

Review

Phytochemical Diversity, Bioactivity and Bioeconomic Potential of Selected Woody Flora from the Karditsa Region (Central Greece): A Comprehensive Review

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Abstract

The Karditsa region of Central Greece hosts a rich diversity of woody plant species that represent valuable sources of bioactive phytochemicals with significant ecological, nutritional, and industrial importance. This review provides a comprehensive overview of the phytochemical composition, biological activities, and bioeconomic potential of five selected woody species occurring in the region, namely *Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa*, and *Satureja montana*. Particular emphasis is placed on the occurrence of phenolic compounds, flavonoids, anthocyanins, tannins, terpenoids, and essential oils, which are responsible for a wide range of biological activities, including antioxidant, antimicrobial, anti-inflammatory, and neuroprotective effects. Current extraction technologies and analytical approaches used for the recovery and characterization of these bioactive compounds are also discussed, highlighting recent advances in green and sustainable extraction methods. Furthermore, the potential applications of these plant-derived metabolites in functional foods, nutraceuticals, pharmaceuticals, cosmetics, and other bio-based products are critically evaluated. Finally, the review discusses the importance of conserving regional plant biodiversity while promoting the sustainable utilization of natural resources through environmentally responsible valorization strategies. By integrating available phytochemical, biological, and applied research, this review provides an updated synthesis of the scientific evidence and identifies future research directions for the sustainable exploitation of selected woody flora from the Karditsa region.

Keywords: woody flora; phytochemical diversity; bioactive compounds; antioxidant activity; sustainable valorization



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1. Introduction

The Mediterranean Basin is widely recognized as one of the world's most important biodiversity hotspots because of its exceptional plant species richness and high floristic diversity [1]. Greece represents one of the principal centres of Mediterranean plant diversity, hosting more than 6700 vascular plant species, approximately 13% of which are endemic to the country [2,3]. This remarkable floristic richness is the result of the country's complex geological history, pronounced topographical heterogeneity, climatic variability, and

long-term evolutionary processes that have promoted plant diversification and ecological specialization [2,3].

Recent evidence further highlights the importance of Greece as a centre of medicinal and aromatic plant diversity. According to Solomou et al. [4], the country hosts an exceptionally rich MAP flora supported by long-standing ethnobotanical knowledge and traditional uses, while modern research emphasizes the need for sustainable management and conservation of these resources. Their work underscores that documenting phytochemical diversity and promoting environmentally responsible utilization strategies are essential for safeguarding Greece's natural capital and advancing the national bioeconomy. These considerations align with the objectives of the present review, which examines representative woody species of the Karditsa region within the broader context of biodiversity conservation and sustainable valorization.

In addition to its exceptional biodiversity, Greece possesses one of the richest assemblages of medicinal and aromatic plants in Europe. These plant resources have attracted increasing scientific interest because they constitute valuable natural sources of bioactive secondary metabolites and represent an important component of the country's natural capital [4]. Numerous woody and herbaceous species have traditionally been used in food, folk medicine, and aromatic applications, while modern phytochemical research has demonstrated their considerable pharmaceutical, nutritional, and industrial potential [4].

The qualitative and quantitative composition of these phytochemicals is strongly influenced by environmental conditions. Mediterranean ecosystems are characterized by high solar radiation, seasonal drought, temperature fluctuations, and other abiotic stress factors that stimulate the biosynthesis of secondary metabolites involved in plant adaptation and protection [5,6]. Consequently, populations of the same species growing under different ecological conditions frequently exhibit significant variations in their phytochemical profiles and biological activities [5,6].

Mediterranean woody plant species are particularly rich in polyphenols, flavonoids, phenolic acids, anthocyanins, tannins, terpenoids, and essential oils. These metabolites play essential roles in plant defence mechanisms and exhibit a broad spectrum of biological activities, including antioxidant, antimicrobial, anti-inflammatory, and neuroprotective effects [7]. Consequently, these species have attracted increasing attention as promising natural resources for the development of functional foods, nutraceuticals, pharmaceuticals, and cosmetic products [8,9].

The regional unit of Karditsa, located in Central Greece and including part of the Pindus mountain range, represents an environmentally heterogeneous area characterized by pronounced altitudinal gradients, diverse geological substrates, and contrasting microclimatic conditions. These environmental characteristics favour the development of woody plant populations with considerable phytochemical variability and biological potential. Despite the ecological importance of this region, the available scientific information remains dispersed among individual phytochemical, pharmacological, and ecological studies, while a comprehensive synthesis integrating the available evidence for representative woody species has not yet been reported.

The present review focuses on five representative woody species naturally occurring in the Karditsa region, namely *Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa*, and *Satureja montana*. These species were selected because they are well represented within the regional woody flora, possess well-documented phytochemical compositions and biological activities, and exhibit considerable potential for applications in functional foods, nutraceuticals, pharmaceuticals, cosmetics, and other bio-based products. Specifically, *Rosa canina* has been extensively investigated because of its high content of vitamin C and phenolic compounds [10], *Cornus mas* for its bioactive phytochemicals and antioxidant

properties [11], *Prunus spinosa* for its phenolic profile and biological activities [12], *Rubus fruticosus* for its functional food potential and phytochemical composition [13], and *Satureja montana* for the remarkable chemical variability and biological properties of its essential oils [14]. Although these species are naturally distributed in several Mediterranean and European countries and are therefore not endemic to the Karditsa region, they constitute characteristic components of its woody vegetation and provide an appropriate framework for investigating the relationship between environmental conditions, phytochemical diversity, biological activity, and sustainable valorization.

Growing demand for natural bioactive compounds has stimulated the development of sustainable extraction technologies capable of improving extraction efficiency while reducing environmental impacts. Green extraction approaches, including ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, have emerged as environmentally friendly alternatives to conventional techniques, enabling improved recovery of high-value phytochemicals with lower solvent consumption and energy requirements [15,16]. These technological developments support the sustainable utilization of plant resources and contribute to the production of high-value natural products with reduced environmental impact.

Therefore, the aim of this review is to provide a comprehensive synthesis of the current scientific knowledge regarding the phytochemical diversity, biological activities, extraction technologies, and potential industrial applications of selected woody flora from the Karditsa region (Central Greece). Particular emphasis is placed on the occurrence of bioactive secondary metabolites, the influence of environmental conditions on phytochemical variability, and the sustainable valorization of these plant resources within the framework of biodiversity conservation and the circular bioeconomy. Furthermore, current knowledge gaps are identified, and future research directions are discussed to support the sustainable exploitation of Mediterranean woody plant resources.

2. Review Methodology

This review was prepared following a structured literature search aimed at identifying and critically evaluating published studies concerning the phytochemical composition, biological activities, extraction technologies, and potential applications of selected woody plant species occurring in the Karditsa region (Central Greece) and the broader Mediterranean area. The objective was to integrate current scientific knowledge regarding the phytochemical diversity and sustainable utilization of these species while providing a comprehensive overview of their ecological, biological, and industrial significance.

The literature search was conducted using the scientific databases Scopus, Web of Science, PubMed, and Google Scholar. Searches were performed between January and March 2026 using combinations of keywords including *Mediterranean woody flora*, *Greek medicinal plants*, *Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa*, *Satureja montana*, *phytochemistry*, *polyphenols*, *bioactive compounds*, *antioxidant activity*, *green extraction*, *functional foods*, and *bioeconomy*. Additional publications were identified through manual screening of the reference lists of relevant research articles, review papers, book chapters, and official reports.

The five woody species included in this review (*Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa*, and *Satureja montana*) were selected according to predefined scientific criteria. Specifically, the selected species occur naturally in the Karditsa region and the wider Pindus ecosystem, possess well-documented phytochemical profiles and biological activities, and demonstrate considerable potential for applications in functional foods, nutraceuticals, pharmaceuticals, cosmetics, and other bio-based products.

Only peer-reviewed publications written in English were considered. Eligible studies reported data on phytochemical characterization, biological activities, extraction methodologies, or potential industrial applications of the selected species. Particular emphasis was placed on investigations describing phenolic compounds, flavonoids, phenolic acids, anthocyanins, tannins, terpenoids, and essential oils, as well as modern extraction approaches, including ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction [15,16].

Studies were excluded if they lacked sufficient methodological information, were available only as conference abstracts, represented duplicate publications, or were not directly relevant to the objectives of the review. Publications focusing on plant species outside the Mediterranean region or lacking phytochemical or biological characterization were also excluded.

The final body of literature comprised peer-reviewed research articles, review papers, book chapters, and official reports. Although substantial progress has been achieved in the phytochemical investigation of Mediterranean woody species, considerable methodological heterogeneity remains among published studies regarding plant origin, environmental conditions, extraction protocols, analytical techniques, and the expression of biological activity. These differences limit direct comparisons among studies and emphasize the need for greater methodological standardization in future phytochemical and bioactivity research. For each eligible study, information was systematically extracted regarding the investigated species, plant part, geographical origin, extraction methodology, analytical techniques, principal phytochemical constituents, reported biological activities, and the study's contribution to the objectives of the present review. The extracted information was subsequently synthesized to facilitate the comparative evaluation of phytochemical diversity, biological properties, extraction technologies, and potential applications among the selected woody species. A summary of the principal studies included in the review is provided in Table A1.

3. Ecological and Evolutionary Context of Selected Woody Flora

3.1. Evolutionary Processes and Genetic Reservoirs

The remarkable floristic diversity of the Mediterranean region is the result of long-term evolutionary processes involving geographic isolation, environmental adaptation, and ecological diversification. Complex geological history, climatic oscillations, and topographical heterogeneity have shaped the distribution and diversification of Mediterranean plant species, making the Mediterranean Basin one of the world's major biodiversity hotspots [1] and Greece one of its principal centres of plant diversity [2,3].

Mountain ecosystems play a fundamental role in these evolutionary processes. Mountain ranges such as the Pindus provide highly heterogeneous environmental conditions through pronounced altitudinal gradients, diverse geological substrates, and contrasting microclimates. These characteristics create numerous ecological niches that promote population differentiation, local adaptation, and genetic diversification. In addition, the geographical isolation of plant populations reduces gene flow and facilitates the development of distinct ecotypes and chemotypes adapted to local environmental conditions [2,3].

The Karditsa region, located within the southern Pindus mountain system, represents a characteristic example of this ecological complexity. High-altitude habitats, limestone formations, and seasonal climatic variation create environmental conditions that influence both species distribution and secondary metabolism. Abiotic stress factors, including increased ultraviolet radiation, periodic water deficit, and temperature fluctuations, stimulate physiological responses that enhance the biosynthesis of secondary metabolites involved in plant protection and adaptation [5,6].

Moderate environmental stress is widely recognized as one of the principal factors regulating the accumulation of phenolic compounds, flavonoids, terpenoids, and other specialized metabolites. These compounds contribute to plant defence against oxidative stress, pathogens, herbivores, and other environmental pressures while simultaneously increasing the biological value of plant-derived extracts for food, pharmaceutical, nutraceutical, and cosmetic applications [5,6,17].

Such biochemical plasticity contributes substantially to the phytochemical diversity observed among Mediterranean woody species. Variations in environmental conditions frequently result in significant differences in metabolite composition and antioxidant capacity, even among populations belonging to the same species. Consequently, geographical origin and habitat characteristics should be considered important determinants of phytochemical quality and biological activity when evaluating natural plant resources [17,18].

From a biotechnological perspective, woody species growing under environmentally heterogeneous conditions represent valuable reservoirs of bioactive compounds with considerable potential for food, pharmaceutical, nutraceutical, and cosmetic applications. Their ability to adapt to multiple environmental stresses is closely associated with metabolic flexibility and the production of structurally diverse phytochemicals, characteristics that are increasingly important for the sustainable utilization of plant resources and the development of bio-based products under changing climatic conditions [8,9,19].

3.2. The Greek Flora: A Biodiversity Hotspot

Greece is internationally recognized as one of the richest centres of plant diversity in Europe and the Mediterranean Basin. The Mediterranean Basin has been identified as one of the world's major biodiversity hotspots because of its exceptional floristic richness and high levels of endemism [1]. Within this region, Greece represents one of the principal centres of plant diversity, harbouring more than 6700 vascular plant species, approximately 13% of which are endemic to the country [2,3]. In addition, Greece possesses one of the richest assemblages of medicinal and aromatic plants in Europe, representing an important component of the country's natural capital and a valuable source of biologically active natural products [4].

The exceptional diversity of the Greek flora is closely associated with the country's complex geological history, extensive mountain systems, fragmented insular landscape, and pronounced environmental heterogeneity. Mountain ranges such as the Pindus have functioned as important centres of plant diversification by promoting geographical isolation, ecological specialization, and local adaptation, thereby contributing significantly to the present floristic richness of the region [2,3].

Environmental conditions strongly influence the phytochemical composition of Mediterranean plants. Variations in altitude, geological substrate, solar radiation, water availability, and seasonal climatic fluctuations affect plant metabolism and frequently result in substantial differences in the accumulation of phenolic compounds, flavonoids, terpenoids, anthocyanins, and essential oils [5,6,17]. Consequently, even populations belonging to the same species may exhibit considerable variability in their phytochemical composition and biological activities depending on their ecological conditions [17,18].

This phytochemical variability has attracted increasing scientific interest because it directly influences the biological properties and industrial value of plant-derived products. Numerous Mediterranean woody species have demonstrated significant antioxidant, antimicrobial, anti-inflammatory, and other biological activities, supporting their potential applications in functional foods, nutraceuticals, pharmaceuticals, and cosmetic products [7–9,18].

Within this ecological context, the Karditsa region represents an important yet comparatively underexplored area of Central Greece. Located within the Pindus mountain system, the region combines diverse geological formations, marked altitudinal gradients, and heterogeneous microclimatic conditions that favour the development of woody plant populations with distinct phytochemical characteristics. Although individual studies have investigated several plant species occurring in the area, comprehensive reviews integrating ecological characteristics, phytochemical composition, biological activities, extraction technologies, and sustainable utilization remain limited.

The five woody species selected for the present review (*Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa*, and *Satureja montana*) represent characteristic components of the regional flora and have been extensively investigated because of their richness in phenolic compounds, flavonoids, anthocyanins, terpenoids, and essential oils. Specifically, *Rosa canina* is recognized for its high content of vitamin C and phenolic compounds [10], *Cornus mas* for its rich phytochemical profile and antioxidant properties [11], *Prunus spinosa* for its phenolic composition and biological activities [12], *Rubus fruticosus* for its functional food potential and polyphenol-rich fruits [13], and *Satureja montana* for the chemical diversity and biological properties of its essential oils [14].

The phytochemical characteristics of these species are summarized in Table 1, which presents representative classes of bioactive compounds together with their principal biological activities and potential industrial applications. Overall, the available scientific evidence indicates that the woody flora of the Karditsa region represents a valuable natural resource whose sustainable utilization may support biodiversity conservation while contributing to the development of high-value bio-based products through environmentally friendly extraction technologies and circular bioeconomy strategies [4,8,9,15,16].

Table 1. Phytochemical Profile, Major Biological Activities and Potential Applications of Selected Woody Species from the Karditsa Region.

Botanical Species	Family	Major Bioactive Constituents	Major Biological Activities and Potential Applications	References
<i>Rosa canina</i>	Rosaceae	Ascorbic acid, quercetin, ellagic acid, carotenoids	Antioxidant, nutraceuticals, skin-care products, functional foods	[10]
<i>Cornus mas</i>	Cornaceae	Anthocyanins, iridoids, gallic acid derivatives	Antioxidant, anti-inflammatory, nutraceuticals, natural food colorants	[11]
<i>Satureja montana</i>	Lamiaceae	Carvacrol, thymol, <i>p</i> -cymene, rosmarinic acid	Antimicrobial, antioxidant, essential oils, food preservation	[14]
<i>Rubus fruticosus</i>	Rosaceae	Hydrolysable tannins, anthocyanins, ascorbic acid	Functional foods, antioxidant, anti-aging cosmetics, hypoglycaemic potential	[13]
<i>Prunus spinosa</i>	Rosaceae	Coumarins, flavonols, phenolic acids	Antioxidant extracts, functional beverages, traditional herbal preparations	[12]

3.3. Phytochemical Foundations and Biosynthetic Adaptations

The biological and industrial value of Mediterranean woody plant species is closely associated with their phytochemical composition, which reflects long-term adaptation to diverse environmental conditions. Secondary metabolites, including polyphenols, flavonoids, phenolic acids, terpenoids, tannins, anthocyanins and essential oils, are not directly involved in primary metabolism but play fundamental roles in plant defence, ecological interactions and physiological adaptation. The synthesis and accumulation of these compounds are regulated by both genetic and environmental factors, making phytochemical composition highly dependent on habitat conditions and environmental stress [5,6].

The biosynthesis of plant secondary metabolites is controlled by interconnected metabolic pathways, principally the shikimate–phenylpropanoid pathway, responsible for the production of phenolic compounds, and the mevalonate (MVA) and methylerythritol phosphate (MEP) pathways, which regulate terpenoid biosynthesis. Environmental factors such as ultraviolet radiation, drought, nutrient availability, and temperature fluctuations influence the activity of key biosynthetic enzymes, including phenylalanine ammonia-lyase (PAL), thereby enhancing the production of phenolic compounds and other protective metabolites. These adaptive responses enable plants to improve their tolerance to oxidative stress while increasing their phytochemical richness [5,6,20].

Polyphenols represent one of the most extensively investigated classes of secondary metabolites because of their well-documented antioxidant and health-promoting properties. This heterogeneous group comprises flavonoids, phenolic acids, tannins and anthocyanins, all of which contribute to the neutralization of reactive oxygen species, protection against oxidative damage and maintenance of cellular redox balance [8,9,17]. Considerable concentrations of these compounds have been reported in *Rosa canina*, *Rubus fruticosus* and *Prunus spinosa*, contributing substantially to their antioxidant capacity and supporting their potential use in functional foods, nutraceuticals and pharmaceutical preparations [10,12,13,21,22].

Terpenoids constitute another major class of bioactive metabolites, particularly abundant in aromatic Mediterranean species such as *Satureja montana*. Monoterpenes, including carvacrol, thymol and *p*-cymene, together with several sesquiterpenes, exhibit pronounced antimicrobial, antioxidant and anti-inflammatory activities. Besides their ecological role in protecting plants against pathogens and herbivores, these compounds have attracted considerable interest as natural ingredients for pharmaceutical formulations, cosmetic products, food preservation and essential oil production [14,20].

Phytochemical composition is highly dynamic and varies according to geographical origin, environmental conditions, developmental stage, harvesting period and extraction methodology. Consequently, populations of the same species may exhibit substantial qualitative and quantitative differences in secondary metabolite composition, resulting in distinct chemotypes with different biological properties and industrial potential. Such variability highlights the importance of regional phytochemical investigations, particularly in environmentally heterogeneous areas such as the Karditsa region, where local ecological conditions may significantly influence metabolite accumulation and biological activity [5,6,20].

A comprehensive understanding of phytochemical diversity and biosynthetic adaptation provides the scientific basis for the sustainable exploitation of Mediterranean woody flora. The characterization of plant secondary metabolites and their structure–activity relationships facilitates the identification of plant populations with superior phytochemical profiles and supports the development of standardized extracts and high-value natural products. Recent evidence further demonstrates that the biological activity of plant phenolics depends not only on their concentration but also on their molecular structure and interactions with other phytochemicals, reinforcing their importance for food, pharmaceutical and cosmetic applications [23].

3.4. Mechanisms of Antioxidant Action and Phytochemical Synergy

The biological activity of Mediterranean woody plant species is largely attributed to the complex antioxidant mechanisms of their phytochemical constituents. Polyphenols, flavonoids, phenolic acids, anthocyanins, and other secondary metabolites protect plant tissues against oxidative damage while simultaneously exhibiting significant biological activities relevant to human health. Their antioxidant capacity results from multiple

complementary mechanisms rather than from a single biochemical pathway, explaining the broad therapeutic potential of plant-derived extracts [8,9,17].

The primary antioxidant mechanisms involve hydrogen atom transfer (HAT), single electron transfer (SET), and metal ion chelation. Through these mechanisms, phytochemicals neutralize reactive oxygen species (ROS) and reactive nitrogen species (RNS), thereby preventing oxidative damage to cellular lipids, proteins, and nucleic acids. In addition, numerous phenolic compounds are capable of chelating transition metals such as Fe^{2+} and Cu^{2+} , reducing the formation of highly reactive hydroxyl radicals through Fenton-type reactions. These complementary antioxidant mechanisms constitute the basis of many in vitro antioxidant assays commonly applied for phytochemical evaluation [24].

Beyond direct radical scavenging, plant polyphenols modulate endogenous antioxidant defence systems by regulating signalling pathways involved in oxidative stress responses. Several phytochemicals have been shown to stimulate the expression or activity of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), thereby enhancing cellular resistance against oxidative damage. These indirect antioxidant effects have attracted considerable attention because they contribute to anti-inflammatory, cytoprotective and disease-preventive properties beyond simple free radical scavenging [18,23].

An important characteristic of natural plant extracts is the simultaneous presence of numerous bioactive compounds that frequently interact synergistically. This phytochemical synergy, commonly referred to as the matrix effect, often results in biological activities that exceed those expected from the individual constituents. Interactions among flavonoids, phenolic acids, anthocyanins, tannins and terpenoids may improve antioxidant efficiency, increase bioavailability and enhance biological responses through complementary mechanisms of action [25].

This multi-target behaviour represents one of the principal advantages of plant-derived extracts compared with isolated compounds. For example, extracts of *Rosa canina*, *Cornus mas*, *Rubus fruticosus* and *Prunus spinosa* contain complex mixtures of vitamin C, anthocyanins, flavonoids and phenolic acids that collectively contribute to their antioxidant and health-promoting properties. Similar synergistic interactions have also been reported for essential oils of *Satureja montana*, where multiple terpenoid constituents act together to enhance antimicrobial and antioxidant activities [10–14].

The recognition of phytochemical synergy has important implications for the development of functional foods, nutraceuticals and phytopharmaceuticals. Rather than focusing exclusively on isolated molecules, current research increasingly supports the use of standardized plant extracts that preserve the natural phytochemical composition and maximize biological efficacy. Such an integrated approach is consistent with contemporary strategies for developing high-value natural products and supports the sustainable utilization of Mediterranean woody plant resources within modern bioeconomy frameworks [20,26].

4. Phytochemical Profile and Antioxidant Mechanisms

4.1. Main Classes of Secondary Metabolites in the Mediterranean Woody Flora

Mediterranean woody plant species constitute an exceptionally rich source of secondary metabolites with considerable ecological, nutritional, and pharmaceutical importance. These compounds are synthesized through highly regulated metabolic pathways and play fundamental roles in plant adaptation to environmental stress, defence against pathogens and herbivores, and protection against oxidative damage. Their remarkable structural diversity has attracted increasing scientific interest because many of these metabolites exhibit antioxidant, anti-inflammatory, antimicrobial and other health-promoting biological activities [8,9,17].

Among the various classes of secondary metabolites, polyphenols represent the most abundant and extensively investigated group. Polyphenols comprise flavonoids, phenolic acids, tannins, stilbenes and related compounds, which contribute significantly to the antioxidant capacity of Mediterranean woody species. Their biological activity is primarily associated with free radical scavenging, metal-chelating capacity and modulation of intracellular signalling pathways involved in oxidative stress and inflammation [17,18,26,27].

Flavonoids constitute one of the largest subclasses of plant polyphenols and include flavonols, flavones, flavan-3-ols, flavanones, anthocyanins and proanthocyanidins. These compounds contribute not only to plant pigmentation and ultraviolet protection but also to the stabilization of reactive oxygen species generated under environmental stress conditions. Increasing evidence indicates that flavonoids exhibit multiple biological activities, including antioxidant, anti-inflammatory, cardioprotective and neuroprotective effects, making them valuable ingredients for functional foods and nutraceutical formulations [7,9,27].

Anthocyanins represent another important subgroup of flavonoids that is particularly abundant in the fruits of *Cornus mas*, *Rubus fruticosus* and *Prunus spinosa*. Besides providing the characteristic red, purple and blue pigmentation of fruits, anthocyanins possess strong antioxidant properties and have been associated with beneficial effects against cardiovascular diseases, metabolic disorders and neurodegenerative conditions. Their biological activity is influenced by molecular structure, glycosylation pattern and bioavailability following dietary consumption [21,28].

Phenolic acids, including gallic, caffeic, chlorogenic and ellagic acids, are also widely distributed among Mediterranean woody plants. These compounds contribute substantially to antioxidant defence through hydrogen atom donation, electron transfer and inhibition of lipid peroxidation. In addition, they participate in plant defence responses and exhibit antimicrobial, anti-inflammatory and cytoprotective properties that increase the pharmaceutical value of plant extracts [18,24].

Terpenoids constitute another major group of phytochemicals, particularly abundant in aromatic species such as *Satureja montana*. Monoterpenes including carvacrol, thymol and *p*-cymene are responsible for many of the antimicrobial, antioxidant and anti-inflammatory properties of essential oils. Owing to their broad biological activities and natural origin, terpenoids are increasingly incorporated into food preservation systems, pharmaceutical preparations and cosmetic products [14,20].

The phytochemical composition of Mediterranean woody species is influenced by numerous intrinsic and extrinsic factors, including genotype, geographical origin, altitude, climatic conditions, soil characteristics, harvesting season and extraction methodology. Consequently, substantial variability in both qualitative and quantitative metabolite composition is frequently observed among plant populations. This variability represents an important challenge for product standardization but simultaneously offers opportunities for identifying plant populations with superior phytochemical characteristics suitable for industrial exploitation [5,6,15].

Overall, the remarkable diversity of secondary metabolites found in Mediterranean woody flora provides the biochemical basis for their numerous biological activities and industrial applications. A comprehensive understanding of their chemical composition and biological functions is essential for developing standardized plant extracts, functional foods, nutraceuticals and phytopharmaceutical products while supporting the sustainable valorization of regional plant biodiversity within the framework of the circular bioeconomy [20,25,29].

4.2. Biosynthetic Pathways and Environmental Modulation

The biosynthesis of plant secondary metabolites is a dynamic and highly regulated process that reflects the interaction between genetic background and environmental conditions. Mediterranean woody species have evolved complex metabolic networks that enable rapid biochemical adaptation to environmental fluctuations while maintaining physiological homeostasis. Consequently, the production of bioactive compounds varies considerably according to habitat characteristics, developmental stage, seasonal changes, and abiotic stress factors [5,6].

The principal biosynthetic routes involved in the formation of phenolic compounds and terpenoids in Mediterranean woody species, together with their modulation by environmental stressors typical of the Pindus ecosystem, are summarized in Figure 1.

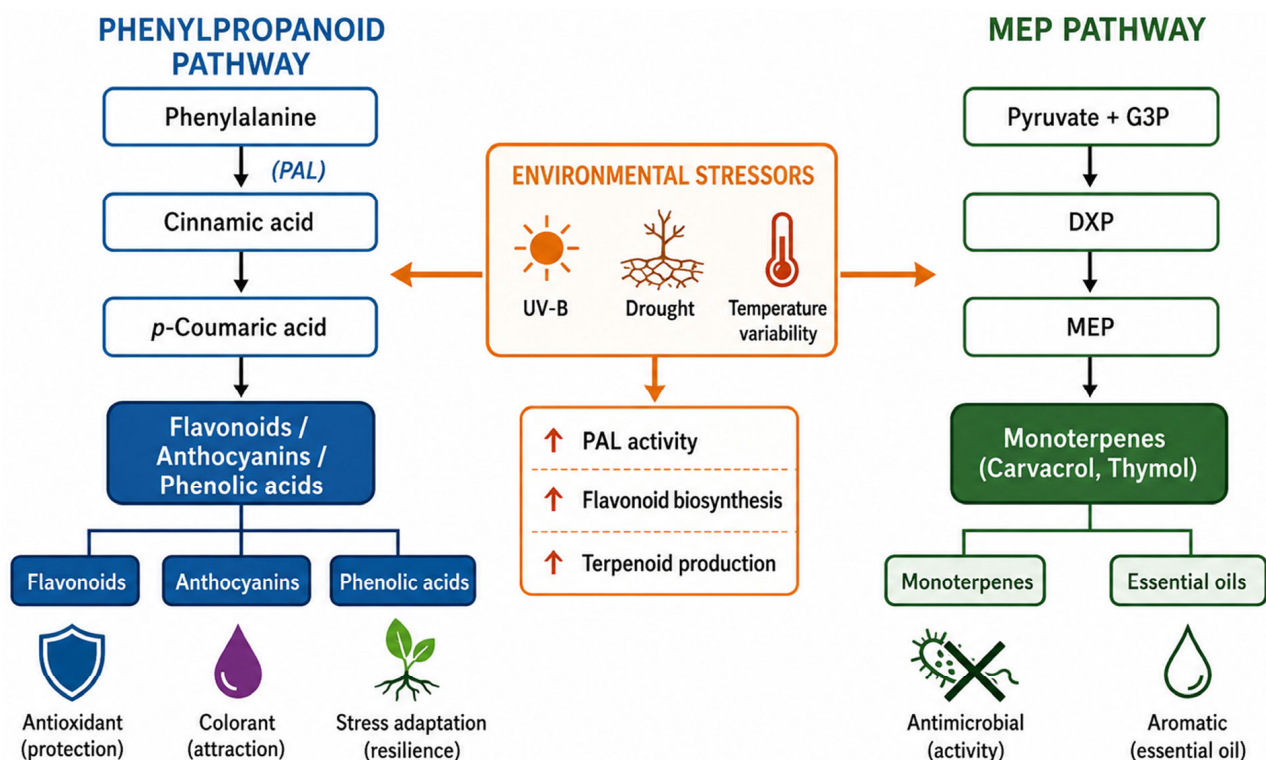


Figure 1. Graphical summary of the phenylpropanoid and MEP biosynthetic pathways leading to the formation of polyphenols and monoterpenes in Mediterranean woody species. Environmental stressors typical of the Pindus mountain ecosystem (UV-B radiation, drought, temperature fluctuations) upregulate key enzymatic steps, enhancing the accumulation of antioxidant and antimicrobial phytochemicals.

Among the principal biosynthetic routes, the shikimate–phenylpropanoid pathway is responsible for the production of most phenolic compounds, including flavonoids, phenolic acids, lignans and tannins. This pathway begins with the conversion of phosphoenolpyruvate and erythrose-4-phosphate into aromatic amino acids, particularly phenylalanine, which subsequently serves as the precursor for numerous phenolic metabolites. The enzyme phenylalanine ammonia-lyase (PAL) represents the first regulatory step of phenylpropanoid metabolism and plays a central role in controlling the accumulation of antioxidant phytochemicals [20].

Terpenoid biosynthesis proceeds through two complementary metabolic pathways: the cytosolic mevalonate (MVA) pathway and the plastidial methylerythritol phosphate (MEP) pathway. These pathways generate the universal isoprenoid precursors required for the synthesis of monoterpenes, sesquiterpenes, and diterpenes that constitute the

major components of essential oils. In aromatic Mediterranean species, particularly *Satureja montana*, environmental regulation of terpenoid biosynthesis significantly influences essential oil composition, resulting in considerable variability among different plant populations and geographical locations [14,22].

Environmental conditions exert profound effects on secondary metabolism through the regulation of gene expression, enzymatic activity and metabolic fluxes. Mediterranean ecosystems are characterized by high solar irradiance, prolonged summer drought, nutrient limitations and pronounced seasonal temperature fluctuations. These environmental constraints induce oxidative stress within plant tissues, stimulating the production of protective phytochemicals that contribute to both stress tolerance and biological activity [5,6].

Ultraviolet radiation represents one of the most important environmental signals regulating phenolic biosynthesis. Increased UV-B exposure activates PAL and other enzymes involved in flavonoid biosynthesis, resulting in enhanced accumulation of flavonols and anthocyanins that protect photosynthetic tissues against photooxidative damage. Similarly, moderate water deficit promotes the accumulation of phenolic compounds by stimulating antioxidant defence systems and reducing oxidative injury during drought conditions [17,20].

Altitude and geographical origin also influence phytochemical composition. Mountain populations frequently experience greater environmental stress than lowland populations owing to increased ultraviolet radiation, lower temperatures and greater daily thermal amplitudes. Consequently, woody species growing within the Pindus mountain system often exhibit higher concentrations of phenolic compounds and enhanced antioxidant capacity compared with populations growing under less stressful environmental conditions [5,6].

Besides environmental factors, harvesting season, developmental stage, and extraction methodology substantially affect phytochemical yield and composition. Appropriate selection of harvesting time and extraction conditions is therefore essential for obtaining standardized plant extracts with reproducible biological activity. Green extraction technologies further contribute to preserving thermolabile phytochemicals while improving extraction efficiency and reducing environmental impacts, thereby supporting the sustainable utilization of Mediterranean woody plant resources [15,16].

Understanding the interactions between biosynthetic pathways and environmental modulation provides valuable information for selecting plant populations with superior phytochemical profiles and for optimizing cultivation, harvesting and extraction strategies. Such knowledge is particularly important for the development of standardized phytopharmaceuticals, functional foods and other high-value bio-based products derived from Mediterranean woody flora [29,30].

4.3. Molecular Mechanisms of Antioxidant Action

The antioxidant activity of Mediterranean woody plant species is primarily attributed to the molecular properties of their bioactive secondary metabolites, particularly polyphenols, flavonoids, anthocyanins, phenolic acids and terpenoids. These compounds exert their protective effects through multiple complementary biochemical mechanisms that collectively reduce oxidative damage and maintain cellular redox homeostasis. Their biological activity depends not only on their concentration but also on their molecular structure, hydroxylation pattern, degree of polymerization and interactions with other phytochemicals [17,18,24].

One of the principal antioxidant mechanisms involves the direct scavenging of reactive oxygen species (ROS) and reactive nitrogen species (RNS). Phenolic compounds readily donate hydrogen atoms or electrons to unstable free radicals, thereby interrupting oxidative chain reactions responsible for lipid peroxidation, protein oxidation, and DNA damage.

This radical-scavenging activity is largely determined by the number and position of hydroxyl groups present within the aromatic structure of each molecule [24].

A second important mechanism involves the chelation of transition metal ions, particularly Fe^{2+} and Cu^{2+} . These metals catalyse Fenton and Haber–Weiss reactions, which generate highly reactive hydroxyl radicals capable of inducing severe oxidative damage. Numerous phenolic compounds effectively bind these metal ions, thereby reducing their catalytic activity and limiting radical formation. Consequently, antioxidant protection results from the combined effects of radical scavenging and metal chelation rather than from a single biochemical mechanism [24].

Beyond their direct antioxidant properties, plant phytochemicals regulate several intracellular signalling pathways associated with oxidative stress and inflammation. Numerous flavonoids and phenolic acids modulate the expression of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), while simultaneously influencing redox-sensitive transcription factors involved in cellular defence. These indirect mechanisms contribute substantially to the cytoprotective, anti-inflammatory and disease-preventive properties associated with diets rich in plant-derived polyphenols [17,18].

Anthocyanins constitute another important group of antioxidant phytochemicals. Besides contributing to fruit pigmentation, these compounds exhibit remarkable free radical scavenging activity and protect biological membranes against oxidative deterioration. Recent evidence suggests that anthocyanins may also improve mitochondrial function, reduce inflammatory signalling and contribute to the prevention of cardiovascular, metabolic and neurodegenerative disorders. These biological activities further increase the nutritional and functional value of anthocyanin-rich Mediterranean fruits [28].

Plant extracts rarely contain a single active constituent. Instead, they consist of complex mixtures of phytochemicals that frequently interact synergistically. Flavonoids, phenolic acids, anthocyanins, tannins, terpenoids and vitamins often exhibit complementary antioxidant mechanisms, resulting in biological activities that exceed the sum of their individual effects. This phenomenon, commonly referred to as phytochemical synergy or the matrix effect, explains why whole plant extracts frequently demonstrate greater biological efficacy than isolated compounds [25].

This synergistic behaviour has important implications for the development of functional foods, nutraceuticals and phytopharmaceuticals. Rather than focusing exclusively on purified molecules, contemporary research increasingly supports the use of standardized plant extracts that preserve the natural phytochemical profile and maximize biological activity. Such an approach is particularly relevant for Mediterranean woody species including *Rosa canina*, *Cornus mas*, *Rubus fruticosus*, *Prunus spinosa* and *Satureja montana*, whose antioxidant capacity reflects the combined action of multiple classes of bioactive metabolites [10–14,31].

Overall, understanding the molecular mechanisms underlying antioxidant activity provides an essential scientific basis for the rational utilization of Mediterranean woody flora. Integrating phytochemical characterization with molecular and biological evidence facilitates the development of standardized natural products with improved efficacy, safety, and industrial applicability while supporting sustainable exploitation of regional plant biodiversity.

5. Extraction and Analytical Techniques

The efficient recovery and characterization of bioactive phytochemicals constitute fundamental steps for evaluating the biological potential and industrial applicability of Mediterranean woody plant species. Extraction methodology has a decisive influence

on both the qualitative and quantitative composition of plant extracts, directly affecting antioxidant activity, biological efficacy, and product standardization. Consequently, the selection of appropriate extraction procedures represents one of the most important stages in phytochemical research [15,16].

Extraction efficiency depends on numerous factors, including solvent polarity, extraction time, temperature, particle size, solvent-to-solid ratio and the physicochemical properties of the target compounds. Since Mediterranean woody species contain chemically diverse metabolites such as phenolic acids, flavonoids, anthocyanins, tannins, terpenoids and essential oils, no single extraction procedure is universally suitable for all phytochemical classes. Instead, extraction protocols should be optimized according to the intended analytical or industrial application [15].

Conventional extraction techniques, including maceration, Soxhlet extraction and hydrodistillation, remain widely employed because of their simplicity and relatively low operational costs. However, these methods often require long extraction times, large solvent volumes and elevated temperatures that may promote degradation of thermolabile phytochemicals and reduce extraction efficiency [15,16].

To overcome these limitations, considerable attention has been directed towards green extraction technologies. Ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pressurized liquid extraction (PLE) and supercritical fluid extraction (SFE) have demonstrated significant advantages over conventional techniques by reducing extraction time, minimizing solvent consumption and improving the recovery of bioactive compounds while decreasing environmental impact. These technologies are fully consistent with the principles of sustainable processing and the circular bioeconomy [15,16].

Among these approaches, ultrasound-assisted extraction has become one of the most frequently applied techniques for phenolic-rich Mediterranean plant materials. Acoustic cavitation disrupts plant cell walls, facilitating solvent penetration and improving mass transfer, thereby increasing extraction yields without extensive thermal degradation. Similarly, supercritical carbon dioxide extraction offers high selectivity for lipophilic compounds and essential oils while eliminating the use of toxic organic solvents, making it particularly attractive for food, cosmetic and pharmaceutical applications [16].

Following extraction, comprehensive phytochemical characterization requires the application of advanced analytical techniques. High-performance liquid chromatography (HPLC), ultra-high-performance liquid chromatography (UHPLC), gas chromatography coupled with mass spectrometry (GC–MS), liquid chromatography–mass spectrometry (LC–MS/MS) and nuclear magnetic resonance (NMR) spectroscopy represent the principal analytical tools currently employed for the identification and quantification of secondary metabolites. These techniques provide detailed information regarding compound identity, concentration and structural characteristics, facilitating quality control and product standardization [15].

The antioxidant capacity of plant extracts is commonly evaluated using complementary *in vitro* assays based on different reaction mechanisms. Electron transfer-based methods such as DPPH, ABTS, and FRAP assays are widely applied because they provide rapid and reproducible estimation of antioxidant potential. Nevertheless, no single analytical assay fully represents the complex antioxidant behaviour of plant extracts. For this reason, the combined use of multiple analytical methods is generally recommended to obtain a more comprehensive assessment of antioxidant activity [24].

The integration of optimized extraction procedures with modern analytical platforms has substantially improved the characterization of Mediterranean woody flora during the last decade. These methodological advances facilitate the identification of novel bioactive compounds, improve extract standardization and support the development of high-quality

phytopharmaceuticals, functional foods and cosmetic ingredients derived from regional plant resources. Furthermore, environmentally friendly extraction technologies contribute to the sustainable exploitation of biodiversity while promoting innovation within the framework of the circular bioeconomy [4,16,27].

6. Species-Level Literature Synthesis: Comparative Profiling

6.1. *Rosa canina* (Wild Rose)

Rosa canina L. (Rosaceae), commonly known as wild rose or dog rose, is one of the most widely distributed woody species throughout Europe and the Mediterranean Basin. It naturally occurs across a broad range of habitats, including forest margins, shrublands, mountainous ecosystems and abandoned agricultural land. In Greece, the species is widely distributed within the Pindus mountain range, including the Karditsa region, where it represents an important component of the native woody flora. Owing to its ecological adaptability and rich phytochemical composition, *R. canina* has attracted considerable scientific interest as a valuable source of bioactive compounds for nutritional, pharmaceutical and industrial applications [10,30].

The fruits (rose hips) are particularly rich in vitamin C, polyphenols, flavonoids, carotenoids, phenolic acids, tannins and organic acids. Among these compounds, ascorbic acid is considered one of the principal contributors to the nutritional value of the fruits, while quercetin, rutin, catechins, ellagic acid and gallic acid contribute substantially to their antioxidant activity. The simultaneous presence of hydrophilic and lipophilic antioxidants provides *R. canina* extracts with a broad spectrum of biological properties that frequently exceed those observed in many cultivated fruit species [10,17,18].

Numerous studies have demonstrated that *R. canina* exhibits remarkable antioxidant capacity owing to its high concentration of phenolic compounds and vitamin C. These phytochemicals effectively scavenge reactive oxygen species, inhibit lipid peroxidation and reduce oxidative damage through both direct radical neutralization and modulation of endogenous antioxidant defence systems. The biological activity of rose hip extracts has therefore been associated with potential protective effects against cardiovascular diseases, chronic inflammation, metabolic disorders and age-related degenerative conditions [9,10,17].

Beyond antioxidant activity, *R. canina* demonstrates significant anti-inflammatory, antimicrobial and immunomodulatory properties. Several investigations have reported inhibitory effects on pro-inflammatory mediators and oxidative stress biomarkers, suggesting potential applications in the prevention and management of chronic inflammatory diseases. In addition, extracts obtained from fruits and seeds exhibit antimicrobial activity against various bacterial and fungal pathogens, further supporting their use as natural ingredients in food preservation and cosmetic formulations [10,18].

The phytochemical composition of *R. canina* is strongly influenced by environmental conditions, geographical origin and harvesting period. Plants growing at higher altitudes frequently accumulate greater concentrations of phenolic compounds and carotenoids, reflecting adaptive responses to increased ultraviolet radiation, temperature fluctuations and other abiotic stress factors characteristic of Mediterranean mountain ecosystems. Such environmental modulation contributes to considerable variability among natural populations and highlights the importance of regional phytochemical investigations, including those conducted within the Pindus mountain system [5,6,30].

Modern extraction technologies have further enhanced the recovery of bioactive compounds from *R. canina*. Ultrasound-assisted extraction, microwave-assisted extraction, and other green extraction approaches have demonstrated improved extraction efficiency while preserving thermolabile antioxidants such as vitamin C and phenolic compounds. These

methodologies support the production of standardized extracts suitable for applications in functional foods, dietary supplements, cosmetics and phytopharmaceutical products, while simultaneously reducing solvent consumption and environmental impact [15,16].

From a bioeconomic perspective, *R. canina* represents one of the most promising Mediterranean woody species because of its broad industrial applicability. Rose hips are increasingly incorporated into functional beverages, nutraceutical formulations, natural antioxidant preparations, cosmetic products and health-promoting food ingredients. The combination of abundant natural occurrence, high phytochemical diversity and established biological activity makes *R. canina* an important candidate for sustainable valorization within regional bioeconomy strategies, particularly in mountainous areas such as the Karditsa region, where wild populations remain relatively underexploited [4,10,27,30].

6.2. *Cornus mas* (Cornelian Cherry)

Cornus mas L. (Cornaceae), commonly known as Cornelian cherry, is a deciduous woody species widely distributed throughout southeastern Europe, the Balkans and the Mediterranean region. In Greece, it occurs naturally in mountainous and semi-mountainous ecosystems, including the Pindus mountain range and the Karditsa region, where it forms part of the native woody vegetation. Owing to its ecological adaptability, nutritional value and exceptional phytochemical composition, *C. mas* has become one of the most extensively investigated Mediterranean fruit species during the last decade [11].

The fruits of *C. mas* are characterized by a particularly rich phytochemical profile comprising anthocyanins, iridoids, flavonoids, phenolic acids, tannins, organic acids and vitamin C. Among these constituents, anthocyanins are responsible for the characteristic deep red coloration of ripe fruits, whereas iridoids represent a distinctive class of bioactive compounds that differentiates *Cornus mas* from many other Mediterranean fruit species. Gallic acid derivatives, chlorogenic acid and rutin also contribute substantially to the antioxidant potential of the fruit [11].

The high concentration of phenolic compounds is directly associated with the remarkable antioxidant capacity of *C. mas*. These phytochemicals efficiently neutralize reactive oxygen species, inhibit lipid peroxidation, and reduce oxidative damage through both direct free radical scavenging and modulation of endogenous antioxidant defence systems. Consequently, Cornelian cherry fruits have attracted considerable interest as natural ingredients for functional foods and nutraceutical products designed to prevent oxidative stress-related disorders [17,18].

In addition to antioxidant activity, *C. mas* exhibits pronounced anti-inflammatory, antimicrobial, antidiabetic and cardioprotective properties. Experimental studies have demonstrated that fruit extracts can modulate inflammatory mediators, improve glucose metabolism and inhibit the growth of several pathogenic microorganisms. Such multifunctional biological activity is attributed to the synergistic interaction of anthocyanins, iridoids, flavonoids and other phenolic constituents naturally occurring in the fruit matrix [11,25].

The phytochemical composition of *Cornus mas* is influenced by genotype, environmental conditions, fruit maturity and geographical origin. Populations growing under Mediterranean mountain conditions frequently exhibit higher concentrations of phenolic compounds owing to increased exposure to ultraviolet radiation, seasonal drought and temperature fluctuations. These environmental factors stimulate secondary metabolism and enhance the accumulation of antioxidant phytochemicals involved in plant adaptation to abiotic stress [5,6].

Recent advances in extraction technology have significantly improved the recovery of bioactive constituents from *C. mas*. Green extraction techniques, including ultrasound-assisted extraction and other low-impact methodologies, provide higher extraction effi-

ciency while preserving thermolabile compounds and reducing solvent consumption. Such approaches facilitate the production of standardized extracts suitable for pharmaceutical, nutraceutical, and food applications while supporting environmentally sustainable processing [15,16].

From a bioeconomic perspective, *Cornus mas* represents a highly valuable Mediterranean woody species with increasing commercial importance. Its fruits are currently utilized in juices, jams, fermented beverages, functional foods, dietary supplements and natural antioxidant formulations. The combination of high phytochemical diversity, well-documented biological activity and broad industrial applicability makes *C. mas* a promising candidate for sustainable exploitation within regional bioeconomy strategies, particularly in mountainous Mediterranean regions such as Karditsa, where natural populations remain an important yet incompletely utilized biological resource [4,11,27].

6.3. *Satureja montana* (Winter Savory)

Satureja montana L. (Lamiaceae), commonly known as winter savory, is an aromatic perennial shrub widely distributed throughout the Mediterranean Basin. The species naturally occurs on dry rocky slopes, calcareous soils, and mountainous habitats, including several regions of continental Greece and the Pindus mountain system. Its exceptional adaptability to xeric environments, together with its rich essential oil composition, has established *S. montana* as one of the most economically important Mediterranean medicinal and aromatic plants [4,14].

The phytochemical profile of *S. montana* is dominated by volatile terpenoids, particularly monoterpenes and oxygenated monoterpenes, which constitute the principal components of its essential oil. Carvacrol and thymol are generally recognized as the dominant bioactive constituents, while *p*-cymene, γ -terpinene, linalool, borneol and rosmarinic acid are also commonly detected depending on genotype and geographical origin. Considerable variability in essential oil composition has been reported among natural populations, leading to the identification of distinct chemotypes associated with specific environmental conditions [14].

The biological properties of *S. montana* are closely associated with the synergistic activity of its essential oil constituents. Carvacrol and thymol exhibit broad-spectrum antimicrobial activity against numerous Gram-positive and Gram-negative bacteria, yeasts, and filamentous fungi by disrupting microbial membrane integrity and interfering with cellular metabolism. In addition, these compounds possess marked antioxidant and anti-inflammatory properties that contribute to the preservation of cellular homeostasis under oxidative stress conditions [14,17,18].

Beyond their antimicrobial effects, the phenolic monoterpenes present in *S. montana* demonstrate significant antioxidant activity through multiple complementary mechanisms. They directly scavenge reactive oxygen species, inhibit lipid peroxidation and contribute to the stabilization of biological membranes. Furthermore, interactions between volatile terpenoids and phenolic compounds enhance the overall antioxidant capacity of whole plant extracts, supporting the concept of phytochemical synergy previously discussed in this review [24,25].

Environmental factors exert a major influence on the chemical composition of *S. montana*. Altitude, soil characteristics, water availability, temperature and solar radiation significantly affect both essential oil yield and the relative abundance of individual constituents. Mediterranean mountain populations frequently produce higher concentrations of oxygenated monoterpenes owing to increased exposure to abiotic stress, which stimulates secondary metabolism and enhances the biosynthesis of defence-related compounds [5,6,14].

Recent advances in extraction technology have considerably improved the recovery and characterization of *S. montana* bioactive compounds. Hydrodistillation remains the conventional method for essential oil isolation; however, green extraction technologies, including ultrasound-assisted extraction and supercritical fluid extraction, provide higher extraction efficiency while preserving volatile constituents and reducing solvent consumption. Modern chromatographic techniques, particularly GC–MS, allow detailed characterization of essential oil composition and facilitate the identification of chemotypic variability among different geographical populations [15,16].

From a bioeconomic perspective, *S. montana* represents one of the most valuable Mediterranean aromatic species because of its wide range of industrial applications. Its essential oils are increasingly incorporated into natural food preservatives, pharmaceutical formulations, veterinary products, cosmetic preparations and functional food ingredients. The combination of high phytochemical diversity, strong biological activity and adaptability to Mediterranean climatic conditions supports its sustainable cultivation and valorization within regional bioeconomy strategies. For mountainous regions such as Karditsa, naturally occurring populations of *S. montana* constitute important biological resources with considerable potential for the development of innovative high-value plant-derived products while promoting biodiversity conservation and sustainable rural development [4,14,29].

6.4. *Rubus fruticosus* and *Prunus spinosa*

Rubus fruticosus L. (wild blackberry) and *Prunus spinosa* L. (blackthorn or sloe) are two widespread woody species of the family Rosaceae that naturally occur throughout Europe and the Mediterranean Basin. In Greece, both species are common components of forest margins, shrublands, and mountainous ecosystems, including the Pindus mountain range and the Karditsa region. Their edible fruits have long been utilized in traditional diets and folk medicine, while increasing scientific evidence has highlighted their remarkable phytochemical composition and broad spectrum of biological activities [12,13,31].

The fruits of *Rubus fruticosus* are characterized by high concentrations of anthocyanins, flavonoids, ellagitannins, hydrolysable tannins, phenolic acids and vitamin C. Anthocyanins, particularly cyanidin derivatives, are largely responsible for the characteristic dark pigmentation of ripe fruits and contribute substantially to their antioxidant capacity. Likewise, ellagitannins and flavonols provide additional antioxidant, anti-inflammatory and antimicrobial activities, making blackberry fruits valuable ingredients for functional foods and nutraceutical products [13,22].

Similarly, *Prunus spinosa* fruits contain abundant flavonoids, phenolic acids, anthocyanins, tannins and coumarins. Chlorogenic acid, caffeic acid, rutin, quercetin derivatives and cyanidin glycosides constitute some of the principal phytochemicals identified in ripe fruits. These compounds contribute to the high antioxidant potential of blackthorn extracts and are associated with numerous biological activities, including antimicrobial, anti-inflammatory and cytoprotective effects [12,31].

The antioxidant properties of both species result primarily from the synergistic action of multiple phenolic compounds. Flavonoids and anthocyanins effectively scavenge reactive oxygen species, inhibit lipid peroxidation and protect cellular macromolecules against oxidative damage. In addition, phenolic acids contribute to metal chelation and modulation of endogenous antioxidant defence mechanisms, further enhancing the biological activity of fruit extracts. This complementary mode of action explains the high antioxidant capacity consistently reported for both species in comparative phytochemical studies [17,18,24].

Environmental conditions strongly influence the phytochemical composition of both *Rubus fruticosus* and *Prunus spinosa*. Climatic conditions, altitude, soil characteristics, fruit maturity and seasonal variability affect both the qualitative and quantitative composition

of secondary metabolites. Mediterranean mountain populations frequently exhibit higher concentrations of phenolic compounds owing to increased exposure to ultraviolet radiation, seasonal drought and temperature fluctuations, all of which stimulate secondary metabolism and antioxidant biosynthesis [5,6].

Recent developments in extraction technologies have facilitated the efficient recovery of bioactive constituents from both species. Ultrasound-assisted extraction and other green extraction techniques have demonstrated improved extraction yields while preserving thermolabile compounds and reducing solvent consumption. Modern chromatographic methods, including HPLC and LC–MS, have significantly improved the characterization and quantification of individual phenolic compounds, supporting quality control and extract standardization for industrial applications [15,16].

From a bioeconomic perspective, both species possess considerable commercial potential because of their nutritional value and high phytochemical diversity. *Rubus fruticosus* fruits are increasingly utilized in functional beverages, jams, dietary supplements, and antioxidant-rich food products, whereas *Prunus spinosa* is widely employed in traditional fermented beverages, herbal preparations, functional ingredients, and natural antioxidant formulations. Their adaptability to Mediterranean environments, together with their established biological properties, supports their sustainable exploitation within regional bioeconomy strategies and highlights their importance as valuable natural resources for mountainous regions such as Karditsa [13,29,31].

The data summarized in Table 2 indicate the major classes of polyphenolic compounds, total phenolic content (TPC), and antioxidant activity of selected Mediterranean woody species based on recent literature. The data indicate substantial variability among species and geographical origins, reflecting the influence of environmental conditions on phytochemical composition and bioactivity.

Table 2. Representative Phytochemical Composition and Reported Antioxidant Activity of the Selected Woody Species.

Species	Major Polyphenols	TPC (mg GAE/g dw)	DPPH IC ₅₀ (µg/mL)	References
<i>Rosa canina</i>	Quercetin, catechin, gallic acid, ellagic acid, ascorbic acid	70–150	20–40	[10,30]
<i>Cornus mas</i>	Cyanidin-3-glucoside, delphinidin, loganic acid, gallic acid	60–120	25–50	[11]
<i>Satureja montana</i>	Carvacrol, thymol, rosmarinic acid, caffeic acid	40–80	15–30	[14]
<i>Rubus fruticosus</i>	Cyanidin-3-glucoside, ellagitannins, quercetin	80–180	15–35	[13,22]
<i>Prunus spinosa</i>	Cyanidin derivatives, quercetin, kaempferol, phenolic acids	60–140	20–45	[12,31]

Abbreviations: TPC, total phenolic content; GAE, gallic acid equivalents; dw, dry weight. Reported values represent representative ranges extracted from different published studies and should not be interpreted as directly comparable because of differences in geographical origin, plant material, extraction methods and analytical protocols.

7. Applications in Food, Nutraceuticals, and Cosmetics

7.1. Industrial Potential of Functional Foods and Nutraceuticals

The increasing consumer demand for naturally derived health-promoting products has considerably expanded the market for functional foods and nutraceuticals. Mediterranean woody species have attracted particular attention because they represent sustainable sources of polyphenols, flavonoids, anthocyanins, phenolic acids, vitamins, and other bioactive constituents that combine nutritional value with multiple biological activities. Consequently, these plant resources are increasingly incorporated into innovative food products designed to provide physiological benefits beyond basic nutrition [8,9,17].

Among the species reviewed, *Rosa canina* represents one of the most valuable raw materials for the functional food industry. Rose hips are naturally rich in vitamin C, flavonoids, carotenoids and phenolic compounds and are widely used in juices, herbal infu-

sions, jams, dietary supplements and antioxidant-rich beverages. Numerous studies have demonstrated that these phytochemicals contribute significantly to antioxidant protection while supporting immune function and reducing oxidative stress, thereby increasing the commercial value of *R. canina* as a functional food ingredient [10,17,29,30].

Similarly, *Cornus mas* fruits have gained increasing recognition owing to their high concentrations of anthocyanins, iridoids and phenolic acids. Their antioxidant, anti-inflammatory and cardioprotective properties have stimulated the development of fruit juices, fermented beverages, fruit concentrates and nutraceutical preparations. In addition to their health-promoting potential, the attractive colour and sensory characteristics of Cornelian cherry fruits increase their suitability for incorporation into novel functional food formulations [11,28,29].

The fruits of *Rubus fruticosus* and *Prunus spinosa* also constitute valuable ingredients for functional food production because of their high concentrations of anthocyanins, flavonoids and phenolic acids. Blackberry fruits have been successfully incorporated into beverages, bakery products and dietary supplements, whereas blackthorn fruits are increasingly utilized in juices, preserves, fermented beverages and natural antioxidant formulations. Their high antioxidant capacity and favourable phytochemical composition make both species attractive candidates for the development of health-oriented food products with enhanced nutritional quality [12,13,22,29,31].

Beyond direct incorporation into food products, concentrated extracts obtained from these species are increasingly employed as nutraceutical ingredients. Standardized polyphenol-rich extracts have demonstrated potential applications in dietary supplements targeting oxidative stress, chronic inflammation, cardiovascular health and healthy ageing. The growing scientific evidence supporting the biological activity of these phytochemicals has reinforced consumer confidence in plant-derived nutraceuticals and stimulated industrial investment in their commercial development [9,17,18,27].

The successful industrial utilization of these Mediterranean woody species depends not only on their phytochemical composition but also on the implementation of efficient and sustainable extraction technologies. Green extraction approaches facilitate the recovery of high-quality bioactive compounds while preserving their biological activity and minimizing environmental impact. Such methodologies are fully consistent with the principles of the circular bioeconomy and support the sustainable valorization of regional plant resources through the production of high-value functional ingredients [15,16].

From a regional perspective, the woody flora of the Karditsa area represents an important natural resource that could contribute to the development of innovative functional foods and nutraceutical products with high commercial value. The combination of rich phytochemical diversity, documented biological activities, and increasing consumer preference for natural products creates favourable opportunities for sustainable exploitation of these species while simultaneously supporting biodiversity conservation, rural development and regional bioeconomic growth [4,29].

7.2. Cosmeceutical and Dermatological Applications

The growing demand for naturally derived cosmetic ingredients has stimulated considerable interest in Mediterranean medicinal plants as sustainable sources of bioactive compounds for skincare and dermatological formulations. Polyphenols, flavonoids, anthocyanins, terpenoids and other secondary metabolites possess multiple biological properties that are highly relevant to skin health, including antioxidant, anti-inflammatory, antimicrobial and photoprotective activities. Consequently, plant extracts obtained from Mediterranean woody species are increasingly incorporated into modern cosmeceutical formulations as natural alternatives to synthetic ingredients [8,17,23].

Among the species reviewed, *Rosa canina* has received particular attention because of its exceptionally rich phytochemical composition. Rose hips contain high concentrations of vitamin C, carotenoids, flavonoids and phenolic acids, which contribute to collagen synthesis, protection against oxidative stress and maintenance of skin elasticity. In addition, seed oil obtained from *R. canina* is characterized by a favourable fatty acid composition that supports epidermal regeneration, improves skin hydration and promotes wound healing. These properties have led to its widespread incorporation into anti-ageing creams, serums, dermatological preparations and skin-repair formulations [10,23].

Essential oils derived from *Satureja montana* represent another valuable source of cosmetic bioactive compounds. Their high concentrations of carvacrol and thymol provide strong antimicrobial activity against numerous skin-associated microorganisms while simultaneously exhibiting antioxidant and anti-inflammatory properties. As a result, *S. montana* essential oils have attracted increasing interest as natural preservatives and multifunctional ingredients in topical formulations intended for acne management, skin cleansing products and antimicrobial cosmetic preparations [14,17].

Extracts obtained from *Cornus mas*, *Rubus fruticosus* and *Prunus spinosa* have also demonstrated considerable potential for dermatological applications. Their abundance of anthocyanins, flavonoids and phenolic acids contributes to protection against oxidative damage induced by ultraviolet radiation and environmental pollutants. These phytochemicals help reduce inflammatory responses, stabilize cellular membranes and preserve extracellular matrix components, thereby supporting skin integrity and delaying premature skin ageing [11–13,18,23].

The biological efficacy of plant-derived cosmetic ingredients is closely associated with the synergistic interaction among multiple phytochemicals naturally present in whole extracts. Rather than acting independently, polyphenols, flavonoids, terpenoids and vitamins frequently exhibit complementary mechanisms of action that enhance antioxidant protection, improve anti-inflammatory activity and increase overall biological effectiveness. This phytochemical synergy represents one of the principal advantages of botanical extracts compared with isolated compounds and constitutes an important scientific basis for the development of multifunctional cosmeceutical products [25].

Recent advances in extraction technologies have further strengthened the industrial utilization of Mediterranean woody plants in cosmetic applications. Green extraction techniques, including ultrasound-assisted extraction and supercritical fluid extraction, improve the recovery of thermolabile bioactive compounds while minimizing solvent consumption and preserving phytochemical integrity. These environmentally sustainable methodologies support the production of standardized cosmetic ingredients with improved quality, reproducibility and safety profiles, in agreement with current principles of sustainable manufacturing and circular bioeconomy [15,16].

From a bioeconomic perspective, the woody flora of the Karditsa region represents an important reservoir of natural cosmetic ingredients with significant commercial potential. The combination of documented biological activities, high phytochemical diversity and increasing consumer preference for naturally derived skincare products creates favourable opportunities for the development of innovative cosmeceuticals based on locally available plant resources. Such applications may simultaneously contribute to biodiversity conservation, sustainable resource management and regional economic development through the production of high-value plant-derived cosmetic products [4,5,29].

8. Socioeconomic and Bioeconomic Perspectives

8.1. Bioeconomy Models and Local Production Clusters

The transition towards a sustainable bioeconomy has emerged as one of the principal strategic priorities of the European Union, aiming to promote economic development while ensuring the sustainable management of biological resources, resource efficiency and environmental protection. Renewable biological resources are increasingly recognized as valuable feedstocks for the production of food ingredients, nutraceuticals, pharmaceuticals, cosmetics and other bio-based products capable of replacing conventional fossil-derived materials. Such an approach simultaneously supports sustainable innovation, circular resource utilization and regional economic development through the establishment of high-value production chains [32,33].

Mediterranean woody species constitute particularly valuable components of the European bioeconomy because they combine high phytochemical diversity with broad industrial applicability. Their rich content of phenolic compounds, flavonoids, anthocyanins, terpenoids and other secondary metabolites provides opportunities for the development of innovative products targeting rapidly expanding markets for natural ingredients. Unlike conventional agricultural commodities, these species offer the possibility of producing multiple high-value products from different plant organs, thereby maximizing biomass utilization and improving overall production efficiency through integrated value chains [29,32].

The Karditsa region possesses several characteristics that favour the implementation of regional bioeconomy models based on native woody flora. The coexistence of mountainous ecosystems, rich plant biodiversity and traditional knowledge regarding the utilization of medicinal and aromatic plants provides a favourable foundation for sustainable resource management. Furthermore, the geographical proximity of natural plant populations facilitates the establishment of localized value chains linking raw material production with processing industries, research institutions and commercial enterprises [4].

One of the most promising approaches involves the development of local production clusters integrating primary producers, cooperatives, research organizations, extraction facilities and manufacturing companies. Such collaborative networks facilitate knowledge transfer, technological innovation and product standardization while increasing the competitiveness of regional plant-derived products. Cooperation among stakeholders also enables the implementation of quality assurance systems, traceability protocols and sustainable harvesting practices that are essential for successful commercialization in international markets [29].

The conceptual integration of native woody flora, phytochemical reservoirs, green extraction technologies and regional innovation pathways into a unified bioeconomy model for the Karditsa region is illustrated in Figure 2, highlighting the transition from natural capital to high-value products and sustainable local development.

The adoption of green extraction technologies further strengthens the economic viability of these production systems. Modern extraction methodologies, including ultrasound-assisted extraction and supercritical fluid extraction, improve the recovery of valuable phytochemicals while minimizing solvent consumption, reducing energy requirements and preserving the biological activity of thermolabile compounds. These technological advances not only improve product quality but also reduce environmental impacts, making them fully compatible with the principles of sustainable bioeconomy, green chemistry and circular resource management [15,16].

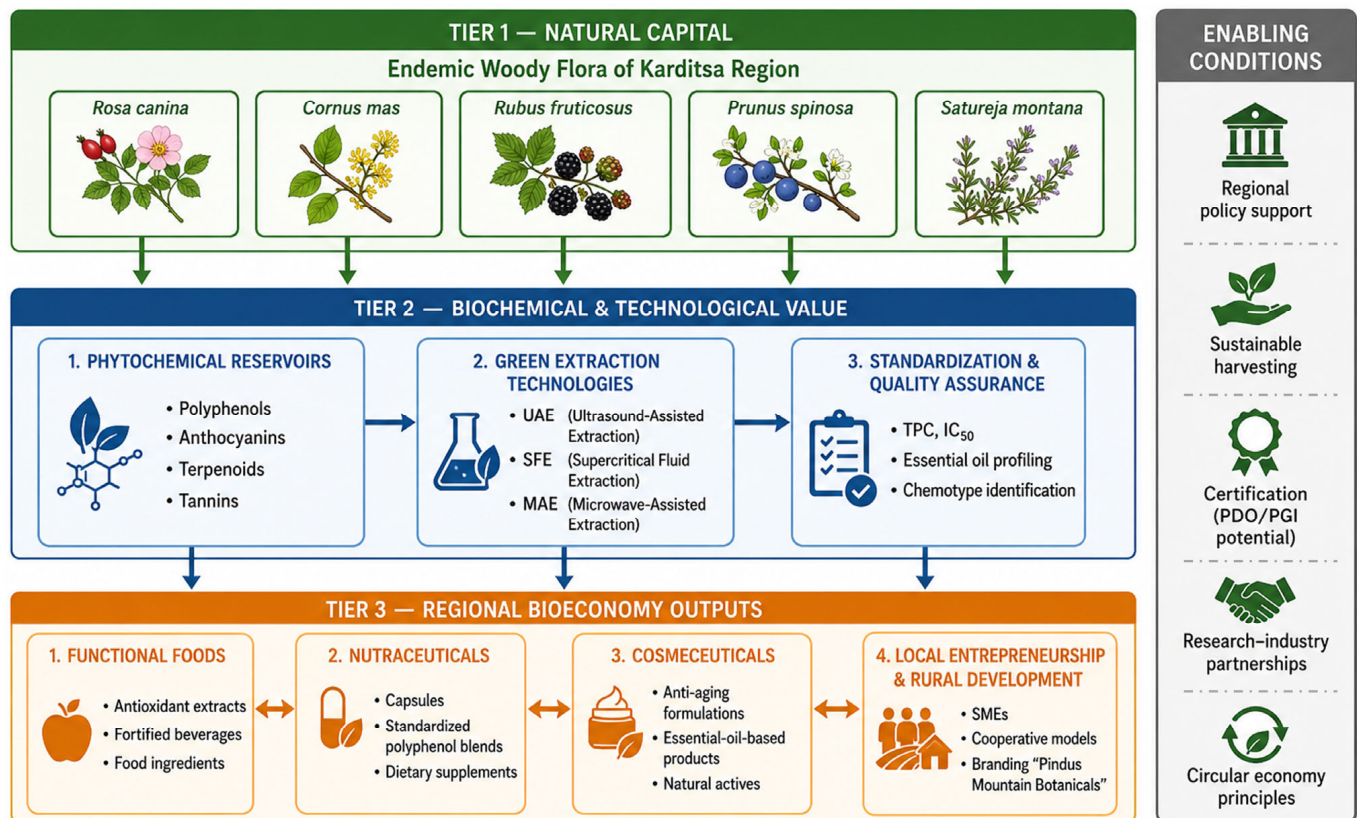


Figure 2. Conceptual framework illustrating the integration of selected woody flora, phytochemical reservoirs, green extraction technologies, and regional innovation pathways into a cohesive bioeconomy cluster for the Karditsa region. The model highlights the transition from natural capital to high-value products and local development.

An important advantage of regional bioeconomy models is the possibility of maximizing biomass utilization through integrated biorefinery concepts. Fruits, leaves, seeds and other plant materials can be processed sequentially to recover multiple categories of valuable compounds, while residual biomass may subsequently be utilized for the production of natural fertilizers, animal feed, bioenergy or other bio-based materials. Such cascading utilization strategies increase resource efficiency, reduce waste generation and improve the overall economic sustainability of plant production systems, fully reflecting contemporary European and international bioeconomy strategies [29,32,33].

Beyond their economic benefits, local production clusters may generate important social impacts for rural communities. The commercialization of high-value botanical products creates opportunities for employment, entrepreneurship, and diversification of agricultural activities while encouraging younger generations to remain in rural areas. In addition, the promotion of locally produced phytochemical ingredients may strengthen regional identity and increase the international visibility of Mediterranean biodiversity through certified products associated with geographical origin and sustainable production practices [4].

The long-term success of these bioeconomic initiatives depends on the establishment of appropriate scientific, regulatory and industrial frameworks. Sustainable harvesting guidelines, cultivation protocols, phytochemical standardization, quality control systems and continuous monitoring of natural populations are necessary to ensure both product quality and biodiversity conservation. Close collaboration among universities, research institutes, local authorities, producers and industrial partners will therefore be essential for

translating scientific knowledge into economically viable and environmentally sustainable production systems capable of supporting long-term regional development [4,15].

Overall, the woody flora of the Karditsa region represents a valuable natural resource that extends well beyond its ecological significance. The integration of phytochemical research, sustainable extraction technologies and regional production networks provides a realistic pathway for the development of innovative bio-based products with high commercial value. Such an integrated bioeconomy model simultaneously supports biodiversity conservation, rural prosperity and the sustainable utilization of Mediterranean plant resources, fully aligning with current European strategies for green growth and circular bioeconomy development [4,15,29,32,33].

8.2. Conservation Strategies and Sustainable Management

The sustainable utilization of Mediterranean woody flora should always be accompanied by effective conservation strategies that ensure the long-term preservation of biodiversity, ecosystem integrity, and the ecosystem services upon which both natural and human communities depend. Although many native woody species possess considerable phytochemical and commercial value, increasing market demand may place additional pressure on natural populations if appropriate management practices are not implemented. Consequently, biodiversity conservation and bioeconomic development should be considered complementary components of sustainable resource management rather than conflicting objectives [1,32].

The Mediterranean Basin represents one of the world's most important biodiversity hotspots, while Greece constitutes one of its principal centres of plant diversity and endemism. Mountain ecosystems, including the Pindus range and the Karditsa region, support highly diverse woody plant communities that have evolved under heterogeneous environmental conditions. These ecosystems provide valuable genetic resources and maintain numerous ecological functions that contribute to ecosystem stability, climate resilience and long-term biodiversity conservation [1–4].

The conservation of woody plant species extends beyond the protection of individual taxa and includes the preservation of ecological interactions that sustain Mediterranean ecosystems. Healthy plant communities support pollinators, seed dispersers and numerous other organisms that collectively maintain ecosystem functioning and biological resilience. Declines in pollinator diversity may negatively affect plant reproduction, genetic diversity and ecosystem stability, highlighting the importance of integrated conservation strategies that protect both plant species and their associated ecological networks [34].

Sustainable management should therefore prioritize habitat protection together with scientifically supported harvesting practices. Excessive or uncontrolled collection of wild plant material may reduce natural regeneration, alter population structure and compromise long-term ecosystem resilience. The implementation of ecological monitoring programmes, seasonal harvesting schedules and selective biomass collection can substantially reduce harvesting impacts while maintaining healthy natural populations and preserving phytochemical diversity [4].

The cultivation and domestication of selected woody species provide an additional strategy for reducing harvesting pressure on natural populations. Establishing cultivation systems based on locally adapted genetic resources may ensure a continuous supply of standardized plant material for industrial applications while simultaneously protecting naturally occurring populations. Such cultivation programmes also facilitate quality control, traceability and phytochemical standardization, thereby improving the commercial value of plant-derived products [29].

Long-term conservation further requires the integration of ecological monitoring with phytochemical research. Continuous assessment of species distribution, habitat quality, genetic diversity and phytochemical variability enables the identification of populations possessing particularly valuable biochemical characteristics while simultaneously supporting evidence-based conservation planning. Such interdisciplinary approaches strengthen both biodiversity protection and sustainable bioeconomic development [4].

Successful conservation programmes also depend on active collaboration among researchers, governmental agencies, local communities, producers and industrial stakeholders. Public awareness initiatives, educational programmes and community participation can significantly improve the implementation of conservation measures while promoting the responsible utilization of native plant resources. These collaborative approaches contribute to maintaining biodiversity while supporting sustainable regional development and reinforcing the relationship between scientific research and local communities [4].

Overall, effective conservation strategies should integrate biodiversity protection, sustainable harvesting, scientific monitoring and responsible commercial utilization within a unified management framework. Such an approach ensures the long-term preservation of Mediterranean woody flora while supporting the continued development of innovative food, nutraceutical, pharmaceutical and cosmetic products. For regions such as Karditsa, conservation should therefore be regarded not only as an ecological necessity but also as a fundamental prerequisite for sustainable bioeconomic growth and the long-term valorization of native plant resources [1,4,29,32,34]. To further contextualize the conservation and valorization potential of the selected woody species, a comparative overview of their resource availability, principal industrial applications, current barriers, and overall bioeconomic relevance is presented in Table 3.

Table 3. Comparative overview of the selected woody species regarding resource availability, industrial applications, current barriers, and bioeconomic relevance.

Species	Resource Availability	Main Industrial Applications	Current Barriers	Bioeconomic Relevance	References
<i>Rosa canina</i>	Widely distributed in Greece and Europe; naturally abundant in mountainous and semi-natural ecosystems.	Functional foods, herbal beverages, nutraceuticals, dietary supplements, cosmetic formulations.	Seasonal variability in phytochemical composition; limited cultivation standardization; variability among wild populations.	High	[10,17,23,29,30]
<i>Cornus mas</i>	Naturally distributed in Greece, the Balkans and Western Asia.	Functional foods, fruit juices, fermented beverages, nutraceuticals, natural antioxidants.	Limited commercial cultivation; insufficient standardization of processing technologies.	High	[11,28,29]
<i>Rubus fruticosus</i>	Widespread throughout Europe, including the Mediterranean region and Greece.	Functional foods, fruit products, dietary supplements, natural antioxidant ingredients.	Phytochemical variability influenced by environmental conditions and genotype.	Moderate–High	[13,22,29,31]
<i>Prunus spinosa</i>	Widely distributed across Mediterranean and temperate European ecosystems.	Fruit preserves, juices, fermented products, phytopharmaceutical and nutraceutical ingredients.	Limited industrial exploitation and lack of standardized cultivation and processing protocols.	Moderate	[12,22,29,31]
<i>Satureja montana</i>	Native to the Mediterranean region; naturally abundant in rocky habitats and cultivated in several countries.	Essential oils, food preservation, natural flavourings, cosmetics, pharmaceutical preparations.	Chemotype variability; environmental effects on essential oil composition; need for cultivation standardization.	High	[14,17,23,29]

9. Conclusions and Future Directions

The present review highlights the remarkable phytochemical diversity and bioeconomic potential of selected woody plant species naturally occurring in the Karditsa region of Central Greece. Species such as *Rosa canina*, *Cornus mas*, *Satureja montana*, *Rubus fruticosus*, and *Prunus spinosa* constitute valuable sources of polyphenols, flavonoids, anthocyanins, terpenoids, and other bioactive secondary metabolites associated with antioxidant, antimicrobial, anti-inflammatory, and other health-promoting biological activities. These phytochemical characteristics support their increasing importance in functional foods, nutraceuticals, pharmaceuticals, and cosmetic applications while highlighting their contribution to the sustainable utilization of Mediterranean plant resources.

The available scientific evidence demonstrates that environmental conditions characteristic of Mediterranean mountain ecosystems strongly influence both phytochemical composition and biological activity. Altitude, climatic variability, soil characteristics, and abiotic stress contribute to significant phytochemical variability among natural populations, emphasizing the importance of ecological factors in determining the quality and biological value of plant-derived products. At the same time, recent advances in green extraction technologies and modern analytical techniques have substantially improved the efficient recovery, characterization, and standardization of these bioactive compounds, thereby facilitating their industrial utilization while reducing environmental impacts [15,16].

Beyond their scientific importance, the selected woody species represent valuable biological resources for regional bioeconomy development. Their sustainable exploitation, combined with biodiversity conservation, environmentally friendly extraction technologies, innovative processing strategies, and local production systems, offers promising opportunities for the development of high-value bio-based products while simultaneously supporting rural economies and environmental sustainability. The Karditsa region, owing to its rich woody flora and ecological diversity, provides an excellent model for integrating biodiversity conservation with sustainable regional development within the framework of the European circular bioeconomy [4,29,32,33].

Despite the considerable progress achieved during the last decade, important knowledge gaps remain. Most published studies have focused primarily on phytochemical identification or in vitro antioxidant activity, whereas comparatively limited attention has been devoted to multidisciplinary investigations integrating phytochemistry, ecology, biotechnology, pharmacology, and bioeconomy. Furthermore, considerable methodological heterogeneity among published studies, including differences in plant origin, harvesting season, extraction procedures, analytical techniques, and biological activity assessment, continues to limit direct comparisons among datasets. The establishment of standardized sampling protocols, extraction methodologies, and analytical procedures would substantially improve the reproducibility and comparability of future investigations while facilitating the development of quality standards for industrial applications [15,16].

Future research should therefore focus on comprehensive multidisciplinary approaches that combine ecological monitoring, phytochemical characterization, metabolomics, molecular biology, and biological validation through well-designed in vivo and clinical studies. Additional efforts are also required to optimize green extraction technologies, improve industrial scalability, and strengthen quality control procedures in order to facilitate the production of standardized phytopharmaceutical, nutraceutical, food, and cosmetic products supported by robust scientific evidence [15,16,35].

Finally, greater collaboration among universities, research institutions, producers, industrial stakeholders, and public authorities will be essential for establishing integrated regional value chains based on native woody plant resources. Such collaborative initiatives will promote technology transfer, product innovation, biodiversity con-

servation, and the sustainable commercialization of plant-derived bioactive compounds, thereby strengthening both regional competitiveness and the transition towards a circular bioeconomy [29,32,33].

Overall, the integration of biodiversity conservation, phytochemical research, sustainable extraction technologies, and bioeconomy strategies provides a comprehensive framework for the sustainable valorization of the selected woody flora of the Karditsa region. Continued interdisciplinary research will not only advance scientific knowledge but also support the development of innovative, high-value natural products capable of contributing to human health, environmental sustainability, and regional economic growth [29,32,33,35].

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Appendix A

Table A1. Summary of the principal studies included in the review, including information on plant species, plant part, geographical origin, extraction methodology, analytical techniques, major phytochemical constituents, reported biological activities, and each study's contribution to the objectives of the review.

Ref.	Source Type	Species/Scope	Plant Part/Material	Country/Region	Extraction Method	Analytical Method	Key Compounds/Evidence	Bioactivity/Outcome Endpoints	Contribution to the Review
[10]	Review	<i>Rosa canina</i> L. and its by-products	Rose hips, seeds, oils, pomace and other processing by-products	Europe and other regions covered by the reviewed literature	Various conventional and emerging extraction procedures reported across the reviewed studies	Various chromatographic and spectrophotometric methods reported across the reviewed studies	Vitamin C, phenolic acids, flavonoids, carotenoids, tocopherols and fatty acids	Antioxidant, anti-inflammatory, antimicrobial and application-related evidence	Updated species profile; evidence on bioactive composition, health-related properties, by-product valorization and food, nutraceutical and cosmetic applications
[11]	Comprehensive review	<i>Cornus mas</i> L.	Fruits, leaves, seeds and bark; juices, powders and extracts	Southern and Eastern Europe, Southwest Asia and other locations represented in the reviewed studies	Water, ethanol, methanol, acetone and other solvent systems; preparation-specific procedures varied among studies	HPLC, HPLC-DAD, UHPLC, LC-MS/MS, GC-MS, HPTLC and related methods	Anthocyanins, iridoids, phenolic acids, flavonoids, tannins, vitamin C, organic acids and minerals	Antioxidant, antimicrobial, antidiabetic, anti-inflammatory, cardioprotective, hepatoprotective and other endpoints; clinical evidence limited	Comprehensive basis for Cornelian cherry phytochemistry, biological properties, methodological variability and functional-food/nutraceutical relevance
[12]	Primary experimental study	<i>Prunus spinosa</i> L.	Fresh ripe fruits	Southeastern Serbia	Extraction with ethanol, methanol, water and aqueous solvent mixtures; solvent-polarity comparison	UV-Vis spectrophotometry and HPLC; microbiological assays	Neochlorogenic and caffeic acids; quercetin, myricetin; cyanidin-3-O-glucoside, cyanidin-3-O-rutinoside and peonidin-3-O-glucoside	TPC, total flavonoids, anthocyanins, DPPH radical scavenging; antibacterial and antifungal activity	Primary evidence for solvent-dependent phenolic recovery, compound identification, antioxidant capacity and antimicrobial activity of blackthorn fruit
[13]	Primary experimental study	<i>Rubus fruticosus</i> complex (identified in the study as <i>Rubus praecox</i> Bertol.)	Wild blackberry fruits at three ripening stages; dried fruit powder; muffin formulations	Hegyeshalom, Győr-Moson-Sopron County, Hungary	Ultrasound-assisted extraction optimized for solvent, time, acidification and solid-to-solvent ratio; optimum: 60% methanol, 20 min, 0.5% HCl, 1:40 g/mL	Spectrophotometric determination of TPC, TFC, total monomeric anthocyanins and DPPH activity; sensory evaluation of muffins	Extractable polyphenols, flavonoids and anthocyanins	TPC, TFC, anthocyanins, DPPH and IC50; ripening-stage effects; functional-food performance and consumer acceptance	Direct evidence for green extraction optimization, ripening-related variability and successful incorporation of blackberry powder into a food matrix

Table A1. Cont.

Ref.	Source Type	Species/Scope	Plant Part/Material	Country/Region	Extraction Method	Analytical Method	Key Compounds/Evidence	Bioactivity/Outcome Endpoints	Contribution to the Review
[14]	Primary experimental study	<i>Satureja montana</i> L. (subsp. <i>montana</i> , <i>variegata</i> and <i>macedonica</i>)	Aerial material from individual wild plants; essential oils	Fourteen wild populations in the Western Balkans, spanning coastal and continental climatic zones	Simultaneous distillation and extraction of individual essential oils	Essential-oil compositional analysis with chromatographic profiling and multivariate chemotype evaluation	Carvacrol, thymol, p-cymene, linalool, geraniol and cis-sabinene hydrate; monoterpenes dominated the oils	Intra- and interpopulation chemical variability; chemotype distribution in relation to geography and environmental variables	Primary evidence for geographic and genetic control of essential-oil composition, chemotype diversity and selection of commercially desirable profiles
[15]	Book chapter/methodological review	Plant materials and phytochemicals (general)	Leaves, stems, roots, flowers, fruits and seeds	International literature	Conventional solvent extraction and advanced methods, including MAE, UAE, aqueous, enzymatic and supercritical-fluid extraction	LC-MS, HPLC, UPLC and other physicochemical characterization methods	Phenolics, vitamins, amino acids, minerals, volatile and non-volatile compounds, fatty acids and nutrients	Extraction efficiency, physicochemical characterization and suitability for nutraceutical and functional-food use	Methodological overview of extraction technologies, solvent polarity, process variables and analytical platforms used to characterize plant extracts
[16]	Methodological review	Natural products (general)	Renewable plant resources and natural-product matrices	International/laboratory and industrial contexts	Green extraction framework: alternative solvents, energy reduction, process intensification, innovative technologies and co-product generation	Not applicable as a single analytical protocol; conceptual and process-level synthesis	Six principles of green extraction, including renewable resources, safer solvents, energy efficiency, co-products, fewer unit operations and non-denatured extracts	Environmental performance, resource efficiency, product quality and biodiversity protection	Conceptual foundation for the green-extraction discussion and for linking extraction technology with sustainability and biodiversity conservation
[29]	Review/development framework	Functional foods and bioactive ingredients (general)	Natural and processed food matrices and functional ingredients	International	Product-specific processing and delivery technologies summarized across the literature	Efficacy testing, safety assessment and regulatory evaluation; methods varied by product	Antioxidants, polyunsaturated fatty acids, probiotics, prebiotics and other functional ingredients	Product efficacy, safety, technological feasibility, regulatory compliance and health-claim substantiation	Framework for functional-food development, evidence standards, technological trends, efficacy testing and safety; supports cautious interpretation of application claims
[32]	Official EU policy document	European bioeconomy	Renewable biological resources and bio-based value chains	European Union	Not applicable	Not applicable	Policy framework connecting renewable resources, innovation, circularity and sustainability	Resource efficiency, sustainable production, ecosystem protection, innovation and regional value creation	Authoritative policy basis for the European circular-bioeconomy context and sustainable valorization discussion

Table A1. Cont.

Ref.	Source Type	Species/Scope	Plant Part/Material	Country/Region	Extraction Method	Analytical Method	Key Compounds/Evidence	Bioactivity/Outcome Endpoints	Contribution to the Review
[33]	Intergovernmental policy report	Global bioeconomy and policy scenarios	Biological resources, technologies and bio-based industries	OECD countries/international outlook	Not applicable	Not applicable	Bioeconomy policy scenarios, innovation pathways and governance considerations	Long-term policy, technology development, sustainability and economic organization	Policy context for future bioeconomy development, governance and the design of regional innovation strategies
[35]	Review	Plant phenolics and skin applications	Plant-derived phenolic compounds and botanical extracts	International literature	Extraction/preparation methods varied across reviewed studies	Chemical, cellular, in vitro, in vivo and application-specific methods varied across reviewed studies	Flavonoids, phenolic acids, tannins, lignans, stilbenes and related phenolics	Antioxidant, anti-inflammatory, antimicrobial, anti-ageing, wound-healing and photoprotective outcomes	Scientific support for the cosmeceutical and dermatological relevance of plant phenolics and for distinguishing mechanistic evidence from product-level claims

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