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Multifunctional Bioactive Compounds from Medicinal Plants: Antioxidant, Antimicrobial and Corrosion Inhibition Perspectives

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Title: Multifunctional Bioactive Compounds from Medicinal Plants: Antioxidant, Antimicrobial and Corrosion Inhibition Perspectives.

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Abstract

Medicinal plants are valuable sources of phenolics, flavonoids, alkaloids, terpenoids, glycosides and essential oils. Phytochemicals extracted from medicinal plants find application in different biological systems due to their varied biological activities. Rising environmental concerns along with requirement for sustainable substitutes have gained interest in multifunctional compounds from plants. Plants possess phytochemicals with antioxidant, antimicrobial and corrosion inhibition potential which make them applicable in pharmaceutical industries, food processing, environmental and industrial applications. Antioxidant potential involves free radical scavenging activity, metal chelating ability and regulation of redox reaction. Antimicrobial activity is due to alteration of the microbial cell membrane structure, enzyme inhibition and binding with microbial DNA. Corrosion inhibition potentials involve adsorption of bioactive compounds present in plants on metal surface and forming a protective layer over metal surface that reduces metal dissolution in acidic corrosive media. The multifunctional nature of these compounds is associated with the presence of aromatic rings and electron rich functional groups such as hydroxyl, carbonyl, and heteroatom containing groups. Compared with synthetic chemicals, plant-based compounds are biodegradable, eco-friendly and less toxic. Advances in extraction, characterisation and mechanistic studies have further enhanced their potential applications. The review covers multifunctional properties of medicinal plant-derived bioactive compounds, particularly their antioxidant, antimicrobial, and corrosion inhibition activities. In addition, the review highlights current challenges, recent advances in green and sustainable approaches, and future perspectives involving nanotechnology and hybrid multifunctional systems.

Keywords: Medicinal plants, Bioactive compounds, Antioxidant activity, Antimicrobial activity, Corrosion inhibition, Green inhibitors.

1. INTRODUCTION

Medicinal plants have been vital role in human healthcare since earliest times, forming the foundation of traditional systems such as ayurveda, traditional medicine, and several native healing practices. Advances in phytochemistry and pharmacology have enabled the identification, isolation, and characterization of plant-derived compounds with potent biological activities. A widespread variety of plant species have the potential to be used for medicinal purposes. Generally, plant-based drugs are well tolerated by the human body and are easily accessible, cost-effective, safe, and therapeutically effective compared to synthetic drugs [1]. In modern science, the significance of plants has expanded beyond traditional uses, gaining attention in pharmaceutical, biomedical, and industrial research. Of the numerous medicinal plants have been used for various treatments, that shows multifunctional properties such as antimicrobial, anti-inflammatory, antioxidant, and anticancer activity. Nearly 80% of people rely on traditional medicine, frequently using plant-based remedies for healthcare purposes. However, more detailed studies are required to better understand their safety, efficacy, and other critical factors associated with their use [2].

Bioactive compounds are naturally occurring substances originate in plants, microorganisms, and other biological sources that exert specific effects on living organisms or cells. These bioactive compounds are not essential nutrients but play an important role in influencing biological processes and maintaining health. Medicinal plants have a common classes of bioactive compounds such as flavonoids, alkaloids, phenolic acids, tannins, and terpenoids, which are the therapeutic properties of medicinal plants [3, 4]. The significance of these compounds lies in their broad range of biological activities, such as antioxidant, antimicrobial, anti-inflammatory, and anticancer effects. They help in neutralizing free radical, preventing the growth of dangerous microorganisms, and modulating several physiological pathways. In addition to their uses in pharmaceuticals and medicines, these are also used in food preservation, cosmetics and environment protection.

The expanding environmental concerns and the limitations associated with synthetic chemicals have led to a growing demand for green and sustainable alternatives. Conventional chemical products, although effective, often pose risks like harmfulness, environmental pollution, and long-term environmental damage. As a result, there is shift toward the use of natural, biodegradable, and environment friendly substances, particularly those obtained from plants and other renewable sources. These bioactive compounds are widely used across several

industrial sectors, including the chemical, pharmaceutical, and fruit industries [5, 6]. In particular, phytochemicals obtained from fruits offer significant health benefits, such as antioxidant affects and the ability to inhibit abnormal cell growth [6, 7]. Therefore, the rising demand for sustainable solutions is driving extensive research into plant-based materials, promoting a transition toward safer, eco-friendly, and renewable approaches in both scientific and industrial fields. Their ability to provide comparable or even superior performance while minimizing environmental impact makes them highly valuable in the development of green technologies.

The concept of multifunctionality in phytochemicals refers to the ability of a single plant derived compound to reveals multiple chemical and biological activities simultaneously. Unlike synthetic agents that are designed for a specific function, phytochemicals include flavonoids, alkaloids, polysaccharides, and phenolic compounds can perform diverse roles due to their complex chemical structures and presence of several functional groups [1, 3, 4]. Such versatility improves their value in multiple fields, like medicine, agriculture and material science. Therefore, the multifunctionality of phytochemicals makes them highly promising candidates for developing sustainable and efficient solutions that address both health-related and industrial challenges [8].

The present review directs to provide a comprehensive overview of multifunctional bioactive compounds derived from medicinal plants, with a particular target on their antioxidant, antimicrobial, and corrosion inhibition properties. It seeks to bridge traditional knowledge and modern scientific advancements by highlighting the chemical nature, resources, and mechanisms of action of these plant-based compounds. Objectives this review summarize the existing understanding of bioactive compounds from medicinal plants, assess their multifunctional properties in various fields, emphasize their importance as eco-friendly and sustainable alternatives to synthetic chemicals, and identifying current research gaps and future perspectives for their effective utilization in industrial and pharmaceutical applications.

2. Classification Of Bioactive Compounds in Medicinal Plants

Bioactive compounds are structurally diverse secondary metabolites that play important roles in plant defense and human health applications. These compounds are not directly involved in primary metabolic processes but are crucial for ecological interactions such as protection against pathogens, herbivores, and environmental stress. These compounds are responsible for the therapeutic properties of plants, like antioxidant, antimicrobial, anti-inflammatory, and

corrosion inhibition activities, makes them greatly valuable in pharmaceutical, food, and industrial sectors. Based on their chemical structure, polarity, and biosynthetic pathways, bioactive compounds are broadly classified (Figure 1). Table 1 displays major classes of phytochemicals, their sources and biological importance.

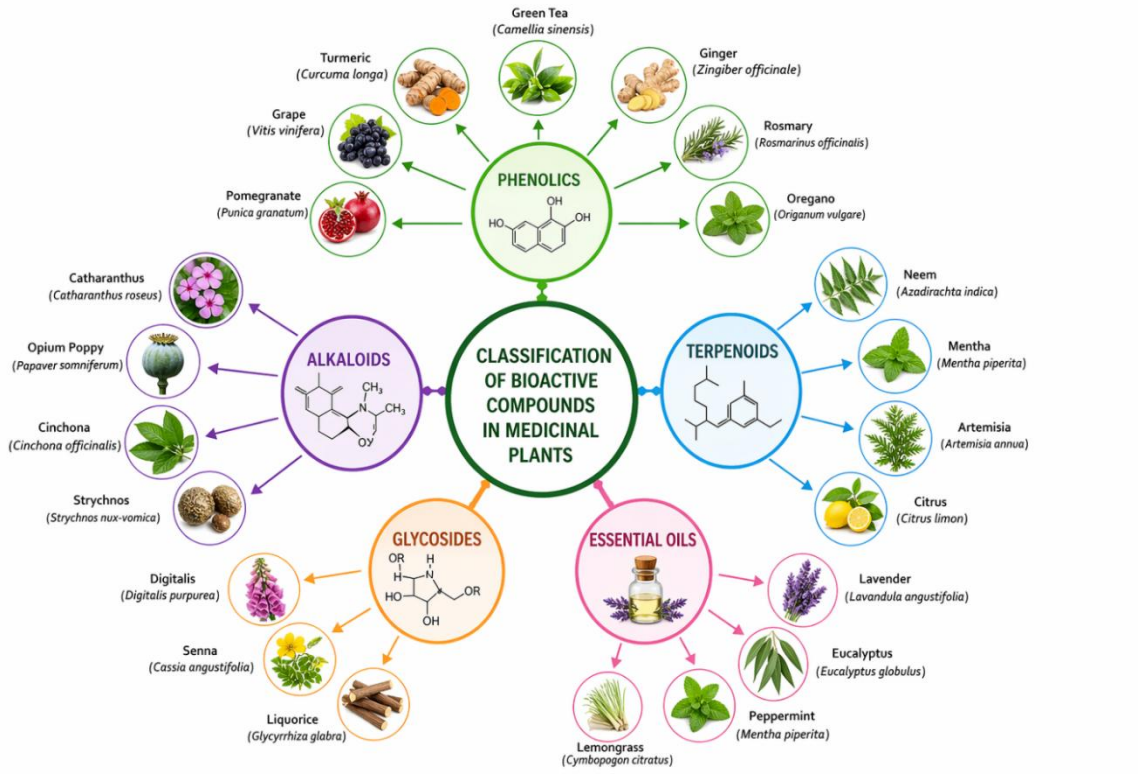


Figure 1. Classification of bioactive compounds in medicinal plants.

2.1. Major Classes

Phenolic compounds

Phenolic compounds constitute a diverse group plant-derived metabolites that are recognized for their antioxidant and anti-inflammatory activities, functioning by neutralizing reactive oxygen species, influencing enzyme activity, and regulating inflammatory signaling pathways [9, 10]. Phenolic compounds such as simple phenols, phenolic acids, tannins, lignans, and flavonoids [11]. These bioactive compounds are characterized by one or more hydroxyl groups attached to an aromatic ring. They are also powerful antioxidants and play an important role in preventing oxidative stress. Tannins, a subclass of phenolics, are particularly important for antimicrobial activity and corrosion inhibition due to their metal binding capabilities. These compounds are utilized therapeutically in the treatment and prevention of conditions include

neurodegenerative diseases, cancer, cardiovascular disorders, and various skin-related ailments [10].

Flavonoids

Flavonoids are a diverse group of polyphenolic compounds broadly distributed in plants. It act as potent antioxidant agents and contribute to the protection of both cardiovascular and liver functions [12]. Flavonoids include quercetin and kaempferol also shows antimicrobial and anti-inflammatory properties, making them multifunctional agents in medicinal applications.

Tannins

Tannins are high molecular weight polyphenolic compounds that can precipitate proteins. They are classified into hydrolysable and condensed tannins. It also possesses antioxidative, antimutagenic, and anticarcinogenic properties [13]. Tannins show powerful strong antioxidant and antimicrobial activities and are studied for their corrosion inhibition properties due to their ability to form protective films on metal surfaces. Their capacity to interact with proteins and metal ions plays an important role in their protective action against metabolic and cardiovascular diseases [10].

Alkaloids

Alkaloids are huge group of nitrogen containing secondary metabolites that show powerful physiological effects. They are typically basic in nature and are known for their pharmacological activities include analgesic, antimicrobial, and anticancer properties. They effect multiple physiological processes by modulating enzyme activity and interacting with receptor systems [14]. Common examples like morphine (analgesic), quinine (antimalarial), berberine (analgesic and antinociceptive), galantamine (used in the treatment of Alzheimer's disease). The broad spectrum of therapeutic effects, ranging from analgesic action to neuroprotective benefits, highlights their significance in pharmaceutical uses [15].

Terpenoids

Terpenoids are obtained from isoprene units and represent one of the largest classes of plant secondary metabolites. These are synthesized through the mevalonate and methylerythritol phosphate (MEP) pathways [10]. They show a range of biological activities include antimicrobial, anticancer, and wound healing effects, while also functioning in ecological interactions as attractants or deterrents [16].

Glycosides

Glycoside consist of a sugar moiety linked to a non-sugar component. Depending on the nature of the aglycone, they are classified into cardiac glycosides, saponins, anthraquinone glycosides, etc. glycosides exhibit both pain-relieving and antioxidant activities and frequently act as precursors for the formation of other biologically active compounds [17].

Essential oils

Essential oils are volatile constituents from aromatic medicinal plants, possess hydrophilic characteristics that enable them to penetrate bacterial members, disrupt their structural integrity, and induce leakage of vital intracellular contents, ultimately resulting in cell death [18-20]. Essential oils mainly composed of terpenoids and phenylpropanoids and they are responsible for the characteristic fragrance of plants and possess antimicrobial, antifungal, and antioxidant properties.

Table 1. Major classes of phytochemicals, their sources and biological importance

Class	***Subclasses/Examples***	***Key Sources/Plants***	***Biological Importance***	***References***
Phenolics	*Flavonoids (quercetin) tannins, phenolic acids (gallic acid)*	*Turmeric (Curcuma longa), green tea (Camellia sinensis)*	*Antioxidant, anti-inflammatory*	*[21, 22]*
Alkaloids	*Caffeine, morphine, berberine*	*Coffee (Coffea spp.), Berberis*	*Antimicrobial, analgesic*	*[23]*
Terpenoids	*Carotenoids (β-carotene), limonene*	*Carrots, citrus peels*	*Anticancer, anti-inflammatory [24]*	*[24]*
Glycosides	*Saponins, cardiac glycosides*	*Ginseng (Panax ginseng)*	*Cardioprotective, immune-modulating*	*[25]*
Essential Oils	*Thymol, eugenol*	*Thyme, clove*	*Antimicrobial, preservative*	*[26]*

2.2. Structural Features and Reactivity

The multifunctional properties of bioactive compounds derived from medicinal plants are primarily influenced by their structural characteristics and chemical reactivity. For example, hydroxyl groups present in phenolic compounds highly significant to their ability to neutralize free radicals. In alkaloids, nitrogen-containing heterocyclic structures facilitate interactions

with neural receptors, influencing various physiological responses. Terpenoids, defined by their isoprene obtained frameworks, show high membrane permeability, which supports diverse pharmacological activities. A thorough understanding of these structural characteristics is important for rational drug design and for carrying out chemical modifications that enhance therapeutic effectiveness and bioavailability [10]. These compounds exhibit diverse biological activities, including antioxidant, antimicrobial, and corrosion inhibition effects, which are closely associated with the presence of specific functional groups and overall molecular architecture. These structural aspects are essential for elucidating their mechanisms of action and enhancing their practical applications.

Functional groups show a vital role in control the reactivity and biological efficiency of bioactive compounds. Structural-activity relationship (SAR) provides insights into how specific molecular features influence these compounds. Hydroxyl groups, commonly found in phenolics and flavonoids, contribute significantly to antioxidant activity by donating hydrogen atoms to neutralize free radicals and stabilize reactive species through resonance. These findings indicate that structural characteristics such as the quantity and placement of hydroxyl groups, the extent of conjugated systems, and the incorporation of heteroatoms like nitrogen, oxygen, and sulfur play an important role in corrosion inhibition efficiency [27, 28]. For example polyphenolic compounds like quercetin and gallic acid show a high affinity for adsorption onto mild steel surfaces, attributed to the presence of multiple hydroxyl and delocalized π-electron systems, which facilitate the formation of stable chemisorbed protective films [27, 29]. Alkaloids like piperine and skimmianine act as corrosion inhibitors by utilizing the lone pair electrons on nitrogen atoms to interact with metal d-orbitals, while their hydrophobic moieties contribute to improved surface coverage and protective barrier formation [30]. Quantum chemical investigations direct that compounds with strong electron-donating ability often reflected by higher HOMO energy values and planar, π-conjugated frameworks exhibit enhanced interaction with metal surfaces, leading to enhanced corrosion inhibition performance. For instance, phthalocyanines, which possess large, planar, and highly conjugated structures, show effective inhibition due to their capacity for extensive electron delocalization and donation. In addition, studies on alkaloid-derived inhibitors using Fukui function analysis determine the specific reactive sites involved in adsorption, offering detailed insight into donor–acceptor interactions at the metal interface [31, 32].

Carboxyl (–COOH) groups are involved in metal ion binding and enhance the ability of compounds to absorb onto metal surfaces, which is particularly significant in corrosion

inhibition process. Aromatic rings, characterized by conjugated π-electron systems, rise molecular stability and facilitate interactions with microbial cell membranes and proteins, thereby improving antimicrobial activity. These rings also support electron delocalization, which further strengthens antioxidant potential. Corrosion inhibition efficiency is strongly governed by molecular architecture rather than occurring efficiency is strongly governed by molecular architecture rather than occurring arbitrarily, and future research should focus on the systematic isolation and evaluation of individual phytochemicals to develop reliable structure activity relationship (SAR) models for predicting anti-corrosive behavior [27].

3. Extraction and Characterization Techniques

3.1. Extraction Methods

The process of extracting bioactive compounds is crucial, as it substantially affects the yield and quality of the ultimate product. Extraction methodologies have evolved from traditional practices to more sophisticates and environmentally conscious techniques, primarily motivated by the desire for enhanced efficiency and diminished ecological consequences (Table 2).

Conventional techniques, including Soxhlet extraction and maceration have historically been employed extensively, owing to their straightforwardness and dependability. Soxhlet extraction facilitates continuous solvent recycling, thereby enabling the thorough extraction of desired compounds; maceration conversely, entails the extended immersion of the sample in an appropriate solvent. These methods, on the other hand, often take a long time to extract, use a lot of solvents, can break down thermolabile compounds. These drawbacks make them useful for modern applications that value efficiency and sustainability [33, 34].

In contrast, green extraction techniques have emerged as promising alternatives that address many of these drawbacks. Ultrasound-assisted extraction (UAE), for instance, utilizes acoustic cavitation to enhance the extraction process. The implosion of microbubbles formed during sonication compromises plant cell walls, thereby promoting superior solvent infiltration and enhancing the liberation of intracellular constituents. As a result, UAE significantly reduces extraction time and solvent usage while improving overall efficiency [34, 35].

Microwave-assisted extraction (MAE) is another advanced technique that has gained considerable attention. It operated by using microwave energy to heat both the solvent and the plant matrix rapidly and uniformly. This internal heating enhances mass transfer, leading to improved extraction yields in a much shorter time compared to conventional methods.

Furthermore, MAE is known for its lower energy requirements and reduced solvent consumption, thus providing an environmentally favourable option [33, 36].

Supercritical fluid extraction (SFE) is another method of extraction used due to its advantages of high efficiency and selectivity. Carbon dioxide (CO2) is usually used in the supercritical state where it allows rapid penetration into matrix like a gas but can dissolve materials like a liquid. It is considered a gentler method of extracting bioactive compounds that may be sensitive to heat or toxic organic solvents. Moreover, the ease of solvent removal and minimal residue make SFE particularly attractive for applications in food and pharmaceutical fields [34, 37].

Table 2. Extraction Techniques for Bioactive Compounds from Medicinal Plants

Extraction Method	***Principle***	***Advantages***	***Limitations***	***Reported Applications (Plant systems)***	***References***
Soxhlet extraction	*Continuous solvent reflux extraction*	*High yield, simple setup*	*Time-consuming, solvent-intensive*	*Traditional phytochemical extraction*	*[33]*
Maceration	*Passive diffusion in solvent*	*Simple, low cost*	*Low efficiency, long duration*	*Crude extract preparation*	*[33]*
Ultrasound-assisted extraction (UAE)	*Acoustic cavitation enhances mass transfer*	*Faster extraction, low temperature*	*Equipment cost*	*Flavonoids, phenolics extraction*	*[34, 35]*
Microwave-assisted extraction (MAE)	*Dielectric heating of plant matrix*	*Rapid extraction, high yield*	*Thermal degradation risk*	*Polyphenols, antioxidants*	*[36]*
Supercritical fluid extraction (SFE-CO_2)	*Supercritical CO_2 solvation*	*Solvent-free, selective*	*High operational cost*	*Lipophilic bioactives*	*[37]*

3.2. Characterisation Techniques

The characterisation of multifunctional bioactive compounds from medicinal plants in a critical step for the understanding of their chemical composition, biological properties, and potential applications in pharmaceuticals and healthcare. Among these, UV-Vis spectroscopy, FTIR, GC-MS/LC-MS, and NMR spectroscopy are the most commonly used and complementary techniques (Table 3).

Table 3. Characterization Techniques for Bioactive Compounds

Technique	***Principle***	***Information Obtained***	***Application in Studies***	***References***
UV–Vis spectroscopy	*Light absorption transitions*	*Functional group presence, conjugation*	*Antioxidant profiling*	*[38]*
FTIR spectroscopy	*Molecular vibration analysis*	*Functional group identification*	*Phenolics, flavonoids confirmation*	*[39, 40]*
GC–MS	*Volatile compound separation + mass analysis*	*Compound identification*	*Essential oils, volatile phytochemicals*	*[39]*
LC–MS	*Liquid-phase compound profiling*	*Non-volatile bioactives*	*Polyphenols, glycosides*	*[40]*
NMR spectroscopy	*Magnetic resonance of nuclei*	*Structural elucidation*	*Complete molecular structure*	*[38]*

3.2.1 UV-Vis Spectroscopy

UV-Visible (UV-Vis) spectroscopy is commonly employed as an initial screening tool for the analysis of plant extracts. It is based on the absorption of light in the ultraviolet and visible regions by chromophores present in bioactive compounds. Compounds like phenolics and

flavonoids display distinct absorption peaks, a consequence of π–π* and n–π* electronic transitions. This methodology is especially valuable for assessing total phenolic content (TPC) and total flavonoid content (TFC), both of which correlate directly with antioxidant activity. Furthermore, UV-Vis spectroscopy facilitates the swift monitoring of extract composition and enables comparisons across diverse samples. While it does not furnish detailed structural data, it functions as a crucial preliminary technique for the qualitative analysis of phytochemicals [38, 41].

3.2.2 FTIR

Fourier Transform Infrared (FTIR) spectroscopy is extensively employed to ascertain the functional groups present within bioactive compounds. It operates by measuring the absorption of infrared radiation by molecular vibrations, which correspond to specific chemical bonds. FTIR spectra provide characteristic peaks that can be assigned to functional groups such as hydroxyl (O-H), carbonyl (C=O), alkane (C-H), and amine (N-H) groups. This makes it as effective tool for confirming the presence of various classes of phytochemicals, including alcohols, acids, proteins, and polysaccharides. FTIR is also valuable for fingerprinting plant extracts and detecting interactions between different components in complex mixtures. Due to its non-destructive nature and minimal sample preparation, it is frequently used in phytochemical characterisation studies [39, 40].

3.2.3 GC-MS / LC-MS

Gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are advanced hyphenated techniques that play a central role in the detailed analysis of bioactive compounds [42]. GC-MS is particularly suitable for volatile and thermally stable compounds such as essential oils, fatty acids, and small organic molecules. This technique separates compounds based on their volatility and interactions with the stationary phase, followed by mass spectral analysis to facilitate identification. On the other hand, LC-MS is more suitable for non-volatile, polar, and thermolabile compounds such as alkaloids, flavonoids and glycosides. It combines high-resolution separation with sensitive mass detection, enabling the identification of compounds even at low concentrations. Both methodologies furnish molecular weight data and fragmentation patterns, which are critical for compound identification and structural elucidation. These techniques are widely employed in metabolite profiling, biomarker discovery, and quality control of herbal formulations [23, 39].

3.2.4 NMR

Nuclear Magnetic Resonance (NMR) spectroscopy is one of the most powerful ways to figure out the structure of bioactive molecules. It works by monitoring how atomic nuclei interact with each other. For example, ^{1}H NMR, ^{13}C NMR, and two-dimensional NMR are often used to figure out the structures of complicated molecules. NMR is different from other methods because it can give a complete structural framework without needing a lot of derivatizations. It is especially useful for confirming the identity of isolated compounds and for studying stereochemistry and molecular interactions [38, 43].

4. Antioxidant Properties of Plant-Derived Bioactive Compounds

The antioxidant properties of properties of plant-derived bioactive compounds are mainly attributed to how easily they can donate electrons and stabilise reactive molecules. Compounds that contain multiple -OH groups are generally more efficient since these functional groups help neutralise unstable species and distribute the extra electron across the molecule through resonance. This stability is further enhanced by the presence of conjugated double bonds, making such compounds, efficient antioxidants [44, 45]. These materials possess low redox potential, which enables them to act as efficient reducing agents. This help in maintaining redox balance by neutralising reactive intermediates with phenolic compounds. These bioactive compounds also exhibit synergistic effects, where combinations of different compounds present in plant extracts produce greater antioxidant activity than individual constituents [45, 46]. Furthermore, their physicochemical versatility allows them to function in both hydrophilic and lipophilic environments, enabling protection across different biological systems including aqueous cellular components and lipid membranes [47].

4.1. Mechanisms of Antioxidant Action

The bioactive compounds derived from plants exhibit antioxidant activity through multiple interconnected mechanisms that are largely governed by their chemical structure, functional groups, and redox properties, the major classes responsible for antioxidant action include phenolic compounds, flavonoids, terpenoids, and alkaloids (Table 4). All of these compounds help lower oxidative stress by reacting with reactive oxygen species (ROS) and reactive nitrogen species (RNS) [48, 49]. These reactive species are made when the body breaks down food and uses enzymes to do so. They are very unstable and can damage biomolecules like lipids, proteins, and nucleic acids [22, 50, 51].

Table 4. Antioxidant Mechanisms of Plant-Derived Bioactive Compounds

Mechanism	***Description***	***Bioactive Compounds Involved***	***Biological Effect***	***References***
Free radical scavenging	*Donation of electrons/H atoms to neutralize radicals*	*Flavonoids, phenolics*	*Reduced oxidative stress*	*[45, 50]*
Metal ion chelation	*Binding Fe^{2+}/Cu^{2+} to prevent ROS formation*	*Polyphenols*	*Inhibits Fenton reaction*	*[46]*
Redox modulation	*Regulation of intracellular oxidative balance*	*Berberine, alkaloids*	*Cellular protection*	*[52]*
Lipid peroxidation inhibition	*Prevention of membrane lipid degradation*	*Phenolics*	*Membrane stability*	*[53]*

The antioxidant activity of the bioactive compounds is mainly attributed to three major mechanisms (Figure 2) - free radical scavenging, metal ion chelation, and modulation of redox potential. The overall protection against the oxidative damage is often enhanced by the synergetic effect of these mechanisms [49].

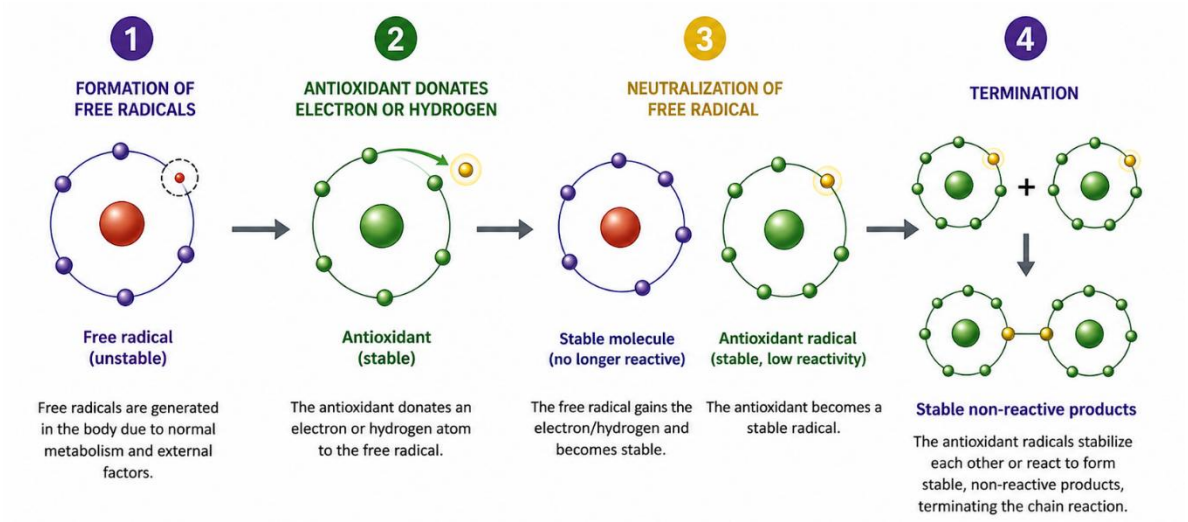


Figure 2. Mechanism of Antioxidant Activity

Free radical scavenging is one of the basic mechanisms by which the plant-based antioxidants neutralise he reactive species. In this mechanism, the phytochemicals such as flavonoids and phenolic compounds convert the reactive radicals into more stable and non-reactive molecules, by acting as the hydrogen or electron donors. This thereby interrupts the oxidative chain reactions. This process is very important for stopping lipid peroxidation the prevention of lipid peroxidation, which is when lipid radicals spread through chain reactions and damage membranes [22, 51].

The structural characteristics potently influence the scavenging capacity of the flavonoids. The electron donation capacity is enhanced substantially due to the presence of the o-dihydroxy (catechol) structure in the B-ring. This makes the molecule more efficient in stabilising radicals. Similarly, the presence of C2-C3 double bond conjugated with a 4-keto group permits electron delocalization across the molecule, thereby stabilising the resultant radical intermediate. Hydroxyl groups at position 3 and 5 also contributes to enhanced antioxidant activity by facilitating electron transfer and hydrogen bonding [49, 54].

These compounds act as chain breaking antioxidants and inhibit the propagation phase of lipid peroxidation. Lipid oxidation is the reaction of lipid radicals with molecular oxygen to form peroxyl radicals which attack other lipid molecules. The phytochemicals terminate this cycle by reacting with the peroxyl radicals. This prevents further oxidative damage. Their radical scavenging ability is often quantified using model systems such as DPPH assay, where a decrease in absorbance reflects the compound's ability to neutralise stable radicals [22, 55].

Metal ion chelation is another important mechanism underlying the antioxidant properties of plant-derived compounds. Transition metals such as iron and copper catalyse the formation of highly reactive hydroxyl radicals via Fenton and Haber-Weiss reactions. These radicals are among the most damaging reactive species due to their high reactivity and ability to initiate lipid peroxidation [49-51, 56].

Flavonoids possess specific structural features that enable them to chelate metal ions effectively. The primary chelation sites include the o-dihydroxy groups in the B-ring and the combination of a 4-keto group with hydroxyl groups at third or fifth position in the C-ring. Upon binding to metal ions, flavonoids form stable complexes that prevent the metals from participating in radical-generating reactions [48, 56].

The chelation mechanism not only reduces the formation of reactive species but also stabilises the antioxidant molecule itself. The catalytic activity of metal ions is suppressed by forming metal-flavonoid complexes, thereby inhibiting oxidative processes such as lipid peroxidation and protein oxidation. The metal chelation also contributes to regeneration and stabilisation of antioxidant species, enhancing their persistence and effectiveness in biological systems [49, 56].

Alkaloids such as berberine also exhibit metal-binding properties, contributing to their antioxidant activity. Further, to chelation, berberine inhibits lipid peroxidation and reduced oxidative stress markers such as malondialdehyde. It also suppresses oxidative enzymes including lipoxygenase and xanthine oxidase, additionally reducing ROS generation [52, 57, 58].

The antioxidant activity of plant-derived bioactive compounds is closely associated with their redox potential. The mechanism of antioxidant activity based on redox potential explains how bioactive compounds neutralize reactive species by transferring electrons. Redox potential (E°) is a thermodynamic parameter that shows how likely a molecule is to gain or lose electrons. Antioxidant naturally possess relatively low redox potentials, enabling them to act as electron donors (reducing agents) and thereby neutralize the ROS and free radicals formed during metabolic processes or environmental stress [59].

Reactive species such as superoxide anion ($O_2^{\bullet -}$), hydroxyl radical (•OH), and peroxyl radical (ROO•) are very unstable because they have unpaired electrons [60]. Antioxidants reduce their reactivity by giving away an electron or hydrogen atom, which turns these radicals into more stable, non-reactive species. The redox potential difference between the antioxidant and the

radical species determines how easily the electron is transferred. A compound with a lower redox potential can effectively reduce radicals with higher redox potentials, thus stopping oxidative reactions [61, 62].

Phenolic compounds are among the most effective plant derived antioxidants operating through this mechanism. Their antioxidant activity is largely attributed to hydroxyl groups attached to aromatic rings, which allows the donation of hydrogen atoms. Upon donating an electron, the phenolic compounds form phenoxyl radicals which are stabilised through resonance delocalisation across the aromatic system. As a result of this stabilisation, the reactivity is reduced and thereby prevents further propagation of radical chain reactions. The redox potential strongly effects the phenolics' antioxidant efficiency, with lower values corresponding to higher antioxidant capacity [61].

The redox mechanism plays a crucial role in inhibiting lipid peroxidation, which proceeds via chain reactions. During propagation, lipid peroxyl radicals continue the chain reaction by attacking adjacent lipid molecules. Antioxidants with suitable redox potentials donate electrons to these peroxyl radicals, converting them into stable lipid hydroperoxides and thereby terminating the chain reaction. This preserves membrane integrity and prevents cellular damage [53].

In biological systems, redox-based antioxidant activity contributes to maintain cellular redox homeostasis. Endogenous antioxidants like glutathione (GSH) function through redox cycling, where GSH donates electrons to neutralise reactive species and is oxidised to glutathione disulphide. Enzymatic systems subsequently regenerate GSH, facilitating continuous protection against oxidative stress. Plant-based antioxidants can complement these endogenous systems by participating in similar electron transfer reactions and enhancing overall antioxidant defence [63].

4.2. Common Assays

The ability of a bioactive compound to neutralise ROS and inhibit oxidative damage is assessed by applying various antioxidant assays. On the basis of their reaction mechanisms, these assays are classified into electron transfer (ET) and hydrogen atom transfer (HAT) methods. The ET based assays determine the reducing ability of the antioxidants. On the other hand, the HAT based assays assess their radical quenching capacity through hydrogen donation [64, 65]. DDPH, ABTS and FRAP assays along with the lipid peroxidation inhibition assay are the most commonly used assays which provide biologically relevant insights. Further, multiple assays

are combined for more accurate evaluation of the antioxidant potential [22, 45, 49, 55, 59, 66] (Table 5).

The most widely used method for the evaluation of antioxidant capacity is the 2,2-Diphenyl-1-picrylhydrazyl (DPPH) assay. It follows the ET mechanism and is rapid and simple [65]. In this reaction, the stable DPPH radical (DPPH•) (strong absorbance at 515 nm) is reduced due to the donation of an electron from the antioxidant (AH). During this reaction, the deep violet color of the DPPH• undergoes discoloration.

$$DPPH\bullet + AH \rightarrow DPPH - H + A\bullet$$

Table 5. Antioxidant Assays Used for Plant Bioactives

Assay	***Principle***	***Measured Parameter***	***Applications***	***References***
DPPH assay	*Radical scavenging of DPPH•*	*% inhibition / IC_{50}*	*Plant extract screening*	*[55]*
ABTS assay	*Radical cation decolorization*	*Trolox equivalent antioxidant capacity*	*Food & plant extracts*	*[66]*
FRAP assay	*Reduction of Fe^{3+} to Fe^{2+}*	*Antioxidant power*	*Phenolic-rich extracts*	*[59]*
ORAC assay	*Oxygen radical absorbance*	*Radical quenching capacity*	*Nutritional antioxidants*	*[65]*

The degree of discoloration is proportional to the antioxidant capacity. This method is particularly useful for assessing phenolic compounds, which possess strong electron-donating ability due to hydroxyl groups [55].

The 2,2-Azinobis-3-ethylbenzthiazoline-6-sulfonic acid (ABTS) assay is very good at measuring antioxidant capacity in complex systems. It does this by reducing the ABTS radical cation (ABTS•$^{+}$), which is made by oxidizing potassium persulfate. The radical cation has a blue-green color and absorbs light at 734 nm. Antioxidants reduce ABTS•$^{+}$ to its non-radical form.

$$ABTS\bullet^{+} + AH \rightarrow ABTS + A\bullet + H^{+}$$

The ABTS methods follows both HAT and ET mechanisms [64]. Another important feature of the ABTS assay is its applicability across a wide range of pH. Because the ABTS radical cation is stable in different buffer systems, it can be used in a wide range of experimental settings. By using solvent partitioning technique or modifying reaction media, this method has been adapted to evaluate both lipophilic and hydrophilic antioxidants as they soluble in both water and organic solvents [45, 67-69].

Ferric ion reducing antioxidant power (FRAP) assay was developed by Iris F. F. Benzie and J. J. Strain, and are widely used for the evaluation of reducing ability of the antioxidants based on their ability to participate in ET reactions. This assay measures the ability of the antioxidant compounds to reduce ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}) at lower pH ranges, thereby reflecting their redox potential [22, 59].

In this method, the ferric tripyridyltriazine complex (Fe^{3+}-TPTZ) get reduced to a ferrous form (Fe^{2+}-TPTZ) in the presence of an antioxidant. And the resultant complex develops an intense blue color (maximum absorbance at 593 nm) [59, 70, 71].

$$Fe^{3+} + AH \rightarrow Fe^{2+} + A\bullet + H^{+}$$

The reducing power of the antioxidant is directly proportional to the increase in absorbance at 593 nm. This is typically measured spectrophotometrically, and its results are often expressed in terms of Fe^{2+} equivalents or compared with standard antioxidants such as Trolox [59].

Lipid peroxidation inhibition assays provide a biologically relevant evaluation of antioxidant activity by measuring the ability of compounds to prevent oxidative degradation of lipids. Lipid peroxidation functions through free radical mechanism [53].

Initiation:

$$LH + \bullet OH \rightarrow L\bullet + H_2O$$

Propagation:

$$L\bullet + O_2 \rightarrow LOO\bullet$$

$$LOO\bullet + LH \rightarrow LOOH + L\bullet$$

Termination:

$$LOO\bullet + AH \rightarrow LOOH + A\bullet$$

During propagation, lipid peroxyl radicals (LOO•) attacks the neighbouring lipid molecules, and thereby spreads the oxidative damage. The antioxidants disrupt this chain reaction by donating hydrogen atoms or electrons, and thus stabilising radicals and forming lipid hydroperoxides (LOOH) [53]. The extend of lipid peroxidation is commonly assessed by measuring malondialdegyde (MDA) using thiobarbituric acid reactive substances (TBARS) assays, where reduced MDA formation indicates effective antioxidant activity. Lipid peroxidation and its inhibition are widely recognised as critical indicators of oxidative stress and antioxidant defence in biological systems [45, 53, 72].

4.3. Examples from Medicinal Plants

Medicinal plants are known to be effective natural antioxidants that neutralize reactive oxygen species and minimize oxidative stress. There are reports that have quantified free radical scavenging, lipid peroxidation inhibitory activities, and metal-chelating potentials of plant extracts using standard antioxidant assays. Few select case studies demonstrating antioxidant efficacies of medicinal plants are presented below.

Strong antioxidant activity of dry extract of *Zingiber officinale* was found in several in vitro assays by Ivanka Stoilova et al. (2007). The extract contained 70.1 mg/g total phenolics and exhibited 90.1% DPPH radical scavenging activity with an IC_{50} value of 0.64 μg/mL, exceeding the activity of butylated hydroxytoluene (BHT). It also inhibited TBARS formation by 73.2% and hydroxyl radicals by 79.6% at 37 °C, long with significant Fe^{3+} chelating ability, demonstrating its potential as a natural antioxidant source [73].

Chatepa et al. (2024) evaluated the antioxidant activity of leaf extract of *Azadirachta indica* and *Vernonia amygdalina* using different solvents. Methanolic and aqueous extracts showed higher antioxidant capacity than chloroform and ethyl acetate extracts. The methanolic extract of *Azadirachta indica* and aqueous extracts showed 92.422 mg AAE/g. This study also showed high phenolic contents in aqueous and methanolic extracts suggesting polar solvents were better at extracting antioxidant compounds from medicinal plants [74].

Arulselvan Kandasamy et al. (2023) investigated the phytochemical composition and antioxidant activity of *Centella asiatica* extracts obtained from shoot, callus, and cell suspension cultures. Phytochemical screening confirmed the presence of tannins, flavonoids, terpenoids, saponins, and steroids. The callus extract exhibited the highest antioxidant activity with IC_{50} value of 10 µg/mL followed by shoot culture (19 µg/mL) and cell suspension culture (20 µg/mL) than ascorbic acid (26.25 µg/mL).Ultrasonic-assisted extraction showed the highest antioxidant recovery with 79% scavenging activity, highlighting the strong antioxidant potential of *Centella asiatica* extracts [75].

The antioxidant activity of different solvent extracts of *Bergenia ciliata, Achillea millefolium*, and *Aloe vera* was assessed by Ahsan Mehmood et al. (2022) by employing the DPPH assay. The antioxidant activity increased with the concentration of extract, with methanolic extracts showing the highest activity among all solvents. Of all the solvents, the methanolic extracts exhibited the highest activity. The methanolic extracts showed IC_{50} values of 72.33 µg/mL for *A. millefolium*, 60.27 µg/mL for *B. ciliata* and 77.89 µg/mL for *A. vera*, whereas ascorbic acid showed an IC_{50} value of 35.66 µg/mL. The methanolic extract of *B. ciliate* showed the best antioxidant activity among the tested plants, which was attributed to higher total phenolic contents and the presence of polar bioactive compounds [76].

5. Antimicrobial Activity

5.1. Mechanism of action

Numerous bioactive constituents isolated from medicinal plants demonstrate strong antibacterial properties. For example, naturally occurring alkaloids such as berberine (from *Berberis* species) and sanguinarine (found in members of the *Papaveraceae* family) have been reported to exhibit considerable inhibitory activity against a wide range of bacterial pathogens [23, 77, 78]. Flavonoids such as kaempferol and quercetin, present in plants like Allium cepa and Camellia sinensis, have been shown to possess notable antibacterial properties. They exert their effects by damaging bacterial cell membranes and interfering with the activity of key enzymes essential for microbial survival [79, 80].

The antimicrobial actions of bioactive compounds derived from medicinal plants occur through diverse mechanisms. Some compounds compromise the integrity of microbial cell membranes, resulting in cell rupture and eventual death. Others act by suppressing key enzymes required for microbial metabolism and proliferation. In addition, certain phytochemicals can influence the host immune system, strengthening its ability to combat infections [81, 82]. This interaction

disturbs membrane integrity, increases permeability, and causes leakage of vital intracellular constituents such as ions proteins and nucleotides. In some cases, this leads to complete cell lysis. Compounds like carvacrol, obtained from oregano, and thymol, derived from thyme, can disrupt the lipid bilayer of bacterial cell membranes, weakening their structural stability and overall integrity [83-85]. Essential oils and terpenoids are particularly effective in this regard, as they can penetrate lipid layers and destabilize membrane structure, ultimately impairing cellular homeostasis.

A microbial infection develops when a microorganism invades hot tissues, damage cells, and leads to disease or even death. This occurs as the pathogen evades the host's defense mechanisms, releases harmful substances such as toxins into the bloodstream to promote further spread, and produces various clinical symptoms. The skin and mucosal surfaces harbor diverse microorganisms that form part of the body's normal flora. These beneficial microbes help protect the host by competing with pathogens for attachment sites and nutrients, and by producing antimicrobial substances that inhibit harmful bacteria. Infectious diseases can spread through various routes, including direct person to person contact, respiratory transmission, interaction with mucous membranes, entry into the bloodstream, inset vectors, and exposure to contaminated surfaces or object [84, 86]. Phytochemicals can bind to enzymes either reversibly or irreversibly, affecting their catalytic activity. This may occur through interactions with functional groups such as hydroxy or carbonyl groups present in bioactive molecules. Tannins are known to precipitate proteins, while flavonoids can inhibit enzymes involved in nucleic acid synthesis and electron transport chains.

Certain bioactive compounds are capable of intercalating between DNA base pairs or binding to nucleic acids, thereby obstructing replication and transcription processes. This prevents microbial growth and reproduction. Alkaloids and some phenolic compounds have shown the ability to inhibit DNA gyrase and topoisomerase enzymes, which are essential for DNA replication and repair. Bioactive compounds obtained from medicinal plants display significant antimicrobial potential, highlighting their promise as candidates for the development of new therapeutic agents. These natural molecules exhibit a broad range of activities, including antibacterial, antifungal, and antiviral effects. Their modes of action typically involve damaging microbial cell membranes, inhibiting crucial enzymatic functions, and enhancing host immune responses. Continued investigation of these compounds may support the discovery and advancement of effective strategies to combat microbial infections [23].

5.2. Spectrum of Activity

Infectious diseases account 15% of the nearly 57 million deaths reported worldwide each year, producing them an important global health concern in the 21st century [87]. Infectious diseases endure a leading cause of mortality and illness, contributing to nearly 2.2 million deaths among school-aged children and adolescents in 2019. This burden is especially significant in low-and middle-income countries [88]. Human infections are caused by a wide range of microorganisms, including bacteria, fungi, parasites, and viruses. In developing regions, microbial infections responsible for conditions such as diarrhoea, vomiting, respiratory illness, urinary tract infections, and hospital acquired infections continue to be highly prevalent [84, 87]. People with weakened immune systems are highly vulnerable to infections in which normally harmless commensal microorganisms become pathogenic. Usual causative agents include fungus (*Candida albicans)*, Gram-positive bacteria (*Enterococcus faecalis, Staphylococcus aureus)* and Gram-negative bacteria *(Escherichia coli, Pseudomonas aeruginosa)* (Figure 3). Beyond their role in causing infections, *E. coli and S. aureus* are particularly concerning in developing countries because of their potential capacity to develop resistance to antimicrobial drugs [84, 87, 88].

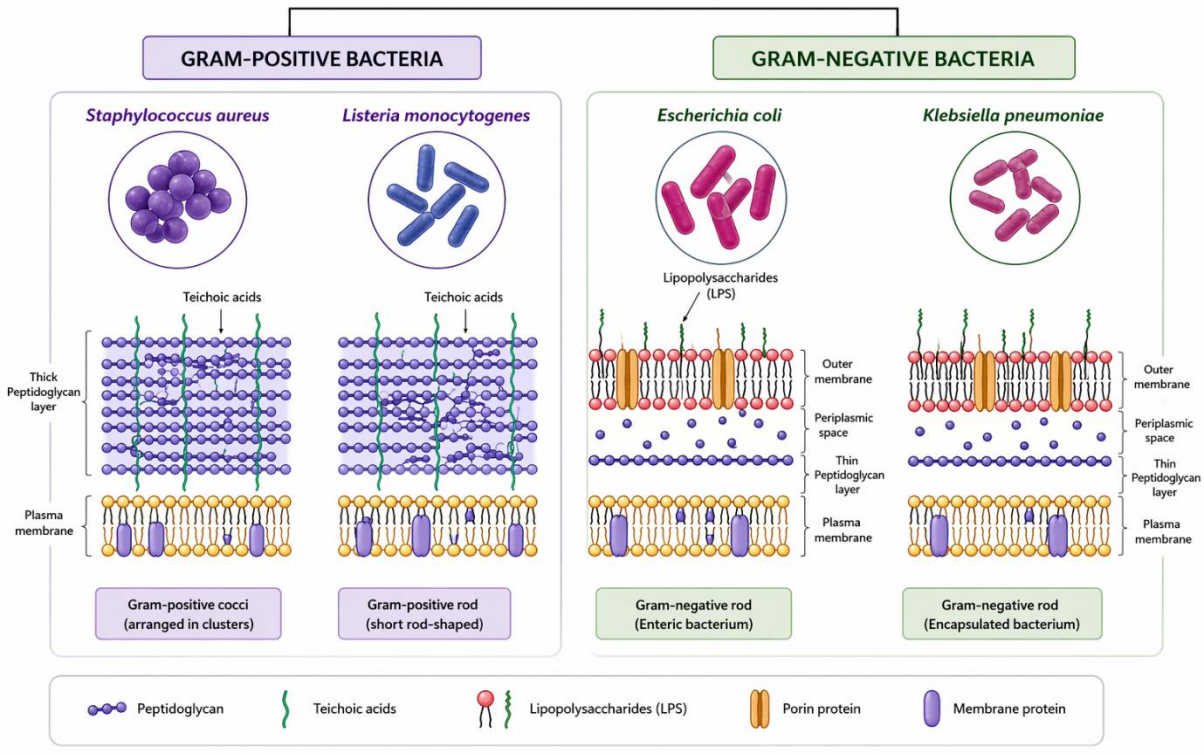


Figure 3. Comparison of Gram-positive and Gram-negative bacteria.

5.2.1. *S. aureus*

Staphylococcus aureus is a Gram-positive, non-motile bacterium that does not form spores, with cell sizes normally ranging between 0.5 and 1.5 μm [89]. it is a normal inhabitant of the human microbiota, particularly found in the anterior nasal passages, but can cause infections when the host's immune defenses are weakened[89]. Around 30% of people are persistent carriers of this organism. The bacterium also possesses a robust, somewhat irregular protective layer on its cell wall, with a thickness of approximately 20-40 nm [90]. Peptidoglycan makes up nearly 50% of the *Staphylococcus c*ell mass and plays a vital role in building its thick, multilayered cell wall while also maintaining the bacterium's high internal osmotic pressure [91, 92].

Staphylococcus aureus initiates infection by penetrating damaged skin or mucosal barriers and can spread locally or through the bloodstream to distant organs, resulting in serious and potentially life-threatening conditions such as septicemia, pneumonia, systemic infections, joint infections, and osteomyelitis [93]. It can also cause toxin-related illness when consumed in contaminated food, leading to conditions like food poisoning and toxic shock syndrome [94, 95]. In some cases, transmission may occur through contact with bodily secretions, like saliva or respiratory droplets released by coughing or sneezing. Additionally, this bacterium can be found in unpasteurized milk and various animal derivatives [96].

Studies have demonstrated that staphylococci species can develop resistance to several antibiotics, including erythromycin, ampicillin, tetracycline, methicillin, and vancomycin. Resistance to vancomycin is associated with the presence of the van gene, which is thought to arise through gene transfer between staphylococcus aureus and vancomycin-resistant enterococci. The sudden worldwide spread of methicillin-resistant vancomycin-resistant *S. aureus* strains has made effective control increasingly difficult, raising concerns about a potential return to conditions similar to the pre-antibiotic era [97]. In areas where methicillin resistance remains low, treatments like penicillin, β-lactam antibiotics, cephalosporins, and clindamycin is still effective [98]. However, the growing prevalence of resistant strains, notably MRSA, has led to a significant increase in the use of non β-lactam antibiotics for managing *S. aureus* infections [84, 99].

5.2.2. *L. monocytogenes*

Listeria monocytogenes is a Gram-positive bacterium responsible for causing listeriosis and is commonly found in moist environments such as soil, water, and decaying plant or animal

matter [100]. It has capability to endure and grow even under refrigeration and standard food preservation conditions. Infection normally occurs through the consumption of contaminated food, often due to improper food processing practises [100]. The duration of symptoms can range from a few days to several weeks, depending on the severity of the infection. Mild symptoms are fever, muscle aches, nausea, vomiting, and diarrhea, whereas severe cases my present with headache, neck stiffness, confusion, loss of balance, and seizures [100]. Listeriosis constitute a severe risk and can be fatal, particularly in newborns, elderly individuals, and those with weakened immune systems [84, 100, 101].

5.2.3. *E. coli*

Escherichia coli is a Gram-negative, rod shaped, facultatively anaerobic coliform bacterium normally present in the lower gastrointestinal tract of warm-blooded animals [102]. Most strains of *E. coli* persist as normal inhabitants of the intestinal microbiota in both humans and animals. Studies have also shown that colonization of the neonatal gut by *E. coli* begins shortly after birth [103]. Pathogenic strains of *E. coli* are divided into two groups: those that cause intestinal diseases and those that direct to extraintestinal infections, including conditions are sepsis and urinary tract infections [104].

Escherichia coli comprises a wide range of pathogenic genotypes that are classified into distinct pathotypes according to their disease-causing potential. Enterotoxigenic *E. coli* is frequently associated with diarrheal illness in neonates in developing regions and is also known to cause secretory diarrhea in animals [105]. Enteropathogenic *E. coli* includes serotypes such as O55:H6 and O127:H6, while atypical variants are more generally linked to diarrhea in developed countries. Many of these infections arise due to fecal contamination [106]. In contrast, enterohemorrhagic *E. coli* is commonly responsible for foodborne illness, often transmitted through the consumption pf contaminated milk or undercooked animal products, mainly meat [106]. These strains produce Shiga like toxins, primarily classified as stx1 and stx2 [107]. Entero-invasive *E. coli* shares several biochemical, genetic, and pathogenic similarities with shigella species and is implicated in various human infections [107]. It directs to conditions such as colitis and watery diarrhea, which differ in presentation from diseases caused by other *E. coli* pathotypes [107].

5.2.4. *K. pneumoniae*

Klebsiella pneumoniae is a Gram-negative bacterium commonly found on human skin, lips, and in the intestinal tract, and it is frequently linked to hospital acquired infections. Individuals with underlying conditions such as cancer, diabetes, liver or biliary disorders, and chronic alcohol use are more susceptible to infections due to weakened immune defenses [108]. This organism is capable of causing a range of illness, including pneumonia, urinary tract infections, skin disorders, and infections of open wounds [108].

Treatment of *Klebsiella* infections often involves the use of cephalosporins, either alone or merged with aminoglycosides [109]. However, the widespread use of strong antibiotics has contributed to the development of resistant strains, specifically those producing extended-spectrum β-lactamases (ESBLs) [110]. Although carbapenems are generally effective against ESBL-producing bacteria, some strains have acquired enzymes known as *K. pneumoniae* carbapenems, which can inactivate these drugs and have spread worldwide[111, 112]. The rise of ESBL- producing organisms remains an important concern due to limited progress in developing new antimicrobial agents. The resistant bacteria increasingly show reduced susceptibility to multiple antibiotic classes, including fluoroquinolones, aminoglycosides, tetracyclines, trimethoprim-sulfamethoxazole, and chloramphenicol [84, 113].

5.2.5. *C. albicans*

Selecting suitable therapies for fungal infections without causing harm to the host remains a major challenge. This difficulty arises because fungal cells share many structural and physiological similarities with human cells, limiting the availability of safe and effective antifungal drugs compared to antibacterial treatments [114]. In recent years, mycoses have surfaced as an vital medical concern, largely due to the rising number of individuals with weakened immune systems, including those undergoing immunosuppressive therapy or suffering from immunodeficiency [115].

Candida species are normally unicellular yeasts that live in a symbiotic relationship with the human host [116]. They are commonly found on the skin, in the gastrointestinal tract, the reproductive system, and on oral mucosal surfaces. *Candida albicans* is a capable of existing in two distinct morphological forms: a budding yeast form and a filamentous form that creates into elongated structures known as pseudomycelia [116]. This morphological flexibility plays a key role in infection, as the hyphal form can invade and spread within host tissues, while yeast cells facilitate dissemination to different body sites [116].

As a commercial organism belonging to the *Candida, C. albicans* is frequently present in areas such as the mouth, skin, digestive tract, and the vaginal canal in females [117]. It typically shows oval to spherical yeast cells, with dimensions ranging from approximately 3-5 μm in width and 5-10 μm in length [118].

Conditions such as HIV infection and diabetes mellitus are commonly associated with *Candida* infections. This yeast widely recognized as a major cause of vulvovaginal and oropharyngeal candidiasis. Infections caused by *Candida* include oral candidiasis is considered an opportunistic infection of the mouth and is particularly common among elderly individuals, especially those who wear dentures [119]. It frequently occurs in immunocompromised patients and may also serve as an indicator of underlying systemic conditions, including diabetes [120].

Compared to bacterial and viral diseases, the number of available antifungal drugs for treating *Candida* infections is relatively limited, and resistance to therapy is increasingly observed [121]. Resistance of *Candida albicans* to azole antifungal agents was first documented in the late 1980s. since the 1990s, Fluconazole has been widely used as a primary treatment for both superficial and systemic fungal infections [121]. However, despite its early success, the emergence of drug-resistant strains has become a crucial concern, specifically among individuals living with HIV [84, 122].

7.2.6 *Candida tropicalis*

Candida tropicalis is a distinct species from Candida albicans and belongs to the group of non *albicans Candida* (NCAC), which are greatly implicated in oral infections [123]. The growing occurrence of hospital-acquired infections caused by NCAC species is connected to various medical conditions and procedures, like cancer therapy, surgical device implantation, HIV/AIDS, and expensive antibiotic usage [123, 124]. Among NCAC species, *C. tropicalis* is considered highly pathogenic due to its capability to adhere to host tissues and secrete protein-degrading enzymes, facilitating invasion of epithelial cells [125]. This organism generally resides on the skin and within the oral cavity and has been allied with infections of the esophagus as well as nosocomial infections [125].

Candida species are capable of forming biofilms on medical devices, which improves their resistance to antifungal treatments [126]. The global incidence of infection caused by *C. tropicalis* is increasing, highlighting its role as an emerging pathogenic yeast. However, the reasons behind its predominance over other NCAC species and its resistance to fluconazole are still not clearly understood [84, 127].

5.3. Synergistic Effects

Herbal medicines often show synergistic interactions when merged with antibiotics, thereby improving their efficacy against multidrug resistant (MDR) pathogens [85, 128]. Phytochemicals can weaken microbial defense mechanisms, making pathogens more susceptible to antimicrobial agents. The combined effects of methanolic extracts from your Algerian medicinal plants are garlic, red onion, cumin, and fenugreek along with various lactic acid bacteria strains against *Helicobacter pylori* [128]. Furthermore, the in vivo antibacterial potential of fenugreek extract combined with *Bifidobacterium breve* was evaluated to confirm its synergistic effect on *H. pylori* colonization [128]. All tested combinations of plant extracts and probiotics showed inhibitory activity against *H. pylori*, although the extent of inhibition varied [128].

Similarly, the synergistic antibacterial effects of ethanolic extracts from *Punica granatum* (pericarp), *Commiphora molmol, and Azadirachta indica* (bark) when applied alongside standard antibiotics such as amoxicillin, metronidazole, tetracycline, and azithromycin against key periodontopathic bacteria, like *Porphyromonas gingivalis*, *Tannerella forsythia, Treponema denticola, and Aggregatibacter actinomycetemcomitans* [129]. Enhanced antibacterial activity was monitored with these combinations, with the powerful synergy reported between *P. granatum* extract and amoxicillin against *A. actinomycetemcomitans* [129]. In another study found that combining *Allium sativum* (garlic) extract with amoxicillin importantly reduced the lowest inhibitory concentration (MIC) against MDR *H. pyroli* [130].

The antibacterial activity and lowest bactericidal concentration (MBC) of thymol, EDTA, and vancomycin against both sensitive and resistant bacterial strains [131]. The study also evaluated the synergistic interaction between thymol and EDTA, as well as their combined effects with vancomycin. Thymol demonstrated strong bactericidal activity, with MBC values ranging from 60-4000 µg/mL, while EDTA exhibited primarily bacteriostatic effects at concentrations above this range. Gram-negative showed MIC values between 0.125 and 16 µg/mL, whereas Gram-negative bacteria required higher concentrations, ranging 32 to 128 µg/mL. The interactions between these compounds and pathogens are MRSA and Escherichia coli were further analysed using checkerboard dilution and time kill assays [84, 131].

Synergistic interaction ore also monitored among different phytochemicals present within or across medicinal plants. These compounds can act on multiple microbial targets simultaneously, creating a more potent antimicrobial effect than individual constituents alone.

Such combinations are phenolics, flavonoids, terpenoids, and alkaloids, which collectively contribute to enhanced antimicrobial, antioxidant, and anti-biofilm activities, the multifaceted mechanisms of action minimise the likelihood of resistance development and improve overall therapeutic outcomes. Consequently, exploring phytochemical combinations provides valuable insights for developing effective, natural, and maintainable antimicrobial formulations.

5.4. Evaluation methods

A range of standardized methodologies is employed to assess the efficacy of antimicrobial agents, with dilution and diffusion techniques being the most normally applied approaches. In addition to these conventional methods, advanced techniques like bioautography, time kill assays, ATP bioluminescence analysis, and flow cytometry are also utilized. However, these sophisticated techniques often require specialized instrumentation and detailed statistical analysis, which may restrict their routine application compared to easier, traditional procedures [1].

Among diffusion-based techniques, agar disk diffusion and well diffusion assays are extensively accepted for analysing antimicrobial susceptibility. Despite their usefulness in preliminary screening, these methods do not distinguish between bacterial and bacteriostatic effects [132]. In contrast, dilution methods are used to determine the minimum inhibitory concentration (MIC), defined as the lowest concentration of an antimicrobial agent that prevents visible microbial growth. Furthermore, the minimum bactericidal concentration (MBC) or minimum fungicidal concentration (MFC) represents the lowest concentration capable of eliminating approximately 99% of the microbial population. To enhance the accuracy of growth assessment, various indicator dyes such as resazurin, 2,3,5-triphenyltetrazolium chloride (TTC), and 3-(4,5-dimethylthiazol-3-yl)-2,5-diphenyltetrazolium bromide (MMT) are frequently employed [1].

The antimicrobial potential of the Proteaceae family, including genera are *Grevillea, Hakea, and Protea,* has been widely explored. Members of this family have demonstrated notable antibacterial activity against a range of pathogens. For example, extracts from the fruit of *Macadamia integrifolia* have shown strong inhibitory effects against *Escherichia coli*, with a reported MIC of 5.3 µg/mL [133]. This activity is considerably higher when compared to other species that exhibit MIC values exceeding 100 µg/mL [134], as well as *Embothrium coccineum* leaves (31.125 ± 0.2 µg/mL) [135] and *Darlingia darlingiana* bark (156 µg/mL) [136]. Likewise, stem extracts of *Roupala brasiliensis* have demonstrated significant activity against

Staphylococcus aureus, with an MIC of 15.6 µg/mL [137]. In addition, aerial parts of *Grevillea avellana* have shown effective antibacterial activity against *Pseudomonas aeruginosa*, with an MIC of 64 µg/mL [138].

The choice of extraction solvent plays a pivotal role in determining the antimicrobial efficacy of plant-derived compounds. By way of illustration, *Embothrium coccineum* leaf extracts prepared using different solvents displayed varying MIC values against E. coli, including 250 µg/mL (hexane), 31.125 µg/mL (dichloromethane), 125µg/mL (ethyl acetate), and 250 µg/mL (ethanol) [135]. Additionally, variations in antimicrobial activity have been observed based on the collection site. Such differences emphasize the notable influence of environmental conditions on the bioactive properties of medicinal plants. Understanding these factors is essential for optimizing the improvement and application of plant-based antimicrobial agents [1].

6. Corrosion Inhibition Properties

Corrosion remains one of the serious challenges which causes environmental and safety hazards, and significant economic losses. Conventional corrosion inhibitors rely on phosphates, chromates and amines which are toxic synthetic chemicals. They pose threat to human health and ecological systems. But in recent years, green chemistry approaches became the main focus the studies [27, 139].

Plant extracts have showed its potential as eco-friendly corrosion inhibitors in more recent years [27, 140-142]. They are rich in phytochemicals that can hinder electrochemical corrosion process by absorbing on the metal surfaces, thereby forming protective films [143]. The efficiency of the corrosion inhibitor is directed by their adsorption characteristics. This can sterically hinder active sites or modify the activation energy of the electrochemical processes and thereby influence the kinetics of cathodic and anodic reactions. These natural compounds are renewable, biodegradable, non-toxic and are often readily available as agricultural by-products [27, 144]. Being non-toxic and cheap, the plant phytochemicals are presently employed for the development of several types of materials such as biosynthesised metallic nanoparticles, carbon quantum dots, which can also be employed in the preparation of corrosive protection layers [145-147].

6.1. Fundamentals of Corrosion

Corrosion is fundamentally an electrochemical process which involves simultaneous anodic oxidation, where metal atoms lose electron and dissolve as ions, and cathodic reduction, where these electrons are consumed by species such as oxygen or hydrogen ions. This occurs on a metal surface on exposure to an electrolyte [28, 148]. This coupled reaction reactions occur at multiple sites on the metal surface, creating localised electrochemical cells which leads to gradual deterioration of the material. The factors such as metal composition, surface condition, temperature, pH and the presence of destructive ions like sulfates and chlorides effect the rate and extent of the reaction [27, 149].

Corrosion is a major threat in industries because it makes materials used in pipelines, storage tanks, marine structures, and chemical processing equipment less durable and reliable. It can cause structural failure, leaks of dangerous materials, and higher costs for maintenance and replacement [27, 28]. The economic burden associated with corrosion is substantial, accounting for significant percentage of global industrial expenditure, while also posing environmental safety risks. Thus, implementation of corrosion management system is crucial for cost saving in many sectors [28]. Consequently, understanding corrosion mechanisms is essential for developing effective prevention and control strategies in engineering applications.

6.2. Mechanism of Green Corrosion Inhibition

Green corrosion inhibitors, especially plant based bioactive compounds, inhibit corrosion primarily through adsorption onto metal surfaces, forming a protective barrier that limits the interaction between the metal and corrosive agents (Figure 4). This adsorption may occur via physisorption, involving electrostatic interactions, or chemisorption, which includes the formation of coordinate bonds between the inhibitor molecules and the metal surface [27, 149]. The nature and extent of the adsorption are often expressed using adsorption isotherms like Freundlich, Temkin, etcetera which provide insight into surface coverage and inhibitor efficiency [150].

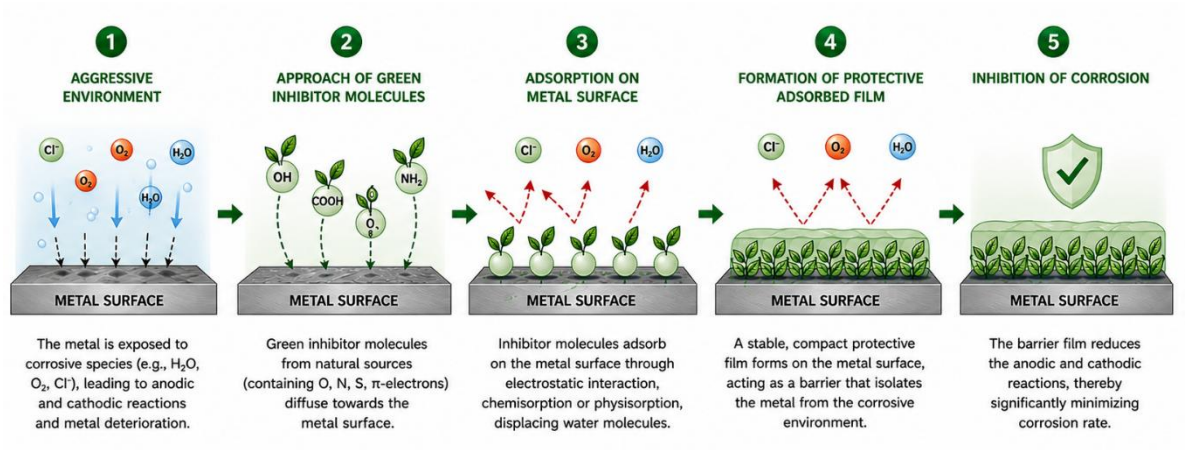


Figure 4. Mechanism of Green Corrosion inhibition

Once adsorbed, inhibitor molecules form a compact and adherent protective film over the metal surface, blocking active anodic and cathodic sites and thus reducing the rate of electrochemical reactions. This decreases metal dissolution and restricts the dilution of corrosive species such as hydrogen ions and chloride ions [151, 152]. In many cases, these inhibitors, are mixed-type inhibitors, that affect both anodic metal dissolution and cathodic reduction reactions at the same time [153].

The effectiveness of green inhibitors is mostly due to the presence of heteroatoms like oxygen, nitrogen, and sulphur, as well as π-electron systems that that help them interact strongly with the metal surface through electron donation mechanisms [140, 153]. Functional groups like –OH, $–NH_2$ and –COOH increase adsorption strength and help the protective film stay stable. Furthermore, synergistic interactions between different phytochemicals in plant extracts further improve inhibition efficiency, making green inhibitors a promising and environmentally friendly way to control corrosion [151, 152].

6.3. Adsorption Isotherms

Adsorption isotherms are commonly used to describe the interaction between corrosion inhibitor molecules and metal surfaces, giving information about the effectiveness of inhibition, the adsorption mechanism, and surface coverage. There are many adsorption isotherms for the interpretation of several research findings [154-156]. Among the various models, Langmuir, Freundlich, and Temkin, isotherms are the most common isotherms used for the evaluation of the adsorption of corrosion inhibitors (Table 6). The function of the fractional surface coverage (θ) is plotted against a function of the concentration of inhibitor (C)

in each case, and the parameter of the adsorption are deduced from the slope or intercept or both [156].

Table 6. Common Adsorption Isotherms in Corrosion Inhibition

Isotherm Model	***Equation Basis***	***Surface Behavior***	***Application in Corrosion***	***References***
Langmuir	*Monolayer adsorption*	*Uniform adsorption sites*	*Most common for plant extracts*	*[154]*
Freundlich	*Heterogeneous surface*	*Multilayer adsorption*	*Organic inhibitor systems*	*[157]*
Temkin	*Adsorbate–adsorbent interaction*	*Linear adsorption heat decrease*	*Metal-inhibitor interaction*	*[158]*

The Langmuir adsorption isotherm is one of the most widely applied models in corrosion inhibition studies, as it assumes that adsorption occurs at specific homogeneous sites on the metal surface, with each site accommodating only one inhibitor molecule, resulting in monolayer coverage. It further assumes that assumes all adsorption sites are energetically equivalent and that there are no lateral interactions between adsorbed species [159, 160].

The isotherm is mathematically expressed in its linear form as

$$\frac{\boldsymbol{C}}{\boldsymbol{\theta}} = \frac{\mathbf{1}}{\boldsymbol{K_{ads}}} + \boldsymbol{C}$$

Where C is the concentration of inhibitor, θ is the degree of surface coverage, and K_{ads} is the adsorption equilibrium constant, which reflects the strength of adsorption. A linear plot of C/ θ versus C with a slope close to unity confirms the applicability of the Langmuir model. The magnitude of K_{ads} can be used to calculate the standard free energy of adsorption, which provides insight into the nature of adsorption. The values ≤ -20 $kJmol^{-1}$ indicate physisorption while values ≥ -40 $kJmol^{-1}$ suggest chemisorption. If the values lie in between these, it is attributed to mixed mechanisms or physiochemisortion [161-169]. In corrosion system, good

adherence to the Langmuir isotherm indicates that inhibitor molecules form a stable and uniform protective monolayer on the metal surface, effectively blocking active corrosion sites and reducing metal dissolution [156].

The Freundlich adsorption is an empirical model that describes adsorption on heterogeneous metal surfaces, where the adsorption sites possess different energies and affinities for inhibitor molecules. Unlike the Langmuir model, it does not assume uniform surface conditions or monolayer coverage. It also allows multilayer adsorption with varying binding strengths [170-172]. The Freundlich isotherm is represented by the following equation [173-175].

$$\boldsymbol{log\theta = logK_{ads} + \frac{1}{n} logC}$$

Where 1/n is the Freundlich isotherm constant, θ represents the degree of surface covering, K_{ads} is the adsorption constant, and C represents the concentration of the inhibitor. A linear correlation between log θ and log C validates the Freundlich model, with the slope (1/n) elucidating the adsorption behaviour, values ranging between 0 and 1 indicate advantageous adsorption and robust interactions between inhibitor molecules and the metal surface [170]. This model is therefore particularly useful in explaining non-uniform adsorption phenomena observed in real corrosion systems, where surface irregularities and multiple adsorption mechanisms coexist [170, 171, 176, 177].

The Temkin adsorption isotherm is frequently used in corrosion inhibition studies to describe the interaction between inhibitor molecules and the metal surface, especially when adsorbate-adsorbate interactions are significant [178]. The Temkin adsorption isotherm proposes that because of interactions between the adsorbent and the adsorbate, the heat of sorption should decrease linearly with sorption coverage on the adsorbent [157, 158, 178-181]. The equation for this model is expressed by the following equation.

$$\boldsymbol{\theta = -\frac{1}{2a} lnC - \frac{1}{2a} lnK}$$

Where a is the molecular interaction parameter, which depending on its sign predicts whether repulsion or attraction occurs in the adsorbed layer [182]; K is the adsorption equilibrium constant, whose value defines how strongly the inhibitor molecules are adsorbed on the metal surface [156].

6.4. Electrochemical Techniques

Electrochemical techniques are widely employed to evaluate corrosion behaviour and the efficiency of corrosion inhibitors, as they provide rapid, quantitative and sensitive information regarding metal-solution interactions. The most commonly employed methods for evaluation are electrochemical impedance spectroscopy (EIS) and potentiodynamic polarisation (Table 7). These techniques helps in understanding whether the inhibition is anodic, cathodic or mixed and analysing the protective performance of inhibitor films formed on the metal surface [183, 184].

Table 7. Common Electrochemical Techniques in Corrosion Studies

Technique	***Principle***	***Output***	***Application***	***References***
PDP	*Current–potential behavior*	*Corrosion current density*	*Inhibition efficiency estimation*	*[185, 186]*
EIS	*AC impedance response*	*Charge transfer resistance*	*Coating/inhibitor performance*	*[187]*

Potentiodynamic polarization (PDP) is a widely used DC electrochemical technique for corrosion measurement, where the electrode potential is swept over a range to induce anodic or cathodic reactions on the metal surface. The resulting polarisation curve (potential versus current density or log current) is used to determine corrosion potential (E_{corr}), corrosion current density (I_{corr}), corrosion rate, passive behaviour and pitting susceptibility [185].

Different methods such as cyclic polarisation, cyclic voltammetry, and potentiostaircase techniques are some of the techniques that are frequently used to study corrosion mechanisms and material behaviour under different conditions [188]. In anodic polarisation, the metal acts as an anode and undergoes oxidation, while in cathodic polarisation electrons are gained at the surface. Tafel slopes and polarisation resistance are key metrics used to assess the corrosion kinetics and inhibitor efficiency [186, 189]. The corrosion current density is often determined using the Tafel extrapolation, whereas the polarisation resistance gives a quick estimate of the corrosion rate [190]. The measurement accuracy is influenced by factors such as solution resistance, scan rate and surface condition [191-195]. Pitting corrosion is often identified through hysteresis behaviour in cyclic polarisation curves [183, 185]. However, in spite of these

limitations, PDP is a fast, reliable, and commonly employed technique for assessing corrosion behaviour, passivation characteristics, and material performance in diverse environments.

Electrochemical impedance spectroscopy (EIS) is an indispensable method which monitors real time electrochemical changes within system. This is possible because in case or passive and active protection or a mix of both, the method offers kinetic and mechanistic information on the corrosion process [184, 196, 197]. It also provides quantitative information on the electrochemical process occurring within the system under investigation [198].

The EIS technique involves applying a small-amplitude sinusoidal potential perturbation, typically 5-10 mV, over a wide range of frequency by using a three-electrode electrochemical cell [199, 200]. The impedance response is analysed using Nyquist and Bode plots. These plots provide information regarding charge transfer resistance, diffusion behaviour double layer capacitance and adsorption processes [200, 201]. Impedance data are commonly interpreted using equivalent electrical circuit models containing materials such as resistors, constant phase elements (CPE), capacitors and Warburg impedance [199, 202, 203]. EIS is considered a non-destructive and highly sensitive technique which is capable of distinguishing electrochemical processes occurring at different frequencies [187, 204]. It is widely applied for studying corrosion mechanisms, protective coatings, inhibitor films, and long-term corrosion behaviour [203, 205, 206]. However accurate interpretation of EIS data requires suitable equivalent circuit selection and a good understanding of the corrosion system [184, 187, 199, 203].

6.5. Case Studies

Table 8. Corrosion Inhibition by Plant Extracts

Plant Extract	***Metal System***	***Medium***	***Mechanism***	***Observed Trend***	***References***
Lawsonia inermis	*Mild steel*	*HCl*	*Adsorption film formation*	*Efficiency increases with concentration*	*[207]*
Aloe vera	*Carbon steel*	*Acidic media*	*Protective layer formation*	*Reduced corrosion rate*	*[163]*

Carica papaya	*Mild steel*	*HCl*	*Surface adsorption*	*Concentration-dependent inhibition*	*[208]*
Fenugreek extract	*Mild steel*	*Acidic solution*	*Mixed-type inhibition*	*Temperature-sensitive efficiency*	*[166]*
Citrus sinensis	*Carbon steel*	*H_2SO_4*	*Adsorbed organic film*	*High inhibition tendency reported*	*[144]*

Plant extracts have been reported as effective green inhibitors due to the presence of phytochemicals such as alkaloids, flavonoids, tannins and phenolic compounds which are adsorbed on the metal surfaces and thereby decrease the corrosion reactions (Table 8). Early studies by Abdel-Gaber A. M. et al. reported that several plant extracts were effective inhibitors of steel corrosion in acidic media, and the inhibition efficiency increased with increasing concentration of the extract due to the enhanced surface adsorption [207]. Similarly, Okafor P. C. and Ebenso E. E. showed that Carica papaya extract significantly reduced mild steel corrosion in acidic solution via adsorption of active phytochemical constituents [208]. The corrosion inhibition efficiency of the plant extracts towards mild steel in hydrochloric acid medium was also reported by Chauhan L. R. and Gunasekaran G [209].

Plant-based inhibitors have also shown great results in performance for aluminium corrosion protection. Abiola O. K. et al. reported that *Delonix regia* extract an efficient inhibitor for aluminium in acidic media by forming an adsorbed protective layer on the metal surface [210]. Recent studies have shown that Camellia sinensis leaf extract was effective in inhibiting aluminium corrosion in H2SO4 solution [211], while a blend of Parkia biglobosa and Delonix regia extracts showed significant inhibition efficiency for AISI 1007 steel in 1 M HCl medium due to the synergistic interaction of phytochemical constituents [212].

Also, recent studies based on electrochemical and computational methods showed good inhibition performance in acidic media. Phenolic-rich compounds from Artocarpus integer extract were identified as a sustainable inhibitor for cast iron corrosion in 1 M HCl [213]. Similarly, extract of Paronychia argentea showed good corrosion inhibition of carbon steel in

1 M HCl. Theoretical and experimental studies confirmed the strong interaction of phytochemicals with the metal surface [214].

These studies shows that the plant extracts could be efficient and environmentally safe corrosion inhibitors in acidic media by the formation of protective films based on adsorption.

7. Applications

Medicinal plant extracts represent a plethora of bioactive compounds with different biological activities and chemical structures. Benefiting from their antimicrobial, antioxidant, anti-inflammatory, and protective effects allows exploiting their applications in pharmaceutical, food, industrial, and environmental industries (Figure 5).

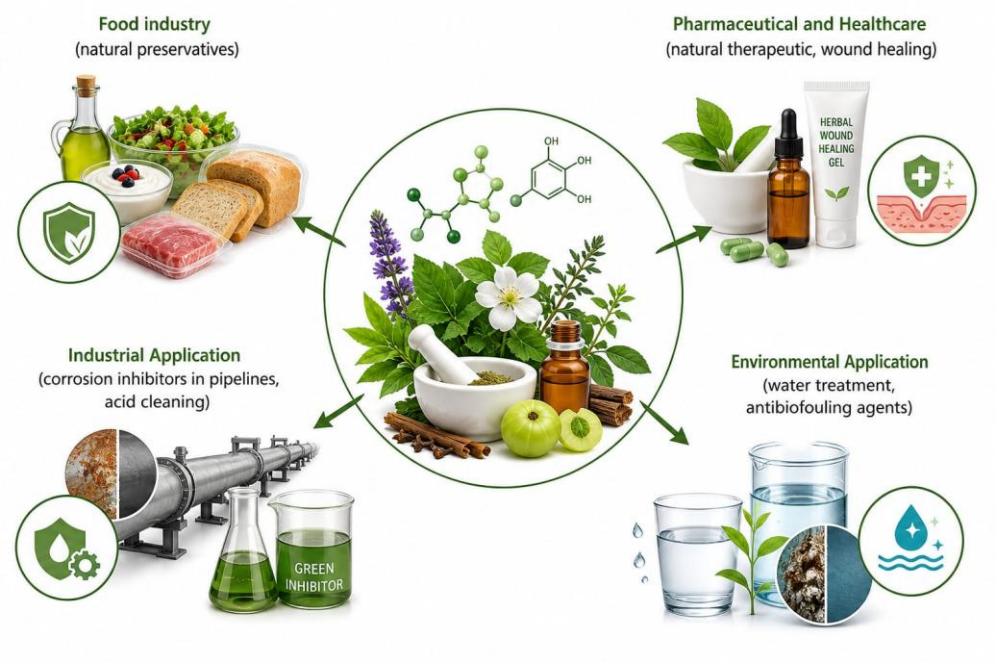


Figure 5. Applications of Bioactive Compounds

7.1. Pharmaceutical and Healthcare

Medicinal plants are important sources of multifunctional bioactive compounds such as phenolics, flavonoids, alkaloids, terpenoids, tannins and glycosides that exhibit significant therapeutic potential [215]. This compounds possess antioxidant, anti-inflammatory, antimicrobial, anticancer and antiviral activities, making them valuable natural therapeutics for the prevention and treatment of various diseases [215, 216]. Phenolic compounds have gained attention because of their ability reduce oxidative stress and regulate signalling pathways associated with immune responses and chronic diseases [216]. Owing to their biocompatibility

and lower side effects compared with many synthetic drugs, medical plant-derived compounds are increasingly explored in pharmaceutical and healthcare applications [215].

Medical plant bioactive compounds also play a major role in wound healing by promoting tissue regeneration and preventing microbial infections [217-220]. Phytochemicals such as flavonoids, tannins, and terpenoids accelerate wound contraction, collagen synthesis, epithelialization and angiogenesis, while reducing oxidative damage and inflammation and oxidative damage at the wound site [217, 220]. In addition, many medicinal plant extracts exhibit strong antimicrobial activity against wound infecting pathogens, thereby supporting faster healing and reducing complications [218, 219]. Pharmaceutical applications of these bioactive plant compounds have allowed their use in wound dressings, hydrogels, ointments and more for advanced wound healing purposes [217-220].

7.2. Food Industry

Food quality deterioration caused by microbial growth, enzymatic and oxidative reactions, and physical damage can negatively affect the safety, sensory characteristics and nutritional value of food products [221-226]. To minimize these effects and extend shelf life, preservatives are commonly added during food processing. Consumer demands for fewer synthetic additives and clean-label food have pushed further plant-derived preservatives such as phenolic-rich plant extracts and essential oils rich in terpenes for their antimicrobial and antioxidant capacity. [227-237].

Bioactive compounds derived from medicinal plants and fruits are increasingly used as natural preservatives in the food industry because of their strong antimicrobial and antioxidant properties. Antimicrobial properties against food spoilage microorganisms and foodborne pathogens are possessed by phytochemicals such as phenolics, flavonoids, tannins, terpenoids and essential oils, thus increasing food safety and shelf life. These compounds also reduce lipid oxidation and maintain the flavour, texture and nutritional quality of food products during storage. Essential oils from clove, oregano, rosemary, cinnamon and thyme have shown effective antibacterial and antifungal activities against several microorganisms associated with food spoilage and contamination [238, 239].

Essential oils and plant extracts with antioxidant activity are utilized as natural preservatives to replace synthetic food additives. The addition of plant bioactive compounds to edible coatings, packaging materials, dairy products, beverages and meat products improves stability and microbial safety. Natural bioactive compounds found in fruits like anthocyanins, organic

acids, and polyphenols can also serve as natural antioxidants and antimicrobials for food preservation. Emerging research suggests these natural preservatives can replace traditional synthetic preservatives while facilitating clean-label and sustainable food applications [237, 240, 241].

7.3. Industrial Applications

The increasing demand for energy production, industrial infrastructure and transportation has led to the extensive use of steel in pipelines, oil wells, and petrochemical systems. However, steel components are susceptible to corrosion, especially in acidic environments encountered during industrial processing and acidic cleaning operations. Although synthetic corrosion inhibitors have been widely used for corrosion control, their growing interest in developing green corrosion inhibitors derived from medicinal plants that are biodegradable, cost effective, eco-friendly and non-toxic [242].

Bioactive compounds derived from medicinal plants have gained from medicinal plants have gained considerable attention as eco-friendly corrosion inhibitors for industrial applications such as petrochemicals, pipelines and acid cleaning processes [27, 242]. Plant extract contain phytochemicals including alkaloids, flavonoids, tannins, terpenoids, phenolics and essential oils that can absorb onto metal surfaces and form protective barriers against corrosive environments [243, 244]. These compounds reduce metal dissolution and suppress electrochemical corrosion reactions in acidic media commonly used during pickling, descaling, and acid cleaning operations [245]. Compared with conventional synthetic inhibitors, plant-based inhibitors are biodegradable, environmentally sustainable, less toxic and renewable, making them attractive alternatives for green corrosion protection technologies [27, 244].

In petrochemical and pipeline industries, green corrosion inhibitors are increasingly explored because they provide effective protection for mild steel and other alloys exposed to aggressive acidic environments [242, 245]. The inhibition efficiency of medicinal plant extracts in mainly attributed to the presence of heteroatoms and π-electron system that facilitate strong adsorption on metal surfaces [243, 244]. In addition, recent studies have reported that plant derived essential oils exhibit antimicrobial and anticorrosion properties and thereby function as dual-purpose agent. This is particularly beneficial in controlling microbiologically influenced corrosion (MIC) in petroleum infrastructure [246]. Therefore, medicinal plant bioactive compounds represent a promising sustainable approach for corrosion prevention in industrial systems and acid cleaning applications [27, 242].

7.4. Environmental Applications

Biofouling, biocorrosion and water contamination are major challenges affecting marine industries, pipelines and water treatment systems, causing significant economic, environmental and health impacts [247-262]. The formation of microbial biofilms on submerged surfaces accelerates material degradation, increases fuel consumption, and promotes MIC in marine and industrial infrastructures [249, 251]. Conventional chemical coagulants and antifouling agents are effective for controlling these problems. However, their toxicity and environmental hazards have encouraged the development of safer and sustainable alternatives [252-262]. Consequently, bioactive compounds derived from medicinal plants and marine organisms are gaining increasing attention because of their biodegradability, antimicrobial activity, low toxicity and ability to inhibit microbial adhesion, biofilm formation and corrosion process [249, 263-287].

Plant based materials and extracts are increasingly investigated for water and wastewater treatment as eco-friendly alternatives to chemical treatment agents. Bioactive compounds from medicinal plants can remove suspended particles, dyes, pathogenic microorganisms and heavy metals from contaminated water through coagulation, adsorption and bactericidal mechanisms [287]. Due to their biodegradable nature and local availability, they are also suitable for sustainable water treatment applications, particularly in rural and resource-limited areas [288].

Extracts containing bioactive compounds from medicinal plants and marine organisms also have significant anti-biofouling properties affecting microbial adhesion, biofilm formation and quorum sensing pathways [271, 286, 289, 290]. Such characteristics are of great importance for many applications including marine environments, pipelines, filtration membranes and other industrial settings where biofilms can lower efficiency and lead to biocorrosion [271, 286]. Natural antifouling compounds from coastal plants, marine microbes and other organisms are becoming increasingly studied as environmentally friendly alternatives to harmful synthetic antifouling agents [289, 290].

8. Challenges And Limitations

The employment of multifunctional bioactive compounds from medicinal plants in antioxidant, antimicrobial, and corrosion inhibition applications is promising, but various limitations restrict their widespread adoption. Medicinal plants are greatly sensitive to environmental and biological factors. The type and concentration of bioactive compounds (like alkaloids, flavonoids, terpenoids, and phenolics) can vary reliant on geographical origin, seasonal

changes, soil composition, plant age and even the specific part of the plant used (leaf, root, bark, or fruit). For example, a plant grown in one region may demonstrate strong antioxidant activity, while the same species grown everywhere may show minimised effectiveness. This inconsistency develops challenges in obtaining reproducible results and affects reliability in industrial applications. Farming practices generate vast quantities of residues each year, including materials like crop straw, fruit peels, nutshells, and other organic by-products. While some of this biomass is recycled for purposes such as energy generation or enhancing soil fertility, a major portion is still disposed of improperly. This management donates to environmental problems, including accumulation of waste, deterioration of soil health, and the release of greenhouse gases due to inefficient disposal practices [27, 291]. Around the world, nearly 140 billion metric tons of biomass are produced each year, with about 1.3 billion tons consisting of agro-industrial waste derived from the non-edible portions of plants [292]. Despite the abundance and diversity of these raw materials, several challenges hinder the large scale utilisation of phytochemical-based products, limiting their effective implementation in industrial applications [27].

The extraction process plays a crucial role in determining the yield and quality of bioactive compounds. Conventional methods include Soxhlet extraction, maceration, and steam distillation often require long processing times and large amounts of solvents. Advanced methods like ultrasonic-assisted or microwave-assisted extraction increase efficiency but may require specialised equipment. Incorporate solvent recovery techniques can help lower operating expenses while minimizing environmental impact. However, selecting an appropriate solvent that effectively matches the focused compounds remains challenge. Another limitation in using organic extracts as corrosion inhibitors is their limited solubility in polar electrolytes, specifically at higher concentrations. In many cases, these extracts tend to form precipitates when added to such polar media [27, 293]. Many plant derived compounds are chemically unstable and prone to degradation. Exposure to environmental factors like heat, light, pressure, and moisture can cause oxidation or structural changes, leading to reduced activity. For instance, phenolic compounds may undergo oxidation, while essential oils can evaporate or lose potency over time. This instability limits their storage, transportation, and long-term usability, particularly in commercial formulations.

Although laboratory-scale studies establish promising results, scaling up these processes to individual levels is complex. Using locally available raw materials is advantageous for lower transportation expenses and minimizing environmental impact. In addition, market demand and

price dynamics play a key role in determining economic sustainability. Therefore, a comprehensive economic evaluation including the cost of raw materials, efficiency of processing, overall production costs, market demand, and price variability, is to assess their practical feasibility. The agro food sector, being one of the largest industries globally, has significant potential to supply raw materials for various other sectors, while also enabling interdisciplinary research focused on the development of value-added products [294].

There is no universally accepted standard for the extraction, characterization, and evaluation of plant-obtained bioactive compounds. other researchers use various methods, solvents, and testing conditions, directing to variations in reported results. This lack of standardization creates problematic to compare studies, validate findings, develop consistent products. Besides, regulatory sanction for industrial or pharmaceutical use requires well-defined composition, safety data, and reproducibility, which are lacking in plant-based systems. These challenges highlight the essential for advanced research targeted on emerging standardized extraction protocols, improving compound stability, and ensuring sustainable large-scale production. Addressing these limitations will remarkably improve the practical application of medicinal plant obtained bioactive compounds across several fields.

9. Future Perspectives

The field of multifunctional bioactive compounds from medicinal plants is quickly evolving, driven by the rising demand for sustainable, eco-friendly, and multifunctional materials. Future research is expected to change beyond conventional extraction and application strategies toward more integrated, technology-driven approaches. Agricultural operations generate vast quantities of residues each year, including crop straw, fruit peels, nutshells, and other organic by-products. While some of this biomass is recycled for energy generation or soil intensification, an important portion remains unwell managed, resulting in environmental concerns like waste accumulation, weakness of soil health, and improved greenhouse gas emissions due to improper disposal practices [291].

One of the most promising directions is the integration of nanotechnology, predominantly the synthesis of plant-mediated nanoparticles. Green synthesis using plant extracts allows the production of metal and metal oxide nanoparticles without the use of toxic chemicals. The development of advanced delivery strategies like liposomal carriers, nanoparticle-based encapsulation, and prodrug approaches helps overcome the inherent bioavailability limitations of many phytochemicals, thereby improving their therapeutic effectiveness while decreasing

the required dosage [215]. The nanoparticles often show enhanced physiochemical properties like increased surface area, improved reactivity, and superior stability. Nanocarrier based approaches have become progressively important in contemporary pharmaceutical research for overcoming the limitations of conventional drug delivery methods. Among these, liposomal systems play a crucial role, utilising phospholipid bilayer vesicles to encapsulate therapeutic agents. Such formulations are particularly effective in improving the solubility and bioavailability of poorly water-soluble drugs [295]. They demonstrate crucially improved antioxidant, antimicrobial, and corrosion inhibition efficiencies compared to their bulk counterparts. Future work should target on controlling particle size, morphology, and dispersion, as well as understanding the role of specific phytochemicals in nanoparticle formation and stabilisation.

Computational studies, specifically, molecular docking and molecular dynamics simulations, are expected to revolutionize the understanding of bioactive compound mechanisms. These in silico approaches can forecast the binding affinity and interaction behavior of phytochemicals with biological targets like enzymes, microbial proteins, and metal surfaces. This will not only decline experimental costs and time but also enable the development of structure activity relationship models. This research should highlight integrating computational predictions with experimental validation to design highly efficient and targeted bioactive compounds.

Green corrosion inhibitors have been widely utilised to control steel degradation, especially in acidic environments, as reported in numerous studies. Among the different categories, plant-derived materials including extracts from peels, roots, flowers, wood, fruits, seeds, bark as well as natural oils represent the most abundant and commonly used sources of eco-friendly inhibitors. A markable limitation of green inhibitors is their poor stability at elevated temperatures and the challenges associated with their storage. Temperature plays a critical role during the extraction of natural compounds: lower temperature decrease the solubility of phytochemicals in solvents, while higher temperatures can lead to their degradation [242]. These hybrid systems can afford improved corrosion resistance by forming highly stable and protective films on metal surfaces. Other studies are needed to optimize composition, compatibility, and long-term stability of these hybrid systems.

The commercialization of plant-derived compounds shows an important promise across multiple industries, including pharmaceuticals, food preservation, cosmetics, and materials engineering. However, various challenges must be addressed to realize their full industrial

potential. These include large-scale extraction and production, variability in phytochemical composition due to environmental factors, standardisation of active components, and compliance with regulatory requirements. Furthermore, interdisciplinary research combining phytochemistry, nanotechnology, materials science, and computational biology will be essential to unlock the full potential of these compounds.

10. Conclusion

Medicinal plants are known to be sources of bioactive compounds that have antioxidant, antimicrobial and corrosion inhibition activities. Different plants possess these characteristics properties due to the abundance of phytoconstituents they contain like phenolics, flavonoids, alkaloids, tannins, terpenoids etc. The antioxidant potential of naturally occurring compounds could be linked with free radical scavenging and chelating activities. Antimicrobial activity can be attributed to cell membrane disruption, inhibition of enzyme activity, alteration of metabolic pathways and microbial growth inhibition. The inhibition of corrosion activity can be related to adsorption of organic compounds from the plant extract onto metal surface thereby, decreasing electrochemical activity in corrosive media. Phytochemical screening by UV-Visible spectroscopy, FTIR, GC-MS/LC-MS, and NMR spectroscopy helps understand the antioxidant and antimicrobial compounds present in the plant extracts by identifying functional groups, phytochemical class, and structural confirmation. Medicinal plant-derived compounds have gained attention over synthetic counterparts due to their biodegradability, low toxicity, renewable nature, and eco-friendliness. Even through considerable research has been done on medicinal plants with antioxidant, antimicrobial, and anticorrosion activities some aspects like phytochemical variation, extraction optimization, mechanistic studies, and scale-up potential needs more exploration. Medicinal plants offer promising compounds that could be explored for designing novel antioxidants, antimicrobials and corrosion inhibitors.

Declarations

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