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Review

Prunus spinosa L. – Source of Bioactive Compounds with Antioxidant and Pharmacological Predicted activity

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Abstract

Prunus spinosa L. (blackthorn) is a valuable source of bioactive compounds, including flavonoids, anthocyanins, phenolic acids, vitamins, and minerals, which confer important antioxidant, antibacterial, and anti-inflammatory properties. This comparative review synthesizes experimental data from our previously published research and from the global literature to highlight the phytochemical composition, variability, and potential application prospects of these fruits. The diversity of results obtained in terms of total phenolic content (TPC), total anthocyanin content (TAC), and total flavonoid content (TFC) and biological activities can be explained by the variability of the extraction method, as well as the geographical origin of *Prunus spinosa* L., and demonstrates its relevance for health applications. The results of this comprehensive review revealed an increased potential of *Prunus spinosa* L. extracts for phytotherapeutic, nutraceutical, and functional product applications.

Keywords: *Prunus spinosa* L., polyphenols, HPLC, antioxidant activity, antimicrobial effect, DPPH, gallic acid, Folin-Ciocalteu, extract, comparative studies

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Introduction

Prunus spinosa L. (blackthorn) is widespread throughout most of Europe, North America, the Northern part of Africa, Asia Minor, New Zealand, and Tasmania. It is a bush or small tree (2-3 m high) of the Rosaceae family [1-4].

In late summer and early autumn, it produces bluish-black fruits with an astringent taste, valued both in food and in traditional medicine [5-7].

Ethnopharmacological studies have highlighted the use of *Prunus spinosa* L. fruits in treating conditions such as urinary tract infections, diabetes, bronchitis, diarrhea, and external inflammations of the mouth and throat [1, 8, 9].

Many of the health benefits associated with the consumption of *Prunus spinosa* L. fruits are attributed to their high polyphenol content. Although anthocyanins are considered among the most important bioactive compounds, research shows that phenolic acids and flavones/flavonols may have comparable or even superior effects, due to synergistic and additive action, compared to the anthocyanin-rich fractions of these fruits [10-13]. Also, the alkali-extracted fraction, rich in arabinogalactan and hemicellulose, has demonstrated a free radical neutralization capacity like that of vitamin C [14, 15].

Given their seasonality, *Prunus spinosa* L. fruits require appropriate processing and preservation methods. However, freezing and storage in a frozen state for several months have been found not to significantly affect the levels of nutritional and bioactive compounds. Among the preservation methods, lyophilization is the most effective, compared to convection or freeze-drying. Even dried fruits, despite a significantly lower content of bioactive compounds compared to fresh ones, have demonstrated notable anti-inflammatory, antioxidant, and antimicrobial properties [16-19].

Prunus spinosa L. extracts can be used in many areas, including the food industry, where they are used as natural colorants and preservatives, due to the high content of polyphenols with antioxidant and antibacterial properties [7, 9, 20, 21]. For example, the addition of *Prunus spinosa* L. fruits to ice cream has led to an increase in the color, texture, appearance, and overall acceptability of the product [1, 22]. The fruits can be eaten raw when they reach maturity in autumn or after the first frost, when they become sweeter and less pungent, or can be used in the preparation of compotes, jams, brandy, and liqueurs [5-7].

Material and Methods

This article is structured as a comparative review, integrating data from peer-reviewed literature with our results already published in scientific journals. The objective is to provide a comprehensive overview of the antioxidant and antimicrobial properties of *Prunus spinosa* L. fruits, presented for comparative purposes, emphasizing similarities and differences across studies in relation to geographical origin, climatic conditions, maturity stage, extraction methods, and analytical techniques.

A comprehensive research literature published in prestigious international scientific journals relevant to the topic addressed was performed through worldwide databases (PubMed, Scopus, SpringerLink, Google Scholar, Embase, Web of Science), using keywords such as: "*Prunus spinosa* L. ", "HPLC", "*antioxidant activity*", "*antimicrobial effect*", "*DPPH*", "*gallic acid*". Previously, our research results were compared with the results obtained from recent research published in the specialized literature.

Experimental methodologies described in the reviewed studies – and in our previously published results – include solvent extraction of bioactive compounds (water, ethanol, acetone, water–ethanol mixtures), antioxidant capacity assessment using the Folin–Ciocalteu method (total phenolic content), high-performance liquid chromatography–mass spectrometry (HPLC–MS) for compound identification, and antioxidant assays such as 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging, oxygen radical absorbance capacity (ORAC), trolox equivalent antioxidant capacity (ABTS), and ferric reducing antioxidant potential (FRAP).

Antibacterial and antifungal activities were evaluated by agar disk diffusion against selected Gram-positive and Gram-negative bacterial strains (*Staphylococcus aureus* ATCC 6538, *Escherichia coli* ATCC 8739, *Pseudomonas aeruginosa* ATCC 9027, *Salmonella abony* NCTC 6017) and fungal strains (*Candida albicans* ATCC 10231), with measurements of inhibition zone diameters (DIZ) and minimum inhibitory concentrations (MIC).

Results and Discussion

The large spectrum of biological effects of *Prunus spinosa* L. fruits is mainly attributed to their high polyphenol content, which is the source of their antioxidant, antimicrobial, antifungal, and anti-inflammatory activities. These properties can be explored from three different perspectives: phytochemical sources, biological activity – *in vitro* analyses, and pharmacological aspects.

Phytochemical Sources

The fruits of the *Prunus spinosa* L. are a rich source of bioactive compounds, including phenolic acids (Fig. 1), flavonoids (Fig. 2), anthocyanins, vitamins, and organic acids [9, 23, 24]. In addition, the plant contains significant amounts of macro and microelements, such as calcium, potassium, iron, sodium, and magnesium [3, 25, 26].

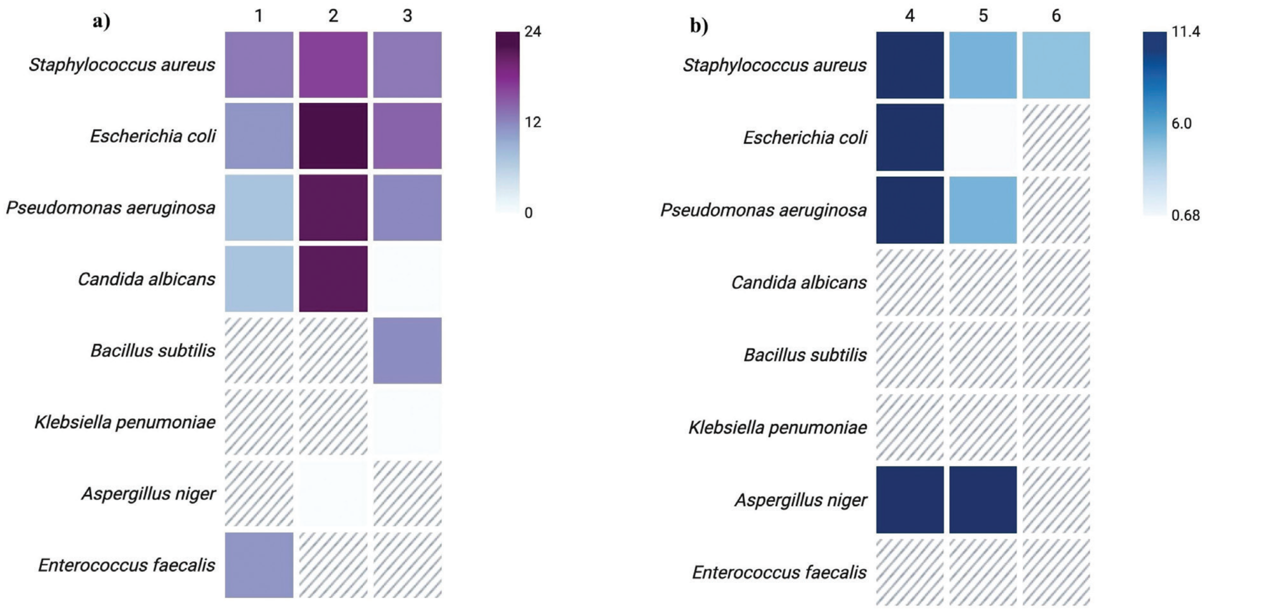

Fig. 1. Comparative analysis of antimicrobial activity of *Prunus spinosa* L. extracts (aqueous, ethanolic, methanolic, polyphenol) from different collection areas; a) inhibition zone (mm), b) minimum inhibition concentration (MIC) (mg/mL); 1 – Aqueous extract – South-eastern Romania [37]; 2 – Ethanolic extract, South-eastern Serbia [6]; 3 – Polyphenol extracts, South-eastern Serbia [88]; 4 – Aqueous extracts, Western Croatia [86]; 5 – Ethanolic extracts, Western Croatia [86]; 6 – Methanolic extract, Southern France [87].

Among them, polyphenols are particularly notable for their significant contribution to the antioxidant capacity, often exceeding the efficiency of other antioxidants such as vitamins C and E or carotenoids [27]. *Prunus spinosa* L. fruits are also recognized as a valuable source of vitamin C [1, 3, 28], with concentrations frequently reported around 25 mg/100 g of fresh product [29].

Among the most common flavonoids found in these fruits are quercetin and its glycosides, such as rutin, which are concentrated mainly in the peel [1, 8, 9, 30]. Previous studies have identified a variety of bioactive compounds in *Prunus spinosa* L. fruits, including caffeic acids, catechin, epicatechin, kaempferol, gallic acid, chlorogenic acid, syringic acid, and p-coumaric acid [31]. Gallic acid stands out for its broad spectrum of biological activities, with antioxidant, anti-inflammatory, antibacterial, antiviral, anti-melanogenic, antimutagenic, and anticarcinogenic effects, reinforcing the therapeutic value of *P. spinosa* fruits [32].

From a nutritional perspective, *Prunus spinosa* L. fruits are rich in available carbohydrates and dietary fiber and are characterized by a high content of monounsaturated fatty acids [1, 33, 34].

The researchers have highlighted their essential role in supporting the body's defense mechanisms, including anti-aging, antimicrobial, anti-inflammatory, and antiproliferative effects and a considerable potential in preventing oxidative stress and its associated diseases [35-39].

Biological Activity – *In vitro* Analyses

Phenolic compounds present in *Prunus spinosa* L. extracts, known for their ability to capture free radicals, are present in varying amounts and significantly reduce the harmful effects of free radicals in the body [40, 41].

These compounds exhibit both strong antioxidants and prooxidant properties, depending on the biological context [42-46]. *In vitro* studies showed an important role in the prevention of neurodegenerative [47-51], cardiovascular, and cancer diseases [52-54]. Due to these characteristics, they can be exploited in the oncological field, either as preventive agents (by neutralizing free radicals) or as prooxidant agents capable of inducing cancer cell death [42-46].

They can also reduce reactive oxygen species (ROS) generation by immune cells such as neutrophils, the most abundant immune cells in human blood, and constitute a first line of defense against proinflammatory stimuli [55-60]. Elevated levels of ROS and biomarkers of oxidative stress have been identified in the blood or inflamed tissue of patients suffering from various chronic diseases, including inflammatory disorders of the digestive tract [54, 61, 62], diabetes mellitus and its vascular complications [63-66] – therapeutic areas in which *Prunus spinosa* L. has been traditionally used [62, 67, 68]. Recent *in vitro* studies on fresh fruits indicate that antioxidant activity at the cellular level may play a key role in their beneficial health effects [11, 69, 70]. For instance, aqueous extracts have demonstrated notable free radical–scavenging potential, correlated with high levels of chlorogenic acid, caffeic acid, and gallic acid (Table 1) [38].

Previous studies by various researchers (detailed in Table 1) have shown marked antioxidant capacity of *Prunus spinosa* L. extracts, as demonstrated frequently by the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay [1, 2, 3, 6, 13, 18, 24, 67, 70-73].

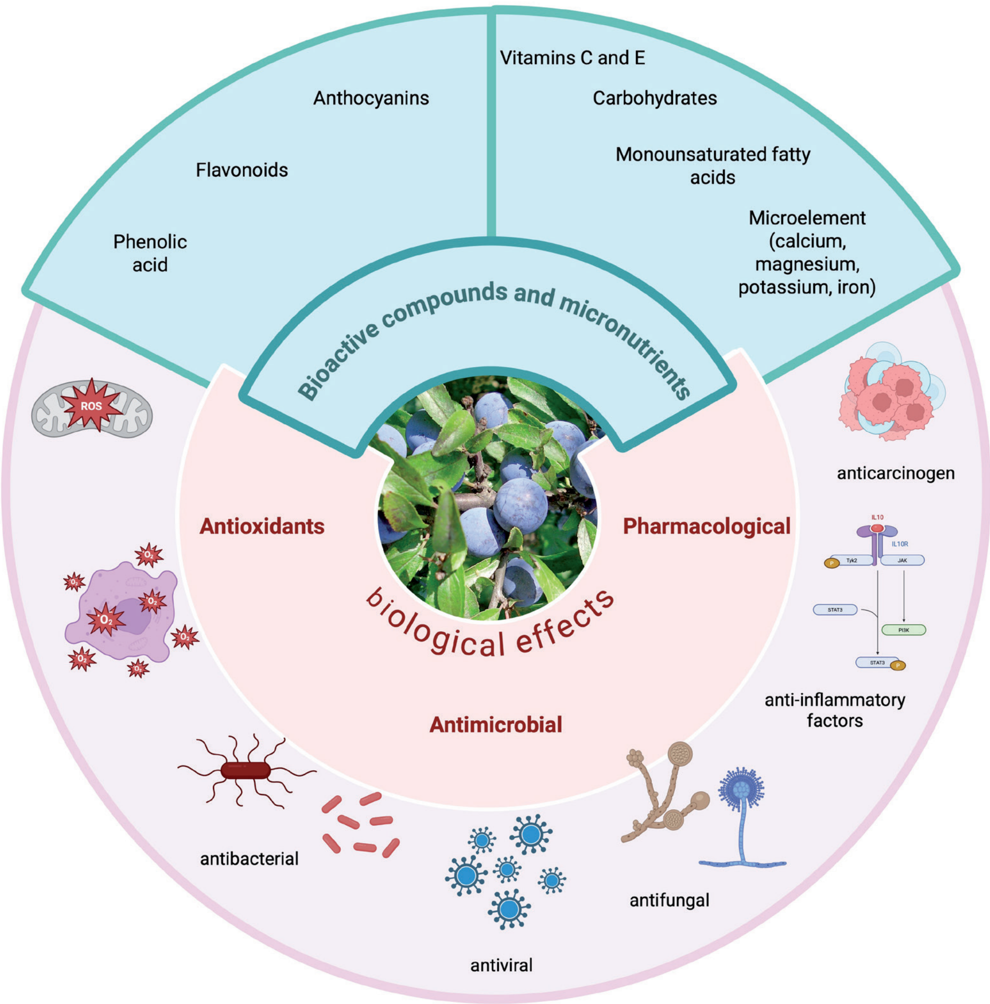

Fig. 2. The diagram of bioactive compounds and biological effects induced by *Prunus spinosa* L. extracts.

Fraternale et al. (2009) analyzed the antioxidant activity of juice obtained from the fruits of *Prunus spinosa* L., comparing it with that of grape juice. The results showed that *Prunus spinosa* L. juice has a significantly higher antioxidant activity than grape juice, with values of 55.13 mg/g DW and 1.15 mg/g DW, respectively [73].

In the study conducted by Kotsou et al. (2023), a comprehensive exploration and optimization of various extraction procedures and factors to obtain the most efficient scheme for extracting bioactive components from whole *Prunus spinosa* L. fruit were analyzed. The optimized extraction conditions can be utilized to produce extracts with enhanced antioxidant properties, contributing to the development of functional foods and nutraceuticals [70].

In one study, 100 micrograms of the crude extracts were applied to silica gel 60 F254 plates (Merck, Darmstadt, Germany), which were developed in appropriate solvent systems: ethyl acetate – methanol – water (35:15:5, v/v/v). Three plates were prepared under the same conditions; one for the DPPH antiradical assay, and the other two were sprayed with plant-specific reagents, Godin and NP/PEG, to establish a correlation between the antioxidant activity and the nature of the active compounds present in the extract [74].

The vitamin C levels observed in *Prunus spinosa* L. berries were consistent with those reported in other studies, ranging from 20.86 mg/100 g in frozen raw material to 23.84 mg/100 g in fresh raw material. It was also found that freezing and frozen storage processes did not significantly affect the antioxidant content of blackcurrant fruits, thus maintaining their functional qualities in the long term [72].

In another study, extracts of *Prunus domestica*, *Prunus cerasifera,* and *Prunus spinosa* L. were compared for their antioxidant activity, and the result of the study showed that the extract of *Prunus spinosa* L., due to its phenolic content, showed a significantly higher antioxidant activity than the other species ($p<0.01$) [40].

The research made by Ruiz-Rodríguez et al. (2014) quantified bioactive compounds, including vitamin C (as ascorbic and dehydroascorbic acid), as well as total phenolic compounds, mainly composed of phenolic acids, flavonols, and anthocyanins. Antioxidant capacity was also assessed using different *in vitro* tests

Table 1. Research on the antioxidant activity of *Prunus spinosa* L.

Nr.	Collection site	Identified Compounds	Evaluation Method	Reported Values	Antioxidant Activity	References
1.	South-eastern Romania	Chlorogenic Acid, Caffeic Acid, Gallic Acid, Tannins, Total Polyphenols.	HPLC Folin-Ciocalteu DPPH	– 15.174 mg/100g of fruit pulp powder, 10.93 mg/100g of fruit pulp powder, 81.468 mg/100g of fruit pulp powder. – 3.37±0.01 g%, 6.94±0.005 g%. – 87.08% at 100 mg/mL, 19.57±0.61 mg/mL.	Antioxidant properties, high scavenging ability suggest potential for oxidative stress-related conditions.	[38]
2.	Southern Poland	β-carotene, Vitamin C, Polyphenols, Anthocyanins	ABTS	– Antioxidant Activity: 43.6 μmol Trolox/g FW. – Vitamin C: 23.84 mg/100 g. – β-carotene: 0.04 mg/100 g	Freezing the fruit did not significantly affect bioactive compounds	[72]
3.	Central Italy	Cyanidin-3-rutinoside, Peonidin-3-rutinoside, Cyanidin-3-glucoside	DPPH, ORAC	– ORAC: 36.0 μmol eq. Trolox/g fruit	Good antioxidant activity compared to Trolox	[73]
4.	North-eastern Spain	Phenolic acids, coumarins, flavan-3-ols, and flavonols	HPLC DPPH	– TPC: 359.11±2.54 mg/g for the ethanol extract and 327.02±4.66 mg/g for the aqueous extract. – DPPH IC_{50}: 22,20 g/mL at 90 min of ethanolic extract from fruits of *Prunus spinosa* L.	Significant reduction in antioxidant activity after digestion, indicating bioavailability concerns.	[74]
5.	Central Spain	Phenolic compounds (e.g., chlorogenic acid, quercetin, anthocyanins)	DPPH Folin-Ciocalteu FRAP ABTS	– 728.81 mg gallic acid/100g fresh weight – 1431.75 mg pelargonidin 3-glucoside/100g fresh weight – TPC: 2294.57 mg/100 fresh weight – from 7.11 to 15.17 mmol Trolox/100g (fresh fruits).	*Prunus spinosa* L. fruits have strong antioxidant activity.	[71]
6.	Eastern Turkey	Phenolic compounds (e.g., chlorogenic acid, malic acid, vitamin C)	HPLC Folin-Ciocalteu, DPPH, FRAP, ABTS, ORAC	TAC: 102 mg ascorbic/100 g, Chlorogenic acid: 12.98 mg/kg, Malic acid: 1,245 g/100 g	*Prunus spinosa* L. exhibits moderate antioxidant capacity.	[40]
7.	Central Greece	Neochlorogenic acid, polyphenols, flavonoids, and anthocyanins	HPLC FRAP DPPH	– Neochlorogenic acid 4.13 mg GAE/g) – 146.09 μmol ascorbic acid equivalent (AAE)/g – 18.56 μmol AAE/g.	*Prunus spinosa* L. fruits exhibit high antioxidant capacity and significant polyphenol content.	[70]

Table 2. Research on the antimicrobial and antifungal activity of *Prunus spinosa* L.

Nr.	Collection site	Type of Extract	Tested Microorganisms	Evaluation Method	Quantified Values	Antimicrobial Activity	References
1.	South-eastern Romania	Aqueous extract	*Staphylococcus aureus*	Disk diffusion (inhibition)	CS-A 10%: 10 mm; CS-A 50%: 12 mm; CS-T 10%: 11 mm; CS-T 50%: 14 mm	Strong antibacterial activity on 50% solutions from the CS-A and CS-T regions Strong antibacterial activity, with an increasing inhibition zone as the solution concentration increases Resistance to both 10% and 50% solutions from both regions, with mutations appearing Moderate antibacterial activity for both 10% and 50% solutions, increased sensitivity Total resistance to 10% solutions from both regions, and to 50% for CS-T; moderate activity for CS-A No antifungal activity observed, all Candida strains were resistant	[37]
			Streptococcus spp.		CS-A 10%: 12 mm; CS-A 50%: 13 mm; CS-T 10%: 12 mm; CS-T 50%: 14 mm		
			Enterococcus faecalis		CS-A 10%, CS-A 50%, CS-T 10%, CS-T 50%: 12mm, resistance mutations occur.		
			Escherichia coli		CS-A 10%: 12 mm; CS-A 50%: 12 mm; CS-T 10%: 13 mm; CS-T 50%: 12 mm		
			Pseudomonas aeruginosa		CS-A 10%: resistance; CS-A 50%: 8 mm; CS-T 10%: resistance; CS-T 50%: resistance		
			Candida albicans		CS-A 10%, CS-A 50%, CS-T 10%, CS-T 50%: resistance		
2.	Western Croatia	Aqueous and ethanolic extracts	*Staphylococcus aureus*	Serial dilution (MIC, MBC)	Water: MIC: 11.36 MBC: 22.73 Ethanol: MIC: 5.68 MBC: 11.36	Antibacterial and antifungal activity. The ethanol extract was more effective against the examined bacteria.	[86]
			Pseudomonas aeruginosa		Water: MIC: 11.36 MBC: 22.73 Ethanol: MIC: 5.68 MBC: 11.36		
			Escherichia coli		Water: MIC: 11.36 MBC: 22.73 Ethanol: MIC: 5.68 MBC: 11.36		
			Aspergillus fumigates		Water: MIC: 11.57 MBC: 23.15 Ethanol: MIC: 11.57 MBC: 23.15		
			Aspergillus niger		Water: MIC: 11.26 MBC: 22.52 Ethanol: MIC: 11.26 MBC: 22.52		
3.	South-eastern Serbia	Ethanolic extract	*Staphylococcus aureus*	Disk diffusion (inhibition)	Inhibition zone for 50 µg: 18.0±0.2 mm	Significant antimicrobial activity	[6]
			Escherichia coli		24.0±0.3 mm		
			Pseudomonas aeruginosa		23.0±0.3 mm		
			Candida albicans		23.0±0.3 mm		
			Aspergillus niger		resistance		

4.	Southern France	Methanolic extract	*Lactobacillus plantarum*		MIC: 2.5 × 10⁻⁴ mg/mL	Significant antimicrobial activity	[87]
			Staphylococcus aureus	Serial dilution (MIC, MBC)	MIC: 5.0 × 10⁻⁴ mg/mL		
			Citrobacter freundii		MIC: 1.0 × 10⁻³ mg/mL		
5.	South-eastern Serbia	Polyphenol extracts	*Staphylococcus aureus*	Disk diffusion (inhibition)	Inhibition zone for 50 µL: 14.2±2.2 mm	Strong antimicrobial and antifungal activity	[88]
			Escherichia coli		15.6±1.3 mm		
			Pseudomonas aeruginosa		12.9±1.1 mm		
			Bacillus subtilis		12.6±1.1 mm		
			Klebsiella pneumoniae		Resistance		
6.	Likely UK/ Western Europe	Crude plant extracts (P70 extract)	*Streptococcus mutans*	Serial dilution (MIC, MBC)	MIC: 2 mg ml⁻¹	Notable antimicrobial activity	[85]

Legend: Minimal inhibitory (MICs) and bactericidal (MBCs), (CS-A=collected site Argeș; CS-T=collected site Tulcea)

(Folin-Ciocalteu, ABTS, DPPH), applied to *Prunus spinosa* L. and *Crataegus monogyna* Jacq. fruits from Spain, collected from different locations and in different seasons. *P. spinosa* fruits showed a vitamin C content ranging from 5.14 to 15.35 mg/100 g fresh matter, predominantly in the form of dehydroascorbic acid. The total phenolic compounds ranged from 1851 to 3825 mg/100 g fresh matter, highlighted by a high level of anthocyanins and phenolic acids [71].

As can be seen from the table, the HPLC method was more efficient in identifying a higher number of antioxidant compounds in Prunus spinosa L. fruits compared to antioxidant activity assays, which are useful to assess overall efficiency but do not provide a complete picture of the diversity of compounds. The combination of HPLC with antioxidant activity test methods (such as DPPH, ABTS, and ORAC) is usually the most efficient approach for a complete assessment of the antioxidant potential of fruits (Table 1).

The structural characteristics of polyphenols, such as functional groups and hydrophobic substituents, significantly influence their effectiveness against various pathogens [75].

Polyphenols enhance antimicrobial and antifungal activity in fruits by inhibiting the growth of bacteria and fungi through mechanisms such as disrupting protein synthesis, destabilizing the cell membrane, and producing reactive oxygen species [76-79], binding to enzymes and interfering with microbial signaling pathways, thus providing a natural defense mechanism against pathogens [80, 81].

In addition, their role is to limit the growth of pathogens and food spoilage organisms, which contributes to food preservation and safety [82].

In a study carried out by Marčetić et al. (2022), an investigation was made on the antimicrobial properties of *Prunus spinosa* L. fruits, and the results showed that the presence of polyphenols contributes to their antimicrobial effects by disrupting microbial cell membranes or inhibiting essential metabolic pathways [1].

Polyphenols, consumed via the fruits, exhibit antimicrobial activities, particularly against *Candida albicans*, by inhibiting mycelial growth, spore germination, and biofilm formation, thus suggesting their potential role in enhancing antifungal effects in chronic oral and systemic fungal infections [83, 84].

In one study, the two aqueous extracts: Argeș collected site (CS-A) and Tulcea collected site (CS-T), prepared in the first stage, showed antibacterial effects against the tested reference strains (10-14 mm). The diameter of the inhibition area increases with increasing aqueous extracts concentration; the best result being obtained at 50% concentration on *Staphylococcus* and *Streptococcus* (14 mm), Fig. 1 (Table 2) [37].

Smullen et al. (2007) demonstrated that polyphenol-rich extracts were effective in inhibiting *Streptococcus mutans*, a bacterium involved in the development of dental caries. In particular, the extract obtained from the peel of *Prunus spinosa* L. berries showed notable antimicrobial activity, with a minimum inhibitory concentration (MIC) of 2 mg/mL. These results suggest the potential of *Prunus spinosa* extracts as natural agents in the prevention of oral infections [85], Fig. 1.

Velickovic et al. (2014) demonstrated the antimicrobial activity of the ethanolic extract of *Prunus spinosa* L. berries using the disk diffusion method. The extract showed inhibitory effects against all tested microorganisms – *Staphylococcus aureus*, *Escherichia coli*, *Salmonella abony,* and *Pseudomonas aeruginosa* – except *Bacillus cereus*, which was found to be resistant to this extract (Table 2). These results highlight the selective efficiency of the ethanolic extract and suggest the need for further investigations into its composition and mechanism of action [6], Fig. 1.

In another research conducted by Veličković I. et al. (2020), various extracts of *Prunus spinosa* L. berries were tested against several microorganisms, including *Bacillus cereus, Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli*, *Aspergillus niger,* and *Penicillium funiculosum*. The results showed that the ethanol extract was the most effective against the investigated bacteria, showing superior antibacterial activity (Table 2). In contrast, the aqueous extract showed greater efficacy against fungi, demonstrating more pronounced antifungal properties compared to the other extracts. These findings highlight the importance of the solvent used in the extraction and plant origin significantly influencing the spectrum of antimicrobial action [86].

The efficacy of methanolic extracts obtained from *Prunus spinosa* L. berries seeds against *Lactobacillus plantarum*, *Staphylococcus aureus,* and *Citrobacter freundii* was confirmed by Kumarasamy et al. (2004), Fig. 1. The tests were performed by the broth dilution method using 96-well microplates. The results revealed significant antimicrobial activity, indicating the potential of *Prunus spinosa* seed extracts as natural antimicrobial agents in pharmaceutical or food applications [87].

Radovanović et al. (2013) reported the antibacterial activity of phenolic-rich extracts obtained from the fruits of the pigweed cultivated in southeastern Serbia, demonstrating significant effects against Gram-positive and Gram-negative bacteria. The recorded minimum inhibitory concentration (MIC) values (0.0156-0.5 mg/mL) were considerably lower than those obtained in our study and those reported by other authors, likely due to the very high content of total phenols, estimated between 152.22 and 321.36 mg/100 g, compared to 9 mg/95.0 g/mL (Table 2) [88].

These results suggest that *Prunus spinosa* L. extracts may be a potential candidate for the development of antimicrobial agents, but further research is needed to better understand the mechanisms of action and to assess possible side effects or long-term bacterial resistance.

Pharmacological Aspects

The promising *in vitro* findings regarding antioxidant, antimicrobial, and antifungal activities support the exploration of *Prunus spinosa* L. extracts in pharmacological contexts, as detailed below.

In the literature, *Prunus spinosa* L. is recognized for multiple phytotherapeutic activities, being used in the treatment of various tea-related conditions. It is known as a mild laxative, diuretic, spasmolytic, and anti-inflammatory. Its antiseptic effect is due to the presence of tannins [54, 89].

In vitro and ex vivo studies show that both dried and fresh extracts of *Prunus spinosa* L. significantly inhibit pro-inflammatory cytokines such as TNF-α and IL-6 while promoting anti-inflammatory IL-10 secretion in human immune cells. The extracts also reduce the release of reactive oxygen species and elastases from neutrophils, indicating a strong anti-inflammatory action [10, 16, 90]. The extracts activate the Nrf2-mediated pathway, reducing reactive oxygen species (ROS) levels in human cells exposed to inflammatory stimuli [91].

A study by Coppari et al. (2021) investigated the wound healing capacity of the ethanolic extract of *P. spinosa* fruits. Human umbilical vein endothelial cells were subjected to a mechanical scratch model in T25 tissue culture flasks, and the regeneration process was monitored by phase contrast microscopy. The results showed that the anti-inflammatory properties of the extract helped accelerate the wound closure process, with a healing rate of up to 70% [92].

Magiera et al. (2022) also evaluated the anti-inflammatory potential of *P. spinosa* extracts. The fruits from Poland were found to be rich in polyphenols, anthocyanins, and flavonols – compounds with a major role in antioxidant and anti-inflammatory activity, Fig. 2. The hydroalcoholic extract demonstrated relevant biological effects, including stimulation of the secretion of important anti-inflammatory factors, such as interleukin-10 (IL-10). These results support the traditional use of *P. spinosa* fruits in the treatment of chronic inflammatory gastrointestinal diseases, given the ability of natural polyphenols to significantly accumulate in the intestine [10].

In summary, the physicochemical characteristics, *in vitro* biological activities, and pharmacological evidence support the therapeutic potential of *Prunus spinosa* L. As indicated in Tables 1 and 2, the composition and bioactivity of *Prunus spinosa* L. vary considerably depending on the origin – from southeastern Romania [38, 37] and southern Poland [72] to central Italy [73], northeastern and central Spain [71, 74], eastern Turkey [40], central Greece [70], western Croatia [86], southeastern Serbia [6, 88], southern France [87], and possibly the United Kingdom/Western Europe [85]. Differences in the phenolic profiles found (e.g., chlorogenic acid, anthocyanins, flavonols), antioxidant values (e.g., DPPH, ABTS, FRAP, ORAC), and antimicrobial efficacy (e.g., inhibition zones, minimum inhibitory concentration (MIC), minimum bactericidal concentration (MBC) reflect not only geographical and climatic influences (possible interaction between soils, temperatures, precipitation, and plants) but also variations in fruit maturity, solvent type (aqueous, ethanolic, methanolic, polyphenol-rich extracts) and analytical approach (HPLC, Folin–Ciocalteu, radical scavenging assays) [93].

Such variability highlights the importance of standardized methodologies when comparing the biological potential of *Prunus spinosa* L. in different studies.

Conclusions

In the present study, relevant research on both bio-compound sources and the biological activity (antioxidant and antimicrobial, pharmacological applications) of extracts from the fruits of *Prunus spinosa* L. was reviewed. The results of this comprehensive analysis revealed high levels of phenolic compounds, flavonoids, and anthocyanins, which are characterized by a pronounced oxidative-stress-reducing effect. This strong antioxidant activity is mainly attributed to the high content of polyphenols, which gives the plants potential value for use in functional food products, nutraceutical supplements, and medical applications, especially in the prevention of diseases associated with oxidative stress and free radicals.

Specifically, it was found that fruit extracts exhibit the highest antioxidant activity, evaluated by the DPPH free radical scavenging assay, regardless of the extraction method applied.

Significant amounts of anthocyanins were obtained in extracts from the fruits of *Prunus spinosa* L.

In addition, fruit extracts demonstrated effective antimicrobial activity against several bacterial strains, including *Bacillus subtilis, Staphylococcus aureus, Enterococcus faecalis,* and *Pseudomonas aeruginosa*, as well as antifungal activity.

In conclusion, the diversity of results obtained in terms of TPC, TFC, TAC, and antioxidant and antimicrobial activities can be explained by the variability of the extraction method, as well as the geographical origin and the part of the plant analyzed. At the same time, these findings support the validity of the traditional use of *Prunus spinosa* L. in phytotherapy and demonstrate its potential values for applications in the field of health and functional nutrition.

Conflict of Interest

The authors declare no conflict of interest.

Some of the data presented has been published and serves as a reference for the concept of the article, including the bibliographic sources where the data was published.

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