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Therapeutic potential of plant oleoresins: Pharmacological activities and nutraceutical applications

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Abstract

Plant oleoresins are concentrated natural extracts obtained from spices, aromatic plants, medicinal herbs and resin-producing species, containing both volatile and non-volatile bioactive constituents. Owing to their rich phytochemical composition, including phenolics, flavonoids, terpenoids, alkaloids, carotenoids, curcuminoids and piperine, oleoresins have gained considerable attention as promising therapeutic and nutraceutical agents. This review comprehensively summarizes the chemistry, extraction technologies, phytochemical composition, pharmacological activities and nutraceutical applications of commercially important plant oleoresins. Conventional and advanced extraction methods, including solvent extraction, supercritical CO_2 extraction, ultrasound-assisted extraction, microwave-assisted extraction and pressurized liquid extraction, are discussed along with modern characterization techniques. The review highlights the diverse pharmacological properties of oleoresins, including antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, cardioprotective, neuroprotective, hepatoprotective, immunomodulatory and antiobesity activities, emphasizing their underlying molecular mechanisms. Furthermore, the role of oleoresins as functional food ingredients, dietary supplements, natural preservatives and components of functional beverages is explored. Emerging delivery systems such as nanoemulsions, liposomes, microencapsulation and nanoparticles are also discussed for enhancing stability and bioavailability. Despite challenges related to standardization, bioavailability and regulatory approval, advances in green extraction technologies and nanotechnology offer significant opportunities for future development. Plant oleoresins hold immense potential for applications in nutraceuticals, pharmaceuticals and functional foods, contributing to disease prevention, health promotion and sustainable healthcare solutions.

1. Introduction

Plant oleoresins are highly concentrated, semi-solid or viscous extracts obtained from various botanical sources, including spices, herbs, aromatic plants and resinous trees. They contain both volatile essential oil fractions and non-volatile resinous components, thereby retaining the complete sensory and bioactive profile of the parent plant. In contrast to essential oils, which primarily consist of volatile aromatic compounds, oleoresins preserve a broader spectrum of phytochemicals, including alkaloids, phenolics, flavonoids, terpenoids, carotenoids, resin acids and other secondary metabolites.

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This unique composition imparts superior flavor, aroma, color, stability and biological activity, making oleoresins valuable ingredients in pharmaceutical, nutraceutical, food, cosmetic and agricultural industries (Kumar and Singh, 2024; Patel *et al*., 2024). The production and utilization of oleoresins have expanded considerably over the past decade due to increasing consumer preference for natural products and growing concerns regarding synthetic additives. Advances in extraction technologies, such as supercritical carbon dioxide extraction, ultrasound-assisted extraction, microwave-assisted extraction and pressurized liquid extraction, have significantly improved oleoresin yield, purity and functional quality while minimizing environmental impacts and solvent residues (Ravindran *et al*., 2024). These technological developments have facilitated the commercialization of high-quality oleoresins suitable for therapeutic and nutraceutical applications.

The multifunctional nature of oleoresins has increased their relevance across several industrial sectors. In the food industry, they serve as natural flavoring agents, colorants, antioxidants and preservatives. In pharmaceuticals, they are utilized as active ingredients in formulations targeting inflammation, microbial infections, oxidative stress and chronic diseases. Similarly, in the nutraceutical sector, oleoresins are increasingly incorporated into dietary supplements, functional beverages and health-promoting foods designed to enhance wellness and prevent disease (Martínez *et al*., 2025). The convergence of traditional knowledge and modern scientific validation has positioned plant oleoresins as promising natural products with significant therapeutic and commercial value. Plant oleoresins are obtained from a diverse range of botanical species, with spice crops constituting the most economically important source. Among these, black pepper (*Piper nigrum* L.) oleoresin is one of the most extensively studied due to its high piperine content and potent antioxidant, antimicrobial, anti-inflammatory and bioavailability-enhancing properties. Piperine has been shown to improve the absorption of several nutrients and drugs, making black pepper oleoresin an important component in pharmaceutical and nutraceutical formulations (Gupta *et al*., 2025). Ginger (*Zingiber officinale* L.) oleoresin contains bioactive compounds such as gingerols, shogaols, paradols and zingerone, which exhibit anti-inflammatory, antioxidant, antiemetic and gastroprotective effects. Likewise, turmeric (*Curcuma longa*) oleoresin is rich in curcuminoids and volatile turmerones that have demonstrated remarkable anticancer, neuroprotective, hepatoprotective and immunomodulatory activities (Ahmed *et al*., 2025). Capsicum and paprika oleoresins contain capsaicinoids and carotenoids that contribute to their antioxidant, analgesic, thermogenic and metabolic health-promoting properties.

Beyond spice crops, aromatic and medicinal plants represent another important source of oleoresins. Species such as rosemary (*Salvia Rosmarinus* L.), thyme (*Thymus vulgaris* L.), basil (*Ocimum basilicum* L.), sage (*Salvia officinalis* L.) and oregano (*Origanum vulgare* L.) produce oleoresins rich in phenolic diterpenes and terpenoids. These compounds exhibit strong antioxidant and antimicrobial activities and are widely investigated for applications in food preservation and therapeutic interventions (López *et al*., 2024). Resin-producing plants constitute a distinct category of oleoresin sources. Species belonging to the genera *Boswellia*, *Commiphora*, *Pinus* and *Copaifera* naturally produce oleoresinous exudates as defense mechanisms against physical injury and microbial invasion. These oleoresins contain resin acids, diterpenes, triterpenes and volatile terpenoids with significant anti-inflammatory, wound-healing, antimicrobial and immunomodulatory properties (Mendes *et al*., 2025). Increasing attention is being directed toward these natural resins due to their applications in complementary medicine, pharmaceutical formulations and biomedical research. The significance of plant oleoresins in human health is closely linked to their rich phytochemical composition and multifaceted biological activities. The bioactive compounds present in oleoresins can modulate numerous physiological and biochemical pathways associated with disease prevention and health promotion. Consequently, oleoresins have emerged as valuable natural resources for the development of preventive and therapeutic interventions targeting chronic and lifestyle-related diseases.

Chronic inflammation is another major factor implicated in the pathogenesis of numerous disorders, including obesity, arthritis, metabolic syndrome, cardiovascular disease and neurodegenerative conditions. Oleoresin-derived compounds such as curcumin, piperine, gingerols, capsaicin and boswellic acids have demonstrated significant anti-inflammatory activity through modulation of key signaling pathways, including NF-κB, MAPK, JAK/STAT and Nrf2 pathways (Singh *et al*., 2025). By suppressing inflammatory cytokines, enzymes and mediators, these compounds help mitigate inflammation-associated tissue damage and disease progression. Plant oleoresins also possess substantial antimicrobial properties. The emergence of multidrug-resistant pathogens has intensified the search for alternative antimicrobial agents from natural sources. Studies have shown that oleoresins can inhibit the growth of bacteria, fungi and viruses by disrupting microbial membranes, interfering with cellular metabolism and preventing biofilm formation (Rahman *et al*., 2024). These findings have encouraged the incorporation of oleoresins into pharmaceutical products, food preservation systems and natural disinfectants. The global demand for plant-based therapeutics has increased substantially due to growing consumer awareness regarding the health benefits of natural products. According to recent market analyses, the nutraceutical and functional food sectors are experiencing rapid expansion, driven by increasing interest in preventive healthcare and personalized nutrition (Martínez *et al*., 2025). Oleoresins are well-positioned within this trend because they offer concentrated sources of bioactive compounds capable of delivering multiple health benefits through dietary consumption. The growing scientific evidence supporting the therapeutic and nutraceutical value of plant oleoresins has generated considerable interest among researchers, healthcare professionals, food scientists and industry stakeholders. Despite extensive research efforts, available information remains dispersed across multiple disciplines, making it challenging to develop a comprehensive understanding of oleoresin chemistry, biological activities, mechanisms of action and practical applications. Therefore, a systematic and integrated review is essential to consolidate current knowledge and identify future research opportunities.

This review aims to provide a comprehensive overview of plant oleoresins, focusing on their phytochemical composition, extraction technologies, pharmacological activities and nutraceutical applications. Particular attention is given to major spice-derived and medicinal plant oleoresins that have demonstrated antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, cardioprotective, hepatoprotective, neuroprotective and immunomodulatory properties.

2. Chemistry and phytochemical composition of plant oleoresins

2.1 Chemical nature of oleoresins

Plant oleoresins are complex, concentrated extracts composed of a diverse mixture of volatile and non-volatile phytochemicals that collectively contribute to their sensory, biological and functional properties. Unlike essential oils, which primarily contain volatile aromatic compounds obtained through distillation, oleoresins retain both volatile and non-volatile fractions, thereby preserving the complete chemical profile of the source plant (Figure 1). This dual composition provides oleoresins with enhanced flavor, aroma, color, pungency and therapeutic efficacy, making them highly valuable in food, pharmaceutical, nutraceutical and cosmetic applications (Ghosh *et al*., 2024; Pereira *et al*., 2025). The volatile fraction of oleoresins consists mainly of essential oil constituents, including monoterpenes, sesquiterpenes, alcohols, aldehydes, ketones, esters, ethers and phenylpropanoids. These compounds are responsible for the characteristic aroma and flavor associated with spice and medicinal plants. For example, ginger oleoresin contains volatile compounds such as zingiberene, β-bisabolene and ar-curcumene, while cardamom oleoresin is rich in 1,8-cineole and α-terpinyl acetate (Nair *et al*., 2024). Similarly, cinnamon oleoresin contains cinnamaldehyde and eugenol, whereas clove oleoresin is dominated by eugenol and β-caryophyllene. These volatile compounds contribute not only to sensory characteristics but also exhibit antimicrobial, antioxidant, anti-inflammatory and insecticidal activities (Rodriguez *et al*., 2025).

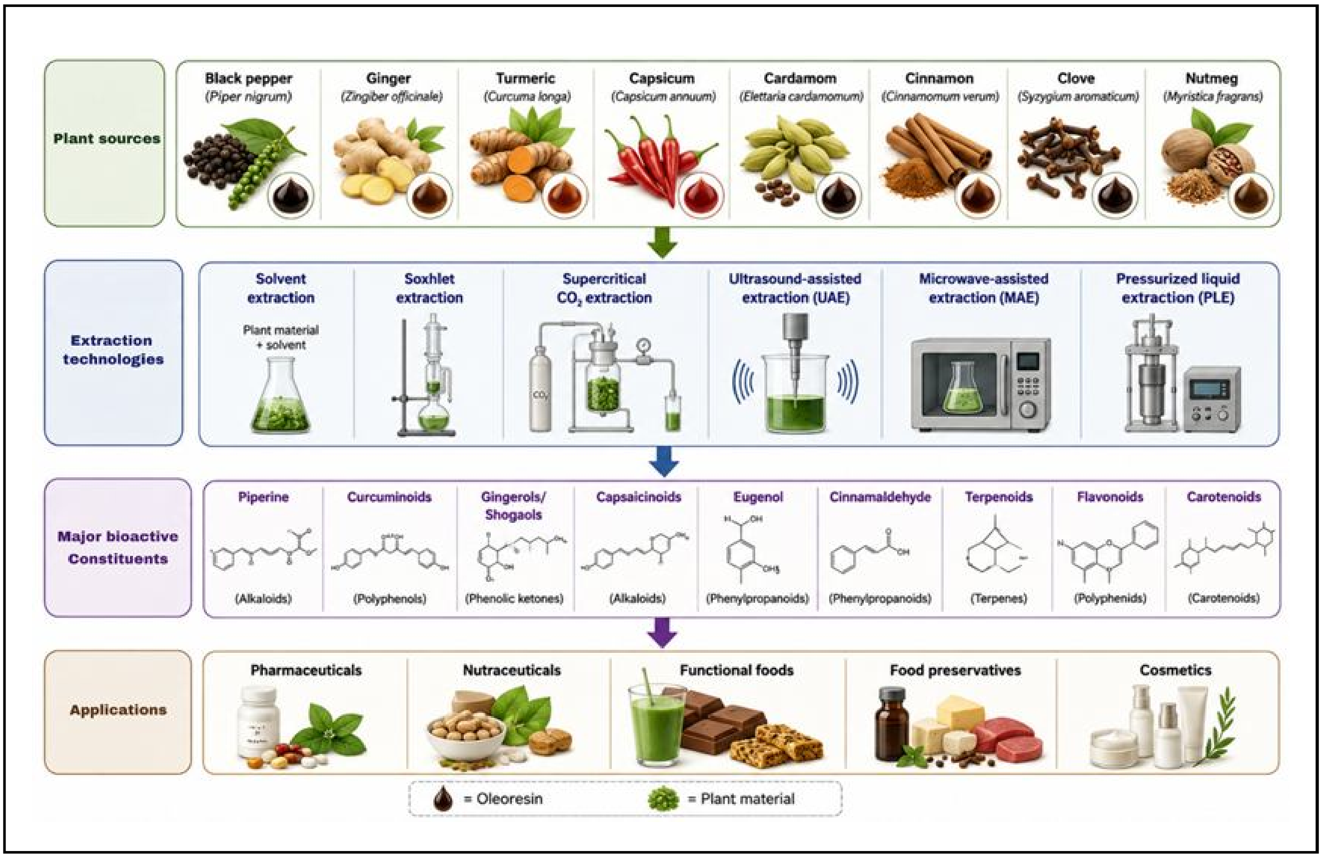

Figure 1: Plant sources, extraction technologies and major bioactive constituents of commercially important oleoresins.

The non-volatile fraction, often referred to as the resin portion, contains a wide range of biologically active constituents including phenolics, flavonoids, alkaloids, diterpenes, triterpenes, carotenoids, curcuminoids, fatty acids, sterols and resin acids. These compounds are primarily responsible for the pharmacological activities of oleoresins. For instance, turmeric oleoresin contains curcuminoids that exhibit potent antioxidant and anti-inflammatory effects, while black pepper oleoresin contains piperine, which enhances nutrient bioavailability and possesses multiple therapeutic properties (Verma *et al*., 2024). The resin fraction generally exhibits greater stability than the volatile fraction, allowing oleoresins to retain their biological activity over extended periods under appropriate storage conditions. The relative proportions of volatile and non-volatile fractions vary considerably among plant species and extraction methods. In spice oleoresins, the volatile fraction may range from 10-40%, while the resinous fraction accounts for the remainder. This balanced composition distinguishes oleoresins from essential oils and crude plant extracts, providing a more comprehensive representation of the plant's phytochemical profile (Silveira *et al*., 2025). Consequently, oleoresins are increasingly recognized as multifunctional phytochemical reservoirs with substantial therapeutic and industrial potential.

2.2 Major bioactive constituents

The therapeutic and nutraceutical significance of plant oleoresins is primarily attributed to their rich diversity of bioactive compounds. These phytochemicals exhibit a broad spectrum of biological activities and often act synergistically to enhance overall efficacy.

2.2.1 Phenolic compounds

Phenolic compounds constitute one of the largest groups of bioactive constituents present in oleoresins. These compounds include phenolic acids, tannins, lignans and related derivatives characterized by one or more hydroxyl groups attached to aromatic rings. Phenolics are recognized for their exceptional antioxidant activity, which enables them to neutralize reactive oxygen species and prevent oxidative damage to cellular components. Common phenolic compounds identified in spice oleoresins include gallic acid, caffeic acid, ferulic acid, vanillic acid and chlorogenic acid (Khan *et al*., 2025). Numerous studies have demonstrated that phenolic-rich oleoresins contribute significantly to anti-inflammatory, cardioprotective, antidiabetic and anticancer activities through modulation of oxidative stress and cellular signaling pathways (Li *et al*., 2024).

2.2.2 Flavonoids

Flavonoids are polyphenolic compounds widely distributed in aromatic and medicinal plants. Structurally, they consist of two aromatic rings linked by a heterocyclic ring and are classified into flavonols, flavones, flavanones, anthocyanins and catechins. Oleoresins derived from rosemary, oregano, thyme and basil are particularly rich in flavonoids such as quercetin, kaempferol, luteolin, apigenin and rutin (Martins *et al*., 2025). These compounds exhibit antioxidant, anti-inflammatory, antiviral, neuroprotective and anticancer properties. Recent studies have highlighted the ability of flavonoids to regulate gene expression, inhibit inflammatory mediators and enhance endogenous antioxidant defense systems, thereby contributing to the health-promoting effects of oleoresins (Wang *et al*., 2024).

2.2.3 Terpenoids

Terpenoids represent one of the most abundant classes of phytochemicals in plant oleoresins. They are biosynthesized from isoprene units and encompass monoterpenes, sesquiterpenes, diterpenes, triterpenes and tetraterpenes. Terpenoids contribute significantly to the aroma, flavor and pharmacological properties of oleoresins. Examples include limonene, pinene, cineole, caryophyllene, zingiberene, turmerone and boswellic acids (Oliveira *et al*., 2025). These compounds exhibit antimicrobial, anti-inflammatory, antioxidant, analgesic and anticancer activities. Recent research has demonstrated that terpenoids can modulate cellular signaling pathways involved in inflammation, apoptosis and immune responses, highlighting their therapeutic potential in chronic disease management (Hernandez *et al*., 2024).

2.2.4 Alkaloids

Alkaloids are nitrogen-containing secondary metabolites with pronounced pharmacological activities. Although, present in relatively lower concentrations compared with phenolics and terpenoids, alkaloids significantly contribute to the biological activity of several oleoresins. These compounds exhibit analgesic, antimicrobial, anti-inflammatory, neuroprotective and anticancer effects. Black pepper oleoresin is particularly rich in piperidine alkaloids, while other medicinal plant oleoresins may contain isoquinoline, indole, or quinoline alkaloids (Das *et al*., 2025). The ability of alkaloids to interact with neurotransmitter systems and cellular receptors makes them important candidates for pharmaceutical development.

2.2.5 Carotenoids

Carotenoids are naturally occurring pigments responsible for the yellow, orange and red coloration of many fruits, vegetables and spices. Paprika and capsicum oleoresins are particularly rich in carotenoids such as capsanthin, capsorubin, â-carotene, lutein and zeaxanthin (Garcia *et al*., 2024). Beyond their coloring properties, carotenoids possess potent antioxidant activity and serve as precursors of vitamin A. They play essential roles in maintaining visual health, immune function and cellular integrity. Increasing evidence suggests that dietary carotenoids may reduce the risk of cardiovascular disease, certain cancers and age-related macular degeneration (Torres *et al*., 2025).

2.2.6 Curcuminoids

Curcuminoids are polyphenolic compounds predominantly found in turmeric oleoresin and include curcumin, demethoxycurcumin and bisdemethoxycurcumin. These compounds are responsible for the characteristic yellow color of turmeric and have been extensively studied for their pharmacological activities. Curcuminoids exhibit strong antioxidant, anti-inflammatory, anticancer, neuroprotective, hepatoprotective and cardioprotective effects (Zhou *et al*., 2024). Their therapeutic efficacy is attributed to the modulation of multiple molecular targets, including NF-κB, STAT3, MAPK and PI3K/Akt signaling pathways. Recent advances in nanoformulation technologies have improved the bioavailability and clinical potential of curcuminoid-rich oleoresins (Shen *et al*., 2025).

2.2.7 Piperine and related alkaloids

Piperine is the principal pungent alkaloid present in black pepper oleoresin and is widely recognized for its diverse biological activities. In addition to its antioxidant and anti-inflammatory properties, piperine enhances the absorption and bioavailability of various nutrients, phytochemicals and pharmaceutical compounds by modulating intestinal permeability and metabolic enzymes (Reddy *et al*., 2025). Related alkaloids such as piperettine, piperanine and piperlongumine also contribute to the therapeutic effects of pepper-derived oleoresins. Recent studies have reported that piperine exhibits neuroprotective, antidiabetic, anticancer and immunomodulatory activities, making it one of the most valuable bioactive constituents among spice oleoresins (Chakraborty *et al*., 2024).

3. Extraction and characterization of plant oleoresins

3.1 Conventional extraction methods

The extraction process plays a critical role in determining the yield, chemical composition, purity and biological activity of plant oleoresins. Traditionally, oleoresins have been obtained through solvent-based extraction techniques that facilitate the recovery of both volatile and non-volatile constituents from plant matrices. The efficiency of extraction depends on several factors, including solvent polarity, extraction duration, temperature, particle size, moisture content and the chemical nature of the target compounds. Although, conventional extraction methods remain widely used in industrial applications due to their simplicity and cost-effectiveness, concerns regarding solvent residues, prolonged extraction times and environmental impacts have stimulated interest in more sustainable alternatives (Sharma *et al*., 2024; Kumar *et al*., 2025).

3.1.1 Solvent extraction

Solvent extraction is the most widely employed method for commercial oleoresin production. In this technique, dried and pulverized plant material is treated with organic solvents such as hexane, ethanol, acetone, methanol, ethyl acetate, or isopropanol, which dissolve the bioactive constituents present within plant tissues. Following extraction, the solvent is removed through evaporation under reduced pressure, yielding a concentrated oleoresin rich in both volatile and non-volatile compounds (Patel *et al*., 2025). The choice of solvent significantly influences extraction efficiency and selectivity. Non-polar solvents such as hexane are particularly effective for extracting lipophilic compounds including essential oils, carotenoids and resinous substances, whereas polar solvents such as ethanol facilitate the recovery of phenolics, flavonoids and alkaloids.

Ethanol has gained increasing preference due to its relatively low toxicity and compatibility with food and pharmaceutical applications (González *et al*., 2024). Despite its widespread use, solvent extraction possesses limitations including high solvent consumption, potential solvent residues, environmental concerns and possible degradation of thermolabile compounds during solvent removal.

3.1.2 Soxhlet extraction

Soxhlet extraction is a classical extraction technique extensively utilized in laboratory-scale oleoresin isolation and phytochemical research. The method involves continuous refluxing of a solvent through plant material contained within a thimble. Fresh solvent repeatedly percolates through the sample, enabling exhaustive extraction of target compounds over an extended period (Rao *et al*., 2025). One of the major advantages of Soxhlet extraction is its ability to achieve high extraction efficiency using a relatively small volume of solvent. The repeated washing action ensures thorough recovery of bioactive constituents from plant tissues. Consequently, Soxhlet extraction is frequently employed for obtaining oleoresins from black pepper, turmeric, ginger, paprika and cardamom (Fernandez *et al*., 2024). However, the method requires long extraction times, elevated temperatures and substantial energy input. Prolonged heat exposure may also result in the degradation of sensitive compounds such as carotenoids, phenolics and volatile terpenes, thereby affecting the quality of the resulting oleoresin.

3.1.3 Maceration

Maceration is one of the oldest and simplest extraction techniques used for obtaining plant-derived extracts and oleoresins. The process involves soaking plant material in a suitable solvent at room temperature or slightly elevated temperatures for a specified period, allowing the solvent to penetrate plant tissues and dissolve bioactive constituents (Lee *et al*., 2025). The simplicity, low equipment requirements and minimal thermal degradation make maceration attractive for extracting heat-sensitive compounds. This method is commonly employed in traditional herbal medicine preparations and small-scale industrial applications. However, maceration is generally associated with lower extraction efficiency, prolonged extraction times and increased solvent consumption compared with other extraction techniques. Recent modifications involving agitation, temperature optimization and solvent selection have improved extraction performance while maintaining the advantages of this conventional approach (Mendes *et al*., 2024).

3.2 Advanced extraction technologies

Growing demand for high-quality oleoresins, coupled with increasing environmental concerns, has accelerated the development of advanced extraction technologies. These modern approaches aim to improve extraction efficiency, reduce solvent usage, shorten processing times and preserve thermolabile bioactive compounds. Green extraction technologies are increasingly favored for producing oleoresins intended for pharmaceutical, nutraceutical and food applications (Singh *et al*., 2025).

3.2.1 Supercritical CO_2 extraction

Supercritical carbon dioxide (SC-CO_2) extraction is widely regarded as one of the most advanced and environmentally friendly techniques for oleoresin production. Carbon dioxide reaches a supercritical state above its critical temperature (31.1°C) and pressure (73.8 bar), where it exhibits properties of both liquids and gases. In this state, CO_2 possesses excellent diffusivity and solvent power, enabling efficient extraction of lipophilic compounds from plant materials (Wang *et al*., 2024). SC-CO_2 extraction offers several advantages, including solvent-free products, low extraction temperatures, high selectivity, rapid extraction rates and preservation of thermally sensitive compounds. The technique is extensively used for extracting oleoresins from black pepper, ginger, turmeric, paprika and cardamom. Studies have demonstrated that SC-CO_2-derived oleoresins often exhibit higher concentrations of bioactive compounds and superior antioxidant activity compared with conventionally extracted products (Almeida *et al*., 2025). Nevertheless, the high initial investment and operational costs associated with specialized equipment remain challenges for widespread adoption.

3.2.2 Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction utilizes high-frequency sound waves to enhance mass transfer between plant tissues and extraction solvents. Acoustic cavitation generated during ultrasound treatment creates microscopic bubbles that collapse violently, disrupting plant cell walls and facilitating the release of intracellular compounds into the surrounding solvent (Zhang *et al*., 2025). UAE has gained considerable attention due to its ability to reduce extraction time, decrease solvent consumption and improve extraction yields. The technique is particularly effective for recovering phenolics, flavonoids, alkaloids and essential oil constituents from aromatic and medicinal plants. Furthermore, UAE operates at relatively low temperatures, minimizing thermal degradation of sensitive compounds. Recent studies have reported significantly enhanced yields of curcuminoids, piperine and carotenoids using ultrasound-assisted extraction compared with conventional solvent extraction methods (Torres *et al*., 2024).

3.2.3 Microwave-assisted extraction (MAE)

Microwave-assisted extraction employs electromagnetic radiation to rapidly heat plant tissues and extraction solvents. Microwave energy causes dipole rotation and ionic conduction within the sample, resulting in rapid temperature increases and cell wall disruption. This process facilitates the release of phytochemicals and improves extraction efficiency (Hassan *et al*., 2025). MAE offers several advantages, including shorter extraction times, reduced solvent requirements, improved extraction yields and enhanced recovery of bioactive compounds. The technique has been successfully applied to extract oleoresins from turmeric, ginger, cinnamon, clove and paprika. Studies have shown that microwave-assisted extraction can significantly increase the recovery of curcuminoids, phenolic compounds and volatile constituents while preserving their biological activity (Liu *et al*., 2024). However, excessive microwave exposure may lead to degradation of heat-sensitive compounds, necessitating careful optimization of operating conditions.

3.2.4 Pressurized liquid extraction (PLE)

Pressurized liquid extraction, also known as accelerated solvent extraction, utilizes elevated temperature and pressure to enhance solvent penetration and extraction efficiency. Under pressurized conditions, solvents remain in the liquid state above their normal boiling points, thereby improving solubility and mass transfer rates of target compounds (Morales *et al*., 2025). PLE offers numerous advantages, including rapid extraction, reduced solvent consumption, high extraction efficiency and compatibility with a wide range of solvents. The technique has proven particularly effective for extracting phenolics, flavonoids, carotenoids and terpenoids from spice and medicinal plants. Compared with conventional extraction methods, PLE often yields higher concentrations of bioactive compounds while significantly reducing processing time. Recent investigations have highlighted its potential for industrial-scale production of high-quality oleoresins intended for pharmaceutical and nutraceutical applications (Garcia *et al*., 2024).

3.3 Characterization techniques

Comprehensive characterization of plant oleoresins is essential for quality control, standardization, authentication and evaluation of biological activity. Advances in analytical chemistry have enabled precise identification and quantification of the diverse phytochemicals present in oleoresins. Modern characterization techniques provide valuable information regarding chemical composition, structural features, purity and stability of oleoresin products (Cheng *et al*., 2025).

3.3.1 Gas chromatography-mass spectrometry (GC-MS)

GC-MS is one of the most widely utilized analytical techniques for profiling volatile compounds in oleoresins. The technique combines the separation capabilities of gas chromatography with the identification power of mass spectrometry, enabling detailed characterization of essential oil constituents and other volatile phytochemicals (Kim *et al*., 2024). GC-MS is particularly valuable for analyzing monoterpenes, sesquiterpenes, aldehydes, ketones, esters and phenylpropanoids present in spice oleoresins. It has been extensively employed for the characterization of ginger, cardamom, cinnamon, clove and black pepper oleoresins. The technique provides high sensitivity, excellent resolution and reliable compound identification through spectral library matching.

3.3.2 High-performance liquid chromatography (HPLC)

HPLC is a powerful analytical tool widely used for the separation, identification and quantification of non-volatile bioactive compounds. The technique is particularly suitable for analyzing phenolics, flavonoids, alkaloids, curcuminoids and carotenoids present in oleoresins (Jiang *et al*., 2025). HPLC has become indispensable for quality control and standardization of turmeric, black pepper, paprika and medicinal plant oleoresins. Quantification of marker compounds such as curcumin, piperine, capsaicin and rosmarinic acid is routinely performed using HPLC-based methods. Recent developments in ultra-high-performance liquid chromatography (UHPLC) have further improved analytical speed, sensitivity and resolution.

3.3.3 Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy is a rapid and non-destructive analytical technique used to identify functional groups and characterize molecular structures within oleoresins. The method measures the absorption of infrared radiation by chemical bonds, generating characteristic spectral fingerprints that facilitate compound identification (Nguyen *et al*., 2024). FTIR is particularly useful for authentication, quality assessment and detection of adulteration in commercial oleoresin products. It provides valuable information regarding the presence of hydroxyl, carbonyl, aromatic and aliphatic functional groups associated with phenolics, terpenoids and other phytochemicals. The technique is increasingly integrated with chemometric analysis to improve classification and quality control of oleoresins.

3.3.4 Liquid chromatography-tandem mass spectrometry (LC-MS/MS)

LC-MS/MS combines chromatographic separation with highly sensitive mass spectrometric detection, allowing comprehensive characterization of complex phytochemical mixtures. The technique provides exceptional sensitivity, selectivity and structural information for identifying trace-level bioactive compounds (Park *et al*., 2025). LC-MS/MS has become a preferred analytical platform for metabolomic profiling of plant oleoresins. It enables simultaneous identification and quantification of hundreds of compounds, including flavonoids, phenolic acids, alkaloids, terpenoids and curcuminoids. The technique is particularly valuable for studying phytochemical diversity, quality control and pharmacologically active constituents.

3.3.5 Nuclear magnetic resonance (NMR) spectroscopy

NMR spectroscopy is one of the most powerful analytical techniques for structural elucidation of natural products. By examining the magnetic properties of atomic nuclei, NMR provides detailed information regarding molecular structure, stereochemistry and intermolecular interactions (Roberts *et al*., 2025). NMR is extensively used to identify novel compounds, confirm chemical structures and authenticate oleoresin products. Both proton (1H-NMR) and carbon (13C-NMR) spectroscopy are employed to characterize terpenoids, alkaloids, phenolics and resin components. Recent advances in multidimensional NMR techniques have further enhanced the ability to analyze complex oleoresin matrices and support metabolomic investigations.

4. Mechanisms underlying therapeutic activities of oleoresins

The remarkable therapeutic potential of plant oleoresins is attributed to their diverse phytochemical composition and ability to modulate multiple biochemical and molecular pathways involved in disease prevention and treatment. Unlike single-compound pharmaceuticals, oleoresins contain a complex mixture of bioactive constituents including phenolics, flavonoids, terpenoids, alkaloids, carotenoids, curcuminoids and resin acids that often act synergistically to produce beneficial health effects (Figure 2). These compounds influence various cellular processes associated with oxidative stress, inflammation, microbial infections, metabolic disorders, neurodegeneration and cancer. Recent advances in molecular biology, transcriptomics, proteomics and metabolomics have significantly improved our understanding of the mechanisms underlying the pharmacological activities of oleoresins (Zhao *et al*., 2025; Ibrahim *et al*., 2024). The therapeutic efficacy of oleoresins is primarily mediated through antioxidant, anti-inflammatory, antimicrobial and cell signaling regulatory mechanisms that collectively contribute to disease prevention and health promotion.

4.1 Antioxidant mechanisms

Oxidative stress is a major pathological factor implicated in ageing and the development of numerous chronic diseases, including cardiovascular disorders, diabetes, cancer, neurodegenerative diseases and inflammatory conditions. Reactive oxygen species (ROS) and reactive nitrogen species (RNS) generated during normal cellular metabolism can damage lipids, proteins, nucleic acids and cellular membranes when produced in excess. Plant oleoresins contain a wide range of antioxidant compounds capable of neutralizing these reactive species and restoring cellular redox balance (Chen *et al.*, 2025).

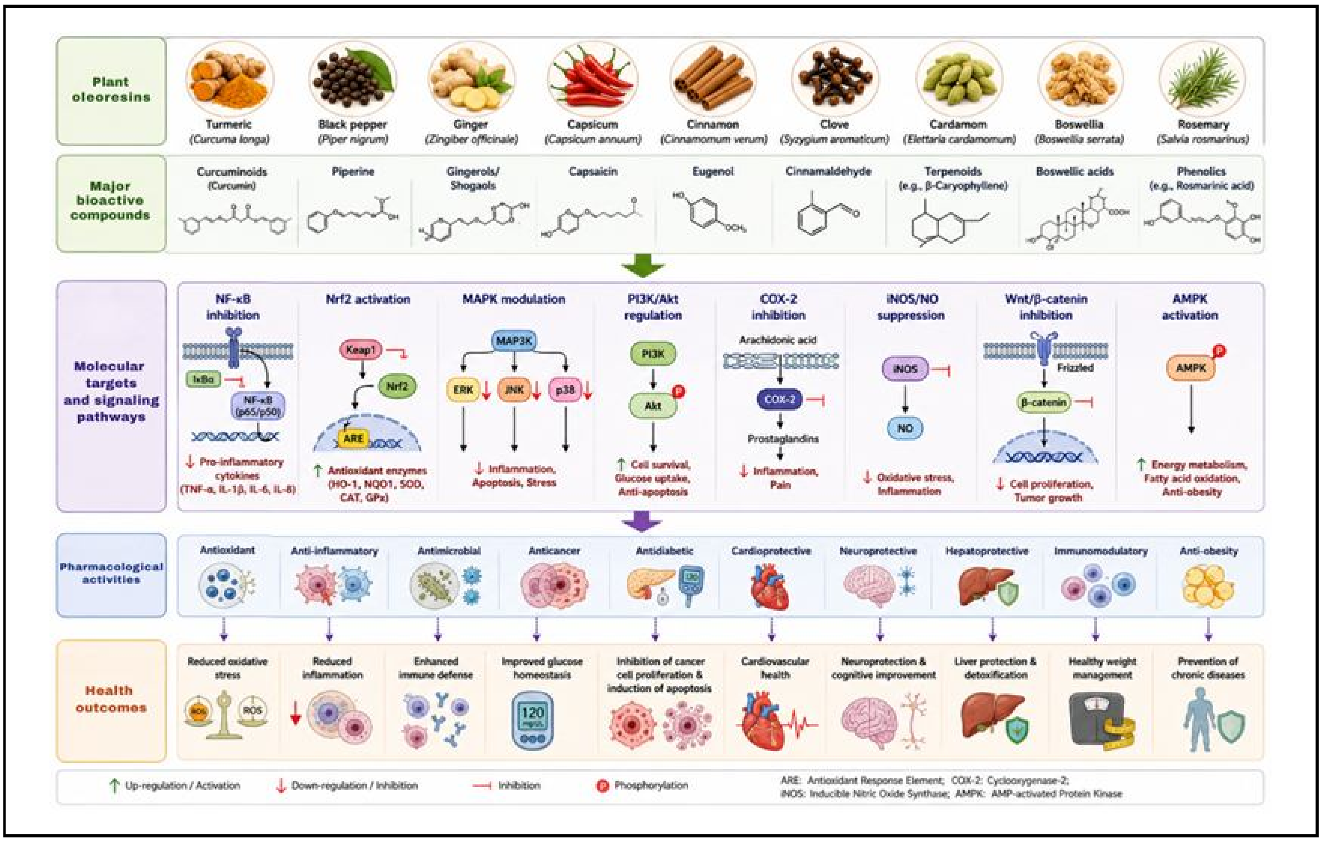

Figure 2: Molecular mechanisms underlying the pharmacological activities of plant oleoresins.

4.1.1 Free radical scavenging

One of the most important antioxidant mechanisms of oleoresins involves direct scavenging of free radicals. Phenolic compounds, flavonoids, curcuminoids, carotenoids and terpenoids possess hydroxyl groups and conjugated double-bond systems that enable them to donate electrons or hydrogen atoms to unstable free radicals, thereby terminating radical chain reactions. Curcumin from turmeric oleoresin, piperine from black pepper oleoresin and gingerols from ginger oleoresin have demonstrated strong free radical scavenging activity against superoxide radicals, hydroxyl radicals, nitric oxide radicals and peroxyl radicals (Alvarez *et al*., 2024). The antioxidant efficacy of oleoresins often exceeds that of isolated compounds due to synergistic interactions among different phytochemicals. Such synergism enhances radical neutralization capacity and contributes to the superior biological activity of whole oleoresin extracts. Recent studies have demonstrated that oleoresins significantly reduce oxidative damage in cellular and animal models by lowering intracellular ROS accumulation and preventing lipid peroxidation (Kaur *et al*., 2025).

4.1.2 Metal chelation

Transition metals such as iron and copper play important roles in catalyzing free radical generation through Fenton and Haber-Weiss reactions. Excessive accumulation of these metals can promote oxidative stress and tissue damage. Several bioactive compounds present in oleoresins exhibit metal-chelating properties, thereby reducing metal-catalyzed oxidative reactions (Santos *et al*., 2024). Phenolic acids and flavonoids contain hydroxyl and carbonyl functional groups capable of binding metal ions and forming stable complexes. By sequestering iron and copper ions, these compounds prevent the generation of highly reactive hydroxyl radicals and reduce oxidative injury. Recent investigations have shown that rosemary, oregano, turmeric and clove oleoresins possess strong metal-chelating activities that contribute significantly to their antioxidant potential (Martinez *et al*., 2025).

4.1.3 Enhancement of antioxidant enzymes

In addition to direct radical scavenging, oleoresins enhance endogenous antioxidant defense systems. Numerous studies have demonstrated that oleoresin-derived phytochemicals stimulate the expression and activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione reductase (GR) and heme oxygenase-1 (HO-1) (Liu *et al*., 2024). Activation of these enzymatic defense systems improves cellular resistance against oxidative damage and maintains redox homeostasis. Curcuminoids, terpenoids and flavonoids have been reported to upregulate antioxidant genes through activation of transcription factors involved in cellular stress responses. Enhanced antioxidant enzyme activity has been associated with improved protection against metabolic disorders, neurodegeneration, cardiovascular diseases and age-related oxidative damage (Park *et al*., 2025).

4.2 Anti-inflammatory mechanisms

Inflammation is a protective physiological response that helps eliminate pathogens and repair damaged tissues. However, chronic inflammation contributes to the pathogenesis of numerous diseases including arthritis, obesity, cardiovascular disorders, diabetes, cancer and neurodegenerative conditions. Plant oleoresins contain several anti-inflammatory compounds capable of modulating inflammatory signaling pathways and suppressing excessive immune responses (Rodriguez *et al*., 2025).

4.2.1 Modulation of NF-κB signaling

The nuclear factor-kappa B (NF-κB) pathway is a central regulator of inflammatory responses. Activation of NF-κB stimulates the expression of numerous pro-inflammatory genes, including cytokines, chemokines, adhesion molecules and inflammatory enzymes. Persistent activation of NF-κB has been implicated in chronic inflammatory diseases and cancer development (Wang *et al*., 2024). Bioactive compounds present in oleoresins, particularly curcumin, piperine, boswellic acids, gingerols and capsaicin, inhibit NF-κB activation by preventing degradation of inhibitory proteins and suppressing nuclear translocation of NF-κB subunits. Consequently, the production of inflammatory mediators is significantly reduced, leading to attenuation of inflammatory responses. Recent molecular studies have confirmed that suppression of NF-κB signaling represents one of the principal mechanisms responsible for the anti-inflammatory effects of spice and medicinal plant oleoresins (Kim *et al*., 2025).

4.2.2 Cytokine regulation

Cytokines serve as critical mediators of immune and inflammatory responses. Chronic diseases are often characterized by elevated levels of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), interleukin-6 (IL-6) and interferon-gamma (IFN-γ). Oleoresin-derived phytochemicals effectively modulate cytokine production and maintain immune homeostasis (García *et al*., 2024). Several studies have demonstrated that curcuminoids, flavonoids and terpenoids suppress pro-inflammatory cytokines while simultaneously promoting anti-inflammatory cytokines such as IL-10. This balanced cytokine regulation contributes to reduced tissue damage, improved immune function and enhanced disease resistance. Such effects are particularly relevant in inflammatory bowel disease, rheumatoid arthritis, metabolic syndrome and neuroinflammatory disorders (Shen *et al*., 2025).

4.2.3 COX and LOX inhibition

Cyclooxygenase (COX) and lipoxygenase (LOX) enzymes play essential roles in the biosynthesis of prostaglandins, leukotrienes and thromboxanes that mediate inflammatory responses. Overproduction of these inflammatory mediators contributes to pain, swelling and tissue damage associated with chronic inflammatory diseases (Rahman *et al*., 2024). Numerous oleoresin constituents act as natural inhibitors of COX and LOX enzymes. Curcumin, gingerols, eugenol and boswellic acids have demonstrated significant inhibitory activity against COX-2 and 5-LOX enzymes. By reducing prostaglandin and leukotriene synthesis, these compounds alleviate inflammation and provide analgesic effects comparable to certain non-steroidal anti-inflammatory drugs (NSAIDs), but with fewer adverse effects (Singh *et al*., 2025).

4.3 Antimicrobial mechanisms

The increasing prevalence of antimicrobial resistance has intensified interest in natural antimicrobial agents. Plant oleoresins exhibit broad-spectrum antimicrobial activity against bacteria, fungi, viruses and parasites through multiple mechanisms that reduce the likelihood of resistance development (Torres *et al*., 2025).

4.3.1 Cell membrane disruption

One of the primary antimicrobial mechanisms of oleoresins involves disruption of microbial cell membranes. Lipophilic compounds such as terpenoids, phenolics and essential oil constituents penetrate microbial membranes and alter their structural integrity. This disruption increases membrane permeability, resulting in leakage of intracellular components and eventual cell death (Hernandez *et al*., 2024). Studies have demonstrated that oleoresins from oregano, thyme, clove, cinnamon and black pepper effectively damage bacterial cell membranes, leading to inhibition of pathogenic microorganisms including *Escherichia coli*, *Staphylococcus aureus*, *Salmonella enterica* and *Listeria monocytogenes*. Similar effects have been observed against fungal pathogens such as *Candida albicans* and *Aspergillus* species (Li *et al*., 2025).

4.3.2 Inhibition of biofilm formation

Biofilms are structured microbial communities encased within extracellular polymeric matrices that provide protection against antibiotics and host immune responses. Biofilm formation significantly contributes to persistent infections and antimicrobial resistance (Morales *et al*., 2024). Recent investigations have revealed that several oleoresins inhibit biofilm formation by interfering with microbial adhesion, extracellular matrix production and biofilm maturation processes. Piperine, eugenol, cinnamaldehyde and thymol have demonstrated significant antibiofilm activity against clinically important bacterial pathogens. Such properties enhance the therapeutic potential of oleoresins in managing chronic and device-associated infections (Pereira *et al*., 2025).

4.3.3 Quorum sensing interference

Quorum sensing is a microbial communication system that regulates virulence factor production, biofilm development and pathogenic behavior. Disruption of quorum sensing represents an innovative strategy for controlling microbial infections without exerting strong selective pressure for resistance development (Ahmed *et al*., 2024). Several oleoresin-derived compounds interfere with quorum sensing signaling molecules, thereby reducing bacterial virulence and pathogenicity. This mechanism has been particularly observed in cinnamon, clove, oregano and black pepper oleoresins. By inhibiting quorum sensing pathways, oleoresins suppress toxin production, biofilm formation and microbial colonization, contributing to their antimicrobial effectiveness (Xu *et al*., 2025).

4.4 Molecular targets and signaling pathways

Recent advances in molecular pharmacology have revealed that oleoresins influence numerous signaling pathways involved in cellular survival, proliferation, inflammation, oxidative stress, metabolism and apoptosis. These pathways represent important therapeutic targets for the prevention and treatment of chronic diseases (Choudhury *et al*., 2025).

4.4.1 MAPK pathway

The mitogen-activated protein kinase (MAPK) pathway regulates cell growth, differentiation, stress responses, inflammation and apoptosis. Dysregulation of MAPK signaling has been implicated in cancer, inflammatory diseases and metabolic disorders (Yang *et al*., 2024). Bioactive compounds present in oleoresins modulate MAPK signaling by regulating extracellular signal-regulated kinases (ERK), c-Jun N-terminal kinases (JNK) and p38 MAPK pathways. Such modulation contributes to anti-inflammatory, antioxidant and anticancer activities. Curcuminoids, terpenoids and flavonoids have demonstrated significant effects on MAPK-mediated cellular responses in experimental studies.

4.4.2 PI3K/Akt pathway

The phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) pathway is essential for regulating cellular metabolism, survival, growth and proliferation. Aberrant activation of this pathway is associated with cancer progression, insulin resistance and inflammatory diseases (Zhang *et al*., 2025). Oleoresin constituents such as curcumin, piperine, capsaicin and boswellic acids modulate PI3K/Akt signaling to inhibit tumor growth, improve insulin sensitivity and reduce inflammatory responses. Regulation of this pathway contributes significantly to the anticancer and antidiabetic activities of oleoresins.

4.4.3 Nrf2 signaling

Nuclear factor erythroid 2-related factor 2 (Nrf2) is a master regulator of cellular antioxidant defenses. Activation of Nrf2 stimulates the expression of genes encoding antioxidant and detoxification enzymes, thereby enhancing cellular protection against oxidative stress (Kim and Lee, 2024). Many oleoresin-derived phytochemicals activate Nrf2 signaling and promote the expression of HO-1, NAD(P)H quinone oxidoreductase-1 (NQO1), glutathione S-transferase (GST) and other cytoprotective enzymes. This pathway is considered a key mechanism underlying the antioxidant, anti-inflammatory, neuroprotective and hepatoprotective effects of oleoresins (Rossi *et al*., 2025).

4.4.4 Apoptosis-related pathways

Apoptosis, or programmed cell death, is essential for maintaining tissue homeostasis and eliminating damaged or malignant cells. Dysregulation of apoptosis contributes to cancer development and treatment resistance. Numerous oleoresin constituents induce apoptosis in cancer cells through both intrinsic and extrinsic pathways (Fernandes *et al*., 2025). Curcumin, piperine, capsaicin, gingerols and boswellic acids regulate the expression of pro-apoptotic proteins such as Bax, caspases and p53 while suppressing anti-apoptotic proteins including Bcl-2 and survivin. These effects promote cancer cell death, inhibit tumor progression and enhance sensitivity to conventional therapies. Consequently, apoptosis modulation is regarded as one of the most important mechanisms underlying the anticancer potential of plant oleoresins (Nakamura *et al*., 2024).

5. Pharmacological activities of plant oleoresins

Plant oleoresins have attracted considerable scientific and commercial interest owing to their diverse pharmacological properties and potential applications in disease prevention and treatment. The therapeutic efficacy of oleoresins is primarily attributed to their rich composition of bioactive compounds, including phenolics, flavonoids, terpenoids, alkaloids, carotenoids, curcuminoids and resin acids. These phytochemicals interact with multiple molecular targets and signaling pathways, thereby exerting antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, cardioprotective, neuroprotective and hepatoprotective effects. Recent advancements in phytochemical research and molecular pharmacology have provided substantial evidence supporting the medicinal value of oleoresins derived from spices, aromatic herbs and medicinal plants (Zhou *et al*., 2025; Martinez *et al*., 2024). Their multifunctional properties make them promising candidates for developing natural therapeutics, nutraceuticals and functional foods aimed at promoting human health and reducing the burden of chronic diseases.

5.1 Antioxidant activity

Among the numerous biological activities associated with plant oleoresins, antioxidant activity is one of the most extensively investigated. Oxidative stress arises when the production of reactive oxygen species (ROS) exceeds the capacity of endogenous antioxidant defense systems, leading to cellular damage and contributing to the pathogenesis of cardiovascular diseases, diabetes, cancer, neurodegenerative disorders and aging-related complications. Oleoresins contain a wide array of antioxidant compounds capable of neutralizing free radicals and protecting biological systems from oxidative damage (Chen *et al*., 2024). Phenolic compounds, flavonoids, curcuminoids, carotenoids and terpenoids present in oleoresins effectively scavenge free radicals by donating hydrogen atoms or electrons, thereby interrupting oxidative chain reactions. Turmeric oleoresin, rich in curcumin and related curcuminoids, exhibits exceptional antioxidant activity and has been shown to reduce lipid peroxidation, protein oxidation and DNA damage in experimental models (Ahmed *et al*., 2025). Similarly, rosemary oleoresin contains carnosic acid and carnosol, which possess potent antioxidant properties and are widely used as natural food preservatives.

Black pepper oleoresin, containing piperine and various phenolic compounds, has demonstrated significant free radical scavenging activity and enhancement of endogenous antioxidant enzymes such as superoxide dismutase, catalase and glutathione peroxidase (Reddy *et al*., 2024). Ginger oleoresin also exhibits strong antioxidant effects through its gingerol and shogaol constituents, which reduce oxidative stress and improve cellular redox balance. Recent studies suggest that the synergistic interactions among multiple phytochemicals within oleoresins contribute to their superior antioxidant efficacy compared with isolated compounds (Khan *et al*., 2025). The antioxidant properties of oleoresins have important implications for human health, as they may reduce the risk of chronic diseases associated with oxidative stress. Furthermore, their application as natural antioxidants in food systems helps prevent lipid oxidation, improve product stability and replace synthetic preservatives, thereby addressing consumer demand for clean-label products.

5.2 Anti-inflammatory activity

Chronic inflammation is a major contributing factor to numerous diseases, including arthritis, obesity, diabetes, cardiovascular disorders, inflammatory bowel disease, neurodegenerative diseases and cancer. Plant oleoresins possess remarkable anti-inflammatory properties owing to their ability to modulate inflammatory mediators and signaling pathways involved in immune responses (Garcia *et al*., 2025). Curcuminoids from turmeric oleoresin represent some of the most extensively studied natural anti-inflammatory agents. Curcumin suppresses the activation of nuclear factor-kappa B (NF-κB), thereby reducing the expression of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β) and interleukin-6 (IL-6) (Singh *et al*., 2024). Likewise, ginger oleoresin inhibits cyclooxygenase (COX) and lipoxygenase (LOX) enzymes, leading to reduced synthesis of inflammatory prostaglandins and leukotrienes. Boswellia oleoresins rich in boswellic acids have demonstrated potent anti-inflammatory effects through inhibition of 5-lipoxygenase activity and suppression of inflammatory cell infiltration. Similarly, piperine from black pepper oleoresin modulates multiple inflammatory pathways and reduces oxidative stress-induced inflammation (Patel *et al*., 2025).

5.3 Antimicrobial activity

Plant oleoresins exhibit broad-spectrum antimicrobial activity against numerous pathogenic microorganisms, including bacteria, fungi, viruses and parasites. The increasing prevalence of antimicrobial resistance has intensified the search for alternative natural antimicrobial agents, making oleoresins attractive candidates for pharmaceutical and food applications (Rahman *et al*., 2025).

5.3.1 Antibacterial effects

Numerous oleoresins possess strong antibacterial activity against both Gram-positive and Gram-negative bacteria. The lipophilic nature of many oleoresin constituents enables them to penetrate bacterial cell membranes, disrupt membrane integrity and cause leakage of intracellular contents. Compounds such as eugenol, cinnamaldehyde, thymol, carvacrol, piperine and capsaicin have demonstrated significant antibacterial effects against pathogens including *Staphylococcus aureus*, *Escherichia coli*, *Salmonella enterica*, *Listeria monocytogenes* and *Pseudomonas aeruginosa* (Morales *et al*., 2024). Clove oleoresin, rich in eugenol, exhibits potent antibacterial activity by disrupting bacterial membranes and inhibiting essential metabolic processes. Cinnamon oleoresin containing cinnamaldehyde effectively suppresses bacterial growth and biofilm formation. Black pepper and oregano oleoresins have also shown promising antibacterial effects, suggesting their potential application in food preservation and infection control (Kim *et al*., 2025).

5.3.2 Antifungal effects

Fungal infections represent a major concern in both clinical and agricultural settings. Plant oleoresins have demonstrated significant antifungal activity against various pathogenic fungi, including *Candida albicans*, *Aspergillus niger*, *Fusarium oxysporum* and *Penicillium* species. The antifungal activity of oleoresins is primarily attributed to their ability to disrupt fungal cell membranes, inhibit spore germination and interfere with cellular metabolism (Torres *et al*., 2024). Clove, cinnamon, oregano, thyme and rosemary oleoresins have shown strong inhibitory effects against fungal pathogens. Recent studies have highlighted their potential as natural alternatives to synthetic fungicides and preservatives. In addition to their applications in human health, antifungal oleoresins are increasingly utilized in crop protection and postharvest disease management (López *et al*., 2025).

5.3.3 Antiviral potential

Recent viral outbreaks and the emergence of drug-resistant viral strains have stimulated interest in natural antiviral compounds. Several plant oleoresins possess antiviral activity against both enveloped and non-enveloped viruses. Curcumin, piperine, eugenol and various terpenoids have demonstrated inhibitory effects against influenza viruses, herpes simplex virus, hepatitis viruses, dengue virus and coronaviruses (Wang *et al*., 2025). The antiviral mechanisms of oleoresins include inhibition of viral attachment, interference with viral replication, suppression of viral protein synthesis and modulation of host immune responses. Although, further clinical investigations are needed, preliminary findings suggest that oleoresins may serve as valuable adjuncts in antiviral therapy and immune support formulations (Zhang *et al*., 2024).

5.4 Anticancer activity

Cancer remains one of the leading causes of morbidity and mortality worldwide. Increasing evidence suggests that plant oleoresins possess significant anticancer properties and may contribute to cancer prevention and treatment through multiple mechanisms. Their ability to target various stages of carcinogenesis, including initiation, promotion, progression, angiogenesis and metastasis, makes them attractive candidates for complementary oncology (Fernandes *et al*., 2025). Apoptosis, or programmed cell death, is an essential process for eliminating damaged or abnormal cells. Many cancer cells evade apoptosis, enabling uncontrolled proliferation and tumor progression. Bioactive compounds present in oleoresins can reactivate apoptotic pathways and promote cancer cell death (Li *et al*., 2024). Curcumin, piperine, capsaicin, gingerols and boswellic acids have been shown to induce apoptosis through activation of caspases, upregulation of pro-apoptotic proteins such as Bax and downregulation of anti-apoptotic proteins including Bcl-2. These mechanisms result in mitochondrial dysfunction, DNA fragmentation and eventual cancer cell death. Numerous *in vitro* and *in vivo* studies have demonstrated the effectiveness of oleoresins against breast, colon, prostate, lung, liver and pancreatic cancers (Ahmed *et al*., 2025).

5.5 Antidiabetic activity

Diabetes mellitus is a global public health challenge characterized by chronic hyperglycemia resulting from impaired insulin secretion, insulin resistance, or both. Plant oleoresins have emerged as promising natural agents for diabetes management due to their ability to regulate glucose metabolism, improve insulin sensitivity and reduce diabetes-associated complications (Sharma *et al*., 2025). Several oleoresin-derived phytochemicals influence glucose metabolism through multiple mechanisms. Curcumin, piperine, gingerols and capsaicinoids enhance glucose uptake in peripheral tissues, improve glycogen synthesis and suppress hepatic gluconeogenesis. These actions contribute to better glycemic control and reduced blood glucose levels (Rao *et al*., 2024). Turmeric oleoresin has been reported to improve pancreatic â-cell function and protect against oxidative stress-induced damage, thereby supporting insulin production. Similarly, black pepper oleoresin enhances nutrient absorption and metabolic efficiency, contributing to improved glucose homeostasis.

5.6 Cardioprotective effects

Cardiovascular diseases (CVDs) remain the leading cause of mortality worldwide and are closely associated with dyslipidemia, hypertension, oxidative stress, chronic inflammation, endothelial dysfunction and atherosclerosis. Increasing evidence suggests that plant oleoresins possess significant cardioprotective properties owing to their rich content of phenolics, flavonoids, terpenoids, curcuminoids and alkaloids. These bioactive compounds exert beneficial effects on lipid metabolism, vascular function, inflammatory responses and oxidative stress, thereby contributing to cardiovascular health (Nguyen *et al*., 2025; Rodriguez *et al*., 2024). Dyslipidemia, characterized by elevated levels of total cholesterol, triglycerides and low-density lipoprotein cholesterol (LDL-C), is a major risk factor for cardiovascular disease. Numerous studies have demonstrated that oleoresins from turmeric, black pepper, garlic, ginger and cinnamon can improve lipid profiles by reducing serum cholesterol and triglyceride concentrations while increasing high-density lipoprotein cholesterol (HDL-C) levels (Patel *et al*., 2025). Curcumin-rich turmeric oleoresin has been shown to suppress hepatic cholesterol synthesis and enhance cholesterol excretion through modulation of lipid-metabolizing enzymes. Piperine present in black pepper oleoresin improves lipid metabolism by regulating genes involved in fatty acid oxidation and lipid transport. Similarly, ginger oleoresin reduces triglyceride accumulation and improves serum lipid parameters in animal models of hyperlipidemia (Zhao *et al*., 2024). These effects collectively contribute to the prevention of cardiovascular complications associated with abnormal lipid metabolism.

5.7 Neuroprotective activity

Neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, Huntington's disease and amyotrophic lateral sclerosis are increasing globally due to ageing populations. Oxidative stress, neuroinflammation, mitochondrial dysfunction and abnormal protein aggregation are key factors involved in neurodegeneration. Plant oleoresins have emerged as promising neuroprotective agents because of their antioxidant, anti-inflammatory and antiapoptotic properties (Wang *et al*., 2025). Oleoresin-derived phytochemicals protect neuronal cells against oxidative and inflammatory damage. Curcuminoids, gingerols, piperine and various terpenoids reduce the production of reactive oxygen species and suppress neuroinflammatory mediators, thereby preventing neuronal injury and degeneration (Liu *et al*., 2024). Recent studies have demonstrated that curcumin-rich turmeric oleoresin attenuates neuronal apoptosis, preserves mitochondrial function and enhances neuronal survival under oxidative stress conditions. Similarly, black pepper oleoresin improves neuronal resilience by reducing oxidative damage and promoting cellular antioxidant defenses. These findings support the role of oleoresins in preventing age-related neurodegenerative disorders (Chen *et al*., 2025).

5.8 Hepatoprotective activity

The liver plays a central role in metabolism, detoxification and nutrient processing, making it highly susceptible to damage from toxins, drugs, alcohol, pathogens and oxidative stress. Hepatic disorders such as fatty liver disease, hepatitis, fibrosis, cirrhosis and hepatocellular carcinoma represent major global health concerns. Plant oleoresins have demonstrated significant hepatoprotective effects through antioxidant, anti-inflammatory and anti-fibrotic mechanisms (Sharma *et al*., 2025). Curcumin-rich turmeric oleoresin is one of the most extensively studied hepatoprotective agents. It protects hepatocytes against oxidative damage, suppresses inflammatory responses and inhibits fibrogenic signaling pathways. Similarly, ginger oleoresin reduces lipid accumulation in hepatic tissues and improves liver enzyme profiles in experimental models of non-alcoholic fatty liver disease (NAFLD) (Kaur *et al*., 2024). Piperine and various terpenoids have also been reported to enhance hepatic antioxidant defenses, reduce hepatocellular apoptosis and improve detoxification processes. Recent studies suggest that oleoresins may mitigate liver injury induced by environmental toxins, pharmaceutical drugs and alcohol exposure, thereby supporting liver health and function (Fernandez *et al*., 2025).

5.9 Gastroprotective and digestive health benefits

Traditional medicinal systems have long utilized spice-derived oleoresins for treating digestive disorders. Modern research has confirmed that oleoresins exert multiple beneficial effects on gastrointestinal health through antioxidant, anti-inflammatory, antimicrobial and mucosal protective mechanisms (Patel *et al*., 2024). Ginger oleoresin is widely recognized for its antiemetic and gastroprotective properties. Gingerols and shogaols stimulate gastric motility, reduce nausea and alleviate gastrointestinal discomfort. Turmeric oleoresin enhances bile secretion and supports digestive processes, while black pepper oleoresin stimulates digestive enzyme production and nutrient absorption (Rodriguez *et al*., 2025). Several studies have shown that oleoresins protect gastric mucosa against ulcer formation by increasing mucus production, reducing gastric acid secretion and suppressing oxidative stress. Additionally, their antimicrobial activity against *Helicobacter pylori* contributes to ulcer prevention and gastrointestinal health maintenance. These findings support the use of oleoresins in functional foods and nutraceuticals targeting digestive wellness (López *et al*., 2024).

5.10 Immunomodulatory effects

The immune system plays a critical role in maintaining health and defending against infections, cancer and chronic diseases. Plant oleoresins contain numerous bioactive compounds capable of modulating both innate and adaptive immune responses. Unlike immunosuppressive agents, many oleoresins exhibit immunoregulatory effects that help maintain immune homeostasis (Kim *et al*., 2025). Curcuminoids, piperine, terpenoids and flavonoids regulate immune cell activation, cytokine production and inflammatory signaling pathways. These compounds enhance macrophage activity, improve lymphocyte proliferation and stimulate natural killer (NK) cell function while simultaneously suppressing excessive inflammatory responses (García *et al*., 2025). Recent studies have demonstrated that oleoresins improve immune resilience and reduce susceptibility to infections. Their ability to regulate cytokine networks and oxidative stress also contributes to improved outcomes in inflammatory and autoimmune conditions. Consequently, oleoresins are increasingly incorporated into nutraceutical formulations designed to support immune health and disease resistance (Xu *et al*., 2024).

5.11 Antiobesity and metabolic syndrome management

Obesity and metabolic syndrome are major global health challenges associated with insulin resistance, dyslipidemia, hypertension, chronic inflammation and increased risk of cardiovascular disease and type 2 diabetes. Growing evidence suggests that plant oleoresins may play an important role in weight management and metabolic health through multiple mechanisms (Hernandez *et al*., 2025). Capsicum oleoresin, rich in capsaicinoids, promotes thermogenesis and energy expenditure by activating transient receptor potential vanilloid 1 (TRPV1) channels. This activation increases fat oxidation and reduces adipose tissue accumulation. Ginger and turmeric oleoresins have also demonstrated antiobesity effects through modulation of lipid metabolism, suppression of adipogenesis and enhancement of mitochondrial function (Lee *et al*., 2024). Curcumin and piperine improve insulin sensitivity, reduce chronic inflammation and regulate adipokine secretion, thereby addressing key components of metabolic syndrome. Furthermore, several oleoresins inhibit digestive enzymes involved in fat and carbohydrate absorption, contributing to reduced caloric uptake and improved metabolic control (Morales *et al*., 2025).

6. Nutraceutical applications of plant oleoresins

The growing consumer preference for natural, health-promoting products has significantly increased the demand for plant-derived nutraceutical ingredients. Plant oleoresins have emerged as valuable nutraceutical resources due to their high concentration of bioactive compounds, including phenolics, flavonoids, terpenoids, alkaloids, carotenoids, curcuminoids and essential oil constituents. These compounds possess diverse biological activities such as antioxidant, anti-inflammatory, antimicrobial, cardioprotective, neuroprotective and antidiabetic effects, making oleoresins attractive ingredients for functional foods, dietary supplements and health-promoting formulations. Unlike crude plant powders or extracts, oleoresins provide standardized concentrations of active compounds and superior stability, thereby ensuring consistent efficacy and quality in nutraceutical products (Fernandes *et al*., 2025; Kumar *et al*., 2024).

6.1 Oleoresins as functional food ingredients

Functional foods are defined as foods that provide health benefits beyond basic nutrition through the presence of physiologically active components. Plant oleoresins are increasingly utilized as functional food ingredients due to their ability to enhance both sensory and health-promoting properties. Their concentrated nature allows incorporation into food products at relatively low levels while delivering significant biological activity (Patel *et al*., 2025). Spice-derived oleoresins such as turmeric, ginger, black pepper, cinnamon, rosemary, oregano and paprika are widely incorporated into functional food products. Turmeric oleoresin contributes antioxidant and anti-inflammatory benefits through its curcuminoid content, while black pepper oleoresin enhances nutrient absorption and digestive function due to piperine. Ginger oleoresin provides gastrointestinal and metabolic health benefits, making it a valuable ingredient in health-oriented food products (Ahmed *et al*., 2024). In addition to their physiological effects, oleoresins improve the sensory quality of foods by imparting characteristic flavors, aromas and colors. Paprika oleoresin serves as a natural coloring agent in processed foods, while rosemary and oregano oleoresins contribute desirable flavor profiles and antioxidant protection. The multifunctional nature of oleoresins allows manufacturers to simultaneously improve product quality, shelf- life and nutritional value, supporting the growing demand for clean-label and functional food products (Garcia *et al*., 2025).

6.2 Dietary supplements and nutraceutical formulations

The dietary supplement industry has experienced substantial growth in recent years, driven by increasing consumer awareness regarding preventive healthcare and wellness. Plant oleoresins have become important ingredients in dietary supplements due to their concentrated bioactive content and scientifically validated health benefits (Chen *et al*., 2024). Turmeric oleoresin is one of the most extensively utilized oleoresins in nutraceutical formulations because of its high curcumin content and broad therapeutic applications. Curcumin supplements are widely marketed for supporting joint health, cardiovascular function, cognitive performance and immune regulation. Similarly, black pepper oleoresin is commonly included in dietary supplements to enhance the bioavailability of curcumin, resveratrol, coenzyme Q10 and other nutraceutical compounds through the action of piperine (Rodriguez *et al*., 2025).

Ginger oleoresin supplements are utilized for digestive health, nausea management, anti-inflammatory support and metabolic regulation. Other oleoresins, including cinnamon, clove, garlic, rosemary and oregano, are increasingly incorporated into formulations targeting cardiovascular health, glycemic control, antioxidant protection and immune enhancement (Liu *et al*., 2024). Modern nutraceutical formulations frequently combine multiple oleoresins to exploit synergistic interactions among bioactive compounds. Such combinations often exhibit greater efficacy than individual components alone. Furthermore, advances in formulation science have enabled the development of tablets, capsules, soft gels, powders, gummies and liquid supplements containing standardized oleoresin extracts with improved stability and therapeutic effectiveness (Wang *et al*., 2025).

6.3 Food fortification applications

Food fortification involves the addition of bioactive compounds or nutrients to food products to improve their nutritional and functional properties. Plant oleoresins have gained considerable attention as natural fortification agents due to their rich phytochemical composition and health-promoting effects (Sharma *et al*., 2025). Oleoresins can be incorporated into a wide range of food products, including dairy products, cereals, bakery products, beverages, meat products and confectioneries. Turmeric oleoresin fortification enhances antioxidant capacity and anti-inflammatory potential, while paprika oleoresin provides natural coloration and antioxidant protection. Ginger and cinnamon oleoresins contribute functional benefits related to metabolic health and digestive support (Fernandez *et al*., 2024). Fortification with oleoresins offers several advantages over synthetic additives. In addition to delivering bioactive compounds, oleoresins improve flavor, aroma, color and shelf stability. Furthermore, their natural origin aligns with consumer preferences for minimally processed foods and clean-label ingredients. Recent studies have demonstrated that oleoresin-fortified foods exhibit enhanced antioxidant activity, improved nutritional quality and increased consumer acceptance, supporting their growing utilization in food innovation strategies (Morales *et al*., 2025).

6.4 Natural food preservatives

Consumer concerns regarding synthetic preservatives have stimulated interest in natural alternatives capable of maintaining food quality and safety. Plant oleoresins possess strong antioxidant and antimicrobial properties that make them highly effective natural food preservatives (Kim *et al*., 2025). The antioxidant constituents of oleoresins inhibit lipid oxidation and prevent deterioration of food quality during storage. Rosemary oleoresin is widely recognized as one of the most effective natural antioxidants and is extensively used in meat products, edible oils, snacks and processed foods. Similarly, turmeric, clove, oregano and cinnamon oleoresins exhibit significant antioxidant activity that helps preserve food freshness and nutritional value (Martinez *et al*., 2024). The antimicrobial activity of oleoresins further contributes to food preservation by inhibiting the growth of spoilage microorganisms and foodborne pathogens. Clove and cinnamon oleoresins effectively suppress bacterial and fungal contamination, while oregano and thyme oleoresins exhibit broad-spectrum antimicrobial activity against numerous foodborne pathogens (Lopez *et al*., 2025).

6.5 Oleoresins in functional beverages

Functional beverages represent one of the fastest-growing segments of the global nutraceutical market. These products are designed to provide specific health benefits beyond hydration and basic nutrition. Plant oleoresins have become valuable ingredients in functional beverages due to their concentrated bioactive content and desirable sensory characteristics (Zhang *et al*., 2025). Turmeric oleoresin is widely incorporated into wellness beverages, immunity-boosting drinks and sports nutrition products due to its anti-inflammatory and antioxidant properties. Ginger oleoresin is frequently used in digestive health beverages, herbal teas and energy drinks, while cinnamon oleoresin contributes flavor and glycemic regulatory benefits (Ahmed *et al*., 2024). Oleoresins also provide natural coloring and flavoring properties that enhance product appeal without the need for synthetic additives. However, challenges associated with poor water solubility and stability have limited their application in beverage systems. Advances in emulsification and encapsulation technologies have addressed these limitations, enabling the development of stable, bioavailable oleoresin-enriched beverages with improved sensory and functional properties (Garcia *et al*., 2025).

7. Safety, toxicity and regulatory aspects

Plant oleoresins are generally recognized as safe (GRAS) when used within recommended limits and have been extensively utilized in food, pharmaceutical, cosmetic and nutraceutical industries. Their natural origin and long history of traditional use contribute to their favorable safety profile. However, despite their numerous health benefits, the safety of oleoresins depends on factors such as botanical source, chemical composition, dosage, extraction method, purity and duration of consumption. Excessive intake of certain oleoresins may lead to adverse effects, including gastrointestinal irritation, allergic reactions, hepatotoxicity, or interactions with medications (Kumar *et al*., 2024). For example, high doses of capsaicin-rich capsicum oleoresin may cause gastric irritation and discomfort, whereas prolonged consumption of cinnamon oleoresin containing coumarin may pose risks of liver toxicity in susceptible individuals. Similarly, piperine from black pepper oleoresin can alter drug metabolism by inhibiting cytochrome P450 enzymes, potentially affecting the bioavailability and pharmacokinetics of co-administered drugs (Patel *et al*., 2025). Therefore, comprehensive toxicological evaluation, including acute, sub-chronic and chronic toxicity studies, remains essential for ensuring consumer safety.

Standardization and quality control are critical challenges in oleoresin commercialization. Variability in phytochemical composition due to differences in plant genotype, cultivation conditions, harvesting stage and extraction methods may affect product efficacy and safety. Advanced analytical techniques such as HPLC, GC-MS and LC-MS/MS are increasingly employed to ensure consistency and authenticity of commercial products (Fernandes *et al*., 2025). From a regulatory perspective, many oleoresins are approved as food additives, flavoring agents and natural preservatives by regulatory agencies such as the Food and Drug Administration, the European Food Safety Authority and the Food Safety and Standards Authority of India. Nevertheless, harmonized international regulations and evidence-based dosage recommendations are still needed to facilitate global commercialization and consumer confidence. Future regulatory frameworks should emphasize quality assurance, safety assessment and clinical validation to support the responsible use of oleoresin-based nutraceuticals and therapeutics.

8. Current challenges and future perspectives

Despite substantial progress in oleoresin research and commercialization, several challenges continue to limit their full therapeutic and nutraceutical potential. One of the major concerns is the significant variability in phytochemical composition resulting from differences in plant species, genotype, environmental conditions, cultivation practices, harvesting time and extraction technologies. Such variability complicates product standardization and may lead to inconsistent biological efficacy (Sharma *et al*., 2025). Another important challenge is the poor bioavailability of several key oleoresin constituents, particularly curcuminoids, carotenoids and certain terpenoids. These compounds often exhibit limited water solubility, rapid metabolism and low gastrointestinal absorption, reducing their clinical effectiveness. Although, advanced delivery systems such as nanoemulsions, liposomes and nanoparticles have shown promising results, further optimization and large-scale commercialization are required (Chen *et al*., 2025).

The lack of comprehensive clinical trials also represents a significant limitation. While numerous *in vitro* and animal studies have demonstrated the therapeutic benefits of oleoresins, robust human studies are needed to establish efficacy, dosage, long-term safety and potential drug interactions. Future research should focus on evidence-based validation through multicenter clinical investigations. Emerging technologies including metabolomics, proteomics, artificial intelligence-assisted phytochemical screening and precision nutrition approaches are expected to accelerate oleoresin research. Furthermore, sustainable cultivation practices and green extraction technologies such as supercritical CO_2 extraction and pressurized liquid extraction will play crucial roles in ensuring environmental sustainability. The integration of nanotechnology, personalized healthcare and functional food development is likely to expand the future applications of oleoresins, positioning them as key ingredients in next-generation nutraceuticals and natural therapeutics.

9. Conclusion

Plant oleoresins represent a valuable class of natural bioactive products with immense therapeutic and nutraceutical potential. Rich in phenolics, flavonoids, terpenoids, alkaloids, carotenoids, curcuminoids and other phytochemicals, they exhibit diverse biological activities including antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, cardioprotective, neuroprotective and hepatoprotective effects. Their growing application in functional foods, dietary supplements, food preservation and pharmaceutical formulations highlights their significance in modern health and wellness industries. Despite challenges related to standardization, bioavailability and clinical validation, advances in extraction technologies, analytical methods and delivery systems are enhancing their efficacy and commercial value. Future interdisciplinary research integrating biotechnology, nanotechnology and clinical sciences will further unlock the potential of plant oleoresins as safe, effective and sustainable agents for disease prevention, health promotion and nutraceutical innovation.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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