




Extraction technologies and structural elucidation of polysaccharides from herbs and spices: Connecting molecular characteristics to biofunctional properties

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ABSTRACT

For a long time, herbs and spices have been known for their medicinal and culinary uses. Beyond their conventional uses, herbs and spices can serve as important sources of polysaccharides, a class of compounds known for their diverse biological activities, hence their potential health benefits. Interest in polysaccharides derived from herbs and spices has increased substantially in recent years; however, there remains a lack of reviews summarizing the findings from all of these studies. Hence, this review aims to evaluate recent major studies on polysaccharides from herbs and spices focusing on the extraction and analytical method used, the physico-chemical properties, bioactivities, and their potential application in pharmaceutical, nutraceutical, food, and cosmetic industries. The extraction methods, along with the different parts of herbs and spices used, significantly impact the structure, and characteristics of the polysaccharides extracted from herbs and spices. These factors ultimately influence the polysaccharides' biological activities including antioxidant, anti-inflammatory, anti-diabetic and immunomodulatory effects.

1. Introduction

In general, polysaccharides are complex carbohydrate molecules composed of long chains of monosaccharide units, interconnected by glycosidic bonds [1]. Examples of monosaccharide units are glucose, mannose, and xylose, among others. It is called homopolysaccharides, or homoglycans if the building block of polysaccharides consists of a single type of sugar monomer [2]. Starch and cellulose are common examples of homoglycans. On the contrary, heteroglycans refer to polysaccharides with different monosaccharide units. According to Mohammed et al. [3], polysaccharides also carry vital tasks including various physiological processes such as immune function and blood clotting. Abundant natural polysaccharides can be obtained from various renewable sources including the various parts of plants such as the leaves and roots, algae and even microorganisms such as fungi. Many studies have been conducted, and the beneficial properties and function of polysaccharides

obtained from these various sources have been demonstrated. However, this review focuses polysaccharides from herbs and spices.

The terms 'herbs' and 'spices' have a distinction in that herbs are the leafy parts of non-woody plants while spices originate from the plant's roots, flowers, fruits, seeds or bark [4,5]. Another accepted definition for 'herbs' is a plant or any part of a plant that can function as medicine, flavoring or food. This general definition is necessary to include known herbs such as rosemary, thyme, and lavender. Other herbs include basil, ginger, galangal, and lime leaves, while commonly known spices include cloves, turmeric, cinnamon, star anise and such. However, many plant species may be classified as both herbs and spices, depending on the plant part utilized and its state of use. For instance, basil can be considered as an herb when their leaves are used but it can also be classified as spice when the basil seed is used.

Peter and Babu [6] note that around 4000 years ago, herb gardens were cultivated in Egypt, often associated with temples as these gardens

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provide essential herbs and sacred flowers for daily worship and rituals. The author also mentions, in earlier times, people used an approach called the Doctrine of Signatures where medicinal plants were selected for the color and shape of their leaves; plants with red flowers were used to treat bleeding disorders while heart-shaped leaves were used to treat heart problems. According to Chaudhary and Lamichhane [7], herbs can be classified into three groups based on their purpose: food herbs, medicinal herbs and poisonous herbs. Food herbs are herbs that have normal and positive effects on the body while medicinal herbs are herbs that are specifically used as medicine. Poisonous herbs are herbs that have potent acute or long-term toxic effects. The use of herbs and spices as medicine is undisputed as these botanical treasures are found to be rich in bioactive compounds that contribute to biological activities including antioxidants, anti-inflammatory, and anti-diabetic. Before the rise of modern medicine, populations worldwide have been using herbs and spices native to their place as the primary medicinal options. Many South Asian countries use turmeric (*Curcuma longa* L.) as an antiseptic and an antibacterial agent for cuts and burns [8]. In traditional Chinese medicine, *Gynostemma pentaphyllum* Makino, commonly known as Jiaogulan in Chinese, has been used as herbal tea to treat illnesses such as diabetes, hepatitis, and cardiovascular diseases [9]. *Sambucus nigra* L., commonly known as elderberry, is a plant from Europe that has been used in folk medicine to treat colds and flu [10].

Recent advances in polysaccharide research have refined current understanding of their structural complexity, functional modification, and application potential. Increasing emphasis has been placed on structure-activity relationships (SAR), with evidence showing that structural parameters, including molecular weight, monosaccharide composition, glycosidic linkages, and functional group substitutions, critically influence biological activities, including antioxidant, immunomodulatory, and hypoglycemic effects [4,11–13]. In parallel, chemical, physical, and biological modification strategies have been developed to address intrinsic limitations such as poor solubility and bioavailability, thereby improving physicochemical properties and functional performance [12,14,15]. Moreover, the emergence of polysaccharide-based delivery systems, particularly nano-structured assemblies, has enabled enhanced stability, bioavailability, and controlled release of bioactive compounds, expanding their therapeutic applicability [16–18]. Despite these advances, current research remains largely focused on primary structural characterization, with limited investigation of higher-order structures, detailed molecular mechanisms, and translational applications [11,13,19]. These limitations highlight the need for integrated, mechanism-driven, and application-oriented research, particularly for polysaccharides derived from herbs and spices, which remain underrepresented in systematic and comparative analyses.

In this context, the longstanding use of herbs and spices in traditional medicine provides a valuable foundation for investigating their bioactive constituents, particularly polysaccharides, which have emerged as key contributors to their therapeutic properties. This prompted early researchers to conduct studies on the constituents and the properties of these medicinal herbs and spices, leading to the discovery of bioactive compounds, including polysaccharides, which demonstrate biological activities such as antidiabetic, immunomodulatory and antibacterial activity. Despite substantial research activity, there is a lack of comprehensive reviews that systematically synthesize the extraction, structural characteristics, and bioactivities of polysaccharides from herbs and spices. Hence, this paper aims to review recent major studies on polysaccharides in common herbs and spices in terms of the extraction and analytical methods, physicochemical properties and biological activity of the polysaccharides. The sources for this review article were collected from ScienceDirect (<https://www.sciencedirect.com/>), Scopus (<https://www.scopus.com/>) and Google Scholar (<https://scholar.google.com/>) in most recent years up to 2026 using ‘polysaccharides’, ‘herbs’, and ‘spices’ as the keywords. The bar chart in Fig. 1 illustrates the number of studies identified using the “polysaccharides”, “herbs”, and

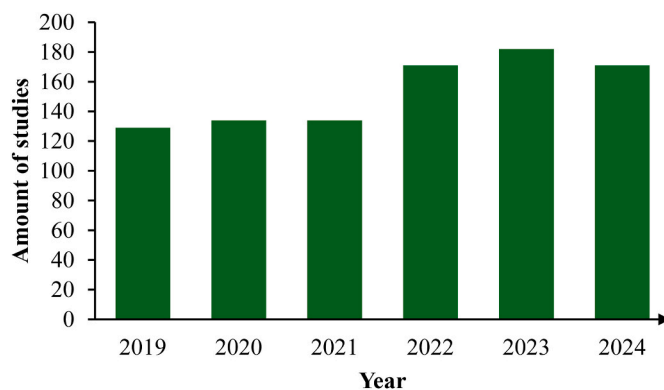


Fig. 1. Trends in published research and review articles with “polysaccharides”, “herbs”, and “spices” as the keywords in the last six years (2019-2024).

“spices” as the keywords. The number of studies related to the used keywords increased steadily from 2019 until 2021. This was followed by a dramatic surge in research from the year 2021 to 2023. The overall increasing trend throughout recent years reflects a growing scientific interest and recognition of the potential benefits of polysaccharides from herbs and spices. Therefore, this review is essential in order to keep pace with the rising surge of articles published in recent years.

2. Economical review

Several countries play a significant role in the world's herb and spice market where 70-80% of the world's spice production is from India alone [20]. Every year, India produces over 1 million tons of turmeric primarily cultivated in states including Tamil Nadu, Telangana, and Maharashtra. Additionally, the country contributes 1.5 million tons of chili pepper annually with China and Mexico also being major suppliers. China is also one of the major suppliers, mainly known for its garlic production, accounting for 80% of the global supply with an output that exceeds 22 million tons each year. Southeast Asian countries such as Vietnam and Indonesia are known for their production of pepper, cloves and cinnamon. According to Jae-Han et al. [21], Vietnam produced approximately 220,000 tons of black pepper in 2021, making them the top global producer followed by Indonesia contributing 60,000 tons of black pepper and India contributing 85,000 tons. Nowadays, the increased awareness among consumers to choose healthy and natural ingredients has inevitably increased the market value of the herbs and spice sector. There is also an increasing demand for exotic flavors in foods and advancements in processing technologies, along with investment in research and development for new spice blends and health-oriented products.

The herb and spice markets have been forecast to grow its compound annual growth rate (CAGR) of 3.6% in 10 years from 2024 to 2034 [22]. India is one of the important suppliers of popular and commonly known spices such as cumin, ginger, turmeric and chili. Throughout the forecast period, the sales of these herbs and spices are expected to grow at a rate of 4.3% per year [22]. The European Union leads the spice imports worth US\$2.2 billion consisting of 44% retail sales to consumers, 15% to the catering sector and 41% to the food manufacturing sector. Meanwhile, the annual spice trade in South Africa is valued at up to US\$94 million and it is expected to increase as consumers seek and desire more flavorful food. This economic overview highlights the expanding economic significance of herbs and spices, reflected in the sustained growth of both production and market value.

The rapid growth of the herb and spices market raises certain sustainability issues. Among them are soil degradation and deforestation due to intensive farming to meet the global demand-supply. In Vietnam and Indonesia, clove and pepper production involve deforestation to expand farmland. Similarly, the production of turmeric and chili in India

can rely heavily on water and fertilizer, which ultimately can contribute to environmental pollution [23]. Therefore, it is crucial to adopt sustainable practices to address these issues. Traditional agricultural practices such as crop rotation, double cropping, and organic farming can help mitigate the adverse effects of climate change [24]. In addition, implementing fair trade and ethical sourcing is vital to ensure the economic benefits from the herbs and spices market reach the local farmers and community, promoting equitable growth on all sides. As global demand for herbs and spices continues to rise, prioritizing sustainability is essential to ensure that the industry can meet future needs without compromising the integrity of the environment or social well-being.

3. Polysaccharides in herbs and spices

Other studies have focused more on chemical components such as flavonoids, phenols, and alkaloids in herbs and spices and their benefits. These phytochemicals, including flavonoids, phenolic compounds, tannins, and alkaloids, present in herbs and spices can be utilized as a treatment for viruses such as Ebola and dengue. For example, ginger extract has been reported to exhibit inhibitory activity against the Chikungunya virus, a mosquito-borne pathogen associated with acute febrile illness and severe rheumatic symptoms [25]. However, there is an increase in recent studies that focus on polysaccharides found in herbs and spices showing that they can be beneficial for human health.

The total number of documents found from Scopus in the year 2019 to 2024, using the keywords “herbs”, “spices” and “polysaccharides”, is 921 documents. The increasing trend of studies on polysaccharides in herbs and spices from the year 2000 to 2024 can be easily seen in Fig. 2. The increasing body of research on polysaccharides of herbs and spices is warranted as there remains considerable unexplored potential for this compound. Furthermore, the growing interest in polysaccharides can be attributed to the availability of herbs and spices in markets. The upsurge of research also supports the time-honored generational traditions of using these plants for health benefits.

Fig. 3 represents the statistics of published findings for keywords “herbs”, “spices” and “polysaccharides” across various fields of study based on Scopus findings for the past 6 years (2019–2024). Published research on polysaccharides from herbs and spices is primarily concentrated in pharmacology, toxicology, and pharmaceuticals (18.21%), with comparatively lower representation in agricultural and biological sciences (15.91%), medicine (15.68%), biochemistry, genetics and molecular biology (15.51%), and chemistry (8.43%). These data indicate that polysaccharides from herbs and spices carry health benefits for humans. Below are some of the studies and research findings on polysaccharides extracted from various parts of herbs and spices as these extractions can unveil distinct physicochemical properties and biological activities.

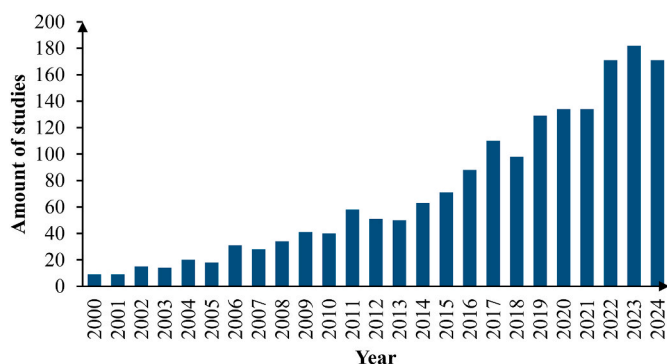


Fig. 2. Bar chart on the number of published findings for keywords “herbs”, “spices” and “polysaccharides” from the year 2000 to 2024.

3.1. Leaves

Thymus quinquecostatus Celak., an edible herb, has been used as a folk medicine for a long time in China for alleviating syndrome and pain from conditions including arthritis, stomachache, and gastroenteritis [26]. Li et al. [27] extracted polysaccharides from *T. quinquecostatus* Celak. leaves which show strong antioxidant activity and strong inhibitory effects on α -amylase and α -glucosidase. The authors found that the inhibitory effects of *T. quinquecostatus* Celak. polysaccharides on α -glucosidase and α -amylase show inhibition rates up to 57% which is near the value of the inhibition rate of the positive control group, acarbose (64%). As for the antioxidant activities, at 1 mg/mL, the polysaccharides from *T. quinquecostatus* Celak. Shows a potent 2, 2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging capacity of up to 85.25% and a strong 2,2'-azino-bis (3-ethyl-benzothiazoline-6-sulfonic acid), also known as ABTS, radical free scavenging activity of up to 96%. This study reveals that the polysaccharides from *T. quinquecostatus* Celak. Can potentially serve as natural hypoglycemic and antioxidant agents. Additionally, *Clinacanthus nutans* Lindau, native to Southeast Asia, exhibits a wide range of pharmacological activities, including antimicrobial, antioxidant, anti-inflammatory, and antidiabetic effects. Its leaf extract has also shown a growth-inhibitory effect on the MDA-MB-231 triple-negative breast cancer cell line with an IC₅₀ value of 0.191 mg/mL at 72 h, suggesting potential therapeutic relevance in breast cancer treatment [28]. Another study by Devasvaran et al. [29] shows that polysaccharides from *C. nutans* Lindau leaves also show potential as good natural antioxidants, having IC₅₀ values of 0.742 mg/mL for DPPH radical scavenging activity and 0.572 mg/mL for ABTS radical scavenging activity for the polysaccharides extracted using acid extraction method. Table 1 below gives an overview of the study done on polysaccharides extracted from different parts of herbs and spices.

Althaea officinalis L., commonly known as the marshmallow plant, is a perennial herb originating from Europe and Western Asia that belongs to the genus *Althaea* of the family Malvaceae [47]. Tests conducted on polysaccharides extracted from *A. officinalis* L. reveal that this compound, along with its good antimicrobial properties especially towards *Escherichia coli*, has the potential to be a treatment for infertility as the sperm reserves [30]. The authors found that the leaf of *A. officinalis* L. polysaccharides most effectively inhibits *E. coli* from inhibition zones of 5.23 mm at a concentration of 4 mg/mL up to an inhibition zone of 15.76 mm at a concentration of 20 mg/mL. At a dose of only 1%, the polysaccharides from *A. officinalis* L. manage to increase the daily sperm production and its efficiency in the testis of the tested rats up to 78%. The plant genus of Zingiber including the *Zingiber mioga* (Thunb.) Rosc, known as Japanese ginger, displayed many biological activities such as antimicrobial, antioxidant, hypoglycemic and anti-inflammatory [48]. The leaves of *Z. mioga* were used for practical uses; the Japanese use the leaves as food wrappers to prevent spoilage, and to impart a pleasant ginger taste and flavor [49]. The polysaccharides from *Z. mioga* leaves show antioxidant activity as well as anticoagulant activity, having great potential to be a novel cardiovascular-protective candidate [31]. The authors observed that the fibrinogen-lowering and activated-partial thromboplastin time (APTT) prolonging activities of *Z. mioga* leaves polysaccharides were comparable with the positive control group, heparin. At a concentration of 5 mg/mL, the APTT of *Z. mioga* polysaccharides was 175.67 s, slightly lower than heparin. At the same concentration, *Z. mioga* polysaccharides managed to lower fibrinogen content to 73.03 mg/dL, slightly higher than heparin.

Overall, polysaccharides derived from leaves are frequently associated with pronounced antioxidant and enzyme inhibitory activities, particularly against α -amylase and α -glucosidase, indicating potential relevance in managing oxidative stress and metabolic disorders. This functional profile may be linked to the exposure of leaves to environmental stressors (e.g., light and oxidative conditions), which can stimulate the biosynthesis and accumulation of bioactive polysaccharides

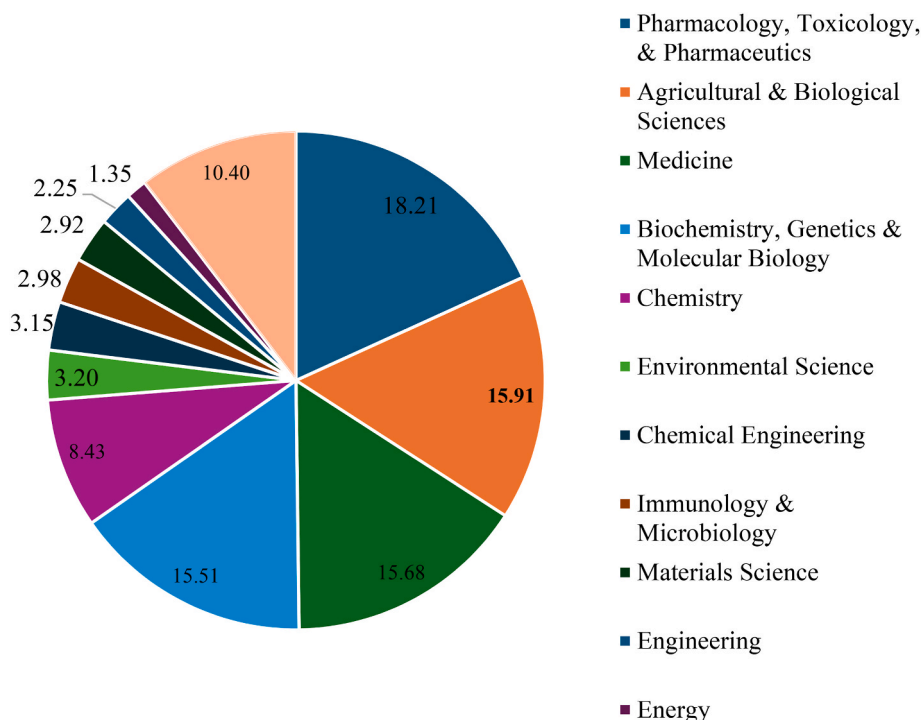


Fig. 3. Statistics of published findings for keywords “herbs”, “spices”, and “polysaccharides” across various fields in recent years (2019-2024).

with enhanced radical-scavenging capacity and interactions with metabolic enzymes. In addition, leaf-derived polysaccharides often exhibit multifunctional bioactivities, including antimicrobial, anticoagulant, and antiproliferative effects, reflecting their structural diversity. Thus, these findings suggest that leaves represent a versatile source of functionally active polysaccharides, particularly suited for applications targeting oxidative and metabolic pathways.

3.2. Roots

The root of *Achyranthes bidentata* Blume, cultivated in many provinces in China including Henan, Shanxi, Shandong and Jiangsu, is a well-known Traditional Chinese Medicine used to treat osteopenia of the lumbar and knees, spasms, and limb flaccidity [50]. Zhang et al. [32] studied the osteoprotective effects of *A. bidentata* Blume polysaccharides; the polysaccharides manage to restore bone mineral content and increase protein levels related to osteogenic gene expression in MC3T3-E1 cells. The authors used alizarin red S (ARS) staining by incubation in 10% cetylpyridinium chloride to visualize mineral deposition on MC3T3-E1 revealed that the treatment of 50 $\mu\text{g}/\text{mL}$ *A. bidentata* Blume polysaccharides managed to enhance mineral deposition by 34.2%. The authors also showed that the protein of Runt-related transcription factor 2 (RUNX2), Bone sialoprotein (BSP), and Osterix (Osx) of MC3T3-E1 cells were upregulated by 51.9%, 22.1% and 40.6% after treated with *A. bidentata* Blume polysaccharides. According to Xue et al. [47], fresh *A. officinalis* (AO) roots contain high amounts of mucilaginous polysaccharides that are traditionally used for the clinical treatment of respiratory tract diseases such as bronchitis, and tracheitis as well as for the development of whitening agents in the cosmetic industry. Meanwhile, a study by Karimi et al. [30] shows *A. officinalis* L. root polysaccharides have strong DPPH radical scavenging activity where the value of IC_{50} is at 1.53 mg/mL . *Panax ginseng* L. (ginseng) root is a common medicinal ginseng as it has been a role as a traditional herb throughout many Eastern countries including China, Korea, and Japan [34]. Ginseng polysaccharides exhibit an inhibitory effect on HCT116 p21 $^{-/-}$ cell and decreased the number of viable HCT116 p21 $^{-/-}$ cells by 29.4% with only an IC_{50} value of 0.09 mg/mL [33,34]. Apart from the

anti-tumor activity, the ginseng polysaccharides also exhibit antioxidant activity; the purified neutral root ginseng polysaccharides exhibit a 43% scavenging effect on DPPH radicals at 1.12 mg/mL [35].

In contrast, root-derived polysaccharides are more commonly associated with structural and storage roles, which are reflected in their biofunctional properties. These polysaccharides frequently exhibit osteoprotective, immunomodulatory, and antitumor activities, likely related to their relatively higher molecular weight and more complex structural organization. Their ability to enhance mineral deposition, regulate osteogenic gene expression, and inhibit cancer cell proliferation suggests a significant role in cellular regulation and tissue remodeling processes. Despite antioxidant activity is also observed, it appears to be secondary to these regulatory functions. Therefore, roots can be regarded as a key source of polysaccharides with therapeutic potential, particularly in applications related to bone health, immune modulation, and chronic disease management.

3.3. Stems

Polysaccharides from the stem of *P. ginseng* L. exhibit stronger DPPH radical scavenging activity (90% scavenging ratio) compared to the root [35]. The polysaccharides from the stem of this herb/spice also display a significant ameliorative effect on amyloid- β_{1-42} ($\text{A}\beta_{1-42}$) induced apoptosis (neuroprotective effect) where it has the potential to be developed as a neuroprotective agent [35]. The authors observed that 10 to 20 $\mu\text{g}/\text{mL}$ of ginseng polysaccharides significantly improved the viability of the PC12 cells that were exposed to $\text{A}\beta_{1-42}$ and managed to reduce $\text{A}\beta_{1-42}$ -induced intracellular ROS level and restore mitochondrial membrane potential. The fresh stem of *Dendrobium officinale* Kimura et Migo, also known as Tiepishu in Chinese, is often used to treat symptoms including throat inflammation, and high blood sugar while in Chinese cuisine, it is often used as an ingredient in soup tea [51]. According to the review done by the same authors, polysaccharides from Tiepishu have demonstrated antioxidant, immunomodulatory, and hypoglycemic activities and the ability to treat enteritis. Another study by Tao et al. [37] discovers that the stem of Tiepishu polysaccharides exhibits immunomodulatory activity where it promotes macrophage

Table 1
Studies done on polysaccharides extracted from different parts of herbs and spices.

Parts of herbs/spices	Herbs and spices	Benefits	References
Leaves	<i>Thymus quinquecostatus</i> Celak	85.25% DPPH radical scavenging activity 96% ABTS radical scavenging activity 57% inhibition on α -glucosidase and α -amylase	Li et al. [27]
	<i>Clinacanthus nutans</i> Lindau	Growth inhibitory effect on MDA-MB-231 breast cancer (IC ₅₀ value of 0.191 mg/mL at 72 h) IC ₅₀ values 0.742 mg/mL for DPPH radical scavenging activity IC ₅₀ values 0.572 mg/mL for ABTS radical scavenging activity	Yong et al. [28] Devasvaran et al. [29]
	<i>Althaea officinalis</i> L.	Inhibition zones of 5.23 mm <i>Escherichia coli</i> (4 mg/mL) Inhibition zones of 15.76 mm (20 mg/mL) Increase up to 78% for daily sperm production and its efficiency in the testis of the tested rats.	Karimi et al. [30]
	<i>Zingiber mioga</i>	APTT = 175.67 s at a concentration of 5 mg/mL Lowered fibrinogen (FIB) content to 73.03 mg/dL	Yang et al. [31]
Roots	<i>Achyranthes bidentata</i> Blume	Enhance mineral deposition on MC3T3-E1 cells by 34.2% Protein levels (RUNX2, BSP, and Osx) of MC3T3-E1 cells were increased by 51.9%, 22.1% and 40.6%	Zhang et al. [32]
	<i>Althaea officinalis</i> L.	IC ₅₀ = 1.53 mg/mL for DPPH radical scavenging activity	Karimi et al. [30]
	<i>Panax ginseng</i> L.	IC ₅₀ value 0.09 mg/mL to decrease the number of viable HCT116 p21 ^{-/-} cells At 1.12 mg/mL, 43% DPPH radical scavenging ratio	King and Murphy [33] Yimsoo et al. [34] Chen and Huang [35]
Stems	<i>Panax ginseng</i> L.	90% scavenging ratio for DPPH radical scavenging activity 20 μ g/mL to improve viability PC12 cells that exposed to A β ₁₋₄₂	Chen and Huang [35] Zhang et al. [36]
	<i>Dendrobium officinale</i> Kimura et Migo	100 μ g/mL increased T-lymphocyte proliferation rate 50 μ g/mL to enhance phagocytic activity of RAW246.7 cells 50 μ g/mL over 48 h, induced macrophages produce 9.30 μ M NO	Tao et al. [37]
Seeds	<i>Coriandrum sativum</i> L.	Hepatoprotective effects	Sfar et al. [38]
	<i>Foeniculum vulgare</i> L.	Hepatoprotective effects	Sfar et al. [39]
	<i>Ocimum album</i> L.	IC ₅₀ value 1.3 mg/mL for DPPH radical scavenging activity Thickening/gelling agent as it has: Intrinsic viscosity = 6.9 dL/g Elastic property within 0.5 and 1.5% At 1% concentration,	Arab et al. [40] Arab et al. [41]

Table 1 (continued)

Parts of herbs/spices	Herbs and spices	Benefits	References
Others	<i>Anethum graveolens</i> L.	thermally irreversible gel behavior Reduce the lipid peroxidation of turkey sausages after 12 days	Hajji et al. [42]
	<i>Cinnamomum burmannii</i> (bark) <i>Crocus sativus</i> L. (petals)	Flavoring and thickening agents (viscosity 80.3 cP) OH-radical scavenging ranged from 23.6% to 37.5% At 5 mg/mL, 31.2% radical scavenging of superoxide O ₂ ⁻ radical	Tjandrawinata et al. [43] Zhang et al. [44]
	<i>Coreopsis tinctoria</i> Nutt. (flowers)	Inhibits α -amylase (IC ₅₀ = 2.79 mM) Inhibits α -glucosidase (IC ₅₀ = 3 mM) Inhibit LPS-stimulated NO production in RAW246.7 and BV2 cells (IC ₅₀ = 70 μ M)	Yu et al. [45] Zhang et al. [46]

proliferation and increases macrophage phagocytosis and nitric oxide (NO) production. The authors prove T-lymphocyte proliferation rate increased significantly when treated with high concentrations of Tiepi-sishu polysaccharides (up to 100 μ g/mL). In addition, the phagocytic activity of RAW246.7 cells were markedly enhanced with polysaccharide concentrations up to 50 μ g/mL. Furthermore, at a concentration of 50 μ g/mL over 48 h, these polysaccharides induced macrophages to produce 9.30 μ M of NO.

Polysaccharides extracted from stems exhibit a distinct functional profile characterized by neuroprotective and immunomodulatory activities, alongside moderate antioxidant capacity. Compared to roots, stem-derived polysaccharides may demonstrate enhanced radical-scavenging efficiency, which could be attributed to differences in structural composition and solubility. More notably, their capacity to modulate cellular responses, such as improving neuronal cell viability, reducing oxidative stress-induced apoptosis, and enhancing macrophage activity, highlights their role in cellular protection and immune regulation. These observations suggest that stems represent a promising yet relatively underexplored source of bioactive polysaccharides, particularly for applications in neurodegenerative and immune-related disorders.

3.4. Seeds

Coriandrum sativum L. commonly known as coriander is an annually grown herbaceous, spice plant, indigenous to the Mediterranean and Middle Eastern, belonging to the *Apiaceae* family and mostly cultivated in China, India, North Africa, and Thailand [52]. The herb itself has a light, fresh flavor; it can be used whole or processed to make the ripe seeds more palatable before being used for flavoring in various dishes [53]. The polysaccharides extracted from the seeds of *Coriandrum sativum* L. have antioxidant activity along with hepatoprotective effects; hindering cadmium-induced oxidation damage and exercising a protective effect against cadmium hepatotoxicity [38]. Another separate study done by Sfar et al. [39] also showed that the polysaccharides from fennel, *Foeniculum vulgare* L., also exhibit hepatoprotective effects. *Ocimum album* L. or mountain basil is an annual herb belongs to the *Lamiaceae* family and in Iran, the seeds are used in the traditional desert, Falodeh, and in drinks like Tokhme sharbati [54]. Their polysaccharides exhibit excellent in inhibiting free radicals DPPH as its IC₅₀ value is only 1.3 mg/mL [40]. Meanwhile, the polysaccharides from the mucilage seed of this herb have unique physicochemical properties that can benefit the food and pharmaceutical industries. A separate study

done by Arab et al. [41] proves that the polysaccharides from mountain basil seed mucilage can be applied as a thickening or gelling agent due to its physicochemical properties; it has an intrinsic viscosity of 6.9 dL/g, having elastic properties of weak gel within 0.5 and 1.5% and exhibited a thermally irreversible gel behavior at 1% concentration. *Anethum graveolens* L. (dill) seeds have been extensively used in traditional medicine for digestive disorders and are reported to possess carminative, antihyperlipidemic, and antihypercholesterolemic properties [55]. Polysaccharides extracted from *A. graveolens* L. (dill) seeds have also been shown to reduce lipid peroxidation in turkey sausages during 12 days of refrigerated storage, while concurrently lowering microbial counts [42]. These findings indicate the potential application of dill-derived polysaccharides as natural food preservatives.

Seed-derived polysaccharides are distinguished by their dual contribution to biological activity and physicochemical functionality, making them particularly relevant for food and pharmaceutical applications. In addition to exhibiting antioxidant and hepatoprotective effects, these polysaccharides often possess distinct rheological properties, including high viscosity, gel-forming ability, and thermal stability, reflecting their roles in energy storage and structural protection within seeds. Furthermore, their capacity to reduce lipid peroxidation and inhibit microbial growth highlights their potential as natural preservatives in food systems. Hence, seeds represent a multifunctional source of polysaccharides that integrate bioactivity with material functionality, offering advantages for both nutraceutical and industrial applications.

Across different plant parts, polysaccharides exhibit distinct yet complementary functional profiles that reflect their biological roles within plant tissues. Leaf-derived polysaccharides are most consistently associated with antioxidant and metabolic enzyme inhibitory activities, which may be related to their exposure to environmental stressors and the need for protective defense mechanisms [56]. In contrast, root polysaccharides, primarily involved in storage and structural support, tend to display more pronounced regulatory bioactivities, including osteoprotective, immunomodulatory, and antitumor effects. Stem-derived polysaccharides occupy an intermediate position, with notable neuroprotective and immune-modulating properties, possibly linked to their roles in transport and structural maintenance. Meanwhile, seed polysaccharides are characterized by a dual functional role, combining biological activities (e.g., antioxidant and hepatoprotective effects) with distinct physicochemical properties, such as viscosity and gel-forming capacity. Thus, these observations indicate that the bioactivity of polysaccharides is influenced not only by plant species but also by anatomical origin, which governs their structural characteristics and functional roles. This comparative perspective provides a more coherent framework for understanding SAR and supports the targeted selection of plant parts for specific nutraceutical, pharmaceutical, and industrial applications.

3.5. Others

Cinnamon is obtained from the inner bark of *Cinnamomum* trees where the four frequently used cinnamons are *Cinnamomum zeylanicum*, *Cinnamomum aromaticum*, *Cinnamomum loureirii*, *Cinnamomum burmannii*. Fresh cinnamon sticks are utilized in cooking, and drinks (to prepare teas) and as a garnish; to be sprinkled on top of toasts, desserts or cereals [57]. Polysaccharides from *C. burmannii* that are treated with mild acid hydrolysis during the decoction process help reduce the viscosity from 1544.8 to 80.3 cP which unlocks its use to be flavoring and thickening agents in the food industry [58]. *Crocus sativus* L., known generally as saffron, has a long history of use as a spice, food coloring, flavoring agent, and herbal medicine. In Islamic Traditional Medicine (ITM), *C. sativus* L. has been prescribed to treat ocular, respiratory, and cardiovascular disorders [43]. The polysaccharides from the petals of *C. sativus* L. are proven to be functional for pharmaceutical industries as they can activate the RAW264.7 cells and promote the production and

mRNA expression of cytokines and chemokines [59]. Meanwhile, another study conducted by Zhang et al. [44] showed that the polysaccharides from the petals of *C. sativus* L. have strong antioxidant activity when tested using 4 assays including DPPH radical scavenging, Hydroxyl (OH[•]) radical scavenging, Superoxide (O₂^{•-}) radical scavenging, and reducing power. The authors noted that the OH[•] radical scavenging of the saffron polysaccharides ranged from 23.6% to 37.5% and at 5 mg/mL, 31.2% radical scavenging for the superoxide O₂^{•-} radical. *Coreopsis tinctoria* Nutt., produced in the Kunlun Mountain in China, is an annual herbaceous plant belonging to *Coreopsis* of the *Compositae* family [60]. This snow chrysanthemum is traditionally consumed by local Uyghur people to treat diabetes, high blood pressure and diarrhea [24]. A study done by Yu et al. [45] proves that the polysaccharides extracted from this flower can be used to alleviate diabetes as it exhibits anti-diabetes activity; inhibits half of the activity of α -amylase and α -glucosidase at 2.79 mM and 3 mM, respectively. Furthermore, this study also shows that the polysaccharides with the IC₅₀ value only at 70 μ M, exhibit anti-neuroinflammation activity by inhibiting LPS-stimulated NO production in RAW246.7 and BV2 cells. Another study shows that this polysaccharide extracted from the snow chrysanthemum can modify myeloid-derived suppressor cells [46]. The authors studied that the splenocytes that were co-cultured with a type of mesenchymal stem cell (MSC-2 cell) were able to recover the proliferation of T cells when treated with the increased concentration (up to 0.5 mg/mL) of snow chrysanthemum polysaccharides. This highlights the potential of the polysaccharide to be a candidate as a drug to improve the tumor microenvironment.

In contrast to the more systematically categorized plant parts discussed above (refer to Section 3.1 – 3.4), polysaccharides derived from “other” sources, such as bark, petals, and flowers, exhibit more heterogeneous and context-dependent functional profiles. These polysaccharides often reflect specialized structural features associated with specific plant tissues, resulting in a broad range of bioactivities, including antioxidant, anti-inflammatory, immunomodulatory, and enzyme inhibitory effects. For example, polysaccharides from *C. sativus* petals and *C. tinctoria* flowers demonstrate notable activity related to immune regulation and metabolic enzyme inhibition, whereas bark-derived polysaccharides may exhibit distinct physicochemical properties, such as viscosity modification, relevant to food applications. Unlike leaves, roots, stems, and seeds, which show relatively consistent functional trends, these “other” plant parts represent a structurally diverse and less predictable group, requiring case-specific evaluation. Nevertheless, they highlight the broader diversity of polysaccharide sources and suggest that non-conventional plant tissues may serve as valuable reservoirs of structurally unique and functionally significant polysaccharides, warranting further systematic investigation.

4. Extraction of polysaccharides

Polysaccharides in herbs and spices can be extracted using several methods. Some of the commonly known methods that will be discussed are hot water extraction (HWE), acid or alkaline extraction, microwave-assisted extraction (MAE), ultrasonic-assisted extraction (UAE), enzyme-assisted extraction (EAE) and other combinations of extraction methods.

4.1. Hot water extraction (HWE)

The conventional method of extracting polysaccharides from herbs and spices is the hot water extraction (HWE) method. They are easily soluble in water, especially hot water, due to the nature of polysaccharides being a highly polar macromolecular compound [61,62]. HWE is typically done by allowing the herbs or spices samples to be soaked or boiled for an extended period in water at high temperatures that range from 80 to 100 °C. The high temperature of the water disrupts the plant cell walls in the sample, thereby allowing the polysaccharides to dissolve into the water. The HWE method is often used due to its low

cost, being easily operable, requiring no special instrument, and being suitable for large-scale industrial use [63]. It can be seen in Table 1 (refer to Section 3.1) that most of the research articles use HWE to extract polysaccharides from herbs and spices. However, despite its widespread use, several practical limitations constrain its efficiency, particularly at larger scales. The process is inherently time-consuming and energy-intensive, as prolonged heating of large solvent volumes is required [64]. In addition, extraction is largely diffusion-driven, resulting in mass transfer limitations when processing compact or lignocellulosic plant matrices. Furthermore, the low selectivity of HWE often leads to the co-extraction of non-polysaccharide components such as proteins, phenolic compounds, and pigments, thereby increasing the complexity of downstream purification. The resulting extracts are typically dilute, necessitating additional concentration steps (e.g., evaporation or alcohol precipitation), which further increase processing time and cost. Prolonged exposure to high temperatures may also induce partial degradation of thermolabile polysaccharides, leading to reductions in molecular weight and potential alterations in their bio-functional properties [64]. Table 2 summarizes the advantages and limitations of conventional polysaccharide extraction methods.

4.2. Acid or alkaline extraction

In acid or alkaline extraction, aqueous acidic or basic solutions are used as the solvent medium. These conditions promote the disruption of plant cell wall structures, thereby facilitating the release and solubilization of polysaccharides into the extraction medium. The common weak acids used in this method are dilute sulfuric or hydrochloric acid while weak bases often use sodium hydroxide. Certain polysaccharides, especially acidic polysaccharides, are better extracted using this method [65]. At times, polysaccharides such as pectin, hemicellulose, and cellulose, are intertwined, forming a three-dimensional primary wall structure that is difficult to extract with only hot water [15]. Hence, the acid or alkaline extraction can be more effective for robust polysaccharides than HWE. According to a study done by Devasvaran et al. [29], the highest yield of polysaccharides of *C. nutans* (14.85%) was obtained using the acid extraction method compared to other methods including alkaline extraction and HWE. However, the improved extraction efficiency is frequently accompanied by structural modifications. Under acidic conditions, excessive cleavage of glycosidic bonds may lead to depolymerization and reduced molecular weight, whereas alkaline conditions may induce β -elimination reactions and

Table 2
Comparison of different extraction methods.

Extraction method	Advantage	Disadvantage
Hot water extraction (HWE)	<ul style="list-style-type: none"> • Low cost • Easily operable • No special instrument • Large-scale industrial use 	<ul style="list-style-type: none"> • Time-consuming • Additional steps for optimization
Acid or alkaline extraction	<ul style="list-style-type: none"> • Effective for robust polysaccharide 	<ul style="list-style-type: none"> • Control acidity or alkalinity of solution
Microwave-assisted extraction (MAE)	<ul style="list-style-type: none"> • Increase extraction rates • Reduce extraction time 	<ul style="list-style-type: none"> • Require special instrument (microwave) • Require combining with solvent (water, acid, or alkaline solution)
Ultrasound-assisted extraction (UAE)	<ul style="list-style-type: none"> • Shortens extraction time • Environmentally friendly • Reduced solvent consumption 	<ul style="list-style-type: none"> • Require combining with other methods (HWE or EAE) • Require special instrument
Enzyme-assisted extraction (EAE)	<ul style="list-style-type: none"> • Environmentally friendly it reduces usage of high temperatures and reduces solvent consumption 	<ul style="list-style-type: none"> • It can be costly, not suitable for large-scale industrial use • Require additional steps before using the enzyme

de-esterification, particularly in uronic acid-rich polysaccharides [66]. These changes can significantly influence the physicochemical properties and biological activities of the extracted polysaccharides. From a practical perspective, this method also presents several operational challenges. Precise control of pH is essential to prevent excessive degradation, and subsequent neutralization steps generate salt by-products that increase both environmental burden and processing cost. In addition, the use of corrosive reagents necessitates appropriate material handling and equipment considerations. Therefore, although acid and alkaline extraction can improve the recovery of structurally complex polysaccharides, their application is limited by concerns related to structural preservation, process control, and sustainability.

4.3. Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) utilizes microwave energy to heat the solvent and the sample. This method is often combined with other methods such as HWE and acid or alkaline extraction. The main source of dielectric heating is the dipole polarization of water molecules present in the solvent. Dipole rotation of molecules and ion migration were caused by the microwaves. These conditions lead to force built in the solvent, and enhanced pressure which ultimately causes the temperature of the solution to rise drastically. The cell wall is broken down, facilitating the release of the polysaccharides into the solvent. In addition, the hydrogen bonds can be disrupted by the electric and magnetic effect, affecting the solubility of the polysaccharides, thereby increasing the extraction rates [67]. This method reduces extraction time and increases extraction efficiency while simultaneously protecting the active components from being destroyed. For instance, Al-Ajalein et al. [68] reported that MAE enabled the extraction of polysaccharides from *Cinnamomum cassia* within approximately 5 min, achieving a yield of 13.48%. Despite these advantages, careful optimization of microwave power, exposure time, and solvent conditions is required, as excessive energy input may lead to overheating, structural degradation, or uneven extraction. Furthermore, scalability remains a challenge due to limitations in microwave penetration depth and the difficulty of achieving uniform heating in large-volume systems.

4.4. Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) is also considered a commonly known method for polysaccharides. UAE utilizes high-frequency sound waves to create cavitation bubbles in the solvent. In an instant, the cavitation bubbles will swell and break releasing the absorbed sound field energy in a concise space and time, forming high-temperature and high-pressure conditions in the solution; disrupting the plant cell walls, and therefore enhancing the release of polysaccharides [69]. This method is accompanied by HWE, acid or alkaline extraction, or enzyme-based extractions. Polysaccharides extracted from ginger by Chen et al. [70] using UAE require 60 min extraction time and managed to have 8.29% yield while using HWE took 5 h of extraction, but the yield percentage of polysaccharides is 6.83%. A study done by Devasvaran et al. [29] obtained a 6.69% yield of polysaccharides from *C. nutans* using UAE with an extraction time of 50 min but using the HWE method yielded 6.59% of polysaccharides within 8 h of extraction time. The enhanced efficiency of UAE is attributed to the physical effects of cavitation, which improve solvent penetration and accelerate solute diffusion [71]. Moreover, UAE is generally considered a mild technique that can preserve the structural integrity of polysaccharides under optimized conditions. However, excessive ultrasonic intensity or prolonged exposure may lead to chain scission and molecular degradation. In addition, challenges related to scale-up, including energy distribution and equipment design, must be addressed for industrial implementation.

4.5. Others

Enzyme-assisted extraction (EAE) is considered environmentally friendly because it reduces the need for high-temperature conditions and the use of organic solvents. EAE is a biological extraction method that uses specific enzymes to hydrolyze free or cell wall polysaccharides, facilitating the release of bioactive compounds [72]. The authors further mentioned this method can also selectively convert primary glycosides into secondary glycosides or aglycones, hence increasing the yield of polysaccharides. Examples of enzymes used in this method are pectinase, hemicellulase, and cellulase. The polysaccharides extract from plant sources using the EAE method has shown enhanced bioactivities including antitumor, antimicrobial and antioxidant activities [73]. This underscores the fact that the EAE method can enhance the biological activity of polysaccharides. However, drawbacks of this method include the cost of the enzyme, the requirement of additional step or pre-processing steps to promote the extraction efficiency, enzyme inactivation, and the limited cellular disruption ability [74,75]. There is also a combination of methods such as ultrasonic-microwave-assisted extraction (UMAE). UMAE is a method that combines the advantage of ultrasonic vibration and microwave radiation for mass transfer and rapid internal heating which possesses extremely high extraction efficiency, higher than the HWE method [49]. Different extraction methods can affect the yield percentage, chemical composition, physical characteristics and bioactivity of the polysaccharides. Choosing the suitable extraction method of polysaccharides from herbs and spices, all boils down to the sample used in the research, the objectives and the budget of the research. The efficiency, measured by yield percentage, of different extraction methods for polysaccharides from various herbs and spices can be seen in Table 3.

5. Analytical techniques

The polysaccharides from herbs and spices can be further analyzed, purified and characterized using analytical techniques such as spectroscopy, chromatography, and mass spectroscopy. The information regarding the molecular weight of the polysaccharides, the glycosidic linkages, monosaccharide compositions, and the branching patterns provide insight into the properties and biological activity of the polysaccharides. Characterization of polysaccharides can only be obtained using advanced analytical techniques including spectroscopy and chromatography.

5.1. Chromatography

Chromatography is the separation of molecular mixtures by distribution between two or more phases where one phase is a surface, and the other is a bulk phase brought into contact with the two-dimensional phase counter-currently [83]. Chromatography can be classified into gas chromatography (GC) and liquid chromatography (LC). This technique is often used in the separation and structural analysis of polysaccharides; for purification, analysis of monosaccharide composition and separation of hydrolysates. Chromatography serves as an important analytical technique to analyze the polysaccharides as it enables precise analysis of their molecular weight, composition and structural properties. Chromatography, the separation technique, plays a vital role in isolating polysaccharides from other impurities including the protein group. The purification of polysaccharides is often associated with improved bioactivity, as the removal of interfering substances enhances the accuracy of SAR analysis and the reliability of biological evaluations.

Analysis of monosaccharide composition using GC requires the polysaccharides to be hydrolyzed to break the long-chain polymer into monosaccharides and afterwards, derivatized to form volatile components. The derivatization method consists of the substitution of the polar groups of carbohydrates to increase their volatility. Examples of common derivatives used are methyl ethers, acetates, trimethylsilyl group

Table 3

Extraction method of herbs and spices polysaccharides.

Extraction method	Herbs/Spices	Yield (%)	Reference	
Hot water extraction (HWE)	<i>Zingiber officinale</i> Roscoe (ginger)	6.83	Chen et al. [70]	
	<i>Thymus vulgaris</i> L. (garden thyme)	11.00	Banerjee et al. [76]	
	<i>Thymus quinquecostatus</i> Celak.	8.60	Li et al. [26]	
	<i>Cinnamomum burmannii</i> (Indonesian cinnamon)	54.70	Nunes et al. [58]	
	<i>Cinnamomum verum</i> (Ceylon cinnamon)	81.80		
	<i>Clinacanthus nutans</i> Lindau	6.59	Devasvaran et al. [29]	
	<i>Coriandrum sativum</i> L. (coriander)	9.10	Sfar et al. [38]	
	<i>Foeniculum vulgare</i> L. (fennel)	11.50	Sfar et al. [39]	
	<i>Pimpinella anisum</i> L. (anise)	8.84	Ghissi et al. [77]	
	<i>Trigonella foenum-graecum</i> L. (fenugreek)	18.44	Rashid et al. [78]	
	<i>Ocimum album</i> L. (mountain basil)	7.10	Arab et al. [40]	
	<i>Crocus sativus</i> L. (saffron)	7.56	He et al. [59]	
	<i>Carthamus tinctorius</i> L. (safflower)	7.45	Wang et al. [60]	
	<i>Althaea officinalis</i> L. (marshmallow plant)	3.20 12.01	Karimi et al. [30] Tahmouzi and Salek Nejat [79]	
	<i>Astragalus membranaceus</i> L.	8.80	Chen et al. [80]	
	Ultrasonic-assisted extraction (UAE)	<i>Anethum graveolens</i> L. (dill)	11.63	Hajji et al. [42]
<i>Gynostemma pentaphyllum</i> (Jiaogulan)		15.34	Wang et al. [81]	
<i>Achyranthes bidentata</i> Blume		29.40	Zhang et al. [32]	
<i>Zingiber officinale</i> Roscoe (ginger)		8.29	Chen et al. [70]	
<i>Carthamus tinctorius</i> L. (safflower)		15.70	Wang et al. [82]	
<i>Gynostemma pentaphyllum</i>		20.31	Wang et al. [81]	
Enzyme-assisted extraction (EAE)		<i>Zingiber officinale</i> Roscoe (ginger)	8.13	Chen et al. [70]
		<i>Cinnamomum cassia</i> L. (Chinese cinnamon)	13.70	Al-Ajalein et al. [68]
Microwave-assisted extraction		<i>Gynostemma pentaphyllum</i>	16.96	Wang et al. [81]
		<i>Clinacanthus nutans</i>	14.85	Devasvaran et al. [29]
Acid extraction	<i>Clinacanthus nutans</i>	6.64	Devasvaran et al. [29]	
	<i>Zingiber officinale</i> Roscoe	11.38	Chen et al. [70]	
Freeze-thaw*	<i>Clinacanthus nutans</i>	4.16	Devasvaran et al. [29]	
	<i>Zingiber mioga</i>	6.22	Yang et al. [31]	

including trimethylsilyl ethers, trimethylsilyl oximes, and alditol acetates. A study by Tabarsa et al. [84] used acetic anhydride for analysis of the monosaccharide composition of *Cuminum cyminum* polysaccharides. GC will separate the non-volatile monosaccharides according to their volatility and interaction with the stationary phase. The retention time shown by monosaccharides present in the polysaccharides will be compared with the standard retention time of monosaccharides meanwhile the amount of monosaccharides present will be shown by the area of the peak. For example, glucose in the polysaccharides can be identified by looking at the retention time of approximately 9 min [85]. As for GC-MS, after the separation process, the analyte will be introduced into MS and break into smaller fragments through ionization. These

fragments will be detected according to their mass-to-charge ratio. Individual sugars will be identified by comparing their fragmentation pattern with known mass spectra. However, pairing GC with mass spectrometry (MS) can provide additional information such as anomeric configuration by determining the individual sugar derivatives through mass fragmentation patterns. GC-MS analysis by Ghilissi et al. [77] shows that the major monosaccharide compositions for *Pimpinella anisum* polysaccharides are galactose (33.47%), β -D-Glucose (26.71%), and α -D-Mannose (18.21%). GC-MS provides information regarding glycosidic linkage through an analysis called methylation analysis. The method involves derivatization of the individual component sugars of a polysaccharide to partially methylated alditol acetates (PMAA) which are analyzed and quantified by GC-MS [86]. The analysis done by Rashid et al. [78] shows that the fenugreek polysaccharides consisting of a backbone of β 1 \rightarrow 4-linked D-mannopyranose residues to which are attached single α 1 \rightarrow 6 linked D-galactopyranose residues at the O6-position of D-mannose.

The basis and concept of liquid chromatography (LC) is similar to GC, but instead of gas, liquid is used as the mobile phase. High-performance liquid chromatography (HPLC) is also one of the instruments that can run the analysis of monosaccharide compositions. HPLC is often used with pre-column derivatization methods, like PMP (1-phenyl-3-methyl-5-pyrazolone) or DNS (3,5-dinitrosalicylic acid) [87]. Meanwhile, certain research studies use ultra-high-performance liquid chromatography (UPLC) such as a study by Jiang et al. [88] used UPLC which managed to identify the pepper leaves polysaccharides are composed of glucose and mannose with a molar ratio of 2.4:1. UPLC can provide faster, and improved resolutions of results compared to HPLC [89]. Gel Permeation Chromatography (GPC) is a type of Size Exclusion Chromatography (SEC) used to separate molecules of a solution into various sizes [90]. The column in GPC is packed with various sizes of porous gel matrix which allows analytes to penetrate the pores according to their hydrodynamic volume. In the analysis of polysaccharides, GPC is used to determine the molecular weight and the homogeneity. Larger polysaccharides, those with heavier molecular weights, will retain longer in the column and the opposite for smaller polysaccharides. Meanwhile, the homogeneity of polysaccharides determined through GPC can be seen from a single peak shown in the chromatogram. The analysis, using sepharose CL-6B chromatography, of polysaccharides from *Gynostema pentaphyllum* L. shows good homogeneity; a single peak is shown in the chromatogram [81].

5.2. Spectroscopy

Ultraviolet-visible (UV-Vis) spectroscopy is a spectroscopic method based on the interaction of a chemical species with light in the ultraviolet and visible ranges of the spectrum [91]. In polysaccharides analysis, UV-Vis spectroscopy is used to ensure the purity of the extracted polysaccharides. Natural polysaccharides lack or do not possess chromophores; hence they do not absorb light in the UV-Visible range [92]. However, impurities like proteins, nucleic acids and phenolic compounds absorb light in the UV range as they contain chromophores. Protein usually absorbs at 280 nm while nucleic acids absorb light at 260 nm. Purified polysaccharides from *Cichorium intybus* L. show no absorption peak between 260 nm and 280 nm, indicating no proteins and nucleic acids [93]. FT-IR spectroscopy is a technology for acquiring emission spectra or infrared absorption from solid, liquid or gas samples [94]. This instrument utilizes samples absorbing frequencies of radiation that match the energy of the natural vibrational frequencies of bonds in organic molecules. Different bonds will absorb at different wavelengths. FT-IR for analysis of polysaccharides helps in identifying the functional groups present, glycosidic linkages, and their anomeric configuration. In addition, FT-IR can ensure the purity of the extracted polysaccharides. Examples of bands shown in the spectra for analysis of polysaccharides, according to Hong et al. [95], are a strong and broad band of 3600 – 3000 cm^{-1} which indicates stretching vibration of the abundance of OH

group in the polysaccharides and a band at 3000 – 2500 cm^{-1} are assigned to stretching vibration of CH and CH_2 . The band in 1800 – 1500 cm^{-1} indicates the presence of a double bond. The appearance of new bands around 1175 – 1140 cm^{-1} is believed to be the result of glycosidic linkage formation while bands at 900 – 800 cm^{-1} indicate configuration of anomeric carbon to be either α or β configuration. The three absorption peaks observed at 1024, 1070, and 1160 cm^{-1} are related to the C–O–C stretching of the glycosidic bond, which indicates that pyranose rings may be present. The spectrum of turmeric polysaccharides labelled TPs-0 shows weak absorption bands at 899 cm^{-1} , which are characteristic of β -glycosidic linkages in polysaccharide chains [96]. The absence of amide bands around 1650 cm^{-1} and 1550 cm^{-1} indicates low amounts of protein (impurities) in *Thymus vulgaris* leaf's polysaccharides [76]. Nuclear magnetic resonance (NMR) has been widely used as an analytical chemistry technique to investigate the molecular structure and conformation of polysaccharides. Combined with 1D NMR spectra, which provide chemical shifts and coupling constants for both homonuclear such as ^1H - ^1H and heteronuclear (e.g., ^1H - ^{13}C) interactions, 2D NMR techniques can elucidate the linkage patterns and sequence of sugar residues in polysaccharides [97].

The α - or β -configuration of the anomeric proton (H1) and anomeric carbon (C1) in sugar residue is recognizable in both ^1H and ^{13}C NMR spectra [98]. Anomeric regions of α -configuration appear in 5.1 – 5.8 ppm (anomeric proton) and 98 – 103 ppm (anomeric carbon), while β -configuration relatively corresponds to 4.3 – 4.8 ppm and 103 – 106 ppm in anomeric regions [99]. A study by Li et al. [27] done on *T. quinquecostatus* Celak. Polysaccharides use 1D (^1H NMR, ^{13}C NMR) and 2D NMR (COSY, TOCSY, HSQC) where the purified polysaccharides of *T. quinquecostatus* Celak. Had a complex structure formed by 14 different residues and the possible backbone for this polysaccharide is \rightarrow 5)- α -L-Araf-(1 \rightarrow 3)- β -D-Manp-(1,6 \rightarrow . NMR spectroscopy, when combined with methylation analysis, enables precise elucidation of glycosidic linkage types and branching structure, thereby providing comprehensive insights into the connectivity of monosaccharide residues in polysaccharide structures.

6. Physicochemical properties of polysaccharides

Physicochemical properties of polysaccharides include monosaccharide compositions, molecular weights, viscosity, and density. These properties are important as they can affect the biological activity and the potential of polysaccharides to be applied in food, pharmaceuticals and medicine.

6.1. Monosaccharide composition

Polysaccharides extracted from herbs and spices are usually heteropolysaccharides, different monosaccharides in certain ratios (Table 4). Common monosaccharide units include glucose, galactose, arabinose, mannose, rhamnose, and xylose, among others. After the purification process, polysaccharides can be divided into two or more fractions, each with specific ratios of monosaccharides. These differing ratios can affect their biological activity despite coming from the same herbs and spices. For example, purified fractions of polysaccharides from *Carthamus tinctorius* L. (safflower). The third and fourth purified fractions, labelled as SSP3 and SSP4 respectively, show relatively high antioxidant properties (high ABTS⁺ scavenging activity and Fe^{3+} reducing activity) as well as high antiproliferative activity. These potent antioxidants and antiproliferative properties can be traced to the differing ratios of monosaccharides; SSP3 and SSP4 contain a high amount of galacturonic acid and glucuronic acid compared to other fractions [82]. Similarly, Zhu et al. [96] obtained four fractions of turmeric polysaccharides (TPs) consisting of a different ratio of monosaccharides which results in slight variations in levels of antioxidant activity. The four fractions of turmeric polysaccharides were labelled TPs-0, TPs-1, TPs-2, and TPs-3 where two of the fractions are neutral polysaccharides (TPs-0 and TPs-1) and the

Table 4
Physicochemical properties of polysaccharides from herbs and spices.

Herbs/Spices	Extraction methods	Type of polysaccharides	Monosaccharides	Molecular Weight	Total carbohydrate content (TCC) (%)	Total protein content	Total phenolic content (TPC)	Total uronic acid (%)	References
<i>Zingiber officinale</i> Roscoe (ginger)	HWE	Crude	Galactose 38.88 mol % Arabinose 28.42 mol % Rhamnose 17.22 mol %	1858.54 kDa	37.85	3.25	0.82	3.29	Chen et al. [70]
	UAE	Crude	Galactose 32.44% Arabinose 28.43% Rhamnose 16.06%	1871.79 kDa	44.65	1.94	0.95	3.85	
	Alkaline solution	Crude	Galactose 34.09% Arabinose 26.72% Rhamnose 16.24%	1833.97 kDa	48.43	3.59	0.99	5.64	
	Enzyme-assisted extraction	Crude	Arabinose 35.55% Xylose 27.94% Galactose 15.31%	1981.27 kDa	41.89	2.95	1.53	3.99	
<i>Allium cepa</i> L.	Hot buffer saline solution	Crude	Mannose 88.68%	7.702×10^3 kDa	72.12	-	-	-	Zhu et al. [100]
	Chelating agent saline solution	Crude	Galactose 31.37%	4.690×10^3 kDa	70.47	-	-	-	
	Concentrated alkaline saline solution	Crude	Galactose 67.59%	4.943×10^3 kDa	76.82	-	-	-	
	Dilute alkaline saline solution	Crude	Mannose 25.80% Galactose 31.37%	1.390×10^3 kDa	71.02	-	-	-	
<i>Cuminum cyminum</i> L. (Cumin)	HWE	Crude	Arabinose 46.3% Galactose 29.7% Mannose 8.9% Glucose 7.2% Rhamnose 5.7% Xylose 2%	191.4×10^3 g/mol	90.3	1.8	-	6.1	Tabarsa et al. [84]
<i>Foeniculum vulgare</i> (Fennel)	HWE	Crude	Galactose 20.4% Glucose 55.8% Arabinose 5.3% Rhamnose 1.3% Mannose 13.6% Xylose 2.1% Fructose 1.5%	-	68.1	0	-	7.3	Sfar et al. [39]
<i>Pimpinella anisum</i> L. (anise seeds)	HWE	Crude	Galactose 33.47% Arabinose 0.67% β -d-Glucose (26.71%)	-	64.75%	1.24%	-	-	Ghliissi et al. [77]
<i>Ocimum album</i> L. (mountain basil)	HWE	Crude	Mannose 35.7% Glucose 33.32% Galactose 19.6% Rhamnose 11.38%	-	94.3	-	-	-	Arab et al. [40]
<i>Piper regnellii</i> (Miq.) C.DC.	HWE	Crude	Arabinose 51.5% Galactose 24.9% Galacturonic acid 11.3% Glucose 5%	-	90	5.3	4.7	-	Campo-Grande et al. [101]
<i>Crocus sativus</i> L. (saffron petals)	HWE	Crude	Galactose Rhamnose Arabinose Xylose	-	95.33	-	-	13.12	He et al. [59]
<i>Althaea officinalis</i> L. (marshmallow plant)	HWE	Purified acidic polysaccharides	Galacturonic acid 51% Galactose 3.71% Rhamnose 32.56% Glucose 12.73%	-	94.63%	-	1.78 mg GAE/g	55.5%	Karimi et al. [30]
<i>Plumbago zeylanica</i> L.	HWE	Crude	Arabinose Galacturonic acid Galactose Rhamnose	-	7.54	2.78	-	7.54	Zhang et al. [102]
		Purified fraction 1	Same monosaccharides, but different molar ratio	285.3 kDa	77.58	1.72	-	22.38	
<i>Carthamus tinctorius</i> L. (safflower)	UAE	SSP1	Mannose 0.54 Rhamnose 0.41 Glucuronic acid 0.31 Glucose 4.81	38.03 kDa	62.45	5.19	-	ND	Wang et al. [82]

(continued on next page)

Table 4 (continued)

Herbs/Spices	Extraction methods	Type of polysaccharides	Monosaccharides	Molecular Weight	Total carbohydrate content (TCC) (%)	Total protein content	Total phenolic content (TPC)	Total uronic acid (%)	References
		SSP2	Galactose 14.35 Xylose 1.05 Arabinose 13.54 Mannose 1.29 Rhamnose 1.23 Glucuronic acid 1.35 Galactose acid 0.10 Glucose 3.10 Galactose 18.53 Xylose 0.53 Arabinose 11.47	43.17 kDa	63.15	5.16	-	6.28	
		SSP3		Mannose 0.73 Rhamnose 1.72 Glucuronic acid 2.32 Galactose acid 0.25 Glucose 6.87 Galactose 13.90 Xylose 0.36 Arabinose 9.03		54.49 kDa	61.77	5.31	-
SSP4	Mannose 1.02 Rhamnose 1.75 Glucuronic acid 2.80 Galactose acid 0.39 Glucose 6.49 Galactose 12.25 Xylose 0.27 Arabinose 9.94		7.34 76.92 kDa	63.89	5.89	-	7.21		

Note: ND: Not detected.

remaining two are acidic polysaccharides (TPs-2 and TPs-3). TPs-2 and TPs-3 contain higher amounts of galacturonic acid (19.6 and 17.2%, respectively).

A study by Karimi et al. [30] revealed that the polysaccharides from the root of *A. officinalis* L. are mainly composed of galacturonic acid (51%) rhamnose (32.56%), galactose (3.71%), and glucose (12.73%). On the contrary, another study by Tahmouzi and Salek Nejat [79] on the leaf polysaccharides of *A. officinalis* L. found a slightly different monosaccharide composition, where the purified fractions contained mannose, galactose, glucose, xylose, rhamnose, and arabinose in varying molar ratios. Likewise, *P. ginseng* root polysaccharides mainly consist of glucose, mannose, ribose, rhamnose, galactose, arabinose, and galacturonic acid with a molar ratio of 67.6:3.75:3.42:1.09:1.56:1.10:1. In comparison, Zhang et al. [36] reported that the polysaccharides from ginseng stem include galactose, rhamnose, glucose, mannose, arabinose, galacturonic acid, and glucuronic acid with the molar ratio of 25.34:22.05:21.93:12.17:9.21:3.51:3.22. The variation in monosaccharide composition between these polysaccharides from the same species may be due to the different parts of the plant used, as well as differences in the frequency or rigor of the purification process applied.

6.2. Molecular weight

Molecular weight also plays an important role in determining the efficiency of biological activities in polysaccharides. According to Jiang et al. [88] polysaccharides with medium molecular weight between 100 and 400 kDa exhibit the highest bioactivity which declines as the molecular weight increases. Polysaccharides with excessively low molecular weight are unable to form a necessary spatial structure for bioactivity, while those with very high molecular weight will have difficulty penetrating the cell membrane and exert their effects. The same

authors show that the second purified fractions of pepper leaf polysaccharides (PLP2) have a higher molecular weight (243 kDa) than the first fraction (PLP1) weighing 123 kDa. It was reported that PLP2 exhibit stronger antioxidant and hypoglycemic activities. It is worth mentioning that apart from the molecular weight, the sulfate content in PLP2 also contributes to its enhanced bioactivities.

Notably, the range of molecular weight for optimum bioactivity depends on the specific sample and does not necessarily have to be within the 100-400 kDa range. For example, *Pueraria lobata* (Willd.) Ohwi polysaccharides (a-PLPs) have a smaller molecular weight of 22.675 kDa which is below 30 kDa, yet they effectively improve the intestinal functions of immunosuppressed mice [103]. Conversely, another study shows that higher molecular weight enhanced the biological activity of the polysaccharides. Tang et al. [104] conducted a study on the *Amaranthus hybridus* L. where the purified fractions are labelled as AHP-H-1 and AHP-H-2. The molecular weights of these two fractions were calculated to be 70.795 and 90.3325 kDa, respectively. Despite having a higher molecular weight, AHP-H-2 demonstrated better antioxidant activity compared to AHP-H-1. In the FRAP assay, AHP-H-2 exhibit strong reducing powers (0.918) than AHP-H-1 (0.695). Additionally, AHP-H-2 show the highest superoxide anion radical scavenging rate, close to 80%, with an IC₅₀ value of 0.999 mg/mL. For DPPH radical scavenging activity, AHP-H-2 had an IC₅₀ value of 0.595 mg/mL, lower than AHP-H-1 (IC₅₀ = 0.908 mg/mL); indicating AHP-H-2 exhibited stronger antioxidant activity.

Yelithao et al. [105] studied the sulfation and partial hydrolysis of *Polygonatum sibiricum* polysaccharides. The fraction of the polysaccharides is labelled F₁ while the fractioned hydrolyzed polysaccharides is labelled HP₂. The authors observed that the molecular weight *Polygonatum sibiricum* polysaccharides plays an important role in the activation of RAW246.7 cells. The HP₂ fraction, with a molecular

weight of 27.1×10^3 g/mol, was able to activate RAW246.7 cells, leading to significantly higher NO induction (44.3%) compared to the heavier F₁ fraction weighing 132.6×10^3 g/mol with only 22.9% NO release. The authors also noted that the modification of the polysaccharides by sulfation and acid hydrolysis causes a decrease in molecular weight. The sulfation process decreases the molecular weight of F₁ from 132.6×10^3 g/mol to 82.1×10^3 g/mol meanwhile the acid hydrolysis treatment reduces the molecular weight of F₁ from 132.6×10^3 g/mol to 18.2×10^3 g/mol after 1 to 6 h for both reactions.

6.3. Total carbohydrate content (TCC)

The total carbohydrate content (TCC) is one of the key indicators of polysaccharide purity and structures while also representing the proportion of monosaccharide units in the polysaccharide. The phenol-sulfuric acid method is the most common method to analyze total sugar content/estimate the amount of carbohydrates in polysaccharides. According to Yue et al. [106], the concentrated sulfuric acid in this method will dehydrate the polysaccharides, forming uronic acid and hydroxyurea formaldehyde. The product will be condensed with phenol to form orange-red compounds. The color depth of the last product is proportional to the sugar content in the polysaccharides. This can be determined by observing the OD (optical density) at 490 nm. TCC differs between crude and purified polysaccharides with purified forms typically having higher TCC levels. Chen et al. [80] demonstrated that crude polysaccharides from *Astragalus membranaceus* contain a lower amount of TCC (64.03%) compared to two purified fractions, APS-1 and APS-2, which have 99.48% and 97.15%, respectively. Similarly, a study by Tang et al. [104] reported the crude *Amaranthus hybridus* L. polysaccharides had a TCC of 35.4% while the purified fractions as AHP-H-1 and AHP-H-2 showed higher TCC values, at 55.6% and 45.7%, respectively. The increase of TCC in purified polysaccharides could be due to the removal of the impurities which increase the proportion of polysaccharides relative to the total mass of the sample.

The presence of impurities alters the polysaccharide structure which ultimately disrupts the compound bioactivity. In their study on the polysaccharides of *Plumbago zeylanica* L., labelled as WPZP), Zhang et al. [102] reported that the purified fraction of WPZP-2-2 had a higher TCC (78.65%) as compared to WPZP-2-1 (77.58%). The authors noted that the WPZP-2-2 structure differed slightly from the WPZP-2-1. The second purified fraction was identified as a pectin polysaccharide of the RG-I type where $\rightarrow 4$ -O-2 and O-3 of α -D-GalpA were slightly acetylated. In contrast, the first fraction was also a pectin polysaccharide with the same RG-I type backbone, but its branches were identified as galactan or arabinan. The preserved structure of WPZP-2-2 was able to reduce the fluorescence intensity of MyD88 and CD14 more than the first fraction, suggesting that WPZP-2-2 effectively reduce the protein level for inflammation.

6.4. Total protein content and total phenolic content

Total protein content is usually determined using the method of Bradford in 1976 using bovine serum albumin as the standard [107]. The protein content in polysaccharides can indicate their purity and determine whether the extracted polysaccharide is a naturally polysaccharide-protein conjugate which may enhance their biological activities. Phenolic compounds might be co-extracted or adsorbed, along with protein, to the polysaccharides of herbs and spices. The presence of phenolic compounds can be tested using the Folin-Ciocalteu assay. The *C. cassia* polysaccharides, optimized for their yield, contain 3.5% TPC using the Folin-Ciocalteu assay [68]. This colorimetric assay detects phenolic compounds by measuring their ability to reduce the Folin-Ciocalteu reagent, producing a blue color that can be measured spectrophotometrically [108]. Multiple studies have noted that the polysaccharides peptide-conjugate along with conjugates of phenolic polysaccharides exhibit strong antioxidant activity; ferulic acids, a type

of phenolic acid conjugates with structural polysaccharides have shown strong antioxidant activity [109–111]. The presence of the phenolic compound in the polysaccharides, like the presence of protein, can significantly contribute to the polysaccharides' antioxidant activity, especially in scavenging DPPH[•] radical, and ABTS^{•+} radical, including metal-reducing properties [110]. Tea polysaccharide (TPS) conjugates are composed of protein, neutral sugars, and uronic acid. Studies have shown that the antioxidant activity of these conjugates depends on their protein content, with higher protein levels generally enhancing antioxidant activity and impacting their physicochemical properties [109]. The strong free radical scavenging ability of TPS conjugates may be due to their ability to donate hydrogen atoms that bond with and neutralize free radicals, effectively stopping the chain reaction. Alternatively, it has been suggested that tea polysaccharide conjugates can directly bind to free radical ions, thereby halting the reaction.

6.5. Total uronic acid

According to the method by Bitter and Muir [112], uronic acid can be estimated by using the sulfuric acid-carbazole method. The basis of this method is adding concentrated sulfuric acid, followed by adding carbazole and heating to form a red-colored solution. The intensity of the red-colored solution is related to the amount of uronic acid present in the sample. Other methods used for checking total uronic acid include using m-hydroxyphenyl, m-hydroxybenzene, or m-phenyphenol method. The amount of uronic acid in the polysaccharides can enhance bioactivities including antioxidant activity and hypoglycemic activity. A study by Chen et al. [70] on *Zingiber officinale* Roscoe (ginger) polysaccharide extracted using UAE show that the ginger polysaccharides contain the highest uronic acid, which exhibits a strong hypoglycemic activity as it demonstrates potent α -glucosidase inhibitors. Another study by Li et al. [27] on *T. quinquecostatus* Celak. leaf polysaccharides reported that the crude polysaccharides (DJP) and those precipitated using 30% ethanol (DJP30) had the highest total uronic acid contents, at 50.75% and 55.14%, respectively. This high uronic acid content may explain why DJP and DJP30 exhibit stronger inhibitory activity against digestive enzymes. The high content of uronic acid in polysaccharides had stronger inhibitory effects on α -amylase and α -glucosidase, possibly through two ways of action: one, the polysaccharide adsorbs on the surface of digestive enzymes, hindering starch hydrolysis; and two, the carboxylic acid groups in polysaccharides bind with amino acid residues in the enzyme structure via hydrogen bonding, resulting in spatial configuration of the digestive enzymes to be altered [27,113,114].

6.6. Viscosity and rheological property

The viscosity and the rheological properties of the polysaccharides give valuable indicators for future uses especially in food and pharmaceuticals sections. High molecular weight and complex structural properties can contribute to the high viscosity. The high viscosity of the polysaccharides from *A. officinalis* L. is attributed to the high molecular weight of 639.27 kDa and a complex backbone structure; 1,3-linked-Rhap, 1,4-linked-Rhap, 1-linked-Rhap, 1,3-linked-GalpA, 1,3,4-linked-Galp and 1,4-linked-Glcp [47]. High-viscosity polysaccharides can be applied in the food industry as thickeners, emulsifiers, and stabilizers. Polysaccharides from *C. burmannii* that have been treated with mild acid exhibit a viscosity of 80.3 cP, lower than the original viscosity of 1544.8 cP. The reduction in viscosity is vital as the high value of the original viscosity could hinder their effectiveness as a thickening or gelling agent in the industrial process [58]. The flow behavior (rheology) of polysaccharide solutions is also important. Some polysaccharides exhibit pseudoplastic (shear-thinning) behavior, where the viscosity decreases with increasing shear rate. This property is beneficial in various industries, allowing products to flow easily during processing but remain thick during storage. Polysaccharides from *O. album* L. (mountain basil) seeds demonstrated pseudoplastic behavior where the

viscosity decreased as the shear rate increased [40]. This behavior can be attributed to the reduced interactions and entanglement between the polysaccharides. An increased number of polysaccharides can cause enhance in physical entanglements and hydrogen bonding between polymer chains, therefore, a higher shear rate results in greater bond breaking and detangling of these chains. This pseudoplastic behavior is

important during processing steps such as filling or pumping where the reduced viscosity allows the process to consume less energy. From another perspective, when eating food in a state of semisolid or liquid, the rapidly decreasing initial viscosity would create a favorable mouthfeel.

Table 5
Biological activities found in polysaccharides of herbs and spices.

Bioactivity	Polysaccharide sources	Value	Model (ex: rats and/or cells)	Reference
Antioxidant	<i>Thymus quinquecostatus</i> Celak.	85% DPPH radical scavenging capacity at 1 mg/mL 96% ABTS radical scavenging capacity at 1 mg/mL	DPPH free radical scavenging ABTS free radical scavenging	Li et al. [27]
	<i>Althaea officinalis</i> L.	IC ₅₀ = 1.53 mg/mL	DPPH free radical scavenging	Karimi et al. [30]
	Green tea	IC ₅₀ = 0.6 mg/mL	DPPH free radical scavenging	Li et al. [117]
	<i>Zingiber Official</i> Roscoe L. (Ginger) leaves	IC ₅₀ = 0.492 mg/mL IC ₅₀ = 1.156 mg/mL IC ₅₀ = 0.574 mg/mL IC ₅₀ = 0.578 mg/mL (EAE-GSLP) EC ₅₀ = 1.478 mg/mL	DPPH free radical scavenging Hydroxyl radical scavenging Superoxide radical scavenging	Chen et al. [70]
	Dried rhizome <i>Curcuma longa</i> L. (Turmeric)	EC ₅₀ = 1.670 mg/mL EC ₅₀ = 3.438 mg/mL EC ₅₀ = 2.305 mg/mL (for TPs-1)	DPPH free radical scavenging Hydroxyl radical scavenging ABTS free radical scavenging	Zhu et al. [96]
	<i>Zingiber mioga</i> leaves	IC ₅₀ = 0.31 mg/mL IC ₅₀ = 1.14 mg/mL IC ₅₀ = 4.08 mg/mL	DPPH radical scavenging activity Superoxide radical scavenging Hydroxyl radical scavenging	Yang et al. [31]
	<i>Amaranthus hybridus</i> L.	IC ₅₀ = 0.595 mg/mL (for AHP-H-2) IC ₅₀ = 0.908 mg/mL (AHP-H-1) IC ₅₀ = 0.999 mg/mL (for AHP-H-2) Reducing power = 0.918 (for AHP-H-2) Reducing power = 0.695 (for AHP-H-1)	DPPH radical scavenging activity Superoxide radical scavenging Fe ³⁺ reducing capacity assay (FRC)	Tang et al. [104]
	<i>Clinacanthus nutans</i> Lindau	AHP-H-2 6.5 total antioxidant capacity per milligram IC ₅₀ values 0.742 mg/mL	Total antioxidant capacity (T-OAC) DPPH radical scavenging activity	Devasvaran et al. [29]
	<i>Ocimum album</i> L.	IC ₅₀ values 0.572 mg/mL IC ₅₀ value 1.3 mg/mL	ABTS radical scavenging activity DPPH radical scavenging activity	Arab et al. [41]
	Immunomodulatory	<i>Crocus sativus</i> L.	5 mg/mL, 31.2% radical scavenging	Superoxide O ₂ radical activity
<i>Curcuma Longa</i> L.		The number of white blood cells (WBC) increased to 10.26 × 10 ⁹ L	Cy-induced mice	Zhu et al. [118]
Anti-inflammatory	<i>Crocus sativus</i> L. petals	Induced secretion of cytokines and chemokines (<i>P</i> < 0.05, <i>P</i> < 0.01, or <i>P</i> < 0.001)	RAW264.7 cells	He et al. [59]
	<i>Coreopsis tinctoria</i> Nutt.	IC ₅₀ = 70 μM IC ₅₀ = 0.12 mM	RAW264.7 BV2 cells	Yu et al. [45]
Antidiabetic	<i>Pimpinella anisum</i> L.	Paw edema after 5h is 0.68 ± 0.02 mm	Carrageenan-induced paw edema in mice	Ghissi et al. [77]
	<i>Piper regnellii</i> (Pariparoba) leaves	Reduction of plasma exudation by 55.45% (2.41 ± 0.65)	Mice	Campo-Grande et al. [101]
	<i>Gynostemma pentaphyllum</i> <i>Trigonella foenum-graecum</i> L. (fenugreek)	Fasting blood sugar decreases to 7.42 mmol/L Fasting blood glucose (FBG) decreased to 6.30 ± 0.44 mmol/L	Diabetic mice Newly diagnosed type-2 diabetics patients between the age of 30–60 years	Wang et al. [81] Rashid et al. [78]
Antitumor	<i>Coreopsis tinctoria</i> Nutt.	IC ₅₀ = 2.79 ± 0.17 mM IC ₅₀ = 2.79 ± 0.17 mM	α-amylase inhibitory α-glucosidase inhibitory	Yu et al. [45]
	<i>Zingiber officinale</i> Roscoe (ginger)	Inhibition rates: 23.339 ± 2.2857% 16.958 ± 0.005% 56.843 ± 2.405% 13.149 ± 0.938% 21.061 ± 1.920%	Inhibition on: H1975 Hela HCT116 B16 MCF-7	Liao et al. [119]
	<i>Ocimum basilicum</i> L. (basil)	400 mg/kg inhibits size (volume) in the human HCC cell lines with high metastatic potential (MH977H)	Mice	Feng et al. [120]
	<i>Astragalus membranaceus</i>	IC ₅₀ values of APS4: 170.59 μg/mL 229.90 μg/mL 294.31 μg/mL	Inhibition on: MGC-803 cells A549 cells HepG2 cells	Yu et al. [121]
	<i>Clinacanthus nutans</i> Lindau <i>Panax ginseng</i> L.	IC ₅₀ value of 0.191 mg/mL at 72 h IC ₅₀ value 0.09 mg/mL	MDA-MB-231 breast cancer HCT116 p21 ^{-/-} cells	Yong et al. [28] King and Murphy [33]
Antiproliferative activity	<i>Carthamus tinctorius</i> L. (Safflower)	Antiproliferative rates: 45.67% (SSP3) 41.52% (SSP4)	A549 cells (lung adenocarcinoma cells)	Wang et al. [82]
Antibacterial	<i>Pimpinella anisum</i> L.	Diameter of inhibition zone: 18.5 ± 0.2 mm 16.5 ± 0.7 mm	<i>P. aeruginosa</i> <i>B. cereus</i>	Ghissi et al. [77]
	<i>Althaea officinalis</i> L.	inhibition zones of 5.23 mm at 4 mg/mL inhibition zones of 15.76 mm at 20 mg/mL	<i>E. coli</i>	Karimi et al. [30]

7. Biological activity of polysaccharides

Polysaccharides from herbs and spices can exhibit many biological activities including antioxidant, anti-inflammatory, immunomodulatory, anti-tumor, and hypoglycemic. These biological activities are heavily associated with the physicochemical properties of the extracted polysaccharides.

7.1. Antioxidant activity

Antioxidants play a critical role in mitigating oxidative stress, which arises from an imbalance between the generation of reactive oxygen species (ROS) and the endogenous antioxidant defense system. This imbalance leads to oxidative damage of lipids, proteins, and nucleic acids and is implicated in the development of chronic diseases, including cardiovascular disorders, diabetes, cancer, and neurodegenerative conditions. Importantly, ROS encompass chemically distinct species, including free radicals such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide anions ($\text{O}_2\bullet^-$), as well as non-radical oxidants such as hydrogen peroxide (H_2O_2). These species differ in reactivity, lifetime, and biological impact, and therefore require distinct scavenging or detoxification mechanisms.

Polysaccharides derived from herbs and spices exhibit antioxidant activity through multiple, mechanism-dependent pathways that vary according to the type of reactive species involved. For relatively stable organic radicals such as DPPH \bullet and ABTS \bullet^+ , commonly employed in *in vitro* assays, antioxidant activity is predominantly governed by single electron transfer (SET) mechanisms [115]. In this process, polysaccharides donate electrons from functional groups such as hydroxyl and carboxyl moieties, reducing the radical species and resulting in measurable changes in absorbance. It is important to note that such assays primarily reflect the electron-donating capacity of polysaccharides rather than direct physiological radical scavenging.

In contrast, highly reactive radicals such as hydroxyl radicals ($\bullet\text{OH}$) are more effectively mitigated through hydrogen atom transfer (HAT) mechanisms and, more importantly, through indirect inhibition of their formation [116]. Due to their extremely short half-life, $\bullet\text{OH}$ radicals cannot be selectively scavenged once formed. Instead, polysaccharides exert protective effects by chelating transition metal ions (e.g., Fe^{2+} and Cu^{2+}), thereby suppressing Fenton-type reactions responsible for $\bullet\text{OH}$ generation. Functional groups such as uronic acids and hydroxyl moieties play a central role in this metal-binding process (Table 5) [122].

For superoxide anions ($\text{O}_2\bullet^-$), direct scavenging by polysaccharides is relatively limited. Rather, polysaccharides enhance antioxidant defense primarily through the modulation of endogenous enzymatic systems, particularly superoxide dismutase (SOD), which catalyzes the conversion of $\text{O}_2\bullet^-$ into hydrogen peroxide (H_2O_2) and oxygen (O_2) [123]. The resulting H_2O_2 , although not a free radical, must be further detoxified by enzymes such as catalase or glutathione peroxidase, highlighting the importance of coordinated antioxidant networks.

The antioxidant efficiency of polysaccharides is strongly influenced by their structural characteristics, including monosaccharide composition, molecular weight, degree of branching, and the presence of uronic acids. These features govern electron density, accessibility of reactive sites, and metal-binding capacity, thereby modulating both SET and HAT processes. In particular, uronic acid-rich polysaccharides exhibit enhanced metal chelation, while lower molecular weight fractions may facilitate improved interaction with reactive species.

Experimental observations support these mechanistic pathways. For instance, the polysaccharide fraction AOP-2A from *A. officinalis* root exhibited notable DPPH scavenging activity ($\text{IC}_{50} = 1.53 \text{ mg/mL}$), which was higher compared to that of vitamin C, reflecting polysaccharides ability to donate hydrogen atoms or electrons to stabilize free radicals (SET-based) [47]. Similarly, green tea polysaccharides (GTPS), which exist as polysaccharide-polyphenol conjugates, demonstrated enhanced scavenging of DPPH \bullet , $\bullet\text{OH}$, and $\text{O}_2\bullet^-$, as well as

reducing power *in vitro* [117]. The improved activity is attributed to the presence of electron-rich functional groups (hydroxyl and carboxyl), which facilitate both SET and HAT processes, as well as metal ion coordination via uronic acid residues, which suppress ROS generation at its source.

In summary, these findings demonstrate that the antioxidant activity of polysaccharides is mechanistically multifaceted and highly dependent on the specific type of reactive species involved. Therefore, antioxidant capacity should not be interpreted as a single unified property; rather, it reflects the combined contributions of multiple mechanisms, including electron transfer, hydrogen donation, metal chelation, and enzyme modulation. This underscores the importance of considering SAR and assay-specific mechanisms when evaluating the antioxidant potential of polysaccharides.

7.2. Immunomodulatory activity

Polysaccharides exhibit immunomodulatory activity through the regulation of both innate and adaptive immune responses, primarily via interaction with immune cell surface receptors and subsequent activation of intracellular signaling pathways. Rather than acting as nonspecific stimulants, polysaccharides function as biological response modifiers, with their activity closely governed by structural features such as molecular weight, monosaccharide composition, glycosidic linkage patterns, and degree of substitution.

At the cellular level, polysaccharides are recognized by pattern recognition receptors (PRRs) expressed on immune cells, including macrophages, dendritic cells, and natural killer (NK) cells. Key receptors involved include Toll-like receptors (e.g., TLR4) and C-type lectin receptors (e.g., Dectin-1), which selectively bind carbohydrate structures. Upon receptor binding, intracellular signaling cascades such as the nuclear factor kappa B (NF- κ B) and mitogen-activated protein kinase (MAPK) pathways are activated, leading to the transcription of genes associated with immune responses, including cytokines and chemokines.

This receptor-mediated mechanism explains the immunological effects observed in various polysaccharide systems. For example, polysaccharides from *Astragalus membranaceus* (APS-II, 25 $\mu\text{g/mL}$) have been shown to significantly enhance macrophage proliferation and phagocytosis, stimulate T and B lymphocyte proliferation, increase NK cell cytotoxic activity, and promote immunoglobulin G (IgG) production by B lymphocytes [124]. When compared to their respective blank group, the *p*-value is less than 0.05 indicating that the difference between the two groups is significant. The immunomodulatory activity of APS-II may be attributed to their monosaccharide residues including 1- α -D-Glcp, 1, 6- α -D-Glcp, 1,4,6- α -D-Glcp, 1,3,4,6- α -D-Glcp, 1,2- α -L-Rhap \rightarrow , 1- α -D-Araf, 1,5- α -D-Araf, and 1,4- β -D-Galp. These effects are consistent with activation of macrophage-associated signaling pathways and subsequent cytokine production. The immunomodulatory activity of APS-II is closely associated with its structural composition, including α -D-glucopyranosyl and arabinofuranosyl residues and complex branching patterns (e.g., 1 \rightarrow 6 and 1 \rightarrow 4,6 linkages), which are likely to influence receptor binding affinity and downstream signaling efficiency.

Similarly, polysaccharides from *Pueraria* root, characterized by \rightarrow 4)- α -D-Glcp(1 \rightarrow and \rightarrow 4,6)- α -D-Glcp(1 \rightarrow linkages, have been shown to promote lymphocyte proliferation and cytokine secretion [125]. These structural features may enhance recognition by PRRs, thereby amplifying immune signaling. In another example, polysaccharides from *C. sativus* petals (PCSPA, 5.0 $\mu\text{g/mL}$) significantly increased macrophage phagocytic activity and stimulated the production of cytokines (IL-1 β , IL-10, IL-12p40, TNF- α) and chemokines (CCL5 and CCL22), indicating activation of pro-inflammatory and immunoregulatory pathways [59].

Structural modifications further modulate immunological activity. For instance, a higher O-acetyl content in PCSPA (5.10 \pm 0.06%) compared to PCSPB (3.33 \pm 0.07%) was associated with enhanced immunopotential, suggesting that acetylation may influence

receptor interaction or molecular conformation [59]. Similarly, the presence of sulfate groups, as observed in *Pimpinella anisum* L. polysaccharides (PAP), can enhance biological activity by increasing negative charge density, thereby improving interaction with immune receptors and facilitating cellular uptake [77]. In vivo, PAP-treated mice exhibited accelerated wound healing, as evidenced by complete scab detachment by day 7, whereas the control and cytol centella-treated groups did not achieve full wound closure within the same period. This observation is consistent with enhanced immune-mediated tissue repair processes. The presence of sulfate groups in PAP (0.83%) may contribute to this effect by strengthening receptor binding and modulating immune responses involved in wound healing.

Thus, these findings demonstrate that the immunomodulatory effects of polysaccharides are mediated through specific receptor-ligand interactions and downstream signaling pathways, rather than nonspecific immune stimulation. Accordingly, the activity is therefore highly dependent on structural characteristics, underscoring the importance of detailed structural elucidation in understanding and optimizing their biological functions.

7.2.1. Anti-inflammatory

The anti-inflammatory activity of polysaccharides can be categorized under immunomodulatory activity. However, anti-inflammatory refers specifically to its ability to suppress the release of pro-inflammatory mediators that are usually upregulated during inflammatory responses. The anti-inflammatory activity of the polysaccharides can be evaluated using an in vitro model of lipopolysaccharide (LPS)-stimulated RAW 264.7 cells since LPS is known to effectively induce the production of many pro-inflammatory mediators while also being an effective activator of macrophages.

The cells will be treated with the polysaccharides from the herbs or spices in various concentrations and the production of pro-inflammatory mediators such as nitric oxide (NO), TNF- α , iNOS, NLRP3, COX-2, and IL-6. At a concentration of only 200 $\mu\text{g/mL}$, the purified fraction of polysaccharides from *Astragalus membranaceus* (APS) effectively suppressed the production of pro-inflammatory cytokines including IL-6 and TNF- α [80]. The same authors also discovered that APS lowers the increased protein levels of iNOS, NLRP3, and COX-2 induced by LPS stimulation. This notable anti-inflammatory activity of the purified fraction of APS polysaccharides (APS-B1) could be attributed to its high uronic acid content (1.16% of uronic acid). Similarly, a study by Zhang et al. [102] discovered that the three purified fractions of polysaccharides from *P. zeylanica* L. (WPZP) – with high uronic acid contents of 18.31%, 22.38% and 21.44% – also exhibited promising anti-inflammatory effects; treatment with WPZP-2-1 and WPZP-2-2, significantly decreased the mRNA levels of TNF- α and IL-1 β while increasing the IL-10, an anti-inflammatory cytokine, thereby help in counteract the inflammation.

Anti-inflammatory can also be checked using in vivo testing; a carrageenan-induced paw edema model in rats. The polysaccharides will be administered orally, and the paw swelling will be measured at regular intervals. After treatment, the levels of inflammatory markers in the serum will also be analyzed. Campo-Grande et al. [101] found that the polysaccharides extracted from *Piper regnellii* polysaccharides managed to reduce plasma exudation in carrageenan-induced paw edema mice by 55.45%. Likewise, Ghilissi et al. [77] demonstrated that using polysaccharides from *Pimpinella anisum* L. can decrease paw edema from 1.30 mm in hour 1 to 0.68 mm in hour 5. The polysaccharides from *Piper regnellii* and *Pimpinella anisum* L. did not undergo a purification process, hence both polysaccharides contain a small amount of protein, sulfate and phenolic compounds. Polysaccharides from *Piper regnellii* contain 4.7% phenolic compounds and 5.3% protein while polysaccharides from *Pimpinella anisum* L. contain 1.24% protein, 0.76% lipid and 0.83% sulfate. These additional components in the polysaccharides can be concluded as one of the factors that contribute to the enhanced anti-inflammatory activity.

7.3. Antidiabetic and hypoglycemic activities

Antidiabetic activity of polysaccharides from herbs and spices focuses more on the management or prevention of diabetes and complications along with it. This can be done by either reducing the absorption of glucose, improving insulin secretion or sensitivity, or preventing the development of insulin resistance. It can also inhibit enzymes (α -amylase and α -glucosidase) involved in carbohydrate digestion. The inhibition of these enzymes slows down the breakdown of carbohydrates into glucose, thereby reducing postprandial blood sugar spikes. The percentage inhibition was calculated and compared with standard antidiabetic drugs like acarbose. Hypoglycemic activity mainly refers to the decrease of sugar blood levels below the standard range to help regulate blood sugar levels. The mechanism for hypoglycemic and antidiabetic activities can be similar, inhibiting α -amylase and α -glucosidase from breaking down carbohydrates into glucose.

Rashid et al. [78] conducted a clinical investigation on newly diagnosed type-2 diabetes by using *Trigonella foenum-graecum* L. (fenugreek) polysaccharides. It is found that the fenugreek polysaccharides significantly reduced the fasting blood glucose (6.30 ± 0.44 mmol/L), HBA_{1C} (6.23 ± 0.44), total blood cholesterol (4.57 ± 0.50), triglycerides (1.88 ± 0.53), and low-density lipoprotein (1.89 ± 0.48) to a normal value after 12 weeks of intervention. A study by Wang et al. [81] shows that the fasting blood sugar of diabetic mice was able to decrease from 17.56 mmol/L to 7.42 mmol/L by only using 0.5 mL of the polysaccharides extracted from *Gynostemma pentaphyllum* (GPP). The same study also showed that the P_{app} (apparent permanent permeability) of the glucose + GPP group in the Caco-2 cells model was lower than that of glucose, suggesting that GPP had an inhibition effect on glucose absorption and could help to control the postprandial glucose level of diabetic patients.

This remarkable antidiabetic activity from both polysaccharides can be attributed to their monosaccharide composition. Fenugreek polysaccharides contain mainly galactose and mannose classifying the polysaccharides as galactomannan where few studies showed that it exhibits good hypoglycemic and hypolipidemic effects on diabetics [78]. Wang et al. [81] found that the *Gynostemma pentaphyllum* polysaccharide also consists of galactose (13.31 $\mu\text{mol/L}$) and mannose (0.91 $\mu\text{mol/L}$), along with other monosaccharides including galacturonic acid (4.75 $\mu\text{mol/L}$), glucose (20.99 $\mu\text{mol/L}$), rhamnose (4.11 $\mu\text{mol/L}$) and arabinose (7.34 $\mu\text{mol/L}$). In this case, the antidiabetic activity/hypoglycemic activity could also be attributed to the presence of galacturonic acid (uronic acid) as uronic acid plays a role in enhancing bioactivity. Polysaccharides *Z. officinale* Roscoe (ginger) extracted using the alkaline extraction method has the strongest α -glucosidase inhibitors ($\text{IC}_{50} = 0.981$ mg/mL). This attribute is said to be related to the uronic acid content as the ginger polysaccharides from alkaline extraction contain the highest uronic acid. In contrast, the ginger polysaccharides from the HWE method contain the lowest amount uronic acid [70].

The remarkable antidiabetic activity of these polysaccharides can be attributed to their monosaccharide composition. Fenugreek polysaccharides, primarily composed of galactose and mannose, are classified as galactomannans. Several studies have demonstrated their significant hypoglycemic and hypolipidemic effects in diabetic models [78]. Similarly, *Gynostemma pentaphyllum* polysaccharides contain a high concentration of galactose (13.31 $\mu\text{mol/L}$), second only to glucose, followed by arabinose, galacturonic acid, rhamnose, and mannose [81]. The specific amounts of these monosaccharides are detailed in Table 3. The combined presence of galactose, mannose, arabinose, and rhamnose has been shown to enhance both hypoglycemic and antidiabetic activity. Additionally, galacturonic acid further strengthens biological activity by increasing the uronic acid content in the polysaccharides.

Further supporting this, one of the purified fractions of polysaccharides from pepper leaves, PLP-2, exhibits superior hypoglycemic and antidiabetic activity compared to PLP-1 [88]. According to the

authors, PLP-2 reduce blood glucose levels in diabetic mice to 15.22 mmol/L after 28 days. PLP-2 also manages to lower the serum levels of TC by 27.03% and TG by 27.22%. These values are comparable to the positive control group receiving metformin. This is likely due to the presence of both galactose and rhamnose in PLP-2, whereas PLP-1 contains only mannose and glucose [88]. Moreover, the additional presence of sulfates (10.30%) in PLP-2 further enhances its biological activity. These studies suggest that the hypoglycemic and antidiabetic activity of polysaccharides from herbs and spices is largely influenced by their monosaccharide composition, particularly galactose, rhamnose, arabinose, and mannose. Furthermore, the presence of galacturonic acid/uronic acid, and sulfates further enhances the bioactivity.

7.4. Anti-tumor activity

Polysaccharides exert their anti-tumor effects through multiple mechanisms, including the induction of apoptosis (programmed cell death) in cancer cells, suppression of angiogenesis (formation of new blood vessels that feed tumors), and enhancement of the body's immune surveillance against cancerous cells. They may also inhibit cancer cell invasion and metastasis. *O. basilicum* L. polysaccharides (BPS) has been shown to inhibit the metastasis and progression of hypoxia-induced hepatocellular carcinoma (HCC) cells [120]. In their study, the authors induced hypoxic conditions in high metastatic HCC cells (MHCC97H) and low metastatic HCC cells (MHCC97L) using CoCl_2 . They found that treatment with 400 $\mu\text{g}/\text{mL}$ BPS reduced the mobility and invasive capacity of MHCC97H cells, indicating BPS inhibits the CoCl_2 -induced cellular response. In addition, BPS suppressed levels of HIF-1 α mRNA and protein under CoCl_2 -induced hypoxic conditions. In vivo, the experiment demonstrated that administrating 400 mg/kg to HCC xenograft tumors in nude mice resulted in decreasing MHCC97H tumor size, as compared to the control group. This study indicates that polysaccharides may exert anti-tumor activity through the suppression of metastasis and progression of HCC cells, with anti-proliferative effects representing an important underlying mechanism. For instance, polysaccharides from *Carthamus tinctorius* L. (SSP3 and SSP4) demonstrated measurable anti-proliferative activity against A549 (lung adenocarcinoma) cells, with inhibition rates of 45.67 and 41.52%, respectively [82].

Yu et al. [121] extracted *Astragalus membranaceus* polysaccharides (APS) at different temperatures (4 and 90 °C) where the polysaccharides were labelled as APS4 and APS90, respectively. The author tested APS anti-tumor ability on human non-small lung cancer (A549) cells, human gastric carcinoma (MGC-803) cells, and human hepatoma (HepG2) cells. They found that APS4 exhibited the highest inhibitory effect on these cancer cells with the IC_{50} values of 229.90 $\mu\text{g}/\text{mL}$ for A549 cells, 170.59 $\mu\text{g}/\text{mL}$ for MGC-803 cells, and 294.31 $\mu\text{g}/\text{mL}$ for HepG2 cells. Notably, the growth inhibitory effects of APS4 (400 $\mu\text{g}/\text{mL}$) were comparable to those of those commonly used chemotherapy drug 5-Fu at 50 $\mu\text{g}/\text{mL}$. Meanwhile, Chen et al. [70] demonstrated the ginger polysaccharides extracted by ultrasonic cell grinder extraction (UGP1 and UGP2) at 200 $\mu\text{g}/\text{mL}$ had significant inhibition rates on the H1975 (human lung adenocarcinoma) cell line, and human cervical cancer HeLa cell line and on human colon cancer HCT116 cell line and mouse melanoma B16 cell at a dose of 150 $\mu\text{g}/\text{mL}$.

Based on the study done by Yu et al. [121] and Chen et al. [70], the temperature during extraction affects the anti-tumor activity. Specifically, polysaccharides extracted at cold temperatures enhance anti-tumor activity due to the structural changes that high temperatures can induce. For instance, Yu et al. [121], the APS consisted of 1, 2-linked-Glcp but the molar ratio of 1,2,6-linked-Glcp in APS4 was significantly higher than the other APS fractions; stipulating APS4 has a higher degree of branching. This higher degree of branching is associated to effective anti-tumor activity as cold extraction methods help retain the higher branched structure of polysaccharides. Similar to the APS polysaccharides (temperature-wise), the ultrasonic cell grinder

extraction was done at a cold temperature (in an ice bath) allowing UGP1 to possess and retain a special structure of $\rightarrow 6$ - β -D-Galp-(1 \rightarrow . Chen et al. [70] noted that β -D-galactopyranose may be linked to anti-tumor activities, especially with human colon cancer cells. This can be seen from Table 4 where UGP1 has the highest inhibition on the HCT116 cell line.

8. Application

8.1. Pharmaceutical and nutraceutical applications

Polysaccharides exhibiting immunomodulatory and anti-inflammatory activities can be useful in the development of drugs or supplements to manage chronic inflammatory conditions or boost immunity. According to Zhang et al. [32], polysaccharides extracted from *Ophiopogon japonicus* (dwarf lily) display remarkable bioactivity including antioxidant, anti-diabetic, cardiovascular protection, and anti-obesity. The China Food and Drug Administration (CFDA) has approved patent drugs namely Shen Mai injection/granule, Xuan Mai Gan Jie capsule/granule, etc., which contain *O. japonicas* as the main medicinal ingredient [32,126]. Meanwhile, another study done by Tabarsa et al. [84] found that *Cuminum cyminum* L. (cumin) polysaccharides have the potential to be natural immunostimulants as they stimulate the production of RAW264.7 and NK-92 cells. Findings from Zhang et al. [50] reveal that polysaccharides *A. bidentata* Blume roots have osteoprotective effects; restoring bone mineral content, improving trabecular bone, and decreasing serum levels of bone turnover biomarkers. This suggests that polysaccharides can be an alternative drug therapy for osteoporosis. Polysaccharides from herbs and spices also play a significant role in the nutraceutical industry due to their health-promoting properties. These compounds can be incorporated into functional foods, beverages, or dietary supplements to provide added health benefits. For example, turmeric polysaccharides have the potential to be a functional food due to their strong antioxidant, regulating intestinal flora and enhancing immunity abilities [96,118]. Incorporating these polysaccharides into food products provides an avenue for natural health improvement through diet.

8.2. Cosmetic and skincare applications

Polysaccharides extracted from herbs and spices are increasingly utilized due to their moisturizing, anti-ageing, and skin-soothing properties. *Aloe vera* polysaccharides, for instance, are well-known for their hydrating and healing effects, making them a common ingredient in skincare products designed to alleviate skin irritation and promote skin repair. Licorice (*Glycyrrhiza glabra*) polysaccharides also find use in skincare formulations due to their antioxidant properties and ability to lighten hyperpigmentation. *C. cassia* polysaccharides can be a therapeutic source to treat skin hyperpigmentation due to their potent ability to inhibit tyrosinase [68]. The findings from the authors also suggest that this polysaccharide has a high sun protective factor (SPF), antioxidant, and further indication that this compound is beneficial for the skin. These natural polysaccharides offer a safer and eco-friendly alternative to synthetic chemicals in personal care products. *Eriodictyon californicum*, a medicinal plant to treat skin wounds also known as yerba santa, is a source of moisturizing ingredients such as mucopolysaccharides and glycoproteins that act via hydrogen bonding of water by their sugar moieties [127,128].

8.3. Food industry applications

In the food industry, polysaccharides from herbs and spices serve as natural additives to improve the texture, stability, and shelf life of food products. Their gelling, thickening, and emulsifying properties make them useful in a variety of food formulations. Nunes et al. [58] suggest that the polysaccharides from *C. burmannii* and *Cinnamomum verum* have

the potential to be a flavoring and thickening agent in the food industry as these polysaccharides possess high viscosity. *Allium cepa* L. polysaccharides extracted using concentrated alkaline saline solution have high foam stability along with high foaming capacity; making it beneficial for food processing and food formulations [100]. High foaming stability and capacity help in stabilizing foams in food and improve the texture and mouthfeel of the food. The polysaccharides extracted from *O. album* L. demonstrate high thermal stability that can improve food formulations by acting as a stabilizing compound [40]. Polysaccharides from the seeds of *A. graveolens* L. improved bacterial stability, reduced lipid peroxidation, and preserved the pH and color of the turkey sausages during cold storage for 12 days, hence suggesting the polysaccharides act as potent meat preservatives, comparable to ascorbic acid, for food industries [55]. Their potential health benefits, including antioxidant and antimicrobial properties, contribute to improving food safety and quality.

9. Limitation and challenges

There are several limitations and challenges involving polysaccharides from herbs and spices. Firstly, choosing a suitable overall method to preserve the biological activity of the polysaccharides. Certain methods might favor the yield of the polysaccharides but might alter the structure and the composition of the product which leads to low bioactivity of the polysaccharides. Secondly, the relationship between the physicochemical properties and the bioactivity of the polysaccharides from herbs and spices remains largely elusive. This may be due to the complexity of the mechanisms and the structure. Thirdly, lack of study/exploration on the application and potential of polysaccharides from herbs and spices as real-world products. All of these require deep and extensive research which might be constrained due to limited time, energy and budget.

10. Future recommendations

Despite considerable advances in the extraction and characterization of polysaccharides from herbs and spices, several critical gaps remain that must be addressed to advance both fundamental understanding and practical applications. Future research should prioritize the development of integrated and controllable extraction strategies that balance extraction efficiency with structural preservation. Although techniques such as EAE, UAE, and MAE have demonstrated improved performance, their effects on fine structural attributes, including molecular weight distribution, branching structure, and functional group integrity, remain insufficiently characterized. Systematic and standardized comparative studies are therefore required to establish structure-preserving extraction protocols, particularly at pilot and industrial scales.

Apart from that, there is a clear need for mechanistically grounded SAR studies. Despite existing research frequently reports correlations between physicochemical properties and bioactivities, causal relationships are rarely established. Future investigations should focus on elucidating the relationships between specific structural parameters, such as monosaccharide composition, glycosidic linkages, molecular weight, and degrees of substitution (e.g., sulfation and acetylation), and biological function. This will require the integration of advanced structural characterization techniques (e.g., NMR spectroscopy and chromatographic methods) with molecular and cellular assays to enable predictive, rather than descriptive, models.

Furthermore, deeper insight into the molecular mechanisms underlying bioactivity is essential. Although antioxidant, immunomodulatory, and enzyme inhibitory effects have been widely reported, the underlying biochemical and cellular pathways remain incompletely defined. Future investigations should integrate mechanistic methodologies, including receptor-binding assays, detailed analysis of signaling pathways (e.g., NF- κ B and MAPK), and enzyme kinetic studies, to define the molecular mechanisms underlying polysaccharide-mediated bioactivity.

Other than that, the translation of laboratory findings into practical applications remains limited. There is a need for well-designed *in vivo* studies, pharmacokinetic analyses, and clinical evaluations to validate efficacy, safety, and bioavailability. In parallel, the development of polysaccharide-based formulations for functional foods, nutraceuticals, and pharmaceuticals should be advanced, with careful consideration of stability, dosage, and delivery systems.

Moreover, future research should emphasize sustainability and resource efficiency, including the valorization of underutilized plant parts and agro-industrial by-products as alternative polysaccharide sources. These approaches not only improve resource utilization but also align with the increasing demand for green and sustainable processing technologies. These directions will support a transition from largely descriptive research toward mechanistically informed and application-oriented studies, enabling the rational development of polysaccharide-based functional materials and therapeutics.

11. Conclusion

Polysaccharides derived from herbs and spices represent a structurally diverse and functionally versatile class of biopolymers with considerable potential across nutraceutical, pharmaceutical, and industrial domains. Accumulating evidence indicates that these polysaccharides exhibit a wide range of biological activities, including antioxidant, antimicrobial, anti-diabetic, anti-inflammatory, and immunomodulatory effects. Importantly, these activities are not intrinsic properties alone but are strongly influenced by structural characteristics, which are, in turn, governed by extraction methods and plant anatomical origin. This review demonstrates that variations in extraction strategies, plant parts, and molecular structure collectively shape the physicochemical properties and biological functions of polysaccharides. However, despite the growing body of literature, the field remains largely descriptive, with limited mechanistic insight and insufficient integration between structure, function, and application. To fully realize the potential of these biopolymers, future research must move beyond activity screening toward mechanistically driven and application-focused investigations. This includes the development of structure-preserving and scalable extraction strategies, such as the optimization of microwave-, ultrasound-, and enzyme-assisted extraction systems under controlled conditions to minimize polysaccharide degradation while improving yield. In addition, future investigations should prioritize the elucidation of molecular mechanisms, including receptor-mediated signaling pathways (e.g., TLR4, NF- κ B, and MAPK) and enzyme-substrate interactions, to establish the relationships between structural features and biological activity. Furthermore, there is a critical need to advance application-oriented research, particularly through *in vivo* validation, pharmacokinetic evaluation, and the development of targeted formulations for functional foods, nutraceuticals, and therapeutic interventions. In this context, polysaccharides from herbs and spices should be viewed not merely as bioactive extracts, but as engineerable functional biomaterials whose properties can be tailored through controlled extraction and structural modification. Advancing this perspective will be essential for unlocking their full potential and for establishing their role in next-generation natural product development.

CRedit authorship contribution statement

Abu Hurairah Darwisy Alias: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Insyirah Syahirah Aisyah Mohammad Rizal:** Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **Muhammad Afif Yusof:** Formal analysis, Investigation, Methodology, Visualization. **Muhammad Redza Mohd Radzi:** Data curation, Formal analysis, Investigation, Visualization. **Muhammad Hakimin Shafie:** Conceptualization, Data curation,

Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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