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REVIEW

# Medicinal and Aromatic Plants as Potential Sources of Bioactives Along with Health-Promoting Activities

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## Abstract

**Purpose of Review** This review aims to highlight the therapeutic potential and diverse applications of medicinal and aromatic Plants (MAPs), emphasizing their bioactive compounds. The primary goal is to discuss their roles in traditional medicine, pharmaceuticals, cosmetics, and functional foods, while addressing the challenges of standardization and sustainable cultivation.

**Recent Findings** Recent studies have demonstrated the antioxidant, anti-inflammatory, antimicrobial, anticancer, and neuroprotective properties of MAPs. These properties are increasingly recognized and utilized across various industries, indicating their significant potential in advancing healthcare.

**Summary** MAPs are rich in bioactive compounds such as polyphenols, alkaloids, terpenoids, and flavonoids, which contribute to their health benefits. This review synthesizes peer-reviewed literature on the bioactive properties, therapeutic efficacy, and safety profiles of MAPs, and their integration into modern healthcare. It also addresses methodological challenges and proposes solutions for standardization and sustainable cultivation to ensure consistent quality and availability. The review is based on a comprehensive analysis of recent scientific studies and meta-analyses to provide a clear understanding of the current state of MAP research.

**Keywords** Bioactives · Aromatic plants · Human health · Antioxidant · Polyphenols

## Introduction

In present-day times medicinal and aromatic plants (MAP's) were broadly classified as plants utilized for therapeutic purposes, either to prevent or treat diseases, and for various other applications. The World Health Organization (WHO) indicates that a significant portion of medical and pharmacological advancements is derived from extensive research and understanding of natural plants [1]. Medicinal and aromatic plants have diverse applications,

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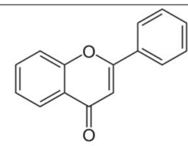
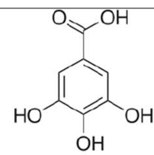
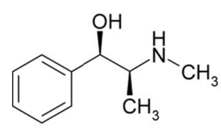
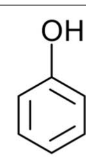
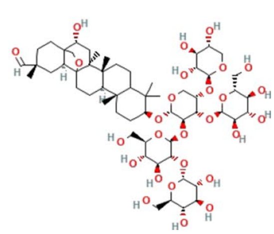
including sanitation, nutrition, cosmetics, body care, and incense, with some plants serving both medicinal and aromatic roles. They contribute significantly to global trade and are used in various forms, such as leaves, roots, flowers, and extracts. More than a quarter of pharmaceutical drugs globally are derived from plants [2]. India, with a rich herbal medicine heritage in Ayurveda, Siddha, and Unani systems, is a major exporter of medicinal and aromatic plant products. The Indian government's initiative in 2003 to transform the Department of Indian Systems of Medicines and Homoeopathy into Ayurveda, Yoga & Naturopathy, Unani, Siddha, Sowa Rigpa and Homoeopathy (AYUSH) has advanced educational standards, quality control, drug standardization, research, and awareness [3]. Moreover, natural constituents obtained from various medicinal and aromatic plants have garnered recognition as alternative therapies and essential raw materials for diverse applications. Medicinal plants serve as reservoirs of bioactive compounds that function as therapeutic agents in traditional treatments [4], whereas aromatic plants offer valuable reserves of essential oils renowned for their aroma and flavour-enhancing properties [5]. Natural compounds from medicinal and aromatic plants are respected as alternatives to synthetic drugs and as raw materials for various industries. Christaki et al. [6] emphasize the rising popularity of medicinal and aromatic plants in functional beverages (FBs), which offer health benefits and sensory appeal. Various studies were conducted on the bioactive molecules in medicinal and aromatic plants, enhancing functional beverages development. Fierascu et al. [7] highlight their biologically active compounds, which provide health benefits like antimicrobial and antioxidant properties. Males et al. discuss extraction techniques, scalability, and applications in medicine, industry, and nanotechnology, emphasizing medicinal and aromatic plants potential in innovative healthcare solutions [8]. Even though synthetic drugs are common, issues like resistance and side effects make plant-based drugs appealing. This growing interest is focused on finding natural extracts to work alongside synthetic medicines for safer and more effective treatments. Despite lots of research on aromatic plants, some, like frankincense, myrrh, ginger, and turmeric, haven't been studied as much even though they show great promise [9]. Thus, integration of natural remedies with synthetic medications has been suggested to potentially enhance treatment outcomes, thereby promoting a holistic approach to healthcare. The exploration of multifaceted roles of medicinal and aromatic plants, ranging from traditional medicinal applications to contemporary uses, holds promise for the development of safer and more efficacious therapeutic interventions. However, using the wide variety of medicinal and aromatic plants and their healing properties in healthcare can greatly improve people's health around the world.

## Bioactives in Medicinal and Aromatic Plants

Plant secondary metabolites, commonly known as 'bioactive compounds,' are essential for inducing a variety of pharmacological effects that benefit human health [10]. These metabolites, found abundantly in MAPs possess biological and pharmacological properties, making them valuable for drug discovery. The plant metabolome consists of around 4000 compounds, including over 2 million reported plant secondary metabolites found throughout the plant kingdom, each fulfilling various functions [11]. Friedrich Serturner's isolation of morphine from the opium poppy plant in 1804 marked a pivotal moment, highlighting the therapeutic potential of plant bioactive compounds [12]. While many plants possess both medicinal and aromatic properties, not all members of the plant kingdom exhibit this dual characteristic. Essential oils and aromatic chemicals found in some plants offer anti-inflammatory, antibacterial, expectorant, and sedative properties. Conversely, plants like *Jasminum* spp. are primarily valued for their aromatic qualities [13]. Despite their differences MAPs constitute distinct groups with varying bioactive constituents and properties (Table 1). The composition and concentration of bioactive compounds in MAPs are influenced by factors such as species, genotype, physiology, developmental stage, and environmental conditions during growth, which in turn affect the adaptive responses of different plant taxonomic groups to stress and defensive stimuli [14]. The vast array of known plant-derived bioactives, exceeding 200,000, are categorized into non-nitrogen and nitrogen compounds based on criteria like chemical structure, composition, solubility, biosynthetic pathway, and function [15]. Nitrogen secondary metabolites, comprising alkaloids, are synthesized from amino acids and number around 12,000, while non-nitrogen secondary metabolites, including terpenoids, steroids, and phenolics, are biosynthesized via pathways involving malonic, mevalonic and shikimic acids [16].

Alkaloids, among the oldest known plant bioactives, exist as salts of organic acids, esters, and tannins. It is estimated that approx. 14–20% of plants contain alkaloids. Some examples are morphine, nicotine, caffeine, theacrine, theobromine, hygrine and pilocarpine (Fig. 1) [21]. Examples of plants rich in alkaloids include *Datura stramonium*, *Atropa belladonna*, *Nicotiana tabacum*, *Solanum* sp., *Rauvolfia serpentina*, *Camptotheca acuminata*, *Papaver somniferum*, and *Catharanthus roseus* [22]. Polyphenol family contains 8000 structurally different compounds mainly categorized as phenolic acids, flavonoids, stilbenes, tannins, and lignans, are synthesized through phenylpropanoid and shikimic acid

**Table 1** General classification and characteristics of bioactves in plants

| Class | Biological activity | General structure | Source | Characterstics | Uses | Reference |
|---|---|---|---|---|---|---|
| Flavonoids | Antioxidant, anti-carcinogens, antimicrobial, antitumor |  | *Camellia sinensis, Matricaria chamomilla, Melissa officinalis* | Water-soluble, super antioxidant, and free radical scavenger | In prevention of oxidative cell damage, allergies, free radicals, microbes | [17] |
| Tannins | Anti-inflammatory, diuretics |  | *Quercus* sp., *Hamamelis virginiana, Rubus fruticosus* | Unpleasant taste, tans leather | Production of ink and leather; hemorrhoids, wounds | [18] |
| Alkaloids | Analgesic, bactericidal effect, anti-spasmodic, |  | *Datura stramonium*, *Nicotiana tabacum*, *Rauvolfia serpentina*, *Camptotheca acuminata*, *Catharanthus roseus* | Colourless, bitter taste, crystalline | Raw material in drugs development | [18] |
| Phenols | Antimicrobial, antiseptic |  | *Origanum vulgare, Thymus vulgaris, Syzygium aromaticum* | Hydroxyl group with aromatic ring | Disinfection | [19] |
| Saponins | Expectorant, haemolytic activity |  | *Panax ginseng, Glycyrrhiza glabra, Saponaria officinalis* | Bitter taste, haemolytic effect on red blood cells | Emulsifying agent | [20] |

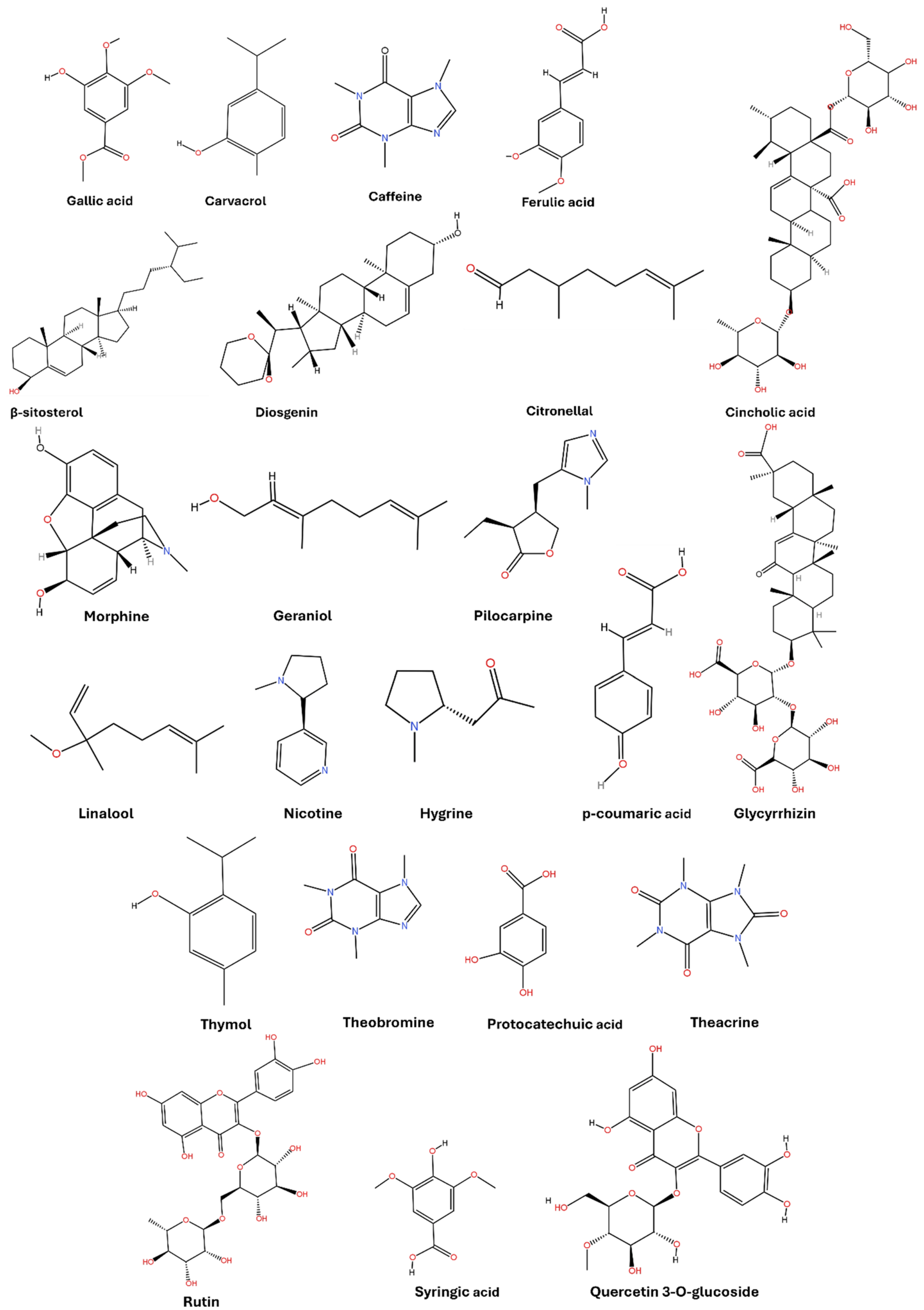



**Fig. 1** Representation of bioactive compounds from some MAPs

pathways in MAPs [23]. For instance, *Moringa oleifera* contains rutin, syringic acid, gallic acid and quercetin 3-O-glucoside, while *Salvia officinalis*, *Origanum vulgare*, *Thymus vulgaris* (Table 2), and *Ocimum basilicum* contain caffeic acid and p-coumaric acid. Additionally, *Polygonum cuspidatum* contains piceatannol glucoside, resveratroloside, and piceid, *Phyllanthus amarus* contains lignans, and *Punica granatum* contains ellagitannins [24]. It is worth noting that phenolic acids such as caffeic, vanillic, protocatechuic and ferulic acids were distributed in almost all plants.

Terpenoid or terpenes are class of bioactive compounds that count up to 40,000 different chemicals. The major compounds of this class are oxycarotenoids and carotenes belonging to tetraterpene family [25]. Terpenoids or terpenes are group of secondary metabolites found abundantly in plants, obtained from biosynthetic pathway of isopentenyl diphosphate via the mevalonic acid pathway [26]. Their chemical structure comprises an unsaturated hydrocarbon backbone, often present in essential oils and resins. These compounds exhibit cytotoxic effects against bacteria, fungi, insects, and vertebrates, functioning as defence mechanisms [27]. Terpenes are utilized in medicine, flavouring, and perfume, exhibiting ecological roles and a range of toxicities, including antimicrobial properties [28]. Examples of terpenoids include artemisinin in *Artemisia annua*, tetrahydrocannabinol in *Cannabis sativa*, azadirachtin in *Azadirachta indica*, and saponins found in *Chenopodium quinoa* [29].

Saponins, found in various plants like *Gynostemma*, *Panax*, and *Salvia*, exhibit unique properties including foaming in water due to presence of lipophilic sugar group [30]. They are classified as steroid glycosides with examples including cardiac glycosides and steroidal alkaloids [31]. These compounds possess diverse pharmacological effects, such as antifungal, antitumor, and blood coagulation effects. Cardiac glycosides, neurotoxic in nature, are utilized in treating cardiac insufficiency [32]. Saponins like diosgenin and cincholic acid exhibit anticancer and hypolipidemic properties [30]. They are also employed in traditional medicine for anti-infection purposes and as expectorants. Moreover, saponins play a role in inhibiting lipid peroxidation, regulating liver enzymes, reducing blood cholesterol and sugar levels, stimulating the immune system, and demonstrating chemotherapeutic potential [33]. Specific saponins like mussaendoside *O* obtained from *Mussaenda pubescens* possess hemolytic, and immune-promotive activities [34].

Plant steroids, including cardenolides and bufadienolides, are diverse compounds found in various plants, such as *Digitalis* and *Drimia maritima*. Plants such as *Dioscorea* species contain diosgenin, a compound utilized in steroid industries. Sterols like β-sitosterol (Fig. 1) are widely distributed in plants and can impact physiological processes [33]. Glucosinolates, a large group of natural secondary metabolites containing nutritional and biologically active compounds [35], are primarily present in cruciferous plants such as those in Brassicaceae family [36]. Chemically, glucosinolates are glycosides of β-d-thioglucose, with an aglycone that can produce an isothiocyanate, a nitrile, or a thiocyanate upon hydrolysis, contributing to pungent taste of plants like *Brassica* sp., *Armoracia rusticana* and *Nasturtium officinale* [37].

Aforementioned earlier, MAPs contain bioactive compounds in their different parts, extraction of these compounds or specific bioactives is required. There are three extraction methods: acid/base, liquid/solid and liquid/liquid, with solvent extraction being the most popular [52]. Both conventional and non-conventional methods can be used for this purpose. The choice of extraction procedure depends on several factors, including extraction temperature, duration, solvent-to-sample ratio, particle size of tissues, and solvent pH. Classical extraction methods, like soxhlet, steam distillation, maceration and hydro-distillation, are straightforward and use of solvents with varying polarities. On the other hand, non-conventional or innovative extraction techniques, such as microwave-assisted, pressurized liquid, supercritical fluid, enzyme-assisted extraction, turbo-distillation, ultrasound-assisted, pulsed electric field, and high-voltage-assisted extraction, have advanced extraction technology. These "greener" methods offer benefits like high sensitivity, overall yields, selectivity, lower solvent consumption, and shorter duration. They are environmentally friendly, cutting down on energy and organic solvent use, with a main advantage being continuous mode of operability, which is crucial for industrial and economic viability [53]. Regardless of the extraction procedure, the resulting solution should be filtered to remove any particulate matter. The choice of extraction procedure should be based on the plant matrix and compost type, following clear selection criteria [54]. Analysis of bioactives often involves isolation and purification using chromatographic methods. Structural analysis requires molecular data from spectroscopic techniques such as Infrared (IR), UV–visible, nuclear magnetic resonance (NMR), and mass spectroscopy (MS). For instance, compounds from pith were isolated and purified using bioactivity-guided solvent extraction, column chromatography, and high-performance liquid chromatography (HPLC) [55]. These techniques were used to characterize structure of bioactive molecule. Additionally, molecules may undergo hydrolysis, and their derivatives characterized. The combination of MS and HPLC enables accuracy in identification of chemical compounds in plants, especially in absence of a pure standard. LC/MS has been frequently utilized for analysis of phenolic compounds [56].

**Table 2** Source of some pharmacologically active plant secondary metabolites derived from MAPs and their effects

| Family | Botanical name | Secondary metabolites | Pharmacological effect | Reference |
|---|---|---|---|---|
| Asteraceae | *Calendula officinalis* | Faradiol-3-O-palmitate, arnidiol-3-O-laurate, faradiol-3-O-laurate, faradiol-3-O-myristate, calenduladiol-3-O-myristate arnidiol-3-O-palmitate, calenduladiol-3-O-palmitate, arnidiol-3-O-myristate | Anti-inflammatory, immunostimulant, antibacterial, antiviral, antiproliferative | [38] |
| | *Ageratum conyzoides* | β-Farnesene, echinaline, eugenol, brassicasterol, precocene I, stigmasterol, limonene, β-caryophyllene, β-sitosterol, lycopsamine, quercetin, eupalestin, sinensetin, linalool, kaempferol | Anti-hyperglycemic, anti-asthma, anti-diarrheal, anti-inflammatory, antitumor, hemostatic, antimicrobial, antioxidant, antimalarial, anti-ulcer, analgesic | [39] |
| | *Achillea millefolium* | Flavonoids, sesquiterpenes, cosmosiin II, cynaroside I | Anti-inflammatory, antiulcer, Anticancer | [40] |
| Lamiaceae | *Thymus vulgaris* | Rosmarinic acid, thymol, caffeic acids, carvacrol, linalool, trans-thujan-4-ol/terpinen-4-ol geraniol, α-terpineol | Antiseptic, antimicrobial antioxidant, | [41] |
| | *Rosmarinus officinalis* | Rosmarinic acid, betulinic acid, camphor, isoscutellarein 7-O-glucoside, caffeic acid, ursolic acid, luteolin, hesperidin, carnosic acid, 3'-O-β-D-glucuronide, diosmin, carnosol, epirosmanol, eriocitrin, rosmanol, diosmin, apigenin | Anti-inflammatory, antibacterial, antiviral, anti-rheumatism, antitumor, antioxidant, analgesic, diuretic, neuroprotective, anti-cerebral ischemia, antidepressant, antidiabetic, anti-dyslipidemia, anti-hepato-nephrotoxicity, cholinergic | [42] |
| | *Mentha piperita* | Hesperidin, buddleoside, menthone, rosmarinic acid, diosmin, menthol, didymin, | Carminative, antidiabetic, antitumor, antinociceptive, antibacterial, antifungal | [43] |
| Liliaceae | *Allium cepa* | S-trans-prop-1-enyl cysteine sulfoxide | Antimicrobial, antihypertensive, analgesic, hypolipidemic, antioxidant, immunoprotective, anti-inflammatory, antidiabetic | [44] |
| Plantaginaceae | *Digitalis purpurea* | Cardenolides | Cardiotonic, anticancer, cardioprotective | [45] |
| Solanaceae | *Withania somnifera* | Withanine, withaferin A withananine, withanolides, somniferine, somnine | Antioxidant, antifibrotic, amnesia, antineoplastic, antiproliferative, anti-inflammatory, neurodegenerative disorders | [46] |
| | *Solanum nigrum* | (+) Syringaresinol (II), solasodine, solamargine solanidine, (+)-medioresinol (III), β-solamarine, scopoletin (IV), nicotine, tetracosanoic acid (V), solanine, steroidal glycosides, beta-sitosterol (IV) | Anti-rheumatism, antiulcer, anti-inflammatory, antifungal, sedative, antitumor, anticonvulsant, antioxidant, stimulant, anticancer, hepatoprotective, antidiabetic | [47] |
| | *Datura stramonium* | Apoatropine, atropine, aposcopolamine, scopolamine, tropane alkaloids, hyoscamine, tigloidin | Anti-cholinergic, anti-inflammatory, anti-myopia, antimicrobial, antifungal, anti-asthma, anesthetics, bronchodilators, anti-cholinergic, anticancer | [48] |

**Table 2** (continued)

| Family | Botanical name | Secondary metabolites | Pharmacological effect | Reference |
|---|---|---|---|---|
| Verbenaceae | *Vitex negundo* | Viridiflorol, protocatechuic acid, flavonoids, 4-terpineol, oleanolic acid, β-caryophyllene, globulol, sabinene | Anti-arthritic, febrifuge, emmenagogue, expectorant, demulcent, astringent, appetizer | [49] |
| Zingiberaceae | *Zingiber officinale* | Gingerols, geranyl acetate, zingiberene, geranial | Anti-rheumatoid, antispasmodic, osteoarthritis, dyspepsia, anti-diarrheal, anti- anti-anorexia | [50] |
| | *Curcuma longa* | Curcumin | Anti-Alzheimer's, anti-arthritic, anti-inflammatory, antioxidant | [51] |

## Health-Promoting Activities of MAPs

### Antioxidant Properties

MAPs contain various compounds, such as phenolic compounds, known for their antioxidant properties and potential anticancer, anti-inflammatory, and neuroprotective actions [6]. Aromatic plants and their essential oils are rich sources of antioxidants, contributing to prevention of oxidative-stress related diseases such as heart diseases, diabetes, cancer, and Alzheimer's. Plant phenols, including flavonoids, exhibit antioxidant activity by inhibiting lipid peroxidation, making them protective for unsaturated lipids against oxidative damage [57]. Essential oils (like eugenol, carvacrol, and thymol) also influence lipid metabolism in animals by enhancing the activity of antioxidative enzymes and affecting the composition of fatty acids [58]. Various studies have reported the role of plant bioactives as potential antioxidants. In a study by Ashawat et al. [59], ethanolic extracts from *Areca catechu* demonstrated significantly higher antioxidant potential compared to extracts from *Punica granatum*, *Centella asiatica* and *Glycyrrhiza glabra*. Zahin et al. [60] examined *Acorus calamus* to evaluate its antioxidant potential and total phenolic content, establishing a significant relationship between phenolic content and antioxidant activity. Lu and Foo [61] investigated *Salvia officinalis* for its antioxidant activity and polyphenol content, highlighting rosmarinic acid and its derivatives as responsible for radical scavenging activity. They also noted that the high superoxide dismutase (SOD) activity of rosmarinic acid was due to its radical-scavenging catechols and the xanthine oxidase-inhibiting caffeic acid moieties (Table 3). In a study by Zhao et al. [62], the antioxidant activity of *Panax notoginseng* and *S. miltiorrhiza* and was compared, revealing that *S. miltiorrhiza* exhibited higher reducing power and scavenging activities against superoxide and hydroxyl radicals, although it showed weak hydrogen peroxide scavenging activity. Djeridane et al. [63] evaluated the free radical scavenging capacity and phenolic content of 11 Algerian medicinal plants using the 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) method, highlighting *Artemisia campestris* for its significant antioxidant activity compared to caffeic acid and ascorbic acid. HPLC analyses indicated a positive correlation between antioxidant activity and hydroxycinnamic derivative content. Singh et al. [64] investigated the antioxidant activity of *Vitex negundo* seeds using various methods, including tests for superoxide, hydroxyl, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity. They found that both raw and dry heated seed extracts exhibited the highest antioxidant activity, while lower activity was observed in

**Table 3** Health promoting activities of MAP extracts

| Name of MAPs | Type of extract | Bioactive compounds | Type of cell lines/type of study | Results/outcome of study | Reference |
|---|---|---|---|---|---|
| **Antioxidant properties** | | | | | |
| *A. catechu* | Ethanolic extract | Phenolic compounds | In-vitro | Antioxidant activity of *A. catechu* was found to be significantly higher compared to extracts from *Centella asiatica*, *Punica granatum*, and *Glycyrrhiza glabra* | [59] |
| *H. indicus, H. antidysenterica, P, zeylanica, A. calamus* | Methanolic extract | Phenols | In-vitro | Reduction of antioxidant for DPPH was recorded maximum for *H. indicus* (77.0%) followed by *P. zeylanica*, *A. calamus* and *H. antidysenterica* | [60] |
| *S. officinalis* | - | Flavone glycosides and rosmarinic acid derivatives | - | Significant reduction capacity of Mo(VI) to Mo(V) and superoxide radical scavenging activity, with values ranging from 220–300 SOD units/mg | [61] |
| *P. lentiscus, T. garganica, A. campestris, A. herba halba, A. arvensis, A. arboresens, O. africana, G. alypum, T. polium, R. alaternus, T. hirsuta* | - | Phenolic compounds | - | All extracts showed significant antioxidant activity compared to caffeic acid and were almost 3 times as high as ascorbic acid | [63] |
| *Pinus tabulaeformis, P. tabulaeformis f. shekanensis, P. tabulaeformis var. mukdensis, P. tabulaeformis var. umbraculifera, P. henryi, P. massoniana* | Essential oil | α-Pinene, bornyl acetate, β-caryophyllene, α-guaiene, germacrene D | In-vitro | Essential oil showed acceptable antioxidant activity, strongly correlated with total phenolic content | [96] |
| *Rosmarinus officinalis* | Essential oil | 1,8-cineole, camphor, α-pinene | | Essential oil exhibited more than 50% radical inhibition activity at 3.2 mg/ml | [97] |
| **Anti-inflammatory effects** | | | | | |
| *C. longa* | - | Curcumin | Human articular chondrocytes treated with IL-1β and TNF-α | Inhibition of IκBα phosphorylation, IκBα degradation, p65 phosphorylation and p65 nuclear translocation by suppression of IL-1β-induced NF-κB activation | [67] |
| *C. longa* | Essential oil-depleted turmeric fraction | Curcuminoids | Streptococcal cell wall (SCW)-induced arthritis | Reduction of joint inflammation in acute and chronic phases | [68] |

**Table 3** (continued)

| Name of MAPs | Type of extract | Bioactive compounds | Type of cell lines/type of study | Results/outcome of study | Reference |
|---|---|---|---|---|---|
| *Z. officinale* | - | 6-shogaol | Monosodium urate crystal-induced inflammation in mice | Reduction in paw volume, lysosomal enzymes, lipid peroxidation and pro-inflammatory cytokine TNF-α | [70] |
| **Antimicrobial activity** | | | | | |
| *O. majorana, N. cataria, O. vulgare, P. graveolens, C. winterianus* | Essential oil | Terpinen-4-ol, Nepetalactone, Citronellal, Thymol, Citronellol | MIC (% v/v) | MIC values showed *O. majorana* essential oil having highest effectiveness against *M. luteus* (1%), *B. subtilis* (0.5%), and *S. aureus* (1%). *C. winterianus* essential oil showed no inhibition against any bacterial strains | [77] |
| *C. citratus* | Essential oil | Geranial, Neral, Geraniol, Sulcatone, Linalool, β-Pinene | MIC (% v/v) | *S. aureus* (0.13), *S. epidermis* (0.35), *A. baumannii* (0.25–0.5), *P. aeruginosa* (> 1), *S. pyogenes* (0.0.6–0.13) | [78] |
| *C. nardus* | | Citronellal, Cis-geraniol, Citronellol, Elemol, Menthol, τ-Cadinol | | *S. aureus* (0.25–0.5), *S. epidermis* (0.5–1), *A. baumannii* (0.25), *P. aeruginosa* (> 1), *S. pyogenes* (0.13) | |
| *C. giganteus* | | p-Mentha-1(7),8-dien-2-ol, Carvone, Carveol, Cosmene | | *S. aureus* (0.13), *S. epidermis* (0.13–0.25), *A. baumannii* (0.03–0.06), *P. aeruginosa* (0.5–1), *S. pyogenes* (0.13) | |
| *O. gratissimum* | | β-Cymene, Iso-β-caryophyllene, Carvacrol, γ-Terpinene, β-Selinene, Trans-sabinene hydrate, p-Cymenene, Terpinen-4-ol, α-Selinene | | *S. aureus* (0.13–0.25), *S. epidermis* (0.35), *A. baumannii* (0.13), *P. aeruginosa* (> 1), *S. pyogenes* (0.06–0.13) | |
| *O. basilicum* | | Linalool, Eugenol, α-Bergamotene, γ-Cadinene, α-Ocimene | | *S. aureus* (0.25), *S. epidermis* (0.5), *A. baumannii* (0.13–0.25), *P. aeruginosa* (> 1), *S. pyogenes* (0.06) | |
| *L. multiflora* | | Pinocarveol, Terpineol, Linalool, Trans-β-farnesene, Caryophyllene, Myrtenal, Germacrene D | | *S. aureus* (0.25), *S. epidermis* (0.5), *A. baumannii* (0.25), *P. aeruginosa* (> 1), *S. pyogenes* (0.13) | |
| *E. camaldulensis* | | Terpinolene, β-Cymene, α-Terpineol, Terpinen-4-ol, Spathulenol, α-Gurjunene | | *S. aureus* (0.13–0.25), *S. epidermis* (0.25–0.5), *A. baumannii* (0.13–0.25), *P. aeruginosa* (0.5), *S. pyogenes* (0.25) | |

**Table 3** (continued)

| Name of MAPs | Type of extract | Bioactive compounds | Type of cell lines/type of study | Results/outcome of study | Reference |
|---|---|---|---|---|---|
| *Cinnamon* | Essentialal oil | Trans-cinnamaldehyde, trans cinnamyl acetate, β-phellandrene | MIC (% v/v) | MIC values against *P. Aeruginosa* (clinical isolates: 72) 0.05 (30.55%; n = 22), 0.025 (33.33%; n = 24), 0.0125 (47.22%; n = 34) | [79] |
| *C. odorata* | Essential oil | Linalool, Phenolylpropanoids benzyl acetate, Tricyclic sesquiterpene, α-Gurjunene, Monoterpene linalyl acetate | MIC | MIC up to 500 μg/ml inhibited growth of *E. coli* (MMCC24) and *S. aureus* (MMCC22) | [80] |
| *Hedychium coronarium* | Essential oil | β-Pinene; eucalyptol; linalool; coronarin-E; α-pinene; p-cymene; γ-terpinene, 10-*epi*-γ-eudesmol | *Candida albicans*, *Fusarium oxysporum* | Essential oil exhibited MIC of 3.12–400 μg/ml | [98] |
| *Juglans regia* | | α-Pinene,<br>β-Pinene,<br>β-Caryophyllene, germacrene, D limonene | *S. aureus,*<br>*E. coli,*<br>*S. typhi,*<br>*S. dysenteriae,*<br>*K. pneumonia,*<br>*B. subtilis,*<br>*S. epidermidis,*<br>*P. vulgaris,*<br>*P. aeruginosa* | Essential oil exhibited MIC of 15.62–62.50 μg/ml for the tested strains | [99] |
| **Anticancer activity** | | | | | |
| *P. nigrum,*<br>*C. sativa,*<br>*C. aurantifolia, T. triandra,*<br>*A. galanga,* | Mixture ethanolic extract | Total phenolic content of CBL-P: 648.19 mg GAE/mg, Total flavonoid content of CBL-P: 265.82 mg QE/mg | Cell lines:<br>SW620, HCT116,<br>A549, NCI-H460 | Inhibited cell proliferation in a concentration-dependent manner<br>Showed potent antimigration activity, particularly against NCI-H460 cells | [83] |
| *C. colocynthis* | Fraction extract: Hexane, Dichloromethane, Ethyl acetate, Butanol, Aqueous layer | Ferulic acid, Isovaleric acid, 1,4-Dideoxy-1,4-imino-D arabinitol, 4-Hydroxy-L-threonine, Lysine, Syringic acid, Chrysin, L-Carnitine, Cinnamic acid, Vanillic acid, Ascorbic acid, Apigenin, Palmitic acid, Kaempferol 3-*O*-(6″-*O*-acetyl) glycoside, *m*-Coumaric acid | Viability assay by MTT (cell line: MIAPaCa-2<br>A-431) | EtOAc extract inhibited MIA PaCa-2 and A431 cells by 54.4% and 68.3%. $IC_{50}$ values for PaCa-2 and A-431 cells were 17.4 μg/ml and 13.1 μg/ml. MD simulations indicated *C. colocynthis* extract's anti-pancreatic cancer activity through EGFR inhibition by Cucurbita-5(10),6,23-triene-3β,25-diol | [84] |

**Table 3** (continued)

| Name of MAPs | Type of extract | Bioactive compounds | Type of cell lines/type of study | Results/outcome of study | Reference |
|---|---|---|---|---|---|
| *F. racemose, D. loureirin, H. perforate* | Ethanolic extract | Loureirin A, Rutin, Hesperidin, Quercetin, Resveratrol, Quercitrin, Catechin, Loureirin B, Hesperetin | Cell viability of A549 cells by SRB assay | Extract of *D. loureirin* showed inhibition on growth of A549 cells with $IC_{50}$ values 38.45 μg/mL for 48 h and 76.25 μg/mL for 24 h<br>Extract of *D. loureirin* induces G0/G1 cell cycle arrest, down-regulates cyclin D1<br>Treatment of extract of *D. loureirin* promotes apoptosis by modulating apoptotic protein expression | [85] |
| *T. vulgaris,*<br>*T. serpyllum* | Essential oils (TVEO and TSEO) | TVEO: p-cymene, Thymol, Linalool; TSEO: p-cymene, Geraniol, Linalool, Geranyl acetate, Borneol | Cytotoxicity against human cell cancer line: cervical adenocarcinoma HeLa cells | EOs showed potent cytotoxic effects on human cancer cells with $IC_{50}$ values TVEO: 0.20–0.24 μL/mL and TSEO: 0.32–0.49 μL/mL. TVEO induced apoptosis via caspase-3 and caspase-8 activation<br>EOs reduced oxidative stress in normal cells<br>TVEO treatment increased tumor-suppressive miRNA expression in cancer cells | [87] |
| **Neuroprotective effects** | | | | | |
| *S. subspicata* | Solvent fractions | Apigenin, ellagic acid, myricetin-3-galactoside, vanillic acid, p-coumaric acid, syringic acid, | In vitro<br>Cytotoxic effect in SH-SY5Y neuroblastoma cells | SSPE is cytotoxic at ≥ 200 μg/mL, whereas SSW1 and SSDE display cytotoxic effects at ≥ 400 μg/mL<br>Remaining extract were cytotoxic at ≥ 800 μg/mL<br>$EC_{50}$ (μg/mL) value in cell viability assay (SSW2: 601.71, SSPE: 249.09, SSB: 631.59, SSM: 451.85, SSEA: 470.65, SSW1: 534.18, SSDE: 362.39) | [89] |
| *L. officinalis*,<br>*O. vulgare*, *S. officinalis,*<br>*M. piperita*,<br>*R. officinalis* | Essential oil | Carvacrol, thymol, limonene, 1,8-cineole, linalool, linalyl acetate, terpineol | In vitro<br>Scopolamine-induced toxicity in SH-SY5Y cells | Lavender essential oil pretreatment increased cell viability (75%) compared to scopolamine-only group at (50%)<br>Linalool (at dose: 10 and 30 μM) increased cell viability (53%) compared to scopolamine alone (38%) | [91] |

**Table 3** (continued)

| Name of MAPs | Type of extract | Bioactive compounds | Type of cell lines/type of study | Results/outcome of study | Reference |
|---|---|---|---|---|---|
| **Cardiovascular health benefits** | | | | | |
| *D. guineense* | Ethanol extract | - | In vivo<br>STZ-induced DM Male Wistar rats (mean weight = 215 ± 15 g and n = 25) | Diabetic rats treated with MEDG stem bark exhibited reductions in circulating lipid profile levels, except for HDL-C, which increased<br>Treatment with MEDG decreased in atherogenic index of plasma, atherogenic coefficient, and cardiac risk ratio ($p < 0.05$) | [93] |
| *T. terrestris*, *C. amada* | Aqueous extract | Phenols, Flavonoids, Alkaloids | In vivo anti-hyperglycemic activity<br>STZ-induced diabetic Albino Wistar rats male | CA and TT extract lowered blood glucose, increased glycogen and insulin<br>Urea, HbA1c and creatinine levels reduced significantly compared to Glibenclamide-treated groups | [94] |
| *M. suaveolens*, *L. stoechas*, *A. visnaga* | Essential oils | LSEO: Fenchone and camphor; AVEO: Linalool;<br>MSEO: piperitenone oxide | In vitro-α-amylase and α-glucosidase enzymes | $IC_{50}$ value of essential oils against alpha-amylase and α-glucosidase enzymatic activity. Against α-amylase LSEO: 3.00 mg/mL, AVEO: 3.37 mg/mL, MSEO: 3.51 mg/mL. Against α-glucosidase LSEO: 2.74 mg/mL, AVEO: 3.02 mg/mL, MSEO: 2.58 mg/mL | [95] |

*SSPE* petroleum ether extract, *SSW1* initial aqueous extract, *SSDE* diethyl ether extract, *SSDM* dichloromethane extract, *SSM* methanolic extract, *AIP* atherogenic index of plasma, *SSEA* ethyl acetate, *SSB* butanol organic phase extract, *AC* atherogenic coefficient, *CCR* cardiac risk ratio, *TT Tribulus terrestris*, *CA Curcuma amada*, *LSEO L. stoechas* essential oil, *AVEO A. visnaga* essential oil, *MSEO M. suaveolens* essential oil hydrothermally processed samples. These studies collectively suggest a relationship between phenolic composition and reducing capacity. The literature also extensively discusses the antioxidant capacity of various MAPs through in vitro and in vivo studies, indicating the significance of these plants in antioxidant therapy.

## Anti-Inflammatory Effects

Inflammation, a pivotal component of the cell-defense system, is triggered by cellular tissue loss, damage, infection, or irritation. These manifestations are integral to tissue repair and remodeling [65]. While synthetic anti-inflammatory drugs are available for treating various inflammation related disorders, their prolonged use is hindered by associated side effects [66]. Consequently, numerous MAPs have been investigated for their effective and convenient dosage forms in modern medicine. For instance, polyphenolic compound "curcumin," derived from rhizome of *Curcuma longa*, demonstrates potent anti-inflammatory effects. Curcumin achieves this by suppressing NF-kB-mediated pathways and inhibiting enzymes such as lipoxygenase (LOX), matrix metalloproteinase-9 (MMP-9), and cyclooxygenase (COX) [67] (Table 3). Additionally, curcumin modulates immune responses by inducing dendritic cells to promote intestinal T cells with a hyporesponsive phenotype. An in-vivo study reported, curcuminoids reduced inflammation in acute (75%) and chronic phases (68%) in arthritis and induce apoptosis, showing anti-arthritic efficacy [68]. Additionally, curcumin shows efficacy in inflammatory bowel disease, idiopathic inflammatory orbital pseudotumours, and neuroinflammatory disorders by suppressing inflammatory mediators and pathways. Its anti-proliferative activity in breast cancer and protective effects against human immunodeficiency viruse (HIV) and herpes simplex virus-2 infection suggest its broad therapeutic potential. Comparative studies indicate that a bio-enhanced formulation of turmeric exhibits significant anti-inflammatory effects, surpassing curcumin alone. These findings highlight curcumin as a promising therapeutic agent for various inflammatory disorders.

*Zingiber officinale*, commonly known as ginger and a staple in Indian cuisine. It has been used since ancient times to treat various ailments including arthritis, rheumatism, indigestion, constipation, ulcers, atherosclerosis, hypertension, vomiting, diabetes mellitus, and cancer [69]. The therapeutic effects of ginger are attributed to its pharmacologically active compounds such as 6,8,10-gingerol, 6,8,10-shagoal, and zingiberene. Research on 6-shagoal, a compound found in ginger, has investigated its clinical efficacy in gouty arthritis using a monosodium urate-induced inflammation model in mice. Studies have shown that 6-shagoal can reduce inflammation in gouty arthritis by decreasing levels of β-glucourinidase, TNF-α, and lactate dehydrogenase [70]. In vitro studies using extracts from ginger rhizome and callus have demonstrated a significant decrease in pro-inflammatory cytokines (TNF-α, IL-1, and IL-6) and an increase in anti-inflammatory cytokines (IL-10 and TGF-β), indicating its potential in managing various inflammation-mediated disorders [71]. Various in vivo and in vitro models have been used to assess potential of ginger in preventing inflammation. The improvement of rat paw edema and downregulation of pro-inflammatory cytokines TNF-α, myeloperoxidase, PGE2, IL-6 and monocyte chemoattractant protein-1 and suggest that the anti-inflammatory activity of ginger is due to inhibition of macrophage and neutrophil activation as well as by affecting monocyte and leukocyte migration [72]. Furthermore, numerous chemical constituents of MAPs belonging to different families have been investigated for their anti-inflammatory effects. For example, *Salvia officinalis* (targeting AST, ALT, PGE2) [73] and *Arctium lappa* targeting IL-6, MAdCAM-1, TNF-α, MIP-2, MCP-1, Th1, MAPK, Th17, ICAM-1, and VCAM-1 [74].

## Antimicrobial Activities

The increasing interest in replacing synthetic antimicrobial agents with natural alternatives has spurred significant research into natural reservoirs demonstrating antimicrobial effectiveness in diverse applications [75]. Numerous studies have documented the antibacterial properties of MAPs against plant bacterial pathogens [76]. Rathore et al. [77] investigated the antimicrobial potential of essential oils (EOs) derived from MAPs grown in the Western Himalayan region, including *Origanum majorana*, *O. vulgare*, *Pelargonium graveolens*, *Cymbopogon winterianus*, and *Nepeta cataria*. EOs from *O. majorana* and *O. vulgare* exhibited broad-spectrum antimicrobial activity against various bacterial strains, including *Bacillus subtilis*, *Escherichia coli*, *Micrococcus luteus*, *Klebsiella pneumoniae*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*. *O. majorana* essential oil was particularly effective, with minimum inhibitory concentration (MIC) values of 0.5% against *B. subtilis* and 1% against *M. luteus* and *S. aureus*, while *O. vulgare* showed significant efficacy with MIC values of 2% against *E. coli* and *K. pneumoniae*. Additionally, *P. graveolens* and *N. cataria* EOs inhibited *M. luteus* at concentrations of 1% and 0.5%, respectively. A study conducted in Benin and Burkina Faso assessed 23 plant samples against 20 bacterial and fungal isolates from skin lesions. Nine EOs exhibited MICs below 0.35% v/v, indicating significant activity. Further, GC–MS analysis revealed these active EOs to be rich in oxygenated monoterpenes, particularly aldehydes, alcohols, phenols, and their derivatives [78]. In another study, antimicrobial activity of 16 EOs against multidrug-resistant (MDR) *P. aeruginosa* clinical isolates was investigated, along with their impact on mex efflux pumps gene expression. Cinnamon EO was identified as the most potent antimicrobial agent, with effectiveness at concentrations as low as 0.05% v/v against all MDR *P. aeruginosa* isolates. RT-PCR analysis indicated under-expression of mexA and mexB (66.5%) upon exposure to cinnamon EO, suggesting disruption of RNA messaging system. This study highlighted cinnamon EO's potential as an adjuvant treatment against MDR *P. aeruginosa*, offering significant therapeutic properties [79]. Elkenawy et al. [80] explored *Chromolaena odorata* essential oil (YY-EO) as an antimicrobial agent against twelve multidrug-resistant pathogens. YY-EO exhibited efficacy up to 536 μg/ml, with varying susceptibilities among different pathogens. Additionally, YY-EO showed cytotoxicity against normal skin tissue culture at concentrated doses, emphasizing its concentration-dependent toxicity concerns. Aleksandra et al. [81] reported on antimicrobial activity of EOs extracted from *Piper cubeba* (cubeb pepper) and *P. nigrum* (black pepper). Cubeb pepper EO exhibited greater inhibitory effects against *Candida albicans,* and *B. cereus* compared to black pepper essential oil, although neither oil showed bactericidal activity against *Salmonella enterica* and *B. cereus*. These studies underscore significant antimicrobial potential of MAPs from diverse sources against various pathogens, highlighting their promising role as natural alternatives to synthetic antimicrobial agents.

## Anticancer Potential

Natural plant extracts play a vital role in cancer chemotherapy, with over 50% of chemotherapeutic drugs derived from them. Despite their extensive use, only about 15% of these extracts have been thoroughly studied for bioactive compounds [82], highlighting the underexplored potential of MAPs in cancer treatment and the need for further research into their anti-cancer properties. One investigation focused on exploring anticancer and antimigration attributes of Clear Belongs Plus extract (CBL-P), consisting of five medicinal plants: *P. nigrum*, *Cannabis sativa*, *Citrus aurantifolia*, *Tiliacora triandra*, and *Alpinia galanga*. The efficacy of CBL-P in suppressing cell growth was assessed, revealing significant antiproliferative effects on four cell lines: SW620, NCI-H460, HCT116 and A549. CBL-P inhibited cell viability in a concentration-dependent manner, with distinct $IC_{50}$ values observed for each cell line at 24, 48, and 72 h of incubation, demonstrating comparable effects between colorectal cancer (SW620 and HCT116) and non-small cell lung cancer (A549 and NCI-H460) cell lines. Moreover, CBL-P exhibited effective antimigration activity, with concentrations of 3.75, 7.5, and 15 μg/mL significantly inhibiting cell migration in all tested cell lines, particularly demonstrating efficacy against the aggressive NCI-H460 cell line [83]. Another study aimed to characterize components of *Cucumis colocynthis* fruit and assess their anticancer potential against MIAPaCa-2 and A431 cells. The MTT test was employed to evaluate anticancer activity, revealing the EtOAc fraction to exhibit the highest cytotoxic effect, inhibiting MIAPaCa-2 and A-431 cells by 54.4% and 68.3%, respectively, while exerting minimal impact on normal cells (BJ-1). Furthermore, EtOAc extract displayed $IC_{50}$ values of 17.4 μg/ml and 13.1 μg/ml against MIAPaCa-2 and A-431 cells, respectively, significantly surpassing positive control drug, doxorubicin. LC/MS analysis tentatively identified Cucurbita-5(10),6,23-triene-3β,25-diol as a major cucurbitacin derivative in the extract, with docking experiments and molecular dynamics simulations suggesting its potential as an EGFR inhibitor, contributing to the observed anti-pancreatic cancer activity [84]. Huang et al. [85] evaluated efficacy of extracts obtained from *Ficus racemose*, *D. loureirin*, and *Harrisonia perforate* against A549 lung adenocarcinoma cells. Among these extracts, only *D. loureirin* exhibited cytotoxicity, inducing cell cycle arrest at the G0/G1 phase and apoptosis in A549 cells by downregulating cyclin D1, CDK-4, CDK-2, anti-apoptotic proteins (Bcl-2, surviving, Bcl-xl), and upregulating apoptotic proteins (cleaved-caspase-3, cleaved-PARP-1), thus demonstrating the anti-cancer potential of *D. loureirin* extract against non-small-cell lung cancer [85]. In another investigation, the cytotoxic potential of the ethanolic extract obtained from *Cymbopogon schoenanthus* was assessed against various cancer cell lines and HUVEC normal cell lines using MTT assay. The extract exhibited high selectivity and efficacy against prostate (DU 145) and breast cancer cell lines (MDA-MB-435 and MCF-7), with $IC_{50}$ values as low as 30.51, 0.7913, 12.841 μg/ml, respectively. In silico modeling using molecular dynamics revealed that eudesm-5-en-11-ol, piperitone, and 2,3-dihydrobenzofuran exhibited superior binding affinity and stability against Polo-like kinase (PLK1 protein), a cancer molecular target, compared to the reference drug [86]. Preljevic et al. [87] reported anticancer properties of two *Thymus* species, namely *T. vulgaris* and *T. serpyllum* derived EOs (TVEO and TESO). These EOs exhibited potent cytotoxic effects on human cancer cells, with TVEO showing $IC_{50}$ values of 0.20–0.24 μL/mL and TSEO showing 0.32–0.49 μL/mL. Furthermore, TVEO induced apoptosis in HeLa cells via caspase-3 and caspase-8 activation, while TSEO triggered caspase-3-mediated apoptosis.

## Neuroprotective Effects

MAPs exhibit neuroprotective effects primarily through their antioxidant properties, scavenging harmful free radicals to prevent oxidative damage to neurons. Additionally, these plants may modulate inflammatory pathways and promote neurogenesis, further contributing to their neuroprotective mechanisms against neurological disorders [88]. For instance, a study investigated the neuroprotective activity of *Satureja subspicata* by generating different solvent fractions, majority of these fractions were found to be abundant in phenolics and flavonoids. Four SS extracts showed a partial rescue of cell viability in Aβ25–35-treated SH-SY5Y neuroblastoma cells, with original aqueous extract exhibiting highest effectiveness. This protective effect was also observed in retinoic acid differentiated cells, indicating the potential therapeutic significance of *S. subspicata* in combating neurodegenerative disorders [89]. Another study investigated the neuroprotective effect of Lily bulb and Rehmannia decoction drug having serum (LBRDDS) against chronic corticosterone (CORT)-induced nerve cell cytotoxicity. The findings of Pan et al. [88] demonstrate that LBRDDS has the potential to enhance cellular activity, reduce lactate dehydrogenase cytotoxicity, restore neurotransmitter balance, alleviate inflammatory damage, downregulate miRNA-144-3p expression, increase mRNA and protein expression levels of VGAT and Gad-67 and enhance synthesis and transport of GABA. In a study by Caputo et al. [90], the neuroprotective and anti-cholinesterase effects of carvacrol and p-Cymene were investigated. Neuroprotective effects were evaluated on $H_2O_2$-induced stress in SH-SY5Y cells, with caspase-3 expression analyzed using Western blotting assays. Carvacrol demonstrated inhibitory activity against butyrylcholinesterase ($IC_{50}=32.7$ µg/mL) and acetylcholinesterase ($IC_{50}=3.8$ µg/mL), while its anti-alpha-amylase activity yielded an $IC_{50}$ value of 171.2 µg/mL. Pretreatment with maximum non-toxic dose of carvacrol and p-cymene reduced caspase-3 expression compared to cells treated with $H_2O_2$ alone. These results suggest that carvacrol and p-cymene may serve as neuroprotective agents against oxidative stress and possess in vitro anti-enzymatic activity. Chen et al. [91] investigated neuroprotective and anticholinesterase activities of EOs obtained from plants of the Lamiaceae family (*Lavandula officinalis*, *O. vulgare*, *Mentha piperita*, *R. officinalis*, and *S. officinalis*). Results showed that oregano leaf EO exhibited inhibitory activity against butyrylcholinesterase and acetylcholinesterase, and pretreatment with lavender flower EO provided protection against scopolamine-induced toxicity at 30 µg/mL. Furthermore, at a concentration of 100 µg/mL, peppermint, sage, rosemary, and oregano leaf EOs exhibited neuritogenic activity, with the highest activity observed for oregano leaf.

### Cardiovascular Health Benefits

According to a report from the World Heart Federation, global deaths attributable to cardiovascular disease (CVD) increased from 12.1 million in 1990 to 20.5 million in 2021. CVD maintained its status as the leading cause of mortality worldwide in 2021, with approximately four-fifths of all CVD-related deaths occurring in low- and middle-income nations [92]. Given this alarming trend, research into the cardiovascular health benefits of medicinal plants is increasingly encouraged for their potential in managing CVD. In a study the impact of ethanol extract (methanol fraction) of *Dialium guineense* (MEDG) stem bark on cardiovascular risk factors in diabetic rats is investigated where streptozotocin (STZ)-induced diabetes mellitus (DM) was treated with metformin or MEDG for 21 days. Results indicated that STZ-induced DM elevated plasma lipid levels and atherogenic indices while reducing HDL-C. Further, MEDG treatment significantly mitigated lipid profile abnormalities and improved atherogenic indices, indicating potential cardiovascular protection in diabetic rats [93]. In another study diabetic-induced rats were treated with a combined herbal aqueous extract of *Curcuma amada* and *Tribulus terrestris* and for 37 days. Results demonstrated that treatment with *C. amada* and *T. terrestris* and extracts increased glycogen, insulin levels, and reduced blood glucose levels in diabetic rats. Additionally, levels of creatinine, HbA1c and urea were reduced in extract treated groups as compared to those treated with the antidiabetic drug Glibenclamide. Furthermore, by the end of the study period rats treated with the herbal extracts exhibited significant net body weight gain [94]. Another study reported antidiabetic activity of essential oils obtained from *Lavandula stoechas*, *Mentha suaveolens* and *Ammi visnaga*. Results showed that essential oils exhibited inhibitory effects ($p<0.05$) on α-glucosidase and α-amylase in dose dependent manner [95].

## Conclusion and Future Directions

MAP's hold great significance as sources of bioactive compounds with a range of health benefits. Their diverse phytochemicals, such as essential oils and antioxidants, offer potential therapeutic effects including antimicrobial, anti-inflammatory, and immunomodulatory properties. Beyond traditional remedies, MAPs are valuable in modern pharmaceuticals, cosmetics, functional foods, and natural dyes, reflecting their versatility and economic significance. Looking forward, future research should focus on exploring the specific bioactive compounds in MAPs and understanding their mechanisms of action, especially in terms of synergistic effects and combination therapies. Sustainable practices are essential to protect MAPs, by focusing on responsible farming, habitat conservation, and fair-trade initiatives. Additionally, exploring MAPs' role in adapted medicine and precision nutrition could lead to customized therapeutic approaches based on individual responses to MAPs' bioactives. Increasing awareness and integration of MAPs into healthcare systems is also important. This involves educating healthcare professionals and the public about their health benefits. By advancing research, promoting sustainability, and incorporating MAPs into healthcare practices, we can unlock their full potential to address global health challenges and improve well-being.

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**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

**Competing Interests** The authors declare no competing interests.

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