



REVIEW ARTICLE

Exploring the potential of *Quercus* in Morocco: Distribution, applications, gaps and future directions

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Abstract

Climate change is increasingly affecting ecosystem stability and food security in Morocco, highlighting the need to better understand and utilise resilient forest resources. In this context, *Quercus* species stand out for their wide distribution, adaptability and multiple uses. This review synthesises current knowledge on their distribution, phytochemical composition and potential applications, while identifying key research gaps and perspectives. *Quercus ilex* L. dominates approximately 23.5 % of Moroccan forests, reflecting its high adaptability, while *Quercus suber* L. covers about 7 % and retains economic importance due to cork production. However, fragmented and outdated distribution data limit the effectiveness of ecosystem monitoring and management strategies. Phytochemical studies reveal considerable variability in total polyphenol content (TPC), with values for the most studied species (*Q. ilex*, *Q. suber* and *Quercus coccifera* L.) acorns ranging 2.39–450 mg GAE/g depending on origin and climate. In contrast, relatively similar TPC values reported for leaves across different origins and climatic conditions suggest a potential effect of genetic stability. Bark contains the highest number of identified phenolic compounds (38 compounds), followed by acorns (32 compounds), leaves (25 compounds) and wood (13 compounds), reflecting their functional roles. Despite this potential, several species remain understudied (*Quercus faginea* Lam., *Quercus pyrenaica* Willd. and *Quercus lusitanica* Lam.) and the translation of these resources into practical applications remains limited. Overall, this review highlights the strong influence of environmental and genetic factors on phenolic variability as well as the imbalance in research efforts. It advocates for a more integrated approach combining ecological, biochemical and ethnobotanical perspectives to support the sustainable use of *Quercus* species in Morocco.

Keywords: applications; chemical profile; diversity; Morocco; *Quercus*

Introduction

According to official records, 2024 represents a point when the Earth's average surface temperature is 1.5 °C more than pre-industrial levels (1), underscoring that climate change is now one of the greatest challenges facing global sustainable development goals, while directly impacting food security. Indeed, literature suggests that the effects of climate change in Morocco may be more severe than in other regions (2). Generally, forest tree species are distinguished by a low domestication degree, significant genetic variability and potential ecological functions, providing numerous goods and services (3). In terms of species-rich clades, the genus *Quercus* has been distributed over millennia across Eurasia, North and Central America and North Africa (4), reflecting both its ecological dominance and economic value (5). This scenario enhances the genus's ability to adapt to climatic fluctuations (6, 7), in addition to its functional roles, which include soil and water conservation, carbon sequestration and industrial and medicinal applications (8). From a cultural perspective, *Quercus* has long

played a central role in human life and subsistence (5). Additionally, various parts of the tree, including wood, bark, leaves, roots and acorns, have been widely used in traditional medicine across different cultures and remain valuable sources of therapeutic compounds (9).

Accordingly, a vision for a sustainable global bio economy and food production system, anchored in plant biology, encompassing forestry and ecosystem conservation, is needed to sustainably produce food, feed, fibre and fuel and to address current challenges (10). Furthermore, adaptation strategies may include changes in dietary patterns (11), particularly by leveraging wild relative species and varieties, which can be used to expand the genetic base (12). In this context, agroforestry has demonstrated considerable potential to contribute to food security while promoting ecological and social balance (13). This approach is based on the principle of supporting diversity (14), as exemplified by forest biodiversity, which plays a critical role in enhancing food security (15) and providing a wide range of ecosystem services, such as carbon

sequestration, nutrient cycles and species conservation. These include small-scale, indigenous and wild edible species (15), highlighting the importance of conserving species with socioeconomic and cultural importance (16).

In Morocco, forests cover nearly 9 M ha and consist mainly of broadleaf formations (71 % of the total area), including holm oak, cork oak and Tauzin oak. These ecosystems are organised into two main groups, including (i) coastal formations dominated by *Quercus suber* L. near Rabat and Kenitra and (ii) formations in the Middle Atlas dominated by *Quercus ilex* L. and *Cedrus atlantica* (Endl.) G.Manetti ex Carrière. The forestry sector contributes nearly 1 % of Morocco's annual gross domestic product (GDP) (17).

Although *Quercus* species are recognised as important genetic resources shaping Moroccan forest ecosystems, their potential for sustainable use, such as the provision of food, fodder and firewood across various agro-climatic zones of hilly regions (13) remains underestimated and insufficiently acknowledged. In addition, their adaptability and phenotypic diversity (18) play a key role in maintaining ecosystem sustainability, highlighting their value as multifunctional tree species. However, this gap limits their potential contribution to Morocco's GDP growth, particularly in rural areas. Therefore, there is a clear need to develop a research and policy framework to address this issue and unlock the potential of these species.

At present, *Quercus* species represent a valuable source of germplasm for addressing current and future challenges, underscoring their potential for sustainable use within national exploitation and valorisation systems. Realising this potential requires a deeper understanding of their phytochemical profiles and multifunctional applications. Such efforts would help fill existing knowledge gaps in Morocco and provide a solid foundation for future research, ultimately supporting the integration of interdisciplinary approaches for the development of the *Quercus* sector.

In this context, recognising the importance of *Quercus* forests and their role in Morocco's ecological and economic systems is essential for addressing current challenges and shaping future perspectives. This review aims to provide an integrated overview of *Quercus* species in Morocco by synthesising existing studies on their geographical distribution across the country. In addition, it examines the phytochemical profiles of different tree components including acorns, leaves, bark and wood, to better understand their potential applications. Finally, this work seeks to identify existing knowledge gaps and highlight key research priorities needed to support the sustainable valorisation of *Quercus* resources in Morocco.

Methodology

To develop a robust systematic review, the methodology proposed earlier was applied (19). It consists of six structured steps designed to minimise bias and enhance repeatability:

1. Establishing the "Specific research question"
2. Choosing the database
3. Defining the time interval
4. Establishing the keywords used in the search phase
5. Selecting relevant publications
6. Extracting and analysing the data

Research question, database and time interval

The first part of this study involved defining a specific research question focusing on the phenolic potential of *Quercus* species found in the Moroccan landscape as multipurpose trees, by identifying their phenolic profiles, across all tree parts: acorns, bark, leaves and wood. A bibliometric analysis was conducted using Scopus, one of the most comprehensive databases of scientific publications. Given the scarcity of national data on the distribution of *Quercus* species in Morocco, as well as the limited number of studies on deciduous species, particularly *Quercus pyrenaica* Willd. and *Quercus lusitanica* Lam., Google Scholar was also consulted to access a broader range of data, including national and international reports. In addition, tables and cartographic data were collected from the national water and forestry agency of Morocco. No specific time interval was defined, as it was necessary to broaden the scope of the research as much as possible. Although most relevant studies are generally published in international journals in English, *Quercus* forests, specifically *Q. suber* in the Maâmora Forest-play a prominent role in Moroccan literature. Therefore, studies published in French were also included to account for nationally circulated journals.

Establishing the keywords

This literature review is based primarily on previous articles and recent research conducted on *Quercus* species in Morocco and the Mediterranean region. The focus is mainly on the six *Quercus* species found in Moroccan forests. The search was conducted using keywords such as "*Quercus*", "Moroccan *Quercus* species", "chemical composition", "phenolic compounds", "acorn", "bark", "leaves" and "wood". In addition, each of the six *Quercus* species was entered separately into the search engine.

Selection of relevant publications

Based on the articles downloaded in the previous phase from the Scopus and Google Scholar databases, relevant publications were selected using a double-step filtering process (Fig. 1). The first step relied on the title and abstract to exclude articles not aligned with the objectives of this study. The second filtering step involved full-text screening to verify more precisely whether these articles fell within the scope of this review.

In total, 66 publications (Fig. 1) addressing the phenolic profile and chemical composition of six *Quercus* species were identified. These articles were published between 1990 and 2024, with the majority originating from Portugal, Spain, Turkey, Tunisia, Algeria and Morocco.

Extraction and analysis of the information

Finally, all selected articles underwent a detailed full-text review following a traditional literature review approach. A database spreadsheet was compiled, including the number of isolated compounds, total polyphenol content (TPC), origin of the *Quercus* samples, climate and sampling period, as well as the *Quercus* species studied and the tree parts analysed.

Results of the search phase

Out of the 66 papers screened, only 34 (Fig. 1) were considered relevant to the objectives of this study. Among these, *Q. ilex* accounted for the highest number of studies (n = 12), followed by *Q. suber* (n = 10), *Quercus coccifera* L. (n = 6), *Quercus faginea* Lam. (n = 4) and *Q. pyrenaica* and *Q. lusitanica* (n = 1 each). In parallel, acorns were the most frequently investigated organ, followed by *Q. suber* cork, due to their economical place and functional applications.

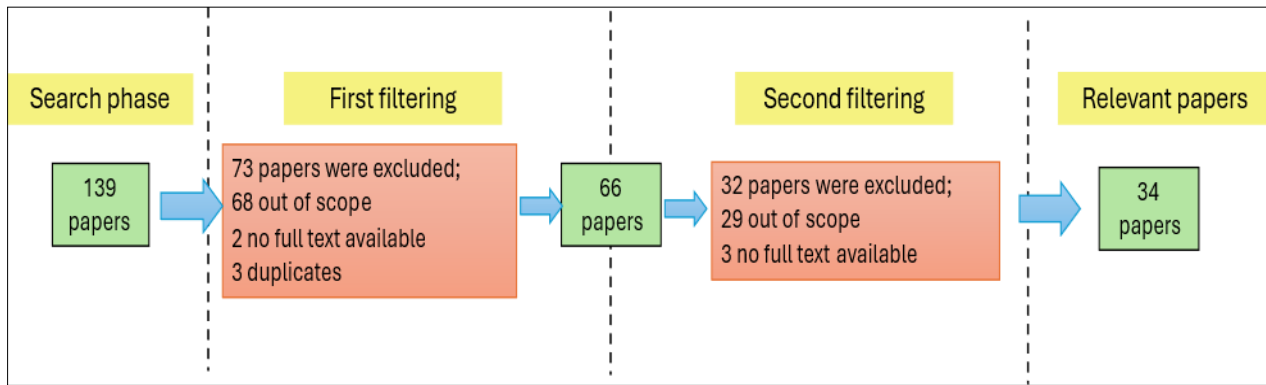


Fig. 1. The different steps performed in the search phase returned 34 relevant papers.

Based on the available literature, investigations on the *Quercus* genus relevant to Morocco have mainly been conducted in six Mediterranean countries, three of which are in North Africa: Morocco, Algeria and Tunisia. Portugal and Spain account for the highest number of published studies ($n = 6$ each), followed by Algeria ($n = 5$). Turkey and Tunisia, meanwhile, have the same number ($n = 3$ each), while in Morocco, there was only one study that investigated phenolic compounds in the acorns of two *Quercus* species.

Generalities

The total number of species in the *Quercus* genus is around 400–600 globally (9). However, the most widely accepted classification divides the genus into two subgenera: *Quercus* and *Cerris* (Fig. 2), based on morphological, molecular and ecological traits. In the Moroccan flora, *Quercus* species include the *Ilex* group (*Q. suber*, *Q. ilex* and *Q. coccifera*) as well as the *Cerris* group (*Q. faginea*, *Q. pyrenaica* and *Q. lusitanica*) (17) (Table 1). In this regard, *Quercus* species, with special reference to *Q. ilex* and *Q. suber* are dominant in Moroccan forests, play an important role in biodiversity conservation and provide 1.5–2 billion forage units annually, which account for 17 % of total livestock feed (17). At the global scale, recent studies indicate that the genus *Quercus* is taxonomically complex due to frequent hybridisation and adaptations to different environments (23). Intrageneric groups such as *Cyclobalanopsis*, *Lobatae*, *Protobalanus* and *Quercus* exhibit clear geographical differences, which contributes to their ecological and economic significance (24).

Moreover, introgression within the genus *Quercus* has led to numerous taxonomic synonyms across many species, reflecting a weak correspondence between inter-individual phenotypic variability and clearly defined populations or coherent

geographical groups, particularly in the Iberian Peninsula and North Africa. Regarding the Maghreb region, including Morocco, limited historical and taxonomic information on *Quercus* species makes it difficult to clearly distinguish them and compare them with European taxa (25). In Morocco, taxonomic classifications of this complex group have not been recently updated and current genetic research remains largely focused on *Q. ilex* and *Q. suber* (26, 27). This highlights the need for further studies to better understand the genetic diversity of *Quercus* species in Morocco, particularly in relation to their adaptation to diverse environmental and climatic conditions (28). Addressing these gaps requires a clearer understanding of their national geographical distribution, which is essential for improving sampling strategies and facilitating future research.

National distribution

A literature review, combined with tables and cartographic data provided by the National Water and Forestry Agency of Morocco, enables the determination of the geographical distribution of *Quercus* species in Morocco (Table 1, Fig. 3).

Notably, *Q. ilex* has a wide geographical distribution across regions (Fig. 3) (23.5 % of forests) (27), particularly in the North, the Central Plateau, the Middle Atlas, the High Atlas and the Anti-Atlas. It covers an average of 1,415,201 ha (29) and reaches elevations of 400–2,700 m above sea level (22). This broad distribution reflects its high adaptability and phenotypic plasticity across diverse bioclimatic conditions within the Moroccan Kingdom, making it one of the most drought-tolerant *Quercus* species in the country.

In contrast, *Q. suber* is less abundant than *Q. ilex* (30), covering approximately 320,200 ha. This includes about 64,000 ha of pure cork oak in the Maâmora forest, the largest cork oak forest in the world, which alone represents around 16 % of the species'

Table 1. Main locations of *Quercus* species in Morocco

Species	Location of distribution	Density (ha)	Reference
<i>Q. ilex</i>	North (35°20'2.94"N-5°55'1.01"W)	1.415.201	(20, 21)
	Rif (35°00'0.00" N-4°00'0.00" W)		
	Center Plateau (33°92'0.43" N-6°36'7.60" W)		
	Middle Atlas (33° 29' 59.99" N-4° 29' 59.99" W)		
	High Atlas (31° 25' 59.99" N-6° 55' 59.99" W)		
<i>Q. suber</i>	Anti-Atlas (30° 00' 0.00" N-8° 29' 59.99" W)	350.000	(20, 22)
	North (35°20'2.94"N-5°55'1.01"W)		
	Rif (35°00'0.00" N-4°00'0.00" W)		
<i>Q. coccifera</i>	Center Plateau (33°92'0.43" N-6°36'7.60" W)	-	(22)
	Middle Atlas (33° 29' 59.99" N-4° 29' 59.99" W)		
	High Atlas; (31° 25' 59.99" N-6° 55' 59.99" W)		
<i>Q. faginea</i>	Rif (35°00'0.00" N-4°00'0.00" W)	-	(21)
<i>Q. pyrenaica</i>	Middle Atlas (33° 29' 59.99" N-4° 29' 59.99" W)	-	(22)
<i>Q. lusitanica</i>	Rif (35°00'0.00" N-4°00'0.00" W)	5.000	(22)
	Rif (35°00'0.00" N-4°00'0.00" W)	-	(22)

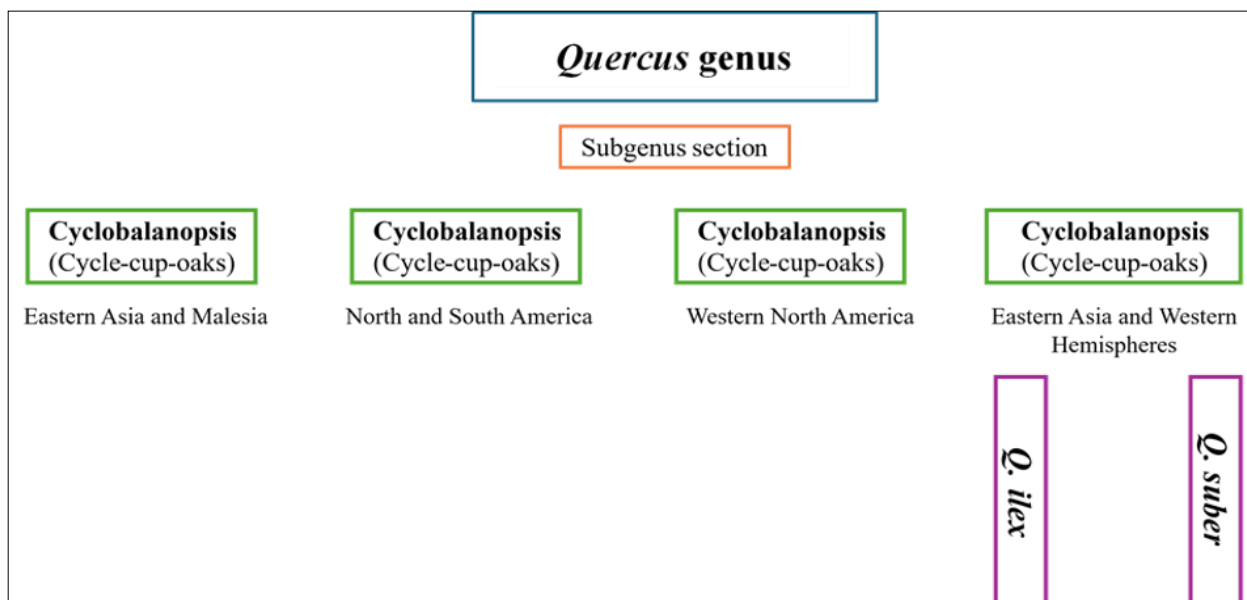


Fig. 2. The fundamental sub-genus group of *Quercus* worldwide.

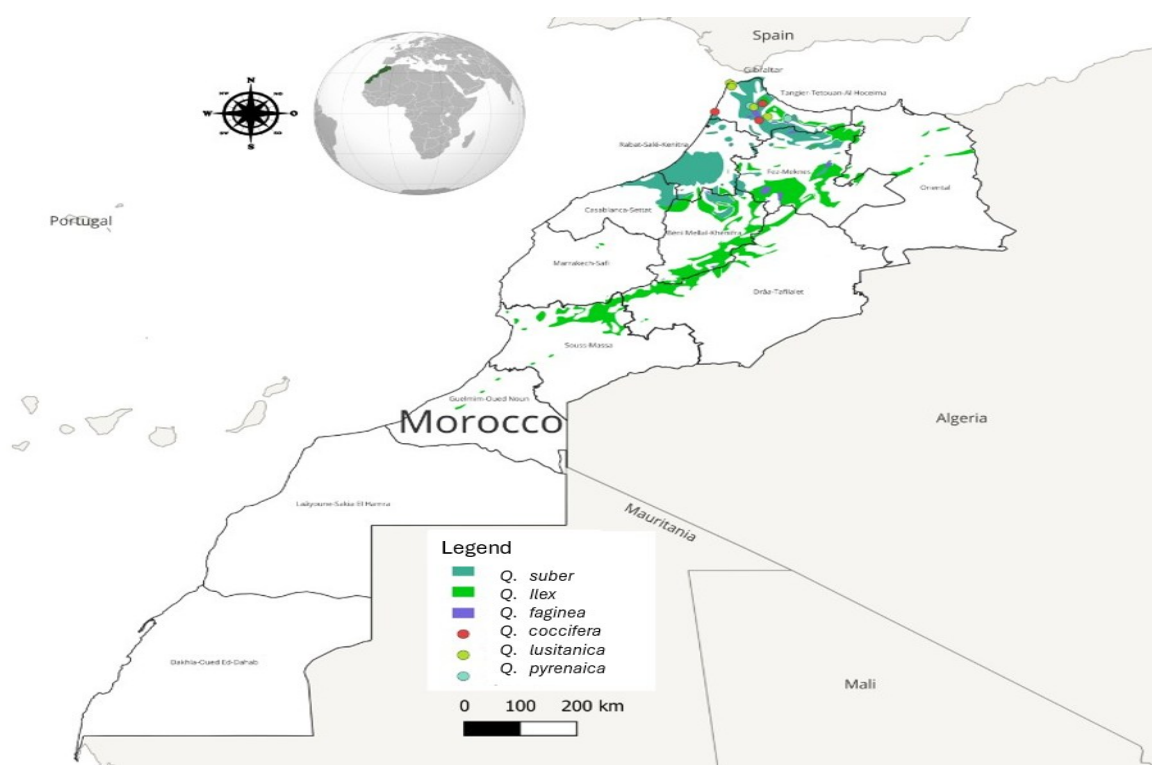


Fig. 3. Geographical distribution of *Quercus* species in Morocco.

global area and about 7 % of Morocco's forest cover (27). *Quercus suber* is recognised as one of the most commercially valuable tree species in Moroccan forests due to its high cork production, which is used in various industrial applications. However, greater attention should be paid to the other deciduous and sclerophyllous *Quercus* species found in Moroccan forests. This species is mainly concentrated in northern regions, while its presence is much more limited in the Central Plateau, the Middle Atlas and the High Atlas. In the southeast of Marrakech, small and isolated patches of *Q. suber*, often mixed with the more dominant *Q. ilex*, can still be found at high elevations (1.600–2.009 m), although they are disconnected from the main distribution range (27).

Quercus pyrenaica is found in habitats such as Jaâba in Azrou (central Middle Atlas) and the Bouhachem massif in the Rif Mountains, covering a total area of 5.000 ha. Similarly,

Q. faginea is found in the Bouhachem massif and in Djbel Kebir (31). Among the remaining two *Quercus* species, *Q. coccifera* is restricted to limited areas in the extreme north, including the Rif and Bni Snassene, as well as a few locations in Taza. In contrast, *Q. lusitanica*, *Q. fruticosa* Brot., *Q. humilis* Lam. are confined to isolated areas below 500 m in the low mountains of the western Rif, including Bouhachem, Djebala and Zemzem (between Ceuta and Tetouan), Mount Khizana (southwest of Bab Taza), Afechtal, Outka and Djbel Kebir in Tangier (31). These species are also native to southern and south-western Iberia, in addition to the Tangier region.

Despite the efforts made by the Water and Forestry Department, restoration initiatives led by Moroccan authorities often fall short. These actions tend to focus primarily on northern

forests, while giving less attention to the socioeconomic realities of rural communities and to the broader biodiversity associated with forest ecosystems (17). Together, the limited and scattered data highlight an urgent need to develop an official, up-to-date map of the geographical distribution of *Quercus* species in Morocco, along with a reassessment of the areas covered by each species. Such efforts would provide a stronger basis for monitoring these ecosystems and guiding management strategies, while also supporting future research-particularly in taxonomy and biochemical characterisation-to better understand their ecological and economic importance. In this context, a detailed analysis of the chemical composition of *Quercus* species becomes essential to further explore their functional potential and possible applications.

Chemical composition

Quercus species worldwide has been thoroughly studied, which has shown diversity in phenolic compounds (32).

Moroccan *Quercus* species phenolic content variability

Variation in TPC across different *Quercus* species and organs has been largely reported in the literature (Table 2) and which can be attributed to a combination of factors.

The analysis revealed that the acorn is the most frequently studied organ in the selected papers, with 15 investigations (Table 2). Taking advantage of the sufficient data available for three *Quercus* species (*Q. ilex*, *Q. suber* and *Q. coccifera*), a comparative analysis of the variability in TPC across different regions was performed (Table 3). This highlights the significant impact of both genetic and environmental factors on both inter- and intra-species variabilities in TPC. A wide range of TPC values was observed among the three species, ranging 2.39–450 mg GAE/g. In this regard, although *Q. ilex* was the subject of the largest number of studies ($n = 8$), indicating the highest degree of geographical documentation, the reported TPC values showed considerable inconsistency. Furthermore, although *Q. coccifera* was investigated in only two studies, it exhibited the greatest variability with a coefficient of variation ($CV = 139\%$) compared to *Q. ilex*. In contrast, *Q. suber* showed relative stability ($CV = 34\%$).

For example, *Q. ilex* acorns from a Mediterranean climate in Tunisia exhibit relatively high TPC values (380 mg GAE/g) (36), whereas acorns from Algeria, grown under a hot-summer Mediterranean climate, show much lower values (2.39 mg GAE/g) (40), reflecting the climate effect. Additionally, strong variability is observed under similar climatic conditions. *Quercus coccifera* acorns from Tunisia and Turkey, both developing under Mediterranean climates, display markedly different TPC values (450 vs. 3.42 mg GAE/g) (Fig. 4). Such discrepancies likely result from differences in geographical origin (local adaptation), sampling period (e.g., maturity stage) and experimental protocols. Indeed, although *Q. ilex* and *Q. coccifera* may occur under similar ecological and climatic conditions in regions such as Tunisia, *Q. coccifera* consistently exhibits higher TPC values. This difference likely reflects intrinsic genetic and biochemical characteristics, or distinct adaptive strategies to environmental stress.

Climatic influence, although significant, does not always produce consistent patterns. For instance, *Q. suber* acorns from different sites in Portugal show relatively similar TPC values: 25.2 mg GAE/g in a semi-arid climate and 28 mg GAE/g in a humid subtropical climate. This apparent contradiction may be explained by the dominant role of genetic stability and similar phenological

stages at sampling, which can override moderate climatic differences.

Overall, the highest TPC values are reported for Tunisian *Q. coccifera* acorns compared to other species and regions despite the relatively limited number of studies on this species. While *Q. faginea* acorns is underrepresented, a single study from Morocco reported a TPC of 98.3 mg GAE/g (Table 2). However, no studies have reported TPC values for acorns of *Q. pyrenaica* and *Q. lusitanica*, highlighting a clear gap in the literature. Notably, in the Moroccan context, research remains particularly scarce. To date, only one study (41) has investigated the phenolic profile of *Q. faginea* and *Q. ilex*, highlighting a significant gap in the literature for other native species.

Concerning the other organs, the leaves of *Q. suber* and *Q. ilex* from Spain and Tunisia, which grew in Mediterranean climates with hot and sub-humid summers respectively, exhibited the lowest TPC values (10.8 and 2.95 mg GAE/g) compared to the other plant parts (Table 2), reflecting tissue specialisation. It is interesting to note that cork bark from Algeria and Portugal, although harvested in similar Mediterranean climates, showed significant variation in TPC values, ranging from 5.9–79.8 mg GAE/g. This suggests that micro-environmental conditions, such as edaphic factors combined with non-standardised extraction protocols, may have a significant impact on TPC results. Furthermore, *Q. faginea* bark recorded a moderate concentration of 40.28 mg GAE/g, suggesting that bark tissues generally retain higher phenolic reserves than foliage.

Moroccan *Quercus* organs phenolic compounds profile

Research conducted on Moroccan *Quercus* species has shown that acorns, leaves, bark and wood are the main contributors to phenolic compound diversity (inter-organ variability) (Table 2). In this regard, a comprehensive synthesis clearly highlights this diversity across *Quercus* organs, with the highest number of phenolic compounds identified in bark (38), followed by acorns (32), leaves (25) and wood (13). This variation in phenolic compound number across organs can be directly related to their functional roles. Bark tissues contain the highest number of phenolic compounds because of their protective function against abiotic and biotic stressors, requiring a rich reservoir of secondary metabolites with antimicrobial and antioxidant properties. This is followed by acorns, which, as reproductive organs, require significant bioactive molecules for seed protection and germination success. Additionally, leaves contain a moderate number of phenolic compounds to fulfil their central role in photosynthesis. In contrast, wood tissues primarily contribute to structural support and the transport of xylem and phloem, which generally require lower phenolic variability.

Hence, this interpretation should, however, consider the limited data regarding leaves and wood. In contrast, acorns and cork bark have been more extensively studied, likely due to their economic value in industrial and food applications. Thus, both limited literature and biological factors may explain this imbalance.

Although each organ is characterised by diverse phenolic compounds, their practical applicability remains insufficiently explored. In this context, optimising the production of these bioactive compounds to enhance their commercial value represents an important research direction. Due to their

Table 2. The phenolic profiles of the six *Quercus* species shaping the Moroccan oak forest

Species	Part analysed	Number of the compounds isolated	Total polyphenol content (mg GAE/g)	Origin	Climate	Period of sampling	Reference
<i>Q. ilex</i>	Acorn	14	121	Spain (Aldea de Cuenca)	Hot-summer Mediterranean climate	November-December	(33)
		5	227	Algeria (Aichoune)	Mediterranean climate	-	(34)
		7	13.6	Portugal (Alentejo)	Semi-arid climate	October	(35)
		-	380	Tunisia (Nabeul)	Mediterranean climate	Harvest season	(36)
		-	31	Portugal (Trás-os-Montes)	Humid subtropical climate	September	(37)
		-	52.5	North-West of Tunisia (Fernana)	Mediterranean climate	December	(38)
		32	-	Spain (Extremadura)	Continental climate	February	(39)
		14	2.39	Algeria (Chemini, Willaya of Bejaia)	Hot summer Mediterranean climate	September and December	(40)
		-	212.5	Morocco (Boulmane and Tetouane)	Semi-arid (Boulmane) Mediterranean climate (Tetouan)	-	(41)
		20	0.12	East of Algeria	-	November	(42)
	Leaves	2	2.95	Tunisia (the Park of Djebel Zaghouan)	Mediterranean sub-humid climate	-	(43)
	Bark	2	-	Spain (Nisano Huesca)	Humid subtropical climate	-	(44)
	Acorn	32	-	Spain (Extremadura)	Continental climate	February	(39)
		-	25.2	Portugal (Alentejo)	Semi-arid climate	October	(35)
		4	49	Portugal (Algarve)	Mediterranean climate	October	(35)
		-	28	Portugal (Trás-os-Montes)	Humid subtropical climate	September	(37)
<i>Q. suber</i>	Acorn oil	20	-	East of Algeria	Mild, Mediterranean climate	November	(42)
	Leaves	10	10.8	Spain (Caceres)	Hot-summer Mediterranean climate	Autumn season	(45)
		38	-	Portugal	-	-	(46)
		29	-	Portugal	-	-	(47)
	Cork	18	79.8	Algeria (El kala parc)	Mediterranean climate	July	(48)
		15	5.9	South of Portugal (Herdade da Moinhola, Amorim Florestal)	Mediterranean climate	-	(49)
	Acorn	-	3.42	Turkey (Kilis province)	Mediterranean climate	November	(50)
		-	450	Tunisia (Nabeul)	Mediterranean climate	Harvest season	(36)
	Shell	-	3.34	Turkey (Kilis province)	Mediterranean climate	November	(50)
	Cup	-	3.37	Turkey (Kilis province)	Mediterranean climate	November	(50)
<i>Q. coccifera</i>	Leaves	11	-	Algeria (El Kala National Park, Province of Attaref)	Mediterranean climate	April and November	(51)
		25	-	Spain (Sierra Morena, a mountain range in the province of Jaen, Andalucia, southcentral)	Hot-summer Mediterranean climate	October	(52)
		4	-	Turkey (Middle-South Anatolia; Sertavul-Akçesme)	Semi-arid continental climate with hot, dry summers and cold, snowy winters	August	(53)
	Acorn	-	98.3	Morocco	Mediterranean climate	-	(41)
	Acorn oil	20	-	East of Algeria	Mild, Mediterranean climate	November	(42)
<i>Q. faginea</i>	Bark	-	40.28	Portugal	-	-	(54)
	Wood	13	-	Spain (Alava province)	Sub-Mediterranean	-	(55)
<i>Q. pyrenaica</i>	Wood	16	41.48	Spain (north-west)	Sub-Mediterranean	Oceanic with mild temperature and high precipitation	(56)
<i>Q. lusitanica</i>	Galls	10	-	Turkish	-	-	(57)

Table 3. Comparative analysis of total phenolic content variability across three Moroccan *Quercus* species (*Q. ilex*, *Q. suber* and *Q. coccifera*) from different regions

Species	N (studies)	Mean (mg GAE/ g DM)	Range (min-max)	SD	CV (%)	Variability
<i>Q. ilex</i>	8	130	2.39–380	133	103	Very high
<i>Q. suber</i>	3	34	25.2–49	13	38	Moderate
<i>Q. coccifera</i>	2	226.7	3.42–450	316	139	Very high

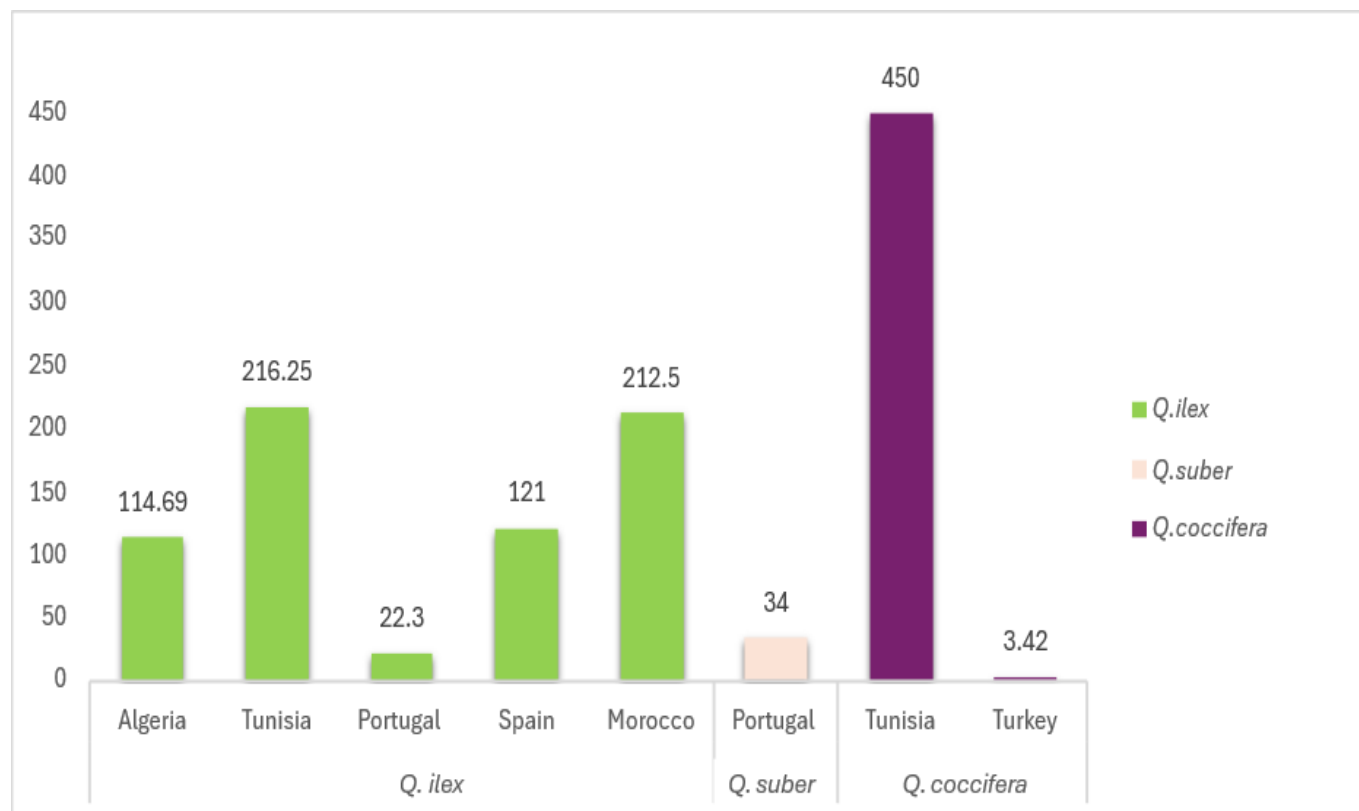


Fig. 4. Species and region effect on total phenolic content (TPC) variability across three Moroccan *Quercus* species.

multifunctional properties, phenolic compounds show strong potential for applications in the timber, food, cosmetic and biological industries (Fig. 5). However, their large-scale valorisation remains limited, highlighting the need to better translate this chemical potential into practical and industrial applications.

Current applications

Nutritional food

In Morocco, *Quercus* species have been a key component of traditional food systems, particularly during periods of food shortage (58). Acorns, which are available in Moroccan markets, are used in several dishes, such as “m'zaït,” a couscous dish from Algeria made with acorns and wheat or barley flour (59). Acorn oil, known for its health benefits compared to olive oil, has been shown to possess stability and a high oleic acid content, which plays an important role in preventing cardiovascular diseases and improving lipid profiles (60, 61). Its antioxidant properties also make it suitable for culinary use and chocolate manufacturing purposes (62).

Academic studies on acorn flour have been conducted, particularly regarding its functionality in gluten-free baking, where it has been recognised for its ability to enhance both texture and nutritional value in baked food products (63, 64). Gluten-free acorn bread and biscuits help address dietary needs, while “dotorimuk,” a jelly-like acorn food product, presents further possibilities for its use in food systems (65).

Forage

Quercus forage, consisting of leaves, twigs and acorns, forms an essential component of livestock systems in Morocco, particularly in silvopastoral systems such as the Maâmora forest (66). Although certain limitations are associated with tannin content, research in Morocco has demonstrated benefits in mitigating methane emissions, retaining nitrogen and acting as antiparasitic agents in

ruminants (67). Seasonal variations in protein content make *Quercus* forage an essential forage during periods of scarcity in Mediterranean climates (68).

Medical and biological applications

Research conducted in Morocco has highlighted the medicinal value of phenolic compounds derived from *Quercus* species, including ellagic and gallic acids, which exhibit antioxidant, antimicrobial, antidiabetic and neuroprotective properties (69, 70). Acorn oil has also been shown to reduce oxidative stress and improve immune responses, likely due to the tocopherol and sterol content (67). In addition, studies conducted in Morocco have demonstrated the healing potential of *Quercus* bark in wound treatment, as well as its potential use in cosmetic applications, such as anti-aging (71, 72).

Ecological applications

Studies in Morocco also highlight the ecological roles of *Quercus* forest types, including carbon sequestration, biodiversity conservation and hydrological regulation (73, 74). Native species such as *Q. ilex* and *Q. suber* have shown impressive carbon sequestration capacity, particularly in dense forest canopies that provide favourable soil conditions for seed regeneration (20, 74, 75). Moroccan forest management policies emphasize the importance of reforestation using native *Quercus* forest types (76).

Gaps and perspectives

Quercus forests play a critical role in Moroccan forest ecosystems and hold considerable potential for both utilisation and conservation. However, the amount of research devoted to *Quercus* species and their phytochemical characteristics remains limited. To date, only one study has investigated the phenolic composition of *Q. faginea* and *Q. ilex*, while genetic research is restricted to *Q. ilex* and *Q. suber* (26, 27, 41). Greater attention should therefore be given to *Quercus* species, which remain

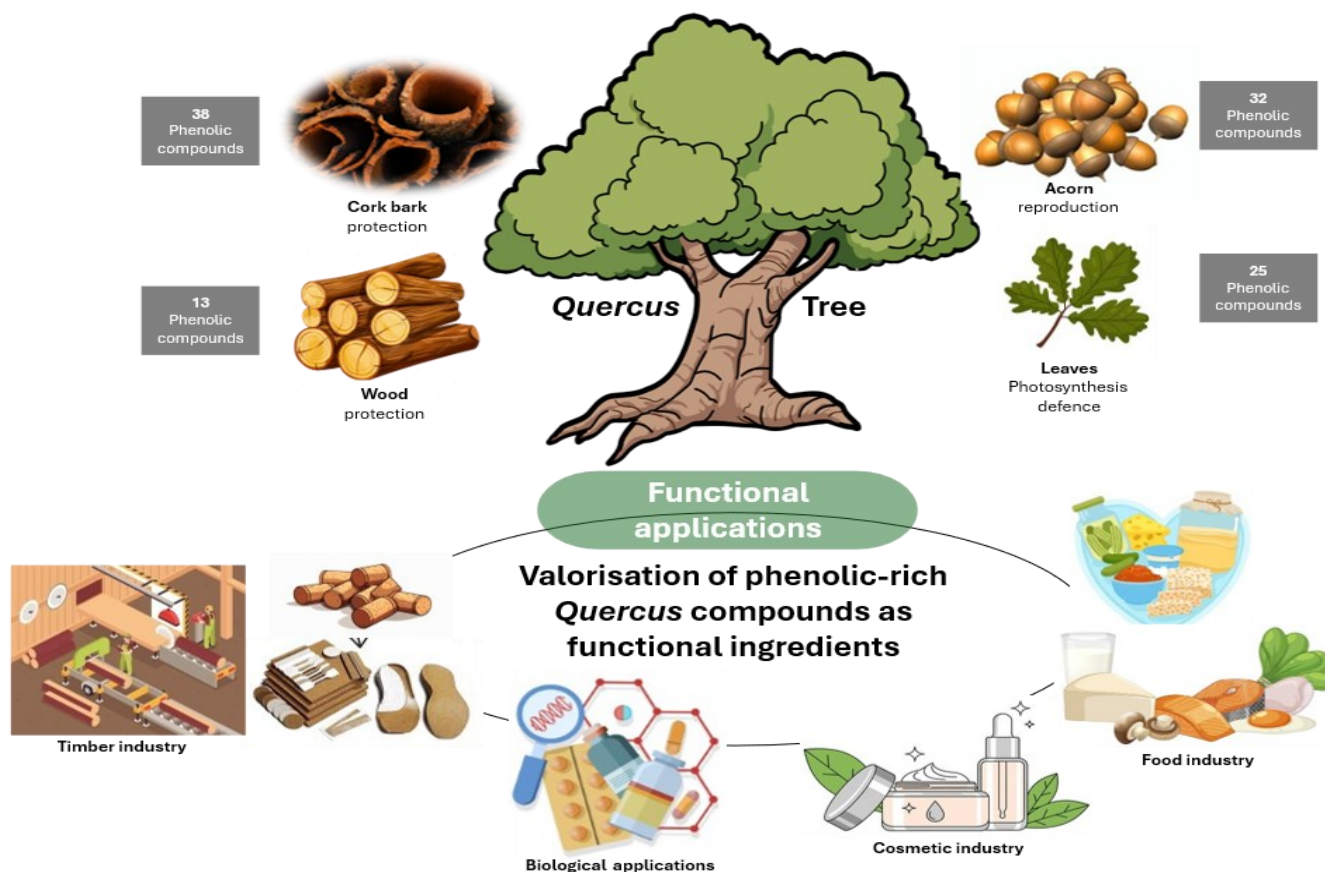


Fig. 5. Distribution and variability of phenolic compounds in different *Quercus* organs and their functional applications in various industrial fields.

relatively understudied compared to commercially prioritised trees such as argan, olive, fig, grapevine and more recently, carob. Despite this imbalance, *Quercus* species constitute a valuable model due to their ecological importance, economic potential and rich biochemical profiles, particularly within the diverse Moroccan ecosystems and in the context of future sustainable development strategies.

To address current knowledge gaps and support biodiversity conservation, a comprehensive and interdisciplinary approach should adopt an integrated framework that interconnects ethnobotanical knowledge, functional trait analysis and the biochemical characterisation of local *Quercus* populations. A key starting point is the documentation of local knowledge, particularly in rural areas, where indigenous communities and elders hold valuable information on species identification, vernacular names, uses and traditional practices. This knowledge provides important insights into the sociocultural and economic relevance of *Quercus* species and can guide the selection of priority species and organs based on traditional uses. These can then be targeted for phytochemical analysis to identify key bioactive compounds, thereby providing a scientific basis for their development in food, industrial and pharmaceutical applications.

In parallel, studies on functional traits are needed to assess the genetic diversity and adaptive capacity of priority species under various environmental and climatic conditions. Such approaches can help to identify resilient species and populations, particularly in the context of climate change.

The establishment of integrated data systems and traceability frameworks can further support decision-making by enabling the identification of high-value and stress-resilient

genotypes, facilitating their domestication and integration of *Quercus* into smallholder agroecosystems. Promoting the cultivation of these species within traditional Moroccan agricultural systems supported by the availability of high-quality genetic material through nurseries can provide practical tools for both forest and agricultural management. The efforts may foster the development of local value chains, functional products and industrial applications, while stimulating local and rural economic development through cooperatives, job creation and sustainable resource management.

Conclusion

In conclusion, adopting a holistic and multidisciplinary framework could support the development of the Moroccan *Quercus* sector by integrating ecological, biotechnological, social and economic dimensions across the entire value chain. The case of argan oil provides a relevant example: over the past two decades, it has become one of the most valuable vegetable oils on the market, largely driven by extensive research, particularly on its biochemical properties, which has generated significant benefits for rural livelihoods and well-being. Similarly, the fruits of *Quercus* species, given their historical importance, hold strong potential for use in nutritional, functional and bioactive products. With sustained research and valorisation efforts, a comparable trajectory could be envisioned for Moroccan *Quercus* species, which represent a promising multipurpose resource and a rich reservoir of genetic diversity. Such an approach could open new opportunities for sustainable rural development, while ensuring a balance between production and conservation through a careful evaluation of potential trade-offs.

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Authors' contributions

EKK, BMA, EFS, LM, MA, AM and HY conceived and designed the study. EKK drafted the manuscript. EKK, BMA, EFS, LM, MA, AM and HY contributed to the revision of the manuscript, read and approved the final version. All authors read and approved the final manuscript.

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During the preparation of this work, the authors used Scispace and Sider to rephrase and detect grammatical errors. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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