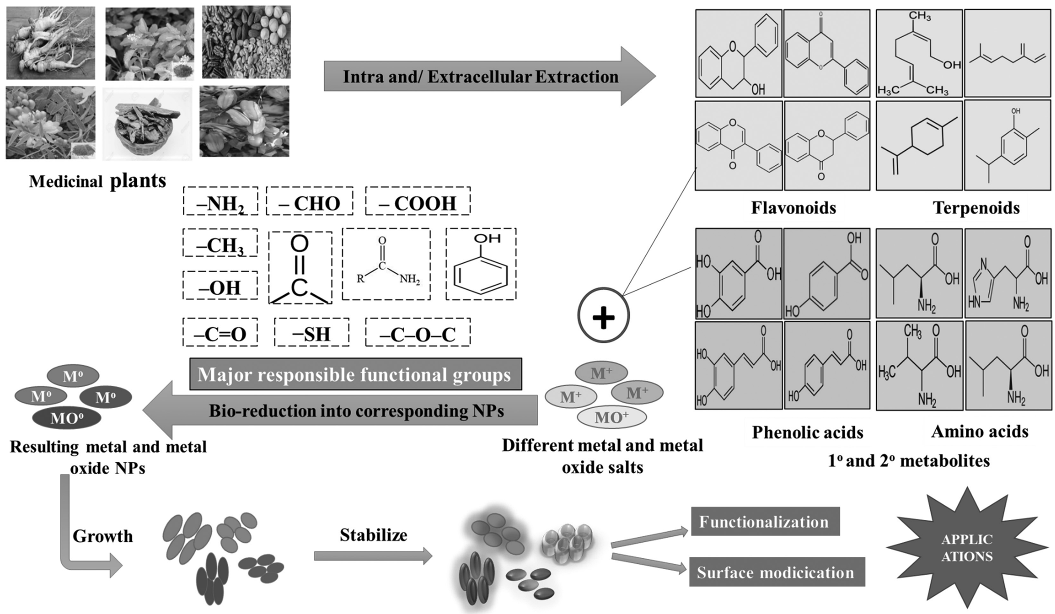


**FIGURE 1.2** Major route for synthesis of metal and metal oxide nanoparticles from medicinal plant metabolites.

magnesium oxide (MgO), and aluminium oxide ($Al_2O_3$) are biologically reduced into corresponding nanoparticles with the help of plant biomolecules (Jeevanandam et al. 2016). Currently, Ag and Au have received more attention among widely reported metal nanoparticles due to their outstanding properties, viz, their inert nature, stability, high disparity, non-cytotoxicity, and biocompatibility (Alaqad and Saleh. 2016). They have been biologically synthesized with different shapes, sizes, and structures for different intended applications.

Recently, Garibo et al. (2020) synthesized a spherical and quasi-spherical shaped AgNPs with an average diameter size of 5 nm using aqueous stem and root extract of *Lysiloma acapulcensis*, a Mexican medicinal plant. Accordingly, secondary metabolites of the plant-like alkyl halides act as reducing agents and protein compounds and ethylene groups detected by FT-IR could act as stabilizing/capping agents. Moreover, AgNPs with the average size of 7 nm were synthesized biologically using chamomile extract for antibacterial applications (Parlinska-Wojtan et al. 2016). The other work by Khatami et al. (2015) reported spherically shaped antifungal AgNPs with an average size of 14 nm synthesized using the seed exudate of *Sinapis arvensis*, an Iranian medicinal crop. In this case, the –C=O, –OH, andamine (N–H) groups in seed exudates confirmed by FT-IR spectra mainly participate in the reduction of $Ag^+$ ions to $Ag^0$ nanoparticles. Furthermore, a phenolic compound-rich hot water extract of *calendula officinalis* with strong antioxidant properties was used by Baghizadeh, et al. (2015) to reduce $AgNO_3$ precursor to AgNPs.

The other extensively studied metal nanoparticles after Ag are Au nanoparticles (AuNPs). They have been synthesized extracellularly and intracellularly using medicinal plants' living and dead biomass. For instance, AuNPs for antimicrobial application have been synthesized extracellularly using leaf extract of *Simarouba glauca* in an aqueous medium (Thangamani and Bhuvaneshwari 2019). In this report, the plant extracts possess different biomolecules such as aldehyde, carboxylic acids, alcohol, alkaloids, flavonoids, and other phenolic groups as confirmed by FT-IR and gas chromatography-mass spectrometry (GC-MS) spectrophotometer. Among these, the oxidation of aldehydes facilitated the reduction of metal ions to AuNPs to carboxylic acid within the solutions.

In the other work, Liu et al. (2019) reported a green route for the synthesis of AuNPs using ethanolic extract of *Euphrasia officinalis* as a major anti-inflammatory agent in lipopolysaccharide (LPS) induced RAW 264.7 cells. The phenolic acid, especially caffeic acid, luteolin-glucoside, and rutin compounds of the plant extract present their reduction and stabilization potential in forming AuNPs. Moreover, the fruit extract of *Dillenia indica* rich in phenolic groups is reported for reduction of $Au^+$ to AuNPs, and the resulting nanoparticle was tested for its in-vitro cytotoxicity (Sett et al. 2016).

In addition to various metal nanomaterials, metal oxide nanoparticles are also promising contenders, especially those synthesized through green technology, which is of interest to research communities. Among different reported metal oxide nanoparticles, green synthesized ZnONPs received attention due to their prominent properties such as a wide bandgap, better electrochemical activities, binding energy, low-cost synthesis, non-toxicity, biocompatibility, chemical and photochemical stability, and high-electron communication features (Mehta et al. 2012; George et al. 2018; Selim et al. 2020). Currently, several medicinal plant metabolites are being engaged in synthesizing ZnONPs for industrial, environmental, and even domestic applications. Ogunyemi et al. (2019) reported the green synthesis of ZnONPs employing an extract of medicinal plants such as chamomile flower (*Matricaria chamomilla*), olive leaf (*Olea europaea*), and red tomato fruit (*Lycopersicon esculentum*). The study reveals that different phytochemicals in these plant extracts such as terpenes, flavonoids, tannins, and glycosides are facilitators in reducing the ZnO precursor to its nanoparticle involved in capping and stabilizing the nanoparticles. Furthermore, medicinal plant metabolites of the leaf extracts of *Abutilon indicum*, *Melia azedarach*, and *Indigofera tinctoria* have been used to reduce $Zn(NO_3)_2.6H_2O$ precursor to ZnONPs to be used in anticancer activity against DU-145 and Calu-6 cancer cells (Prashanth et al. 2018). Their work reveals that various metabolites such as phenolic compounds, glycosides, proteins, terpenoids, etc. present in the leaf extracts of the plants are major biofuels responsible for reducing, stabilizing, and capping the nanoparticles.

The other most important metal oxide nanoparticles that have been receiving current research attention owing to their optical, electrical, and magnetic properties are $Fe_3O_4$ nanoparticles. Due to these and other promising properties, $Fe_3O_4$ nanoparticles, especially those of magnetite ($Fe_3O_4$) are widely engaged in various application fields such as magnetic storage media, ferrofluids, biosensors, catalysts, substrates in cancer treatment, targeted drug delivery in clinical trials, separation processes, and environmental remediation (Balamurugan 2014; Niraimathee et al. 2016). Today, various medicinal plant metabolites have been employed for the synthesis of $Fe_3O_4$ nanoparticles as an efficient and eco-friendly substitute for chemical or physical synthesis methods. For instance, the leaf extract of *Phyllanthus niruri*, an important Indian Ayurveda, was employed as a green reducing agent for synthesis of $Fe_3O_4$ for antibacterial activities (Kumar et al. 2018). The plant active phytoconstituents such as flavonoids, tannins, terpenoids, alkaloids, lignans, polyphenols, coumarins, and saponins found in *Phyllanthus niruri* have a therapeutic effect and are good candidates for capping and reducing $Fe_3O_4$ nanoparticles (Kumar et al. 2018). In addition, spherically shaped maghemite ($\gamma$ -$Fe_2O_3$) was successfully synthesized by Demirezen et al. (2019) using *Ficus carica* (common fig) dried fruit extract as capping and reducing agents. Their FT-IR report reveals that the phytochemicals in the fruit extract of the plant, mainly those of –OH and –C=O-based compounds, are important reductant and capping components.

### 1.4.2 Medicinal Plant Metabolites in Carbon-Based Nanoparticles Synthesis

Carbon-based nanomaterials are among the current research focus and considered a promising material for various applications owing to their interesting properties such as having the highest surface area, better mechanical and thermal strength, and electrochemical activities (Patel et al. 2020). Different architectures of carbon-based nanomaterials with varied structures, shapes, and physicochemical properties have been generated since carbon atoms are able to bond with each other in various ways to form different allotropes of carbon (Rauti et al. 2019). Accordingly, 0D fullerene, nano-diamonds (NDs), carbon dots (CDs), graphene quantum dots (GQDs), 1D carbon nanotubes (CNTs), 2D graphene and its derivatives, and a nitrogen-rich graphene-like nanostructure – graphitic carbon nitride (g-CN) are the most studied categories of carbon-based nanomaterials (Maiti et al. 2019; Xin et al. 2019). Carbon-based nanomaterials have been extensively exploited for various environmental, agricultural, biological, and medical applications. Such materials have been synthesized via non-green pathways (i.e., physically or chemically), which are reported as hazardous and not environmentally benign.

Hence, biological pathways comprising plants, microorganisms, and agricultural and industrial wastes have been implemented as green alternatives to synthesize carbon-based nanomaterial in recent years. Just like they do in the synthesis of metal and metal oxide nanoparticles, medicinal plant phytochemicals participate in the formation of carbon-based nanomaterials, especially in those of fullerene and graphene-based architectures as capping and reducing agents. Some medicinal plant phytochemicals that have been involved in the reducing and capping of carbon-based nanomaterials are given in Table 1.2. For instance, more recently, reduced graphene oxide (rGO) nanosheet was synthesized biologically using leaf extracts of *Tridax procumbens*, an Indian medicinal plant for antioxidant and antibacterial applications (Thiyagarajulu et al. 2020). In addition, an antimicrobial and anticancer rGO nanoparticle was successfully synthesized employing vegetable extract, *Chenopodium album*, as a reducing and stabilizing agent (Umar et al. 2020).

According to Hamedani et al. (2019), the leaf extract of *Pistacia atlantica* is used to modify the surface of multi-walled carbon nanotubes (MWCNTs) for in-situ reduction and immobilization of AgNPs. In this case, the phytochemicals in the *Pistacia atlantica* extracts are first allowed to adsorb on the surface of MWCNTs and coat it completely, and then the adsorbed compounds reduce Ag ions to AgNPs and stabilize them. The other recent work by Vinay (2021) reveals that fullerene [$C_{60}$]-linked AGNPs were successfully synthesized employing neem gum originated from the neem tree (*Melia azedarach*), which is a complex polysaccharide acid salt that has been medicinally used in India as a fuel for many centuries. The synthesized nanocomposites have effective cytotoxic activity against the lung cancer cell line (A549) with $IC_{50}$ value of 87.85 $\mu$g/mL. Therefore, metabolites of medicinal plants not only engage in the synthesis of metal and metal oxide nanoparticles but also participate in reducing, capping, and stabilizing carbon-based nanomaterials and their hybrid forms.

## 1.5 APPLICATIONS OF MEDICINAL PLANT METABOLITE-MEDIATED NANOPARTICLES

### 1.5.1 Antimicrobial Applications

Nowadays, microbes are showing high resistance to antibiotics. This issue needs to be resolved through the production of novel, more advanced platforms for the study and development of more potent antimicrobial agents against multidrug-resistant strains (Chung et al. 2016). Currently, research communities are investigating various novel works, especially green synthesized nanomaterials, and advanced products to be used as antimicrobial alternatives for antibiotic resistant microbes. In this regard, medicinal plant metabolites have been employed for the synthesis of several antimicrobial nanoparticles. Phytoconstituents in *Rumex nepalensis* leaves, *Phytolacca dodecandra* fruits, *Grewia ferruginea* bark and leaves are reported to have prominent antibacterial activities against different organisms, probably due to abundant availability of bioactive compounds (Tura et al. 2017).

It has been reported that plants and their extracts rich in tannins, flavonoids, and saponins are effective against resistant bacterial species (Tura et al. 2017). Recently, a wide variety of nanoparticles synthesized employing medicinal plant metabolites has been engaged in antimicrobial activities against several pathogenic microbes. In particular, pharmacologically important phytochemicals in *Viola betonicifolia* leaf extract used for AuNPs synthesis (VB-AuNPs) has the capability of killing

**TABLE 1.2**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Lysiloma acapulcensis* | Roots, Stems | Alkyl halides, proteins, phenolic, and other aromatic compounds | Ag | 5 nm, spherical and quasi-spherical | FT-IR, XRD, TEM, LC–MS, XPS, and EDS | Antimicrobial activities | Garibo et al. (2020) |
| *Sinapis arvensis* | Seeds | Alcohols, phenols, carbohydrates, and amino acids | Ag | 14 nm, spherical | UV-vis, XRD, TEM, FT-IR, and ICP | Antifungal activities | Khatami et al. (2015) |
| *Helicteres isora* | Roots | Carbohydrates, proteins, fibres, calcium, phosphorus, and iron | Ag | 30–40 nm, crystalline and spherical | UV-vis, SEM, TEM, FT-IR, and XRD | Antibacterial and antioxidant activities | Bhakya et al. (2016) |
| *Rheum palmatum* | Roots | Phenolic compounds, esters, anthraquinone, carbohydrates, aldehydes, and ketones | Ag | 121 nm, cubic, spherical, and hexagonal | UV-vis, XRD, GC-MS, DLS, SEM, TEM, and FT-IR | Antibacterial activities | Arokiyaraj et al. (2017) |
| *Excoecaria agallocha* | Leaves | Phenolic classes, amides, flavonoids, methylene groups, and carboxylate groups | Ag | 20 nm, crystalline, hexagonal and spherical | UV-vis, FT-IR, XRD, FE-SEM, and EDX | Antibacterial, antioxidant, and anticancer ctivities | Bhuvaneswari et al. (2017) |
| *Terminalia arjuna* | Bark | Polyphenols, phenolic acids, and proteins | Ag | 64.6 ± 1.8 nm, spherical | FT-IR, XRD, FE-SEM, UV-vis, and DLS | Antibacterial ctivities | Ahmed et al. (2017) |
| *Croton caudatus* Geisel | Leaf | Polyphenol-based secondary metabolites | Au | 20–50 nm, spherical | UV-vis, FT-IR,XRD, SEM-EDAX, and TEM | Antimicrobial, antioxidant activities | Kumar et al. (2019) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Simarouba glauca* | Leaves | Alkaloids, flavonoids, and phenolic compounds | Au | <10 nm, prism and spherical | UV-vis, XRD, HR-TEM, FT-IR, and GC-MS | Antimicrobial activities | Thangamania and Bhuvaneshwari (2019) |
| *Euphrasia officinalis* | Leaves | Phenolic compounds (phenolic acids and flavonoids) | Au | 5–30 nm, spherical or hexagonal and a few triangular-shaped | UV-vis, FT-IR, XRD, TEM, EDX, and SAED | Anti-inflammatory activities | Liu et al. (2019) |
| *Dillenia indica* | Fruits | Alcohol, carboxylic acid, esters, and ethers | Au | 5–50 nm, spherical, triangular, tetragonal, and pentagonal | FT-IR, XRD, TEM, EDX, HR-TEM, SAED, and TGA/DSC | | Sett et al. (2016) |
| *Corchorus olitorius* | Leaves | Phenolic compounds (such as chlorogenic acid, α-tocopherol, and quercetin 3-galactoside derivatives), ascorbic acid, and proteins | Au | 37–50 nm, quasi-spherical | UV-vis, FT-IR, XRD, TEM, and TGA | Anticancer activities | Ismail et al. (2018) |
| *Sumac* | Fruits | Flavonoid, tannins and other phenolic compounds | Au | 20.83 nm, spherical | UV-vis, FT-IR, XRD, TEM, and zeta potential | Antioxidant activities | Shabestarian et al. (2016) |
| *Dendropanax morbifera* | Leaves | Polysaccharides and terpenoids | Ag and Au | 100–150 nm, polygonal for Ag and 10–20 nm, hexagonal for Au | UV-vis, XRD, EDX, FE-TEM, and DLS | Anticancer activities | Wang et al. (2016) |
| *Acer pentapomicum* | Leaves | Phenolic and alcoholic compounds | Au | 19–24 nm, spherical | SEM, XRD, EDX, UV-vis, and FT-IR | Antioxidant, antibacterial and antifungal activities | Khan et al. (2018) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Xanthium strumarium* | Leaves | Monoterpene such as limonene and borneol | Pt | 22 nm, cubic to rectangular shape | UV-vis, FT-IR, PXRD, SEM-EDAX, and TEM | Antimicrobial and anticancer activities | Kumar et al. (2019) |
| *Taraxacum laevigatum* | Aerial parts | Proteins, flavonoids, and saponins | Pt | 2–7 nm, spherical | UV-vis, XRD, TEM, SEM, EDX, DLS, and FT-IR | Antibacterial activities | Tahir et al. (2017) |
| *Punica granatum* | Fruits | Alkaloids, glycosides, flavonoids, phenolic compounds, reducing sugars, resins, and tannins | Pt | 20.12 nm, spherical | UV-vis, XRD, TEM, FE-SEM, and FT-IR | Antitumour activities | Şahin et al. (2018) |
| *Filicium decipiens* | Leaves | Saponins, tannins, flavonoids, steroids, alkaloids, and other phenolics | Pd | 6.36 nm, spherical | UV-vis, FT-IR, XRD, and TEM | Antibacterial activities | Sharmila et al. (2017) |
| *Withania coagulans* | Leaves | Flavonoid and other phenolics | Pd | <15 nm, spherical | XRD, FE-SEM, FT-IR, EDS, TEM, and VSM | Catalytic activities | Atarod et al. (2016) |
| *Andrographis paniculata* | Leaves | Terpenoids | ZnO | 20.23 nm, hexagonal nanorod | UV-vis, FT-IR, XRD, SEM, $^{1}$H-NMR, and DLS | Drug delivery | Kavitha et al. (2017) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Matricaria chamomilla* L. | Flowers | Terpenes, flavonoids, alkaloids, glycosides, and tannins | ZnO | 51.2 ± 3.2 nm, cubic | SEM, TEM, UV-vis, FT-IR, EDS, and XRD | Antimicrobial activities | Ogunyemi et al. (2019) |
| *Olea europaea* | Leaves | Terpenes, flavonoids, glycosides, saponins, and tannins | | 41.0 ± 2.0 nm, cubic | | | |
| *Lycopersicon esculentum* M. | Fruits | Terpenes, flavonoids, glycosides saponins, tannins, and alkaloids | | 51.6 ± 3.6 nm, cubic | | | |
| *Deverra tortuosa* | Aerial parts | Flavonoids, terpenoids, glycosides, alkaloids, coumarin, steroids, tannin, and other polyphenolic compounds | ZnO | 15.22 nm, hexagonal | UV-vis, FT-IR, XRD, HR-TEM, and HPLC | Anticancer activities | Selim et al. (2020) |
| *Abutilon indicum* | Leaves | Glycoside, tannin, and phenolic compounds | ZnO | 15 nm, spherical | XRD, SEM, TEM, XPS, GC-MS, and TGA | Anticancer activities | Prashanth et al. (2018) |
| *Melia azedarach* | | Proteins, terpenoids, steroids, glycosides, tannins, and phenolic compounds | | 12 nm, spherical | | | |
| *Indigofera tinctoria* | | Saponins | | 21 nm, spherical | | | |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Lippia adoensis* (koseret) | Leaves | Alcohols, ketones, aldehydes, and phenols | ZnO | 19.78 nm, spherical, and hexagonal wurtzite | XRD, SEM-EDX, FT-IR, TEM, UV-vis, and TGA | Antibacterial activities | Demissie et al. (2020) |
| *Beta vulgaris*, *Cinnamomum tamala* | – | Alcohols, ketones, aldehydes,alkanes, alkenes, and proteins. | ZnO | 20 ± 2 nm, spherical<br>30 ± 3 nm, rod-shaped | XRD, SEM, FT-IR, TEM, and UV-vis | Antibacterial and antifungal activities | Pillai et al. (2020) |
| *Cinnamomum verum* | | | | 46 ± 2 nm, spherical | | | |
| *Brassica oleracea* var. Italica | | | | 47 ± 2 nm, spherical | | | |
| *Catharanthus roseus* | Leaves | Aliphatic amines, alcohols, carbohydrates, and proteins | $TiO_2$ | 65 nm, clustered and irregular shapes | XRD, FT-IR, SEM, and AFM | Antiparasitic activities | Velayutham et al. (2012) |
| *Hibiscus rosasenansis* | Flowers | Phenolic groups, proteins, and amines | $TiO_2$ | 7 nm, spherical and monodispersed | FT-IR, SEM, and XRD | Antibacterial activities | Kumar et al. (2014) |
| *Psidium guajava* | Leaves | Alcohols, carboxylic acids, and alkenes | $TiO_2$ | 32.58 nm, clusters and spherical | XRD, FT-IR, FE-SEM, and EDX | Antibacterial and antioxidant activities | Santhoshkumar et al. (2014) |
| *Solanum trilobatum* | Leaves | Vinyl ethers, alkanes, aldehydes, alkynes, beta lactones, and aliphatic amines | $TiO_2$ | 70 nm, oval and uneven spherical | FT-IR, SEM, XRD, EDX, and AFM | Larvicidal and pediculicidal activities | Rajakumar et al. (2014) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Curcuma longa* | | Terpenoids, flavonoids, and proteins | $TiO_2$ | 50–110 nm, spherical | UV-vis, XRD, AFM, and SEM | Antifungal activities | Jalill et al. (2016) |
| *Kalopanax pictus* | Leaves | – | $MnO_2$ | 19.2 nm, spherical | UV-vis, FT-IR, XPS, TEM, and EDX | Dye removal activities | Moon et al. (2015) |
| *Camellia japonica* | Leaves | Phenolic acid, flavonoids, terpenoids and protein molecules | CuO<br>ZnO | 15 nm, spherical<br>20 nm, spherical | UV-vis, FT-IR, EDS, SEM, XRD, and TEM | Optical sensing of metals ions like $Ag^+$ and $Li^+$ | Maruthupandy et al. (2017) |
| *Phyllanthus niruri* | Leaves | Terpenoids, flavonoids, polyphenols, alkaloids, coumarins and saponins | $Fe_3O_4$ | 10 nm, square | XRD, FT-IR, TEM, SEM, and UV-vis | Antimicrobial activities | Kumar et al. (2018) |
| *Eucalyptus globulus* | Leaves | Limonene, 1,8-cineole, α-pinene, p-cymene, γ-terpinene, and α-terpineol | $\beta$-$Fe_2O_3$ | 100 nm, agglomerated cluster | UV-vis, SEM-EDX, TEM, XRD, and FT-IR | – | Balamurugan et al. (2014) |
| *Mimosa pudica* | Roots | Tannin, calcium oxalate crystals, and mimosine | $Fe_3O_4$ | 67 nm, spherical | SEM, XRD, FT-IR, UV-vis, and VSM | – | Niraimathee et al. (2016) |
| *Ficus carica* | Fruits | Vitamins, minerals, sugars, carbohydrates, organic acids, and phenolic compounds | $\gamma$-$Fe_2O_3$ | 9 ± 4 nm, spherical | EDX, TEM, XRD, FT-IR, DLS, and UV-vis | – | Demirezen et al. (2019) |
| *Euphorbia herita* | Leaves | Polyphenols, flavonoids, and alcoholic compounds | $Fe_3O_4$ | 25–80 nm, irregular | SEM, XRD, FT-IR, and UV-vis | Antimicrobial activities | Ahmad et al. (2021) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Laurus nobilis* L. | Leaves | Alcohols, flavonoids, and polyphenols | α-$Fe_2O_3$ | 8.03 ± 8.99 nm, spherical like and partly as a hexagonal | FE-SEM, TEM, FT-IR, XRD, EDS, and UV-vis | Antimicrobial activities | Jamzad and Bidkorpeh (2020) |
| *Terminalia bellirica* | Leaves | Polyphenols, alcohols, and carboxylic acid | α-$Fe_2O_3$ | 21.32 nm, spherical | XRD, FT-IR, TEM, SEM, and UV-vis | Antioxidant, antibacterial and thermoacoustic activities | Jegadeesan et al. (2019) |
| *Moringa oleifera* | Fruits, Leaves | | | 45 nm, irregular shaped | | | |
| *Platanus orientalis* | Leaves | Quercetins, flavonoids, and glycosides | α-$Fe_2O_3$ and γ-$Fe_2O_3$ | 38 nm, spherical | XRD, FT-IR, SEM, TEM, EDX, DLS, and UV-vis | Antifungal activities | Devi et al. (2019) |
| *Psoralea corylifolia* | Seeds | Carboxylic acids, aliphatic amines, alcohols, and phenols | α-Fe2O3 | 39 nm, spherical, rod-like and uneven shapes | FT-IR, UV-vis, XRD, Raman spectrophotometer, SEM, and HR-TEM | Anticancer and catalytic activities | Nagajyothi et al. (2017) |
| *Tridax procumbens* | Leaves | Alkaloids, flavonoids, phenols, saponins, steroids, and tannins | Reduced graphene oxide (rGO) nanosheet | Non-uniform sheet-like structure | Raman spectrophotometer, UV-vis, XRD, FT-IR, FE-SEM, TEM, and EDS | Antioxidant and antibacterial activities | Thiyagarajulu et al. (2020) |
| *Pistacia atlantica* | Leaves | Phenolic compounds and flavonoids | Ag-NP/CNT | Quasi-spherical | XRD, FT-IR, SEM, TEM, and EDAX | Heterogeneous nano-catalyst for degradation of organic dyes | Hamedani et al. (2019) |
| Gum of *Melia azadirachta* | - | - | Ag@$C_{60}$ NPs | 30 nm, bore quasi-spherical | XRD, EDAX, SEM, and TEM | Anticancer activities | Vinay (2021) |

(*Continued*)

**TABLE 1.2 (CONTINUED)**
**Medicinal Plant Metabolites Involved in Synthesis of Different Nanoparticles**

| Medicinal plants | Parts used | Major metabolites participated in reducing, capping and/ stabilizing the nanoparticles | Synthesized nanoparticles | Average Size and shapes | Characterization techniques | Medicinal and other applications of synthesized nanoparticles | References |
|---|---|---|---|---|---|---|---|
| *Chenopodium album* | Leaves | Vitamin C, casein, caffeic acid, and polyphenols | rGO | Scrolled shape and lateral corrugations | FT-IR, UV-vis, SEM, and TEM | Anticancer, antibacterial, antifungal and antibiofilm activities | Umar et al. (2020) |
| *Citrus limon* L. (Lemon juice) | Fruits | Ascorbic acid, citric acid, sugars, and polyphenols | rGO | Exfoliated nanosheets | Raman spectrophotometer, FT-IR, XRD, UV-vis, SEM, and TEM | Dye removal activities | Mahiuddin and Ochiai (2021) |
| *Lotus garcinii* | Leaves | Carbohydrates, triterpenoids saponins, steroids, coumarins, tannins, flavonoids, glycosides, proteins, nucleic acid, and carotenoids | Ag/rGO/$Fe_3O_4$ | Spherical, 7–20 nm | FT-IR, FE-SEM, EDX, XRD, TEM, and UV-vis | Heterogeneous catalyst for reduction of organic pollutants | Maham et al. (2017) |
| *Eucalyptus* twigs | Stems | Flavonoids, eucalyptone, alkanoids, tannins, triterpenes, and several terpenoids. | Full-colour fluorescent carbon nanoparticles (CNPs) | Spherical or oval, 15–50 nm | UV-vis, XPS, FT-IR, FE-SEM, and TEM | Synthetic food colorant sensing and bioimaging | Damera et al. (2020) |

*Abbreviations*: AFM: atomic force microscopy; DLS: dynamic light scattering; DSC: differential scanning calorimetry; EDAX: energy dispersive X-ray; FT-IR: Fourier-transform infrared spectroscopy; FE-SEM: field emission scanning electron microscopy; HE-TEM: high-resolution transmission electron microscopy; HPLC: high performance liquid chromatography; ICP: inductively coupled plasma; LCMS: liquid chromatography mass spectrometry; SAED: selected area electron diffraction; SEM: scanning electron microscope; TEM: transmission electron microscopes; TGA: thermogravimetric analyzer; UV-vis: ultraviolet–visible spectroscopy; XPS: X-ray photoelectron spectroscopy; XRD: X-ray crystallography

*S. aureus*, *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa* bacterial strains effectively (Wang et al. 2021). Flower-based nanoparticles from *Rosa floribunda charisma* possessed promising antibacterial activity against three skin pathogens that pose a significant threat to public health, as *Staphylococcus epidermidis*, *Streptococcus pyogenes*, *and Pseudomonas aeruginosa* (Younis et al. 2021).

### 1.5.2 Applications as Antioxidants

Natural antioxidants derived from various medicinal plants have great potential to reduce different diseases induced by reactive oxygen species (ROS) in the body. Most compounds with antioxidant activities in the human diet typically originate from plant sources (Rauf et al. 2021). Both in vitro and in vivo studies have shown that nanoparticles, especially those of metals and metal oxides exhibit antioxidant activity by scavenging ROS and reactive nitrogen species (RNS), causing unwanted side reactions, promoting degenerative and age-related diseases (Kumar et al. 2021). Plant secondary metabolites, especially those of flavonoid and phenolic compounds in cells and plant tissue have major antioxidant activities (Hussain et al. 2019). Such metabolites have been repeatedly employed for synthesis of various nanomaterials as a green alternative to be used as an antioxidant agent against numerous ailments. In particular, flower-based AuNPs from *Rosa floribunda charisma* showed good radical scavenging activity, demonstrated by inhibition of ROS and RNS (such as superoxide, nitric oxide, hydroxyl radical, and xanthine oxidase) (Younis et al. 2021). Seed-based *Mangifera indica* aqueous extract of AgNPs showed 2,2-diphenyl-1-picrylhydrazyl (DPPH) activity in the concentration range of 160–960 μg/m leading to inhibition of 16–90% with $IC_{50}$ value of 544 μg/m (Donga and Chanda 2021). Thus, it has been widely reported that various nanoparticles synthesized biologically using medicinal plant phytochemicals as reducing and stabilizing agents have been tested for antioxidant activities in vivo and in vitro showed promising effectiveness.

### 1.5.3 Hepatoprotective Applications

Liver damage induced by hepatotoxicity is common in living organisms, which is mainly caused by a medicine, chemical, or herbal or dietary supplement, and it can be the side effect of medications such as HIV drugs. Nanoparticles carefully synthesized employing medicinal plant metabolites have been employed in hepatoprotective applications as a fascinating alternative to chemical-based drugs. In addition to being an alternative to toxic chemical treatments, the plant phytochemicals involved during nanoparticle synthesis can lead to synergetic effects, including antioxidant activities (Zhang et al. 2019). Plant-mediated nanoparticles of selenium, Ag, and Au have been widely used to prevent hepatotoxicity, a common form of liver damage. According to Kumar et al. (2021) report, rats intoxicated by carbon tetrachloride ($CCl_4$) were treated with aqueous leaf extract of *Punica granatum* and generated AgNPs. The results obtained obviously suggested that the aqueous extract of *Punica granatum* had a hepatoprotective effect, as the liver profile is affected by $CCl_4$ toxicity. On the other hand, AGNPs synthesized from *Rhizophora apiculata* have been shown to protect against hepatotoxin-induced liver damage caused by carbon tetrachloride (Zhang et al. 2019).

### 1.5.4 Anticancer Therapeutic Potential

Numerous therapeutic plant extracts and active components have been reported to have anticancer properties since ancient times. Medicinal herbs have been shown to have anticancer and cytotoxic properties in numerous studies. Plant-mediated nanoparticles have been reported to have improved anticancer activities against different cancer cell lines. In particular, those synthesized using secondary metabolites and other non-metallic components of various medicinal plant extracts have shown great effect against various cancer cell lines such as human breast cancer (KB) cell line, Hep

2, HCT 116, and Hela cell lines, and able to control tumour cell growth (Kuppusamy et al. 2016). For instance, medicinal plants containing various metabolites such as terpenoids, alkaloids, glycosides, flavonoids, and other phenolic compounds have been involved in the synthesis of nanoparticles, especially those of Ag and Au for the treatment of cancer (Kathiravanet al. 2014; Wang et al. 2016). The properties and structure of nanoparticles, mainly size, shape, and surface composition determine the effectivities of synthesized nanoparticles against cancer cells.

### 1.5.5 Applications in Drug Delivery

Nanoparticles have been widely involved in drug delivery, such as in anticancer drugs and therapeutic proteins in the field of nanomedicine as drug nanocarriers. Scientific reports reveal that they have the ability to improve the stability and solubility of encapsulated cargos, facilitate transport across membranes, and extend circulation times for better safety and efficacy (Mitchell et al. 2021). Among widely reported nanoparticles, magnetite nanoparticles ($Fe_3O_4$-NPs) biosynthesized using various plant extracts are gaining popularity in drug delivery systems due to their excellent magnetic properties. In addition to superparamagnetic property, the shape, size, surface modification, and stability of the nanoparticles determine the ability of the particles in delivering drugs to specific sites safely and effectively (Yew et al. 2020). Besides, AuNPs are considered one of the most suitable carrier systems in drug delivery carriers and macromolecular carriers, due to their improved biocompatibility, stability, and oxidation resistance (Sengani et al. 2017).

### 1.5.6 Catalytic Applications

Nanoparticles synthesized using medicinal plant phytochemicals have been extensively studied as promising alternatives in the reduction of various organic pollutants such as organic dyes and facilitate catalyst-induced reactions. Currently, nanoparticles are synthesized biologically using metals, and their oxides showed promising catalytic activities. For instance, AuNPS synthesized biologically using a traditional medicinal plant, *Piper longum* fruit, showed potent degradation capacity against the four organic dyes – methylene blue (MB), methyl red, crystal violet, and acridine orange (Nakkala et al. 2016). The other work by Ahmad et al. (2015) reveals that AuNPs synthesized using *Fagonia indica* as a reducing agent presented strong catalytic activity for the photocatalytic reduction of methylene blue (about 80% of MB was photodegraded under visible-light irradiation after 80 min) and chemical reduction of 4-nitrophenol. In another work, biosynthesized ZnONPs showed about 96% photocatalytic degradation of MB dye ($5 \times 10^{-5}$ M MB at pH 12) (Kumar et al. 2018).

In their work, Rostami-Vartooni et al. (2019) biosynthesized Ag and Pd nanoparticles supported on $Fe_3O_4$/bentonite using an aqueous *Salix aegyptiaca* leaf extract. Their experiment reveals that the magnetically recoverable Ag or Pd nanoparticles/$Fe_3O_4$/bentonite nanocomposites exhibited remarkable catalytic activity for the reduction reaction of rhodamine B (RhB), MB, and methyl orange (MO) azo dyes in the presence of aqueous $NaBH_4$ with good reusability. Moreover, AgNPs synthesized employing *Dalbergia spinosa* leaf extract as a biological reducing agent exhibited prominent catalytic activities in reduction of 4-nitrophenol (4-NP) into 4-aminophenol (4-AP) (Muniyappan, and Nagarajan 2014) (Figure 1.3).

## 1.6 CONCLUSION

Green synthesis of nanomaterials is a promising area for various industrial and environmental applications owing to its energy efficiency, low production cost, ease of synthesis, use of few or no toxic chemicals, and reduced environmental challenges. Since our world is blessed with the grace of nature, several natural entities have been utilized to synthesize and modify nanomaterials. Medicinal plants have been employed for modern and folk medicines among various natural resources directly

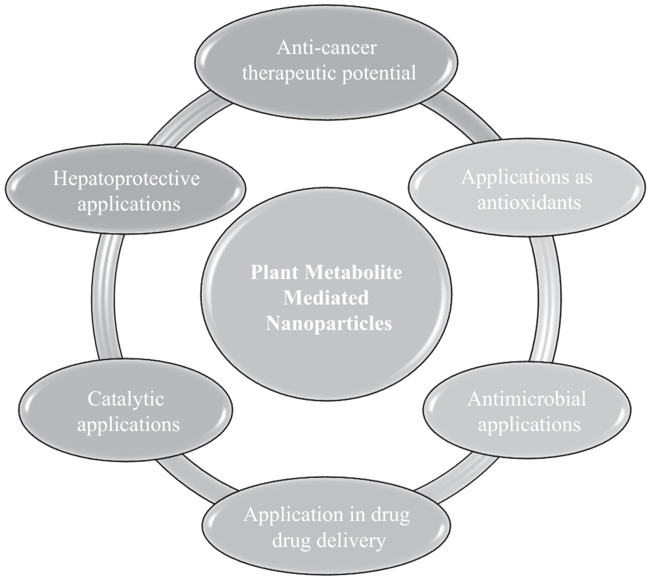


**FIGURE 1.3** Applications of plant metabolite-mediated nanoparticles.

or indirectly throughout human history. Currently, more focus has been given to medicinal plants and their biomass to synthesize nanoparticles, mainly due to ease of availability, the flexibility to choose any parts, and because they encompass several natural compounds that are directly involved in reducing, capping, and stabilizing the resulting nanoparticles. Different metabolites of plants, such as phenolics, flavonoids, terpenes, tannins, glycosides, steroids, proteins, etc., possess several functional groups including hydroxides, carbonyls, thiols, amines, amides, etc. and play a vital role in reducing precursor compounds to intended nanoparticles. The resulting nanoparticles with controlled size, shape, and surface properties can participate in industrial, agricultural, environmental, and health application areas. Even though the properties, characteristics, and applicability of nanomaterials have been thoroughly studied and proved by various scientific communities, their environmental challenge and toxicity and health impact are not well documented. Hence, in addition to synthesis and characterization studies, the attention of future research should focus on the environmental challenges posed by the usage of nanomaterials for various applications. Considering this, nanoparticles critically synthesized from medicinal plant metabolites with extreme caution can be a modern solution to the existing problems encountered by our societies.

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# Medicinal Plant-Based Metabolites in Nanoparticles Synthesis and Their Cutting-Edge Applications


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## Medicinal Plant-Based Flavonoid-Mediated Nanoparticles Synthesis, Characterization, and Applications

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## Medicinal Plant-Based Terpenoids in Nanoparticles Synthesis, Characterization, and Their Applications

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## Medicinal Plant-Based Lignin and Its Role in Nanoparticles Synthesis and Applications

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## Medicinal Plant-Based Alkaloids

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## Sustainable Synthesis of Nanoparticles Using Saponin-Rich Plants and Its Pharmaceutical Applications

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## Synthesis, Characterization, and Application of Nanoparticles from Medicinal Plant-Based Carotenoids


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## Medicinally Important Flowers and Their Role in Nanoparticle Synthesis and Applications


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## Green and Cost-Effective Nanoparticles Synthesis from Some Frequently Used Medicinal Plants and Their Various Applications

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