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Review

Nutraceutical Potential of Argan Tree (*Argania spinosa*): Structure–Function Insights and Health-Promoting Bioactivities of Key Phytochemicals

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Abstract

Argan tree (*Argania spinosa* L. Skeels), an endemic Moroccan species, is widely recognized for its traditional medicinal and nutritional uses. It has long been employed to promote skin and cardiovascular health, regulate blood glucose levels, and support overall wellbeing. Traditionally, different parts of the argan tree, including argan oil, leaves, and other plant-derived preparations, have been used to manage various health conditions such as diabetes, gastritis, gastric ulcers, rheumatism, joint and muscle pain, skin disorders including acne, eczema, and inflammation, as well as wound healing and dental problems. This narrative critical review compiles and evaluates current knowledge on the ethnobotany, phytochemistry, pharmacology, and toxicology of argan tree to support its evidence-based application. Relevant literature was collected from major English and French scientific databases, focusing on studies addressing the plant and its principal bioactive constituents. Ethnobotanical data indicate the extensive use of argan oil, leaves, and other plant parts in traditional remedies and dietary practices. Phytochemical investigations reveal a rich composition dominated by unsaturated fatty acids, tocopherols, phytosterols, and polyphenolic compounds. Experimental studies highlight a broad spectrum of biological activities, including antioxidant, antidiabetic, antibacterial, and anti-obesity effects, along with emerging applications in nanotechnology. Toxicological findings generally suggest low toxicity and good safety profiles under tested conditions. Overall, A. spinosa exhibits substantial ethnopharmacological relevance and diverse bioactivities, supporting its continued exploration for nutraceutical and therapeutic applications.

Keywords: *Argania spinosa*; phytochemistry; bioactive compounds; biological activities; nutraceutical potential; toxicological assessment

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1. Introduction

The argan tree (*A. spinosa* L.), a distinctive species native to the southwestern regions of Morocco, is of immense ecological, cultural, and economic importance. Covering an area of approximately 820,000 hectares, primarily in the Souss-Massa and Anti-Atlas regions, this tree has adapted to thrive under harsh conditions typical of arid and semi-arid climates. These include limited rainfall, extreme temperatures, and nutrient-poor soils. Its remarkable resilience to such environmental challenges positions the argan tree as a crucial player in mitigating land degradation. Beyond its ability to survive in these tough conditions, the argan tree provides essential ecological services, including soil stabilization and erosion prevention. Its presence is vital in combating desertification and maintaining biodiversity, offering shelter and nourishment to numerous plant and animal species that inhabit Morocco's fragile ecosystems [1–5].

One of the most sought-after products derived from the argan tree is its oil, which has been an integral part of Amazigh culture for centuries [6]. Traditionally, argan oil has been used in culinary, cosmetic, and medicinal applications, reflecting the deep-rooted knowledge and sustainable practices of local communities [6]. The oil extraction process is intricate and labor-intensive, involving the collection of argan fruit, drying, de-pulping the seeds, roasting (for culinary oil), grinding, and finally pressing the paste to obtain the oil. These traditional methods have been passed down through generations, predominantly by women, and continue to be practiced in many communities today [7]. In recent years, women-led cooperatives have emerged as key players in the argan oil industry. These cooperatives not only preserve traditional production techniques but also contribute to rural development [6,7]. By providing employment, training, and economic opportunities, they empower women and enhance household livelihoods, helping to build resilience against modern economic challenges [8–13].

Beyond its cultural significance, argan oil is increasingly recognized for its remarkable nutritional and therapeutic properties, which have garnered interest both locally and internationally. Rich in unsaturated fatty acids, tocopherols (notably vitamin E), polyphenols, and plant sterols, argan oil offers numerous health benefits. Its lipid profile, particularly high in oleic acid (45–55%) and linoleic acid (28–36%), has been shown to improve cardiovascular health by reducing low-density lipoprotein (LDL) cholesterol and potentially increasing high-density lipoprotein (HDL) cholesterol. These effects contribute to a reduced risk of heart disease and atherosclerosis [14,15]. The oil's high tocopherol content, especially γ-tocopherol, which constitutes up to 69% of its vitamin E content, provides potent antioxidant properties, protecting cells from oxidative damage. This antioxidant activity has been linked to skin benefits such as anti-aging effects, improved elasticity, and enhanced hydration. Additionally, argan oil contains polyphenols like ferulic and caffeic acids, which exhibit strong anti-inflammatory and antioxidant properties, potentially reducing the risk of chronic diseases such as cardiovascular disorders, metabolic syndrome, and neurodegenerative conditions. The presence of plant sterols such as spinasterol and schottenol also contributes to its health benefits by inhibiting cholesterol absorption, thereby supporting heart health and regulating blood lipid levels [14]. These characteristics position argan oil as a functional food ingredient with clear nutraceutical relevance, as it combines nutritional value with preventive and therapeutic bioactivities against chronic diseases. This dual functionality aligns with the growing global interest in natural products that bridge the gap between nutrition and pharmacology, particularly in the prevention of metabolic, cardiovascular, and degenerative disorders [4,14,15].

Recent scientific studies have expanded our understanding of argan oil's bioactive components, revealing the molecular mechanisms through which they exert their health-promoting effects. These bioactives have been shown to regulate lipid metabolism, enhance

antioxidant defenses, and support cellular repair. The unsaturated fatty acids play a role in modulating enzymes involved in lipid metabolism, influencing gene expression and improving blood lipid profiles. Meanwhile, polyphenolic compounds, particularly those containing hydroxyl groups, help neutralize reactive oxygen species, minimizing oxidative stress and cellular damage [16–18]. These insights are invaluable for the broader application of argan oil in modern health and wellness products. The growing body of evidence not only validates the traditional uses of argan oil but also paves the way for new applications in functional foods, dietary supplements, and pharmaceutical formulations. As research continues to explore its potential, argan oil is increasingly regarded as a valuable natural resource with significant therapeutic potential.

The main objective of this review is to provide an updated synthesis of the phytochemical, biological, pharmacological, toxicological, and clinical aspects of *A. spinosa*, covering not only argan oil but also leaves, fruit pulp, kernels, shells, and other by-products. It also highlights the structural, functional, and biological relevance of key bioactive compounds from these plant parts, with emphasis on their nutraceutical and pharmaceutical potential. In addition, the review briefly addresses the emerging perspective of *A. spinosa* extract-based green nanotechnology as a promising research direction for the green synthesis of nanomaterials and their applications. Overall, it aims to integrate ethnobotanical knowledge with recent scientific advances to valorize *A. spinosa* as a sustainable source of bioactive compounds for safe and innovative applications.

2. Methodology of Research

In preparing this comprehensive review, a structured literature search was conducted to identify, collect, and analyze scientific publications related to Argania spinosa L. Skeels and its derived products. The search was performed using major scientific databases, including Scopus, ScienceDirect, Web of Science, CABI Digital Library and Google Scholar. The search strategy was based on a combination of keywords and Boolean operators to ensure comprehensive coverage of the literature. The search keywords included: "Argania spinosa", "argan tree", "argan oil", "leaves", "fruit pulp", "kernels", "shells", "by-products", "phytochemistry", "phytochemical profile", "bioactive compounds", "polyphenols", "fatty acids", "tocopherols", "phytosterols", "ethnobotany", "traditional medicine", "pharmacological activities", "biological activities", "antioxidant", "antidiabetic", "antimicrobial", "anti-inflammatory", "anti-obesity", "lipid metabolism", "toxicological assessment", "safety evaluation", and "clinical studies". Only peer-reviewed articles published in English and French up to 2026 were considered. All retrieved studies were screened based on their relevance to the topic, scientific quality, and clarity of experimental, ethnobotanical, or clinical information. Studies that did not meet these criteria or lacked sufficient scientific rigor were excluded. The selected literature was then critically analyzed and organized into thematic sections covering ethnobotanical uses, phytochemical composition, pharmacological activities, toxicological profile, and clinical evidence related to A. spinosa and its derivatives, allowing a comprehensive synthesis of current knowledge and research trends.

3. Argan Oil Extraction

For centuries, the extraction of argan oil has been deeply rooted in the cultural and social practices of Amazigh women in southwestern Morocco. This intricate, labor-intensive process has been preserved through generations, reflecting a rich heritage of artisanal craftsmanship. The traditional method begins with the careful hand-harvesting of ripe argan fruits, typically carried out between May and August [19–22]. After collection, the fruits are left to dry naturally under the sun, a step essential for facilitating the subsequent removal of the outer pulp. Once dried, the hardened fruit is manually peeled to access the

argan nuts within. These nuts are then cracked by hand, usually using stones, to extract the valuable kernels (Figure 1). A critical stage in this process involves lightly roasting the kernels on flat clay plates. This task is performed with exceptional care and attention, as the degree of roasting significantly influences the oil's final taste and aroma. Following roasting, the kernels are ground into a thick paste using traditional millstones. This paste is then manually kneaded with the gradual addition of water to form an emulsion, from which the oil is eventually separated. Remarkably, producing just one liter of argan oil can require up to 50 kg of fruit and nearly 24 h of labor, underscoring the time-consuming and physically strenuous nature of this traditional technique [1,23,24]. Moreover, the absence of standardized sanitary conditions during the traditional process raises legitimate concerns about the microbiological safety and shelf life of the final product.

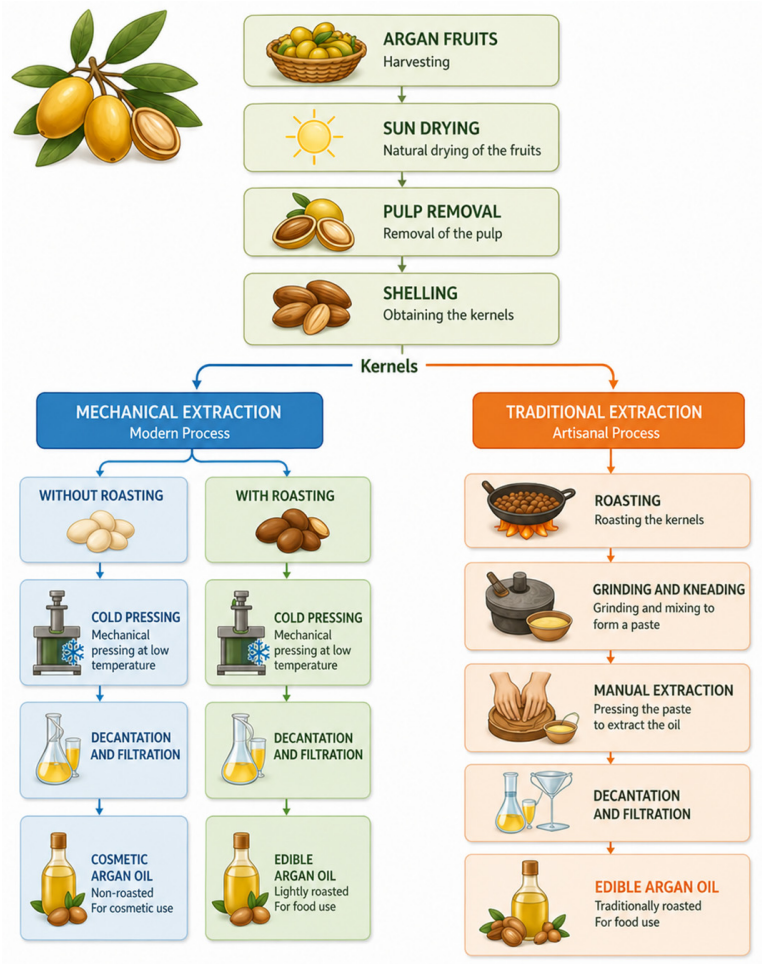


Figure 1. Process flow diagram of argan oil production via mechanical and traditional extraction methods. Designed using Inkscape software (v.1.4.2).

In response to these challenges, the introduction of modern mechanical extraction methods has significantly improved both the efficiency and quality of argan oil production. These contemporary techniques aim to preserve the authenticity and essential characteristics of the traditional process while addressing key limitations such as hygiene, consistency, and scalability. Mechanical extraction typically involves automated peeling and cold pressing, which eliminates the need for water, thereby reducing the risk of microbial contamination and enhancing oil stability. For culinary argan oil, the roasting step is still retained to maintain its distinctive nutty flavor and rich, coppery hue. In contrast, cosmetic argan oil is produced from unroasted kernels, resulting in a lighter-colored oil better suited for skincare applications. The bifurcation of production into edible and cosmetic

oils reflects the versatility and value of argan oil across different markets. Importantly, each phase of both traditional and mechanized processing plays a vital role in shaping the oil's sensory attributes, nutritional profile, and overall quality. Through the integration of technological innovation, the argan oil industry has managed to modernize its practices without compromising the cultural integrity or natural richness of its product. This balance between tradition and innovation not only ensures a sustainable future for argan oil production but also honors the legacy of the women who have safeguarded this craft for generations [1,23,24].

4. Traditional Usages of *Argania spinosa* (L.) Skeels

The traditional uses of different parts of *Argania spinosa*, as summarized in Table 1, demonstrate the extensive ethnomedicinal knowledge surrounding this endemic Moroccan species. Each plant organ, from the trunk bark and leaves to the shell, flowers, pulp, fixed oil, and almonds, has been employed to treat specific ailments or to maintain general health [21,25].

The trunk bark is traditionally administered orally and is used to relieve gastritis, ulcers, and colopathy, reflecting its reputed gastroprotective and anti-inflammatory properties. Similarly, leaves are taken orally to manage diabetes, gastritis, ulcers, fever, and headaches, suggesting hypoglycemic and analgesic effects [18,26].

The shell is used externally in multiple ways. When applied as a cataplasm, it relieves rheumatism, joint pain, and muscle cramps [21]. As a powder dressing, it promotes cicatrization and prevents infection [21], while in paste form, it is applied to treat acne, eczema, boils, and other skin inflammations [21]. Additionally, shell ash or smoke may be used buccally or orally as an antiseptic and analgesic for tooth pain [21]. When macerated in oil and applied topically, it strengthens hair roots, reduces dandruff, and tones the scalp [21,26].

Flowers are used externally in dermal preparations for skin care and other dermatological purposes [21]. The pulp is consumed orally to manage diabetes, gastritis, and ulcers, and also serves as an antimicrobial agent [21]. Fixed oil has both oral and external applications. Orally, it is used to treat rheumatism, hypercholesterolemia, lung and gastrointestinal infections, and to prevent cardiovascular diseases [14]. Externally, it improves skin texture, hydration, and elasticity [21]. Finally, almonds are consumed orally for diabetes management and as a nutritional supplement [21]. Topically, they are traditionally applied for eczema, burns, hair revitalization, and as a remedy for scrofula and venomous bites [21,26].

Overall, Table 1 emphasizes the traditional recognition of *A. spinosa* as a multipurpose plant, with uses spanning internal medicine, dermatology, hair care, and general health maintenance.

Table 1. Traditional usages of *A. spinosa* (L.) Skeels.

Plant Part	Mode of Administration	Traditional Use	Countries	References
Trunk bark	Oral administration	Used to relieve gastritis, ulcers, and colopathy; reputed for its gastroprotective and anti-inflammatory properties.	Morocco	[27–29]
Leaves	Oral administration	Traditionally used to treat diabetes, gastritis, ulcers, fever, and headaches; reported to have hypoglycemic and analgesic effects.	Morocco	[28–30]

Table 1. *Cont.*

Plant Part	Mode of Administration	Traditional Use	Countries	References
Shell	Topical (cataplasm/ external application)	Relieves rheumatism, joint pain, and muscle cramps.	Morocco	[21,28]
	Topical (powder dressing)	Promotes cicatrization and prevents infection.	Morocco	[21]
	Topical (paste application)	Treats acne, eczema, boils, and skin inflammation.	Morocco	[21,28]
	Buccal/Oral (ash or smoke contact)	Acts as antiseptic and analgesic for tooth pain.	Morocco	[21]
	Topical (oil massage)	Strengthens hair roots, reduces dandruff, and tones the scalp.	Morocco	[21]
Flowers	External application	Applied as dermal preparations for skin care and dermatological purposes.	Morocco	[27]
Pulp	Oral administration	Consumed to manage diabetes, gastritis, and ulcers, and used as an antimicrobial agent.	Morocco	[27,31]
Fixed oil	Oral administration	Traditionally used to treat rheumatism, hypercholesterolemia, and respiratory and gastrointestinal infections, as well as to prevent cardiovascular diseases; it is also valued for its antioxidant and hepatoprotective properties, and for alleviating muscle tears.	Morocco	[21,28]
	External application	Applied to improve skin texture, hydration, and aesthetics, the aches of broken teeth.	Morocco	[21,28,32]
Almonds	Oral administration	Consumed for diabetes management and as a nutritional supplement.	Morocco	[33,34]
	External application	Traditionally used topically for eczema and burns, for hair revitalization, and as a remedy for scrofula and venomous bites.	Morocco	[21,28,33,34]

5. Importance of Argan Oil as a Food

Argan oil holds a profound and enduring place in Morocco's traditional and cultural heritage, particularly in the southwestern regions like Souss-Massa and the Anti-Atlas Mountains. For centuries, it has been cherished not only as a vital culinary ingredient but also as a symbol of hospitality, resilience, and community values [20,22,35,36]. In many Moroccan households, especially in rural areas, argan oil remains a daily essential. It is used to finish dishes, accompany bread, or enhance traditional recipes such as Amlou, a nutrient-rich spread made from roasted almonds, honey, and argan oil. More than just a food, Amlou is a cultural expression that is often prepared for family gatherings, festive occasions, and as a welcoming gesture for guests, reflecting deep-rooted customs of generosity and social connection [20] (Figure 2).

The process of producing argan oil is itself a time-honored tradition, frequently carried out by women within community cooperatives. These collective practices, which include harvesting the fruit, cracking the nuts, and hand-pressing the kernels, are passed down through generations and serve as a form of living heritage. Beyond being a livelihood, this artisanal work reinforces bonds among women. It fosters shared knowledge, cooperation,

and the continuity of ancestral skills. Even with the introduction of modern techniques and growing global demand, the traditional know-how remains highly valued and actively preserved [1,22,30].

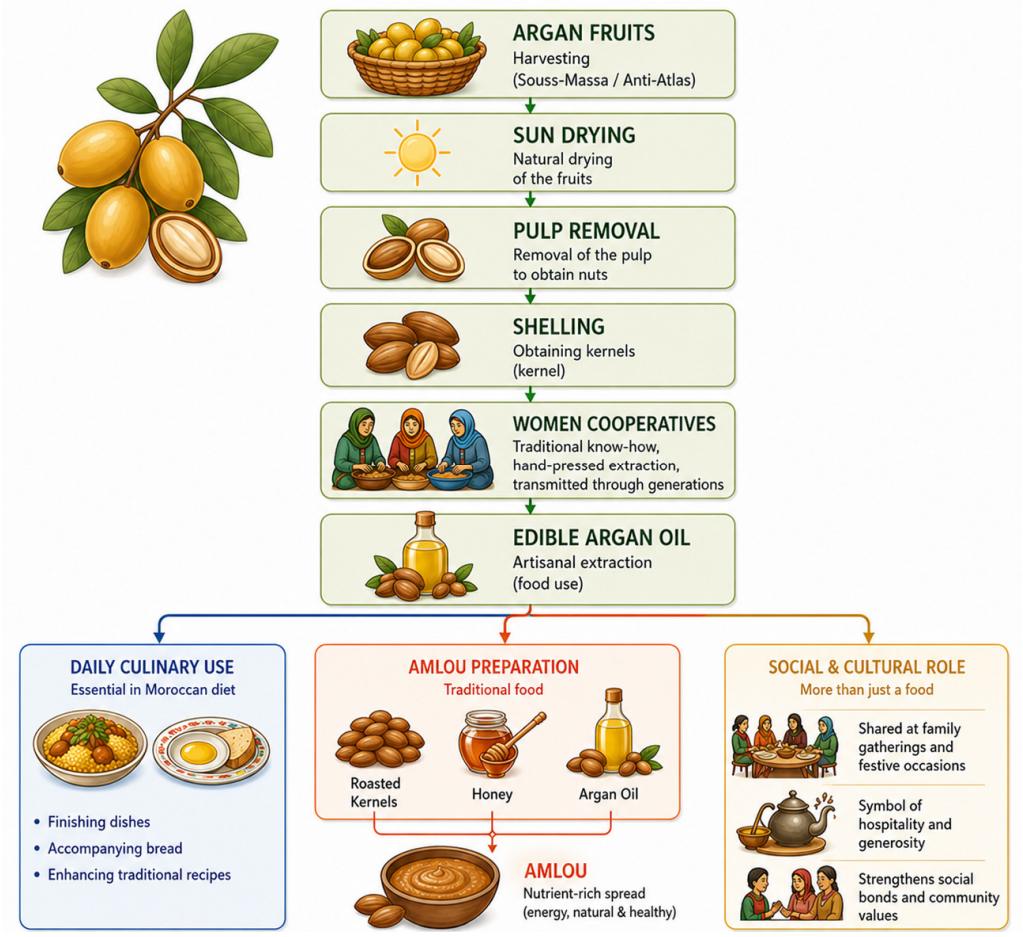


Figure 2. Argan Oil in Morocco: Traditional Production, Food Applications, and Cultural Significance. Designed using Inkscape software (v.1.4.2).

Argan oil also plays a role in rituals and traditional healing practices. It is commonly used during important life events such as childbirth, weddings, and the postpartum period, where it is believed to nourish and strengthen the body. Its topical applications extend to soothing dry skin, easing inflammation, and aiding minor wounds, based on centuries of practical wisdom and cultural belief [30].

On a broader level, argan oil symbolizes the deep interconnection between Morocco's natural environment and its cultural identity. The argan tree (*Argania spinosa*), which thrives in arid and semi-arid climates, is deeply respected as a source of life. It provides food, shade, and economic opportunity. Communities celebrate its significance through regional festivals that highlight music, crafts, cuisine, and storytelling centered on the tree and its oil. In recognition of its cultural and ecological importance, UNESCO inscribed the argan tree and its traditional practices into the Representative List of the Intangible Cultural Heritage of Humanity in 2014. Ultimately, argan oil in Morocco is far more than a culinary product. It stands as a vibrant emblem of sustainability, collective memory, and cultural pride that continues to nourish both body and spirit [35–39].

6. Bioactive Compounds in Argan (*A. spinosa* L.)

Argan oil, often referred to as "liquid gold," is distinguished by a complex and diverse composition of natural compounds, which contribute to its unique biochemical

profile. Its most abundant components are unsaturated fatty acids, making up around 80% of its total fat content. Among these, oleic acid (omega-9) and linoleic acid (omega-6) are predominant, accompanied by smaller amounts of palmitic acid and stearic acid. In addition to its fatty acid content, argan oil contains a considerable concentration of tocopherols, with gamma-tocopherol being the most prevalent form. It also includes a variety of polyphenolic compounds, such as ferulic acid, syringic acid, vanillic acid, and caffeic acid, which contribute to the oil's chemical complexity [40,41]. Phytosterols are another important group of compounds present in argan oil, primarily represented by schottenol and spinasterol, alongside smaller quantities of campesterol, stigmasterol, and beta-sitosterol. The oil further contains squalene, a naturally occurring triterpene hydrocarbon, as well as carotenoids like beta-carotene, lutein, and zeaxanthin. Minor components include coenzyme Q10, melatonin, and various alcohols and alkanes that add to the richness of its chemical profile. Additionally, the unsaponifiable fraction of argan oil, which includes many of these minor constituents, contributes to its overall composition. Traces of other elements such as triterpenic alcohols (like tirucallol), xanthophylls, and sterolic derivatives have also been identified. This wide range of compounds reflects the natural diversity found in argan oil and is influenced by factors such as geographic origin, extraction method, and whether the oil is intended for cosmetic or culinary use [4,14,40].

6.1. Fatty Acids

Argan oil is rich in bioactive fatty acids, with oleic acid (43–55%), linoleic acid (28–36%), palmitic acid (5−16.2%), and stearic acid (4.3−12%) being the most abundant (Figure 3). Oleic acid, a monounsaturated omega-9 fatty acid, is especially beneficial for cardiovascular health, as it lowers levels of Low-Density Lipoprotein (LDL) cholesterol, often referred to as "bad" cholesterol, while maintaining or increasing high-density lipoprotein (HDL) cholesterol, the "good" cholesterol [14,42]. This balance improves lipid profiles and reduces the risk of conditions like atherosclerosis. Oleic acid also has anti-inflammatory properties, helping to reduce the production of pro-inflammatory cytokines, which aids in managing chronic inflammation and inflammatory diseases [15]. Additionally, oleic acid supports skin health by improving the skin's barrier function, enhancing hydration, and preventing conditions such as dry skin, eczema, and psoriasis. It also boosts skin elasticity and shields against environmental damage [4].

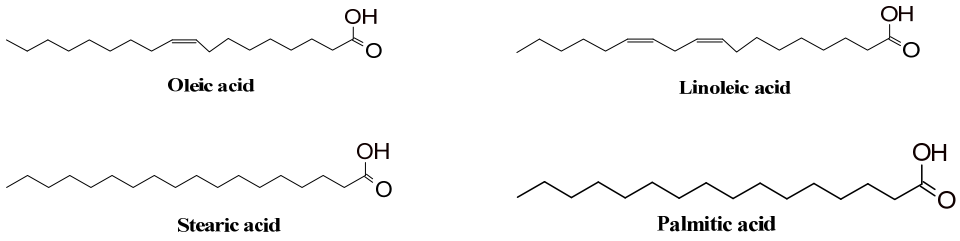


Figure 3. Main fatty acid structures in argan oil. Designed using ACD/ChemSketch (V.2025).

Linoleic acid, an essential polyunsaturated omega-6 fatty acid, is the second most abundant fatty acid in argan oil. It plays a vital role in maintaining the skin's lipid barrier, locking moisture into the skin, and promoting softness and elasticity [15]. Its anti-inflammatory properties help alleviate skin irritation and promote healing in conditions like acne and dermatitis. Linoleic acid also influences the immune system by being a precursor to inflammatory mediators like prostaglandins, which can reduce the risk of chronic conditions such as arthritis and inflammatory bowel disease [14,43]. Furthermore, linoleic acid combats oxidative stress, reducing cellular damage and supporting skin regeneration, which helps maintain a youthful appearance [44]. In addition to oleic and linoleic acids, argan oil con-

tains smaller amounts of other fatty acids such as palmitic acid, stearic acid, and arachidic acid. These contribute to the oil's overall therapeutic effects, with palmitic acid stabilizing the oil's structure, stearic acid improving moisture retention, and arachidic acid offering additional anti-inflammatory and antioxidant benefits [45,46].

6.2. Polyphenols, Flavonoids, and Tannins

Argan oil is rich in polyphenolic compounds, including ferulic acid, caffeic acid, p-coumaric acid, vanillic acid, tyrosol, and various flavonoids (Figure 4), which play a crucial role in its renowned antioxidant, anti-inflammatory, and health-promoting effects [46]. These bioactive molecules contribute to the oil's ability to counteract oxidative stress, reduce inflammation, and mitigate the risk of chronic diseases [46].

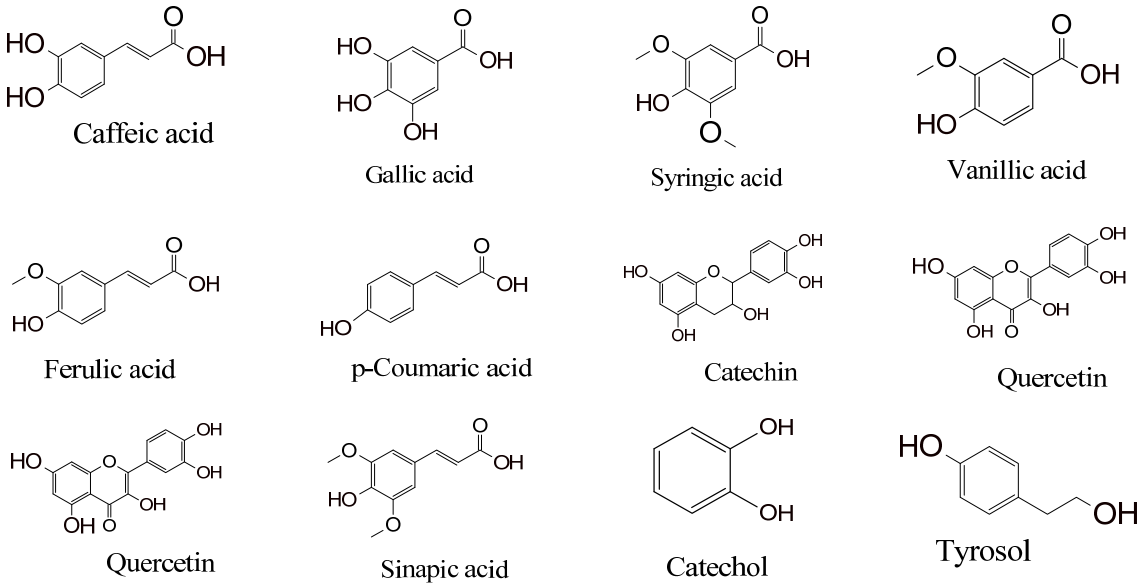


Figure 4. Main phenolic acids found in *A. spinosa* oil. Designed using ACD/ChemSketch (V.2025).

Among these, ferulic acid stands out for its potent antioxidant capacity. It neutralizes free radicals, thereby limiting cellular oxidative damage and preserving the integrity of lipids, proteins, and DNA. Such protective effects are associated with reduced aging processes and a lower risk of conditions such as cardiovascular and neurodegenerative diseases. Additionally, ferulic acid exhibits anti-inflammatory activity by downregulating pro-inflammatory cytokines and modulating the action of enzymes like cyclooxygenase-2 (COX-2), a key player in pain and inflammation [14,17,36].

Caffeic acid, another prominent phenolic compound in argan oil, is well-recognized for its robust antioxidant action. It efficiently scavenges reactive oxygen species and helps prevent oxidative damage, a common pathway in the development of diseases such as diabetes, cancer, and heart disease. Furthermore, caffeic acid contributes to inflammation control by inhibiting cytokines like TNF-α and IL-6 and suppressing COX-2 expression, thereby offering therapeutic potential for managing inflammatory conditions such as rheumatoid arthritis and inflammatory bowel disease [1,7,47].

p-coumaric acid, a derivative of hydroxycinnamic acid, also plays a vital role in the oil's therapeutic profile. It exhibits antioxidant properties by preventing lipid peroxidation and neutralizing oxidative agents. Additionally, it has shown antimicrobial activity against a range of bacterial and fungal species, suggesting its usefulness in skin protection and wound healing [48,49].

Vanillic acid, a methylated form of protocatechuic acid, contributes to argan oil's antioxidant potential by reducing oxidative damage at the cellular level. It also exerts anti-

inflammatory effects by modulating cytokine expression and inflammatory enzyme activity. Its neuroprotective properties are of particular interest, as research suggests vanillic acid may help guard against neurodegenerative conditions like Alzheimer's and Parkinson's disease by reducing oxidative and inflammatory damage to neural cells [15,50].

Tyrosol, a naturally occurring phenolic antioxidant also found in argan oil, adds to its health-promoting profile. Known for its high bioavailability and stability, tyrosol offers protection against oxidative damage by scavenging free radicals and supporting cellular resilience. It has been associated with cardiovascular benefits, particularly in enhancing endothelial function and reducing oxidative stress markers. In addition to its antioxidant effects, tyrosol exhibits anti-inflammatory properties, potentially through the downregulation of pro-inflammatory pathways, and may help protect against metabolic and neurodegenerative disorders [51].

The flavonoid content of argan oil, including compounds such as quercetin, kaempferol, and rutin, further enhances its bioactivity. These polyphenols exert antioxidant effects by scavenging free radicals and chelating pro-oxidant metal ions. Moreover, they regulate inflammatory signaling pathways, contributing to the reduction in inflammation-related mediators. Beyond their systemic health benefits, flavonoids support dermal health by promoting collagen synthesis, protecting skin from UV-induced oxidative damage, and delaying visible signs of aging [4,52].

In the flesh of *A. spinosa* fruits, the tannin fraction is mainly composed of condensed tannins, represented by (+)-catechin and (−)-epicatechin, which are recognized as the principal monomeric units in this species [51,53]. These two flavan-3-ols are widely reported for their strong antioxidant, anti-inflammatory, and cardioprotective activities, mainly due to their ability to scavenge reactive oxygen species, inhibit lipid peroxidation, and modulate cellular signaling pathways involved in inflammation and vascular function [54,55].

Collectively, these polyphenolic constituents endow argan oil with a diverse range of biological functions, supporting its use in nutritional, medicinal, and cosmetic contexts. Their synergistic antioxidant and anti-inflammatory effects make argan oil a valuable agent in disease prevention and health maintenance. As a result, it is increasingly recognized as a functional food and a natural therapeutic, valued for its protective properties across various domains of health and wellness [14,15,56].

6.3. Tocopherols (Vitamin E)

Tocopherols, a group of fat-soluble antioxidants present in *A. spinosa* oil, play a vital role in skin health. This group includes α-tocopherol (12–70 mg/kg), β-tocopherol (2–9 mg/kg), γ-tocopherol (380–494 mg/kg), and δ-tocopherol (16–91 mg/kg) (Figure 5) [57], each contributing distinct protective effects. α-Tocopherol, the most biologically active and abundant in human tissues, is especially effective at neutralizing free radicals. These reactive molecules can damage lipids, proteins, and DNA in skin cells, accelerating aging and causing issues such as loss of elasticity, discoloration, and impaired cellular function. The high tocopherol content of argan oil provides a strong natural defense against oxidative stress, promoting healthy, resilient skin [17,47,57].

These compounds are especially important in counteracting reactive oxygen species (ROS), which are generated by environmental stressors such as ultraviolet (UV) rays, pollution, and metabolic byproducts. γ-Tocopherol, in particular, has shown strong capacity in trapping certain nitrogen-based free radicals, while α-tocopherol excels in lipid peroxidation prevention. Collectively, tocopherols protect essential skin proteins like collagen and elastin from degradation, thus preserving skin firmness and reducing wrinkles. Their photoprotective effects are especially valuable in shielding the skin from UV-induced aging and potential carcinogenesis, helping maintain a youthful and resilient appearance [17,58,59].

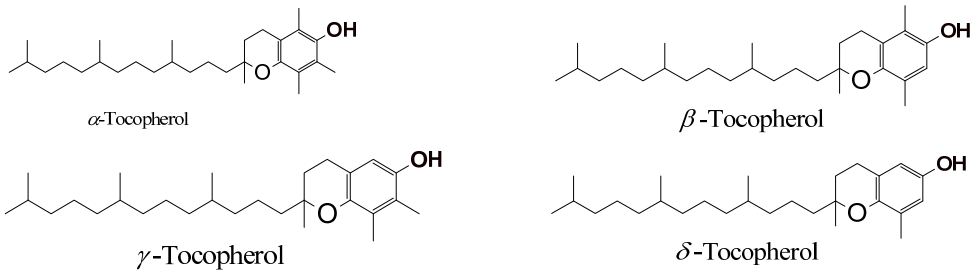


Figure 5. Main tocopherols found in *A. spinosa* oil. Designed using ACD/ChemSketch (V.2025).

In addition to antioxidant activity, tocopherols possess anti-inflammatory properties that are key in alleviating skin conditions such as acne, eczema, and psoriasis. Studies have demonstrated that α- and δ-tocopherols can downregulate inflammatory mediators like interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), reducing redness, swelling, and irritation. Furthermore, they help restore and maintain the skin's barrier function, crucial for moisture retention and protection against external irritants [60]. These functions are especially beneficial for sensitive or dry skin, as tocopherols contribute to the replenishment of epidermal lipids, enhancing hydration and barrier integrity [17,60]. Tocopherols also support skin regeneration and wound healing, making them valuable in treating scarring and chronic wounds. They stimulate collagen production and aid in cell renewal, accelerating tissue repair while minimizing the risk of abnormal scar formation, such as keloids. Their role in photoprotection is further supported by their ability to reduce UV-induced DNA damage and enhance the skin's own antioxidant defenses, including enzymes like superoxide dismutase (SOD) and glutathione peroxidase (GPx). Additionally, tocopherols can inhibit the NF-κB pathway, a major regulator of inflammation and cancer development, offering chemopreventive benefits. The combined antioxidant, anti-inflammatory, and regenerative effects of α-, β-, γ-, and δ-tocopherols underscore their importance in dermatology and cosmetics, where they are increasingly used to promote skin vitality and prevent long-term damage [17,47,57].

6.4. Sterols

Sterols present in *A. spinosa* oil, particularly schottenol and spinasterol, contribute to lipid regulation and cardiovascular health (Figure 6). Their structural similarity to cholesterol enables them to compete during intestinal absorption. This interaction involves the Niemann–Pick C1-Like 1 (NPC1L1) transporter, a key protein responsible for cholesterol uptake in the small intestine. By limiting this pathway, phytosterols reduce the absorption of dietary cholesterol and lead to lower circulating levels of low-density lipoprotein (LDL) cholesterol, which is strongly associated with atherosclerosis and cardiovascular disease [61,62].

These sterols also influence high-density lipoprotein (HDL) cholesterol levels. HDL plays a central role in reverse cholesterol transport by carrying excess cholesterol from peripheral tissues to the liver for elimination. The reduction in LDL combined with improved HDL function supports a more balanced lipid profile and limits the accumulation of arterial plaques, thereby reducing the risk of cardiovascular events such as heart attack and stroke [61,63].

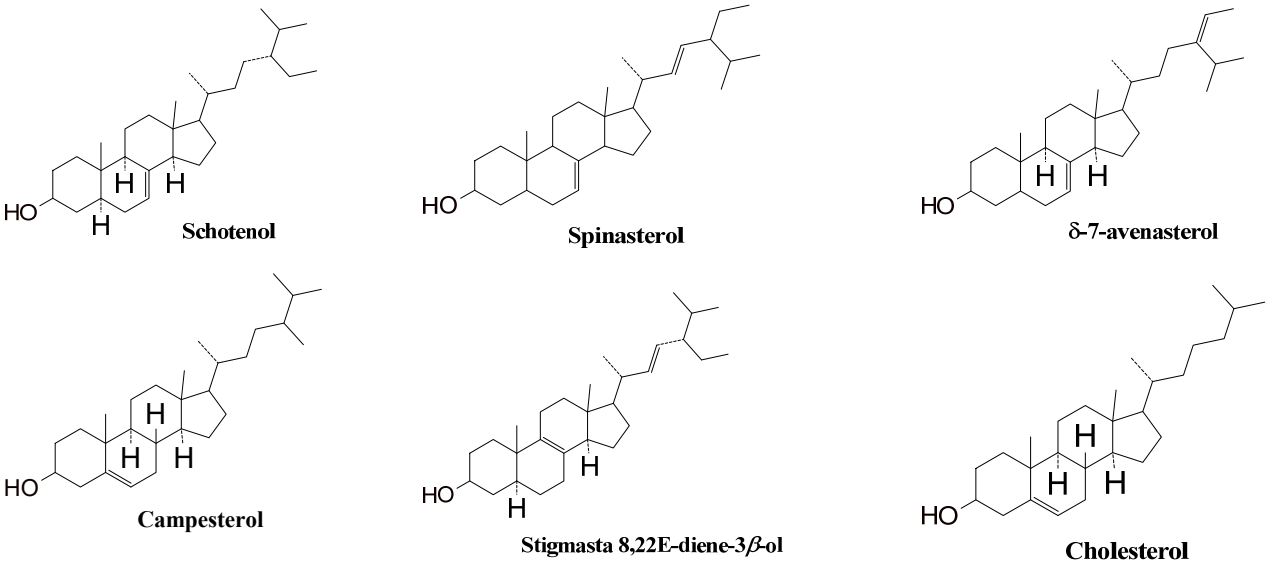


Figure 6. Main sterols present in *A. spinosa* oil. Designed using ACD/ChemSketch (V.2025).

Sterols derived from argan oil exhibit anti-inflammatory properties that support vascular health. Chronic inflammation contributes to the progression of atherosclerosis and leads to endothelial dysfunction and plaque instability. By modulating inflammatory responses and reducing markers such as C-reactive protein (CRP), these compounds help preserve vascular integrity and reduce the risk of plaque rupture [64,65].

Sterols in argan oil also provide antioxidant protection against oxidative stress. Excess free radicals promote the oxidation of LDL particles, which accelerates plaque formation. Through their ability to neutralize reactive species, schottenol and spinasterol limit LDL oxidation and reduce vascular damage. These compounds also influence hepatic enzymes involved in cholesterol metabolism by promoting its conversion into bile acids and facilitating its excretion. Together, these mechanisms support the role of argan oil sterols in cardiovascular protection and disease prevention [4,66,67].

6.5. Proteins and Amino Acids

Proteins and amino acids derived from *A. spinosa* are gaining increasing scientific attention due to their diverse biological properties and promising applications in the cosmetic, food, and pharmaceutical industries. A distinctive feature of argan-derived proteins is their abundance in essential amino acids, which play a vital role in supporting key skin functions such as hydration, elasticity, and collagen production [68].

Studies have shown that protein extracts obtained from argan oil by-products, such as press cakes and leaves, are particularly rich in hydrophilic amino acids including glutamine, proline, and alanine (Figure 7). These compounds are crucial for preserving skin moisture and reducing the appearance of fine lines and wrinkles [69–72]. In addition to their moisturizing effects, these amino acids also aid in tissue repair and inflammation reduction, thereby accelerating wound healing processes [72].

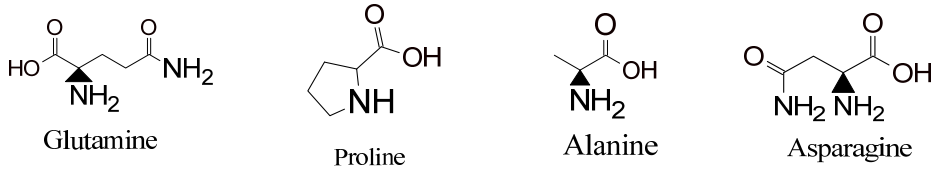


Figure 7. Main amino acids present in *A. spinosa.* Designed using ACD/ChemSketch (V.2025).

Glutamine, for example, plays a pivotal role in cellular regeneration and the repair of damaged tissues. It has been widely employed in topical formulations designed to strengthen the skin's barrier function and promote recovery [73]. Proline, though non-essential, is indispensable for the synthesis of collagen, a structural protein that maintains skin firmness and reduces wrinkle formation [74]. Because of these properties, proline-rich peptides sourced from argan oil are frequently used in cosmetic treatments [74,75].

Alanine and cysteine, also found in argan proteins, contribute to skin flexibility and defense against oxidative damage. Cysteine is particularly effective in protecting skin cells from oxidative stress, which helps delay signs of aging and improve skin radiance [76–79]. Asparagine is another important amino acid present in notable amounts. It enhances skin hydration and regeneration by interacting with components of the natural moisturizing factor (NMF), which plays a key role in maintaining moisture levels [79,80].

The antioxidant capacity of argan proteins and their constituent amino acids has been widely documented. These bioactive molecules are believed to function synergistically in neutralizing free radicals, which are major contributors to skin aging and related disorders. Amino acid-derived antioxidants such as glutathione, synthesized from cysteine and glutamate, provide essential protection against environmental damage [81,82]. In addition, peptides extracted from *A. spinosa* have shown significant anti-inflammatory activity, making them valuable for managing skin conditions such as acne, eczema, and psoriasis [81–83].

Beyond skincare, argan-derived proteins and amino acids have demonstrated potential in both nutritional and medicinal fields. Their balanced amino acid composition and high nutritive value make them suitable for inclusion in functional foods that support overall health. For instance, the amino acids in argan protein isolates contribute to muscle maintenance and recovery, making them beneficial for athletic performance and post-exercise supplementation [81–84]. These compounds have also been linked to improved digestive health due to their role in supporting the integrity of the intestinal mucosa [85–87].

In conclusion, the proteins and amino acids from *A. spinosa* exhibit a wide array of bioactivities, including moisturizing, antioxidant, anti-aging, and anti-inflammatory effects. This versatility supports their use in cosmetics, dermatological treatments, foods, and nutraceuticals. Ongoing research continues to uncover new therapeutic applications, highlighting their potential in the development of innovative, sustainable, and effective health products [88].

6.6. Argan Oil Odor Sensory Profiles

The aroma profile of argan oil, a product deeply rooted in Moroccan tradition and highly valued for its nutritional, cosmetic, and culinary applications, is primarily determined by four major groups of volatile compounds: alcohols (20.94%), pyrazines (27.56%), pyrroles (22.21%), and organic acids (17.48%) (Figure 8). These compounds arise from both enzymatic and thermal reactions that occur throughout the various stages of oil processing, collectively contributing to the rich and characteristic sensory signature of argan oil [89,90].

Alcohols, which make up just over 20% of the total volatile fraction, are mainly produced through lipoxygenase-mediated oxidation of unsaturated fatty acids during the mechanical crushing of kernels. Common alcohols such as 1-hexanol and 1-octen-3-ol impart green, grassy, and mushroom-like aromas that are especially prominent in cold-pressed or minimally processed oils. These notes contribute a sense of freshness and natural vitality and are often regarded as indicators of limited thermal degradation [89,90].

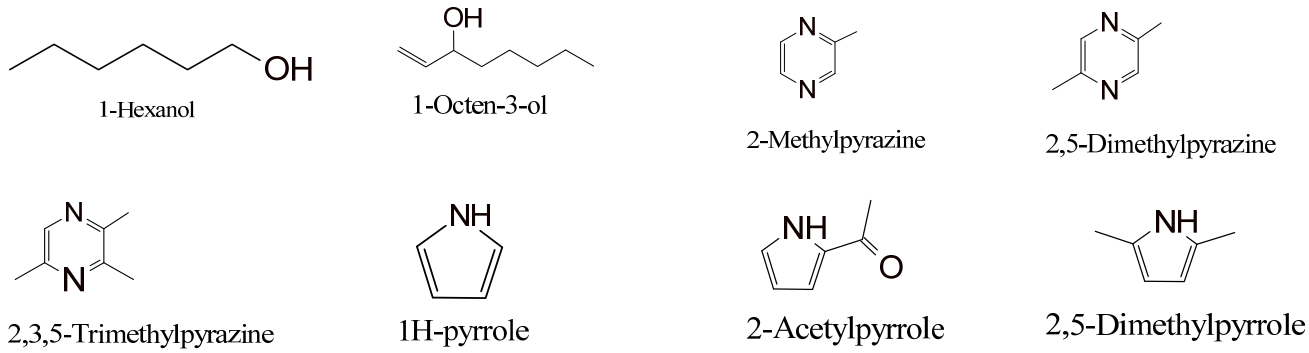


Figure 8. Main sensory odors present in *A. spinosa.* Designed using ACD/ChemSketch (V.2025).

In contrast, pyrazines, the most abundant group at 27.56%, are nitrogen-containing heterocyclic compounds primarily formed during the Maillard reaction, a chemical process that occurs when argan kernels are roasted prior to oil extraction. Widely applied in the preparation of culinary-grade argan oil, this thermal treatment enhances sensory richness by generating a broad array of nutty, toasted, and earthy aromas. Highly odor-active compounds such as 2-methylpyrazine, 2,5-dimethylpyrazine, and 2,3,5-trimethylpyrazine are especially important to the roasted character of the oil and are key contributors to its appeal in gourmet applications [89,90].

Closely related in origin and sensory role are the pyrroles, which account for 22.21% of the volatile profile. These five-membered nitrogen-containing heterocycles are likewise formed during Maillard reactions, especially through the interaction of amino acids such as proline with reducing sugars. Pyrroles are chiefly responsible for sweet, caramelized, and burnt sugar notes, which lend richness and complexity to the oil's flavor profile. Noteworthy examples include 1H-pyrrole, 2-acetylpyrrole, and 2,5-dimethylpyrrole, each contributing slightly different nuances ranging from warm and smoky to subtly amine-like. These compounds soften and round out the roasted character imparted by pyrazines, and their sensory impact extends to both aroma and retro-nasal perception. Their presence and proportions are highly sensitive to processing conditions such as roasting temperature, duration, and kernel moisture content, making them valuable indicators of flavor development and thermal history [89,90].

Organic acids, although less volatile and representing 17.48% of the volatile fraction, play a pivotal role in both aroma and taste. This group includes short-chain acids such as acetic, butyric, and hexanoic acid, which can produce sour, tangy, or even slightly cheesy notes depending on concentration and composition. These acids typically result from lipid hydrolysis or mild fermentation and can either enhance the brightness of the oil's profile or indicate unwanted degradation when present in excess. Additionally, in smaller amounts, they act as precursors to ester formation, leading to the emergence of fruity or sweet-smelling esters that further enrich the aromatic complexity of the oil [89,90].

The distinctive aroma of argan oil, therefore, is not driven by any single volatile compound but emerges from the intricate interplay among these four chemical families. Their individual and combined contributions are profoundly influenced by key processing parameters, including roasting temperature, duration, and extraction method. For example, higher roasting temperatures tend to increase the formation of pyrazines and pyrroles, intensifying roasted and caramelized notes, while diminishing the freshness associated with alcohols. Conversely, cold pressing retains more of the delicate alcohols and preserves enzymatic volatiles, resulting in a fresher but potentially less intense aromatic profile [89,90].

Understanding the relative contributions and sensory roles of alcohols, pyrazines, pyrroles, and organic acids is thus essential for optimizing argan oil production, preserving

product quality, and tailoring flavor profiles to meet a wide range of consumer expectations in both local and international markets [89,90].

6.7. Argan Leaves Essential Oils

In Morocco, the essential oil extracted from *A. spinosa* leaves collected in the Essaouira region along the Atlantic coast is characterized by a chemical profile predominantly composed of oxygenated monoterpenes, with geranyl acetate (19.18%) as the main constituent, followed by methyleugenol (10.98%), linalyl acetate (10.59%), and eucalyptol (8.49%) [91] (Figure 9). In contrast, essential oil samples from the Stidia region on the western coast of northern Algeria exhibit a markedly different composition, characterized by a predominance of sesquiterpenic compounds. In this case, cubenol (31.02%) and 1,10-di-epi-cubenol (22.50%) are the major constituents, along with appreciable amounts of camphor (8.22%), viridiflorol (7.10%), linalool (5.60%), and eucalyptol (5.40%) [92].

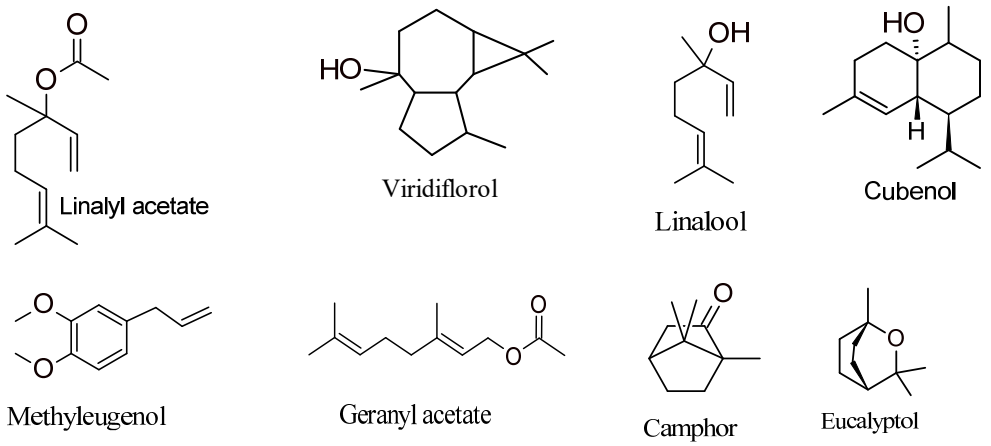


Figure 9. Main compounds present in argan leaves essential oils. Designed using ACD/ChemSketch (V.2025).

These differences in chemical composition clearly highlight the influence of geographical origin, environmental conditions, and potential genetic variability on the biosynthesis of secondary metabolites in *A. spinosa*. Such variability may significantly affect the biological properties and potential applications of the corresponding essential oils [93].

6.8. Squalene and Saponins

Argan oil exhibits a notably high concentration of squalene relative to most vegetable oils, a characteristic it shares with olive oil. In typical vegetable oils, the content of hydrocarbons, primarily squalene, rarely exceeds 0.15% (Figure 10). However, both olive and argan oils present significantly higher levels, with argan oil containing up to 3.2 g/kg [15,94].

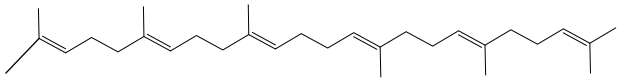


Figure 10. Chemical structure of squalene identified in argan oil. Designed using ACD/ChemSketch (V.2025).

Squalene is a naturally occurring triterpenic hydrocarbon found in argan oil at concentrations ranging from approximately 0.3% to 0.5% (Figure 10). It is extracted from the kernels of *A. spinosa* and contributes substantially to the oil's bioactivity. This compound is recognized for its emollient, antioxidant, and skin-restructuring properties. Due to its structural similarity to human sebum, squalene is highly biocompatible with the skin, enhancing moisture retention and reinforcing the epidermal barrier. However, because of

its unsaturated chemical structure, squalene is prone to oxidative degradation. For this reason, its hydrogenated derivative, squalane, is often used in cosmetic formulations due to its improved oxidative stability. Despite this limitation, the natural presence of squalene in argan oil remains a key factor in its dermatological and therapeutic potential [15,95,96].

The argan tree (*A. spinosa*) is recognized for its remarkable biochemical richness, particularly in triterpenoid saponins that occur throughout its different anatomical parts. Among these, the argan press-cake, obtained as a by-product from the extraction of argan oil from seed kernels, represents one of the most important natural sources of saponins. Detailed phytochemical investigations have led to the identification of seven bisdesmosidic saponins whose aglycones correspond either to protobassic acid (I) or to 16 α-hydroxyprotobassic acid (II) [97–102]. The first structural group includes Mi-saponin A, Arganine F, Arganine D, and Arganine E, which are derived from aglycone (I), while the second group, composed of Arganine C, Arganine A, and Arganine B, is based on aglycone (II) (Figure 11). In terms of composition, the total saponin content in the fresh argan seed kernels reaches around 0.5%, with Arganine A constituting approximately 40% of this fraction. Arganine B is the second most abundant saponin, representing about 8% of the crude saponin extract, while each of the other five identified saponins, Mi-saponin A, Arganine F, Arganine D, Arganine E, and Arganine C, accounts for nearly 4% of the total content [97–102].

Other parts of the argan tree also display significant saponin diversity. The seed shell [97–102]. and fruit pulp [97–102] contain bisdesmosidic saponins associated with both aglycones (I) and (II), such as Mi-saponin A, Mimusopsin, Arganine N, Arganine M, and Arganine K. Notably, Mi-saponin Ais a compound consistently found across the press-cake, seed shell, and fruit pulp, possibly playing a protective role within the plant (Figure 11). In addition, three distinct saponins, Arganine G, Arganine H, and Arganine J, have been isolated from the trunk [97–102], while five others, Arganine R, Arganine Q, Arganine P, Arganine O, and Arganine L, have been characterized in the bark [97–102]. These eight compounds share a common aglycone known as bayogenin (III). Interestingly, the bark exhibits one of the highest saponin levels within the tree, reaching about 5% [97–102]. The overall distribution pattern of these compounds reveals the exceptional chemical complexity of the argan tree and supports its promising potential as a source of bioactive substances for pharmaceutical, cosmetic, and nutraceutical applications [97–102].

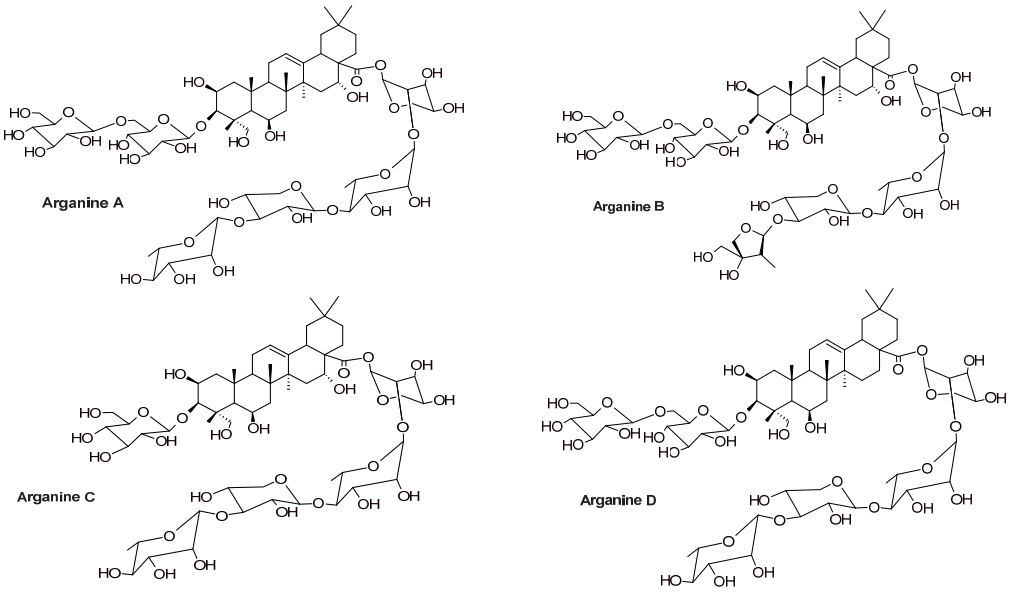


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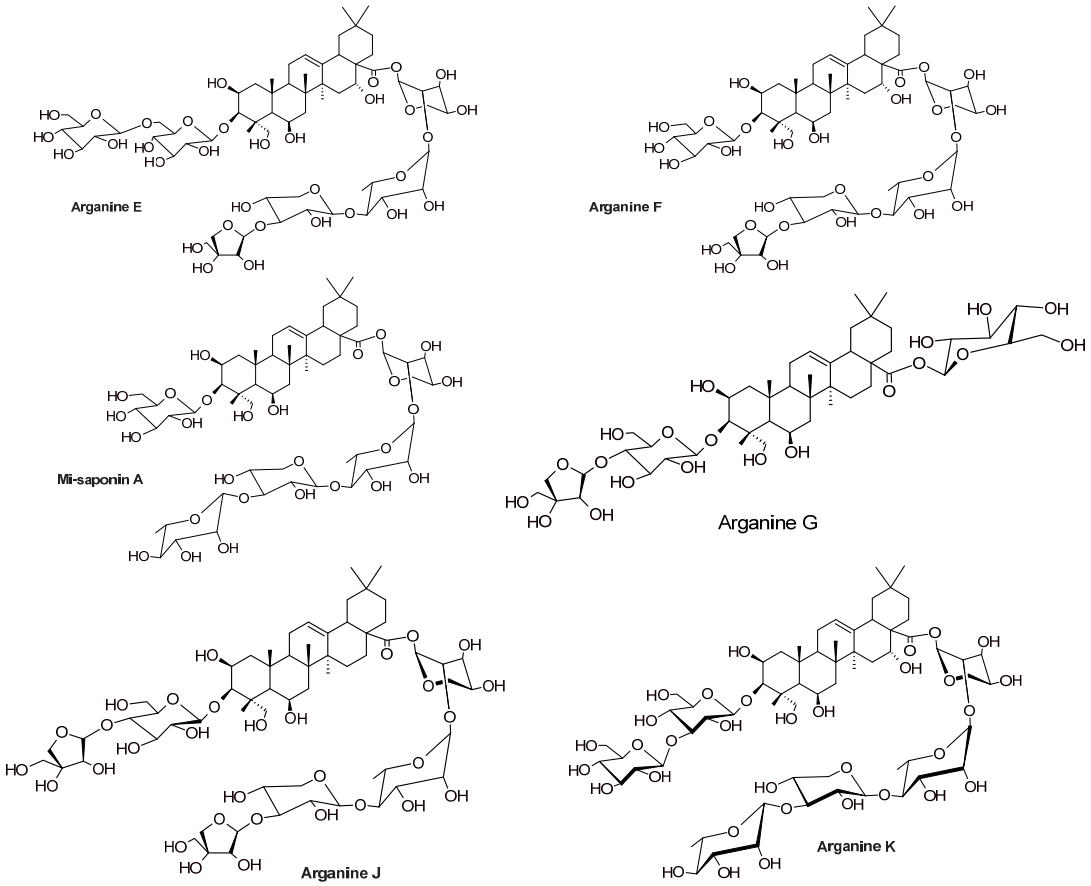


Figure 11. Triterpenoid saponins in different anatomical parts in *A. spinosa*. Designed using ACD/ChemSketch (V.2025).

6.9. Mineral Composition

The mineral composition of *A. spinosa* varies markedly among its different anatomical parts and derived products, reflecting both physiological roles and environmental influences. Leaves appear as the most mineral-rich fraction, with elevated levels of major elements such as potassium, calcium, magnesium, chlorine, sodium, and aluminum, along with substantial amounts of trace elements including manganese, zinc, copper, and rubidium (Table 2). In contrast, elements of toxicological concern (e.g., arsenic, chromium, and antimony) remain at low concentrations. Kernels also show a relatively high mineral content, particularly in potassium, calcium, and magnesium, and are a notable source of nutritionally important trace elements, while maintaining low levels of potentially hazardous elements. Conversely, shells exhibit lower overall mineral concentrations, consistent with their structural function rather than metabolic activity [103].

A distinct profile is observed in argan oils, where mineral content is considerably reduced and influenced by both oil type and extraction method. Edible oils contain small amounts of major minerals, mainly calcium, potassium, and magnesium, along with trace levels of iron, copper, and manganese. Cosmetic oils show slightly greater variability, particularly for potassium and calcium. Furthermore, oils obtained through traditional extraction tend to contain higher concentrations of certain elements, such as chromium, copper, and manganese, compared to mechanically extracted oils, likely due to differences in processing conditions (Table 2). Overall, these results highlight that mineral distribution in *A. spinosa* is strongly part-dependent, and emphasize the importance of both raw material selection and extraction techniques in determining the nutritional quality and safety of argan-derived products [57,104].

Table 2. Mineral composition of *A. spinosa* parts and derived oils.

Part/ Product	Macrominerals	Trace Elements	Potentially Hazardous Elements	Reference
Leaves	K: 26,010 ± 2080 mg/kg	Mn: 69.13 ± 5.53 mg/kg	As: 0.30 ± 0.02 mg/kg	[103]
	Ca: 23,590 ± 1887 mg/kg	Zn: 32.61 ± 2.61 mg/kg	Cr: 1.34 ± 0.11 mg/kg	
	Mg: 4843 ± 387 mg/kg	Cu: 12.52 ± 1.00 mg/kg	Sb: 0.27 ± 0.02 mg/kg	
	Cl: 9890 ± 791 mg/kg	Rb: 17.55 ± 1.40 mg/kg	La: 0.49 ± 0.04 mg/kg	
	Na: 3916 ± 313 mg/kg	–	Sc: 0.01 ± 0.01 mg/kg	
	Al: 482 ± 38 mg/kg	–	Sm: 0.12 ± 0.01 mg/kg	
Kernels	K: 7750 ± 620 mg/kg	Mn: 106 ± 8.5 mg/kg	As: 0.13 ± 0.01 mg/kg	[103]
	Ca: 6120 ± 489 mg/kg	Zn: 45.00 ± 3.60 mg/kg	Cr: 0.50 ± 0.04 mg/kg	
	Mg: 4580 ± 366 mg/kg	Cu: 18.80 ± 1.50 mg/kg	Sb: 0.12 ± 0.01 mg/kg	
	Cl: 2940 ± 235 mg/kg	Rb: 10.70 ± 0.04 mg/kg	–	
	Na: 212 ± 17 mg/kg	–	–	
Shells	K: 3267 ± 261 mg/kg	Mn: 25.80 ± 2.06 mg/kg	As: 0.21 ± 0.02 mg/kg	[103]
	Ca: 1729 ± 138 mg/kg	Zn: 8.02 ± 0.64 mg/kg	Cr: 0.76 ± 0.06 mg/kg	
	Mg: 3500 ± 280 mg/kg	Cu: 10.29 ± 0.82 mg/kg	Sb: 0.16 ± 0.01 mg/kg	
	Cl: 1427 ± 114 mg/kg	Rb: 11.24 ± 0.90 mg/kg	La: 0.26 ± 0.02 mg/kg	
	Na: 186 ± 15 mg/kg	–	Sc: 0.05 ± 0.01 mg/kg	
	Al: 326 ± 26 mg/kg	–	Sm: 0.77 ± 0.06 mg/kg	
Edible Oils	Ca: 6.7–8.45 mg/L	Fe: 0.35–0.64 mg/L	–	[104,105]
	K: 0.91–1.78 mg/L	Cu: 0.01–0.03 mg/L	–	
	Mg: 1.92–2.63 mg/L	Mn: 0.01–0.02 mg/L	–	
Cosmetic Oils	Ca: 6.72–10.58 mg/Lu	–	Cr (Tradi*): 10.8–55.3 µg/kg	[104,105]
	K: 0.62–3.56 mg/L	–	Cu (Tradi*): 160.4–695.7 µg/kg	
	Mg: 1.74–3.17 mg/L	–	Mn (Tradi*): 18.1–70.8 µg/kg	
	–	–	Cr (Mech*): 10.0–48.1 µg/kg	
	–	–	Cu (Mech*): 158.4–385.0 µg/kg	
	–	–	Mn (Mech*): 15.5–68.5 µg/kg	

7. Health Benefits and Functional Properties of *A. spinosa* Extracts

In recent years, the argan tree (*A. spinosa*) has gained significant attention from both scientific and industrial communities, owing to its remarkable abundance of nutraceuticals and bioactive compounds with well-documented health benefits. Among its various constituents, argan oil stands out as particularly rich in polyphenols, vitamins, essential fatty acids, natural pigments, phytosterols, and amino acids. Collectively, these compounds contribute to a wide array of biological activities, including antioxidant, anti-inflammatory, anti-cancer, and cardioprotective effects, as well as benefits for cognitive, metabolic, and immune health (Figure 12). For instance, unsaturated fatty acids and phytosterols are known to support cholesterol reduction and cardiovascular protection, natural pigments enhance vision and detoxification pathways, and amino acids are essential for hormone regulation, neurotransmitter synthesis, and tissue repair. The multifunctional nature of these bioactive compounds not only underscores the nutritional and therapeutic potential of

argan but also emphasizes its value for the formulation of functional foods, nutraceuticals, pharmaceuticals, and cosmetic products [28,106,107].

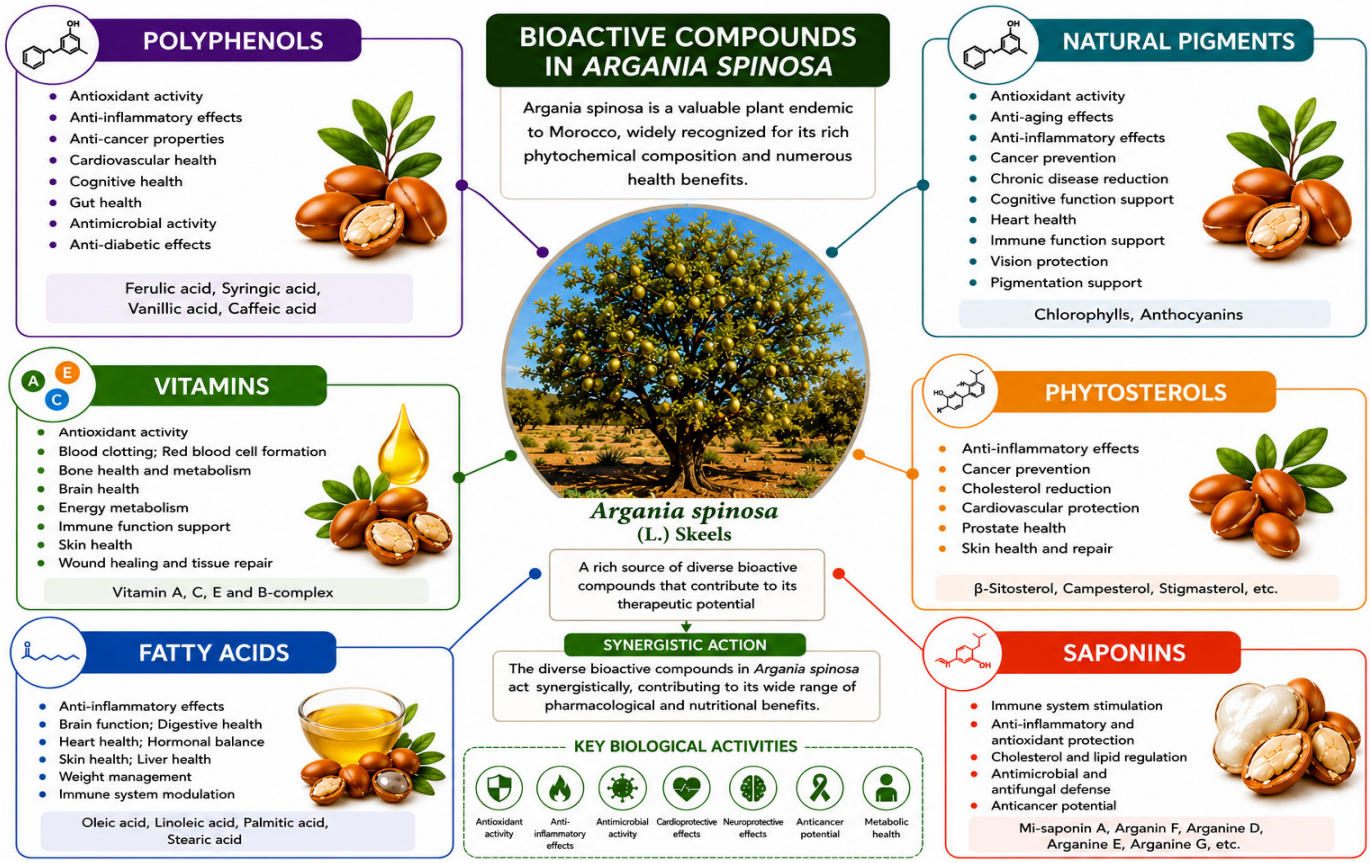


Figure 12. Functional properties of major bioactive compounds in argan extracts and their roles in human health [14,17,40–42,57,61,62,98,101,102]. Designed using Inkscape software (v.1.4.2).

The bioactive components of argan extracts, including polyphenols, fatty acids, vitamins, pigments, saponins, and phytosterols, often act synergistically to promote human health and prevent chronic diseases. Polyphenols, recognized as potent antioxidants, protect cellular structures against oxidative damage, mitigate inflammatory processes, and improve cardiovascular function by enhancing endothelial health and reducing LDL oxidation. They further contribute to antimicrobial defense, cognitive performance, and blood glucose regulation, thereby supporting both metabolic and immune balance. Fatty acids, particularly oleic and linoleic acids predominant in argan oil, play a critical role in maintaining cardiovascular and brain health, regulating hormonal and liver function, and preserving skin elasticity and hydration. Additionally, their anti-inflammatory and digestive benefits help prevent and manage metabolic and inflammatory disorders [14,28,106,107].

Vitamins, most notably vitamin E (tocopherols), provide strong antioxidant protection, bolster immune function, aid tissue repair, and support skin health and red blood cell formation. Natural pigments such as carotenoids enhance functional properties through anti-aging, vision-supportive, and detoxifying effects, and are associated with reduced risks of cancer and chronic diseases. Saponins contribute to immune system stimulation, cholesterol and lipid metabolism regulation, and exhibit both antimicrobial and anticancer activities. Phytosterols further complement these effects by lowering blood cholesterol, protecting cardiovascular health, mitigating inflammation, and promoting skin repair and regeneration. Altogether, the diverse bioactive profile of argan extracts establishes them as a rich source of natural compounds with extensive therapeutic potential,

rendering them highly suitable for applications in functional foods, nutraceuticals, and cosmetics [14,28,106,107].

8. Biochemical Richness and Functional Potential of *Argania spinosa*

The biochemical composition of *A. spinosa* shows remarkable variability depending on geographic origin, plant organ, and extraction method (Table 3). Oils derived from Moroccan seeds, particularly those from Essaouira, Agadir, and Taroudant, are characterized by a predominance of unsaturated fatty acids, with oleic acid (C18:1) ranging between 41 and 52%, linoleic acid (C18:2) between 24 and 36%, and palmitic acid (C16:0) between 11 and 16% [108–110]. This balance confers an optimal nutritional profile and oxidative stability, positioning argan oil between olive and sunflower oils in terms of quality. Total polyphenol contents vary considerably, from 0.07 to 115 mg gallic acid equivalents (GAE)/g in seed oils [62,109] to over 198 mg GAE/g dry weight (DW) in leaf extracts [111], illustrating the strong influence of extraction solvent and plant matrix. Tocopherols are also abundant, ranging from 130 to 357 mg/100 g, together with natural pigments such as carotenoids and chlorophylls (43–246 mg oil absorbance equivalents (OAE)/g), which collectively enhance the antioxidant and nutritional value of the oil [15,109].

Comparative data from Algeria and Tunisia indicate similar qualitative profiles but distinct regional adaptations. Tunisian argan oils exhibit higher oleic acid (52.5%) and lower linoleic acid (24.2%) contents [112], while Algerian oils are slightly richer in palmitic acid (12.6–14.9%) and polyphenols (12–58 mg GAE/g) [113–115]. The presence of phytosterols (145–295 mg/100 g) and moderate saponin levels (0.07–0.24 mg/g) further supports the oil's hypocholesterolemic and anti-inflammatory potential (Table 3) [115,116]. Overall, *A. spinosa* demonstrates a consistent biochemical richness across its distribution range, combining a favorable lipid profile with high antioxidant potential. These characteristics justify its traditional uses in nutrition, dermatology, and cardiovascular protection, and highlight its growing recognition as a functional food and source of bioactive compounds [28,117].

Table 3. Geographical variability in bioactive compounds of argan oil and derived extracts.

Geographic Origin	Parts of Plant	Extract	Polyphenols	Fatty Acids (%)			Total Tocopherol (mg/100 g)	Saponins	Natural Pigments (mg/100 g)	Phytosterols (mg/100 g)	Reference
				Oleic A. (C18:1)	Linoleic A. (C18:2)	Palmitic A. (C16:0)					
Morocco (Essaouira)	Seeds	Argan oil	21.54–22.29 mg GAE/g oil extract	46.50–45.30	34.07–32.94	13.06–12.19	63.09–71.14	43.31–246.28 mg OAE/g	0.068–0.13	166.35–178.64	[109]
	Seeds	Argan oil	3.26 mg/kg oil	44.8	35.7	13.4	63.7	-	-	295	[62]
	Seeds	Argan oil	-	45.05–48.32	31.73–33.74	12.06–12.75	63.39–77.55	-	-	130.0–206.3	
	Seeds	Argan oil	32.63 g/kg	41.2–45.00	36.4	15.6–16.4	62.90–66.00	-	-	272–357	[15,108,109]
Morocco (Oujda)	Seeds	Argan oil	-	48.32	31.73	12.06	77.55	-	-	206.3	[108]
Morocco (Taroudant)	Seeds	Argan oil	-	47.64	31.73	12.75	63.39	-	-	130.0	[108]
	Seeds	Argan oil	112.67–115.30 mg GAE/kg	43.10–49.00	29.30–36.00	11.50–15.00	60–90	-	-	207.80–220.00	[70]
	Seeds	Argan oil	-	43.87–47.88	30.22–35.19	11.80–14.64	-	-	-	-	[110]
Morocco (Ait Baha)	Pulp	Acetone/water/ formic acid extract	59.5 mg/100 g	-	-	-	-	-	-	-	[5]
	Shell	Acetone/water/ formic acid extract	1.75 mg/100 g	-	-	-	-	-	-	-	[5]
Morocco (Agadir)	Seeds	Argan oil	21.64–23.44 mg GAE/g oil extract	44.80–49.06	30.24–30.24	12.08–14.90	65.91–74.90	-	0.14–0.18	163.03–175.54	[109]
	Seeds	Argan oil	2.30 mg equivalents quercetin/g of oil	45.02	33.71	12.11	45.30	-	-	23.30	[45]
	Leaf	Methanolic extract	20.60–31.97 mg/g DW GAE	30.3	29.7	12.4	-	-	-	-	[111]
	Leaf	Ethanolic extracts	15.93–37.34 mg/g DW GAE	26	36.8	15.3	-	-	-	-	[111]
	Leaf	Hexane extracts	123.70–198.26 mg/g DW GAE	37.9	36.5	12.5	-	-	-	-	[111]
	Seeds	Argan oil	0.07 mg equivalents quercetin/g of oil	44.3	33.2	11.9	45.3	-	-	188.3	[118]

Table 3. *Cont.*

Geographic Origin	Parts of Plant	Extract	Polyphenols	Fatty Acids (%)			Total Tocopherol (mg/100 g)	Saponins	Natural Pigments (mg/100 g)	Phytosterols (mg/100 g)	Reference
				Oleic A. (C18:1)	Linoleic A. (C18:2)	Palmitic A. (C16:0)					
Morocco (Berkane)	Seeds	Argan oil	0.60–0.70 equivalents quercetin/g of oil	45.27 -45.75	31.99–33.38	12.22–13.05	38.4–45.80	-	-	188.1–215.00	[45]
	Seeds	Argan oil	-	45.90	34.10	11.80	75.22	-	-	162.40	[116]
	Seeds	Argan oil	0.54 mg equivalents quercetin/g of oil	46.4	32.4	13.2	38.5	-	-	145.36	[118]
	Pulp	Methanol extract	16.84–20 mg/g FW	-	-	-	-	-	-	-	[119]
Tunisia	Seeds	Argan oil	5.5 mg GAE/g oil extract	52.53	24.24	16.13	-	-	0.189	-	[112]
Algeria	Pulp	Methanolic extract	3.43 mg GAE/g extract	-	-	-	-	-	-	-	[28]
	Almond	Methanolic extract	1.34 mg GAE/g extract	-	-	-	-	-	-	-	[28]
	Seeds	Argan oil	30–180 mg EAG/Kg oil)	46.81–48.63	29.94–31.18	12.59–14.91	64.54–71.2	-	0.132–0.246	-	[115]
	Seeds	Argan oil	58.57 mg GAE/g of oil	44.00	35.69	14.17	-	-	-	-	[113]
	Seeds	Argan oil	12.67–17.34 mg GAE/g of oil	47.51–48.13	29.93–30.63	13.07–14.37	62.83–75.14	-	-	139.68–211.42	[114]

9. Pharmacological Properties of *A. spinosa* Extracts

9.1. Antioxidant Properties

Recent studies have highlighted significant differences in the antioxidant potential of *A. spinosa* extracts depending on the extraction solvent and process. Methanolic and n-butanol fractions exhibited the highest radical-scavenging activities, with EC_{50} values of 9.73 and 5.35 µg/mL in the DPPH assay, and 0.338 and 0.271 µg/mL in the ABTS assay, respectively [120]. Their ferric-reducing capacities (30.74–48.03 mM $FeSO_4$/g extract) further confirm the strong presence of phenolic compounds such as flavonoids, tannins, and phenolic acids (Table 4).

In comparison, argan oils display lower antioxidant activity, which varies with the extraction process. Artisanal oils demonstrated better performance (DPPH IC_{50} = 12.2 mg/mL; FRAP IC_{50} = 1.5 mg/mL) than commercial oils (DPPH IC_{50} = 48.88 mg/mL; FRAP IC_{50} = 15.6 mg/mL) [121] (Table 4). Similar trends were observed in roasted and unroasted oils, where roasting slightly improved reducing power [115].

Ethanolic extracts also exhibited remarkable antioxidant properties, with IC_{50} values of 0.38 mg/mL (DPPH), 8.23 mM Trolox equivalents/mL (ABTS), and 0.16 mg/mL (reducing power) [122]. Collectively, these results demonstrate that the antioxidant activity of *A. spinosa* products is strongly dependent on solvent polarity and extraction technique, with polar extracts showing the highest efficiency, followed by artisanal oils and, finally, commercial oils (Table 4).

9.2. Anticancer Properties

The anticancer potential of argan pulp and related extracts has attracted growing attention because of their complex composition of polyphenols, sterols, and triterpenoids, which are well known for their antiproliferative effects. El Babili et al. [84] first demonstrated that cold ethyl acetate extracts of argan pulp obtained through 24 h maceration exhibited significant cytotoxicity against MCF7 human breast cancer cells, with an IC_{50} value of 42 µg/mL. In contrast, petroleum ether extracts and aqueous decoctions showed weaker activity (IC_{50} values above 100 µg/mL), whereas the reference drug doxorubicin was considerably more potent (IC_{50} = 0.218 µg/mL). The observed cytotoxic effects were attributed to the enrichment of medium-polarity compounds such as phenolic acids, sterols, and saponins, which can interfere with cancer cell proliferation and oxidative signaling pathways (Table 4).

Complementary studies on argan oil fractions have confirmed these findings. Methanolic extracts exhibited cytotoxic effects on PC3 human prostate cancer cells at concentrations ranging from 600 to 1000 µg/mL [123]. Furthermore, sterols and polyphenols isolated from argan oil showed selective antiproliferative activity against DU145, LNCaP, and PC3 prostate cancer cell lines, with IC_{50} values varying between 25.07 and 75.03 mg/mL for sterols and between 50.14 and 99.98 mg/mL for polyphenols [124]. Although these concentrations are higher than those required for conventional chemotherapeutic drugs, they still demonstrate a meaningful chemopreventive potential. This potential likely results from several mechanisms, including the reduction in oxidative stress, the induction of programmed cell death, and the inhibition of androgen receptor signaling pathways [124].

Overall, the accumulated evidence indicates that argan pulp and oil extracts contain bioactive constituents capable of producing antioxidant, antidiabetic, and anticancer effects. These pharmacological activities emphasize the promising opportunity to valorize argan by-products as functional ingredients for nutraceutical, pharmaceutical, and therapeutic applications [123,124].

9.3. Antibacterial Properties

Argan derivatives have demonstrated broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria, mainly attributed to their content of phenolic compounds, saponins, and fatty acids. According to Lall et al. [125], both argan oil and crude saponin extracts displayed strong inhibitory activity against *Cutibacterium acnes*, with a minimum inhibitory concentration (MIC) of 500 µg/mL, while showing no effect against Prevotella intermedia at concentrations up to 12,500 µg/mL. This selective inhibition suggests that certain lipid-soluble components and saponins play a major role in the antimicrobial effect (Table 4).

Alaoui et al. [120] further evaluated methanolic extracts and n-butanol fractions of argan pulp against *Pseudomonas aeruginosa*, *Escherichia coli*, *Staphylococcus aureus*, *Salmonella typhi*, and *Enterococcus faecalis*. The methanolic extract exhibited MIC values ranging from 12.5 to 50 mg/mL, with *P. aeruginosa* being the most sensitive strain (MIC = 12.5 mg/mL). The n-butanol fraction showed comparable or slightly improved activity (MIC = 12.5–25 mg/mL), confirming that the antibacterial potential is concentrated in the semi-polar constituents of the extract (Table 4).

Similarly, Bonvicini et al. [126] reported that lipophilic and aqueous extracts of argan leaves and pulp displayed activity against a panel of reference bacterial strains, including *S. aureus*, *S. epidermidis*, *E. faecalis*, *E. coli*, *K. pneumoniae*, and *P. aeruginosa*, with MIC_{50} values between 250 and 2000 µg/mL. The aqueous extract showed slightly higher efficacy, indicating that both hydrophilic and lipophilic bioactives contribute to the antibacterial action (Table 4).

Recent findings by Almuhayawi et al. [127] also confirmed the antibacterial activity of argan essential oil, which inhibited *P. aeruginosa* and *S. aureus* with MIC values of 0.3 and 0.5 mg/mL, respectively, and corresponding minimum bactericidal concentrations (MBC) of 0.4 and 0.7 mg/mL. These results demonstrate the potential of argan essential oil as a natural antimicrobial agent with possible applications in cosmetics, pharmaceuticals, and food preservation (Table 4).

Overall, the antibacterial activity of argan oil, pulp, and derived fractions can be attributed to the synergistic presence of polyphenols, triterpenoid saponins, sterols, and unsaturated fatty acids, which may disrupt bacterial membranes and interfere with vital cellular functions [17,120]. This confirms the significant potential of argan by-products as alternative natural sources of antimicrobial compounds for biotechnological and industrial use.

9.4. Antifungal Activities of Argan Extracts

The antifungal properties of *A. spinosa* extracts have recently gained scientific attention due to their potential application in natural crop protection and in the development of alternative antifungal therapies. Both polar and non-polar extracts of argan fruit and by-products have demonstrated varying degrees of antifungal activity against a broad spectrum of pathogenic fungi, suggesting that the bioactive compounds in these extracts may interfere with fungal growth, membrane integrity, or spore germination.

In the study by El Idrissi et al. [109], ethanolic extracts of argan were evaluated using the disc diffusion method against *Fusarium oxysporum*, a major soil-borne phytopathogen responsible for vascular wilt in several crops. The extract showed a measurable inhibition zone of 1.92 $\pm$ 0.02 mm, indicating a moderate yet significant antifungal effect. This inhibition was attributed to the presence of polyphenolic and triterpenoid compounds capable of disrupting fungal cell wall biosynthesis and oxidative balance (Table 4).

Complementary results were reported by Lfitat et al. [128], who examined both aqueous and ethyl acetate extracts of *A. spinosa* against a series of fungal strains, including *Aspergillus fumigatus*, *Penicillium brasilianum*, *Fusarium dimerum*, and *Aspergillus niger*.

The aqueous extract exhibited minimum inhibitory concentration (MIC) values ranging from 0.133 to 0.223 g/mL, while the ethyl acetate extract showed similar MIC values between 0.133 and 0.146 g/mL, depending on the tested strain. Among these fungi, *Fusarium dimerum* and *Penicillium brasilianum* were the most susceptible, with MIC values of 0.133 g/mL and 0.136 g/mL, respectively [128] (Table 4).

These findings suggest that both polar and semi-polar extracts possess bioactive molecules capable of inhibiting fungal growth, likely through synergistic actions of phenolic acids, flavonoids, and saponins, which may cause membrane destabilization or interfere with fungal enzymatic systems. The comparable efficacy of aqueous and ethyl acetate extracts indicates that antifungal activity is not limited to a specific polarity range, but rather distributed among diverse chemical classes [97,129].

Overall, the antifungal activity of *A. spinosa* extracts highlights their potential use as eco-friendly antifungal agents for both agricultural and pharmaceutical applications. However, the relatively high MIC values suggest that further fractionation and purification of active compounds could enhance efficacy [79,97,129]. Future work focusing on mechanism elucidation, such as membrane leakage assays or ergosterol quantification, could clarify the specific modes of antifungal action of argan-derived compounds.

9.5. Antidiabetic Activities of Argan Extracts

The hypoglycemic and antidiabetic effects of *A. spinosa* have been extensively investigated using various extracts and enzymatic inhibition assays. Several studies have demonstrated that both polar and non-polar extracts of argan exhibit significant inhibitory potential toward carbohydrate-hydrolyzing enzymes, notably α-amylase and α-glucosidase, which are key targets in postprandial glucose control.

According to Alaoui et al. [120], methanolic extracts of argan displayed remarkable α-amylase and α-glucosidase inhibition, with EC_{50} values of 0.68 mg/mL and 0.15 mg/mL, respectively. The n-butanol fraction from the same study revealed even stronger inhibitory activity, recording EC_{50} values of 0.49 mg/mL for α-amylase and 0.23 mg/mL for α-glucosidase. These results suggest that semi-polar constituents, including flavonoids and saponins, may play a central role in modulating enzymatic inhibition and glycemic regulation (Table 4).

Earlier research by El Adib et al. [130] confirmed these findings, showing that ethanolic extracts of argan leaves and oil significantly inhibited α-amylase activity, with inhibition rates ranging between 22.8 and 46.00 mg AE/g DW, while the oil exhibited lower but notable inhibition (3.4–5.7 mg AE/g DW). The methanolic fraction also showed inhibitory capacities in the range of 4.5–8.4 mg AE/g DW, highlighting the influence of extraction solvent on the bioactivity profile (Table 4).

In a later investigation, Daoudi et al. [131] demonstrated the inhibitory potential of argan oil itself, with IC_{50} values ranging from 0.78 to 2.17 mg/mL for α-amylase and from 0.081 to 0.117 mg/mL for α-glucosidase. Similarly, Khammassi et al. [132] reported that argan oil inhibited α-amylase and α-glucosidase activities with IC_{50} values of 310.21 µg/mL and 1310.97 µg/mL, respectively, confirming its potential as a natural dietary adjunct for glycemic management (Table 4).

More recently, Haouame et al. [133] further strengthened these findings by showing that the methanolic extract of argan exhibited IC_{50} values of 868.16 µg/mL against α-amylase and 51.67 µg/mL against α-glucosidase, emphasizing the high potency of polar phenolic fractions. The strong inhibitory action observed across studies is generally attributed to polyphenolic compounds, flavonoids, and saponins, which act synergistically to delay carbohydrate digestion and glucose absorption (Table 4).

Taken together, these results establish that argan oil and its extracts possess substantial antidiabetic potential, acting mainly through inhibition of digestive enzymes involved in carbohydrate metabolism. The methanolic and n-butanol fractions, rich in secondary metabolites, exhibit the most pronounced activity, suggesting a promising application of argan-derived compounds as functional ingredients for the dietary management of diabetes mellitus.

9.6. Anticholinesterase Activities of Argan Extracts

Recent pharmacological investigations have demonstrated that *A. spinosa* extracts and oils also exhibit promising neuroprotective potential through their inhibitory effects on cholinesterase enzymes, which play a critical role in the pathogenesis of neurodegenerative disorders such as Alzheimer's disease. The inhibition of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) enzymes helps maintain higher levels of acetylcholine in synaptic clefts, thereby enhancing cholinergic neurotransmission and cognitive performance.

In the study by Haouame et al. [133], methanolic extracts of argan were tested against both AChE and BChE using in vitro enzymatic assays. The methanolic extract exhibited significant inhibitory activity, with IC_{50} values of 74.90 µg/mL and 15.96 µg/mL for AChE and BChE, respectively. These findings suggest that the polar constituents of the extract, particularly phenolic acids, flavonoids, and possibly triterpenoid saponins, may contribute to this dual inhibitory effect. Such activity supports the potential use of argan-derived compounds in the development of natural cholinesterase inhibitors (Table 4).

Furthermore, Khammassi et al. [132] investigated the anticholinesterase effects of argan oil and confirmed its inhibitory potential. The oil exhibited IC_{50} values of 12.97 µg/mL against AChE and 26.36 µg/mL against BChE, indicating that even non-polar lipidic fractions contain bioactive molecules capable of modulating cholinesterase activity. This activity is likely attributed to minor lipid components such as tocopherols, sterols, and unsaturated fatty acids, which may act synergistically with trace polyphenols to influence enzyme conformation and activity (Table 4).

Overall, these results highlight the potential neuroprotective role of argan-based extracts and oils, suggesting that they could serve as valuable natural sources of cholinesterase inhibitors. The strong inhibition of BChE observed particularly in methanolic extracts points to possible therapeutic implications for conditions involving both central and peripheral cholinergic dysfunctions. Future research focusing on the isolation and structural characterization of the active compounds could provide deeper insight into the molecular mechanisms underlying these anticholinesterase effects.

Table 4. Pharmacological properties of *A. spinosa* oil and extracts.

Pharmacological Assay	Plant Part Used	Extracts	Methods	Results	Reference
Antioxidant		Artisanal Argan oil	DPPH●	IC_{50} = 12.2 mg/mL	[121]
	Kernel	Commercial Argan oil	DPPH●	IC_{50} = 48.88 mg/mL	
		Artisanal Argan oil	FRAP	IC_{50} = 1.5 mg/mL	
	Kernel	Commercial Argan oil	FRAP	IC_{50} = 15.6 mg/mL	
	Kernel	Traditional extraction method/Methanolic extract	ABTS	2.31–14.1 mmol Trolox/kg	[57]

Table 4. *Cont.*

Pharmacological Assay	Plant Part Used	Extracts	Methods	Results	Reference
Antioxidant	Kernel	Traditional extraction method/n-Hexane	ABTS	16.1–28.0 mmol Trolox/kg	[57]
	Kernel	Traditional extraction method/Methanolic extract	DPPH●	0.22–0.87 mmol Trolox/kg	
	Kernel	Traditional extraction method/Methanolic extract	FRAP	0.62–1.84 mmol Trolox/kg	
	Kernel	Semi-industrial oil extraction method/Methanolic extract	ABTS	3.08–8.23 mmol Trolox/kg	
	Kernel	Semi-industrial oil extraction method/n-Hexane	ABTS	14.2–27.5 mmol Trolox/kg	
	Kernel	Semi-industrial oil extraction method/Methanolic extract	DPPH●	0.19–0.58 mmol Trolox/kg	
	Kernel	Semi-industrial oil extraction method/Methanolic extract	FRAP	0.74–2.32 mmol Trolox/kg	
	Kernel	Roasted extracted argan oils	DPPH●	IC_{50} = 22.02 mg/mL	[115]
	Kernel	Roasted extracted argan oils	FRAP	IC_{50} = 7.62 mg/mL	
	Kernel	Roasted extracted argan oils	beta-carotene	IC_{50} = 15.25 mg/mL	
	Kernel	Unroasted extracted argan oils	DPPH●	IC_{50} = 21.57 mg/mL	
	Kernel	Unroasted extracted argan oils	FRAP	IC_{50} = 12.2 mg/mL	
	Kernel	Unroasted extracted argan oils	beta-carotene	IC_{50} = 28.06 mg/mL	
	Pulp	Methanolic extract	DPPH	EC_{50} = 9.73 µg/mL	[120]
	Pulp	Methanolic extract	ABTS	EC_{50} = 0.338 µg/mL	
	Pulp	Methanolic extract	FRAP	EC_{50} = 30.74 mM of $FeSO_4$/g Extract	
	Pulp	n-Butanol fraction	DPPH	EC_{50} = 5.35 µg/mL	
	Pulp	n-Butanol fraction	ABTS	EC_{50} = 0.271 µg/mL	
	Pulp	n-Butanol fraction	FRAP	EC_{50} = 48.03 mM of $FeSO_4$/g Extract	

Table 4. *Cont.*

Pharmacological Assay	Plant Part Used	Extracts	Methods	Results	Reference
Antioxidant	Shell	Ethanol extract	DPPH (mg/mL)	IC_{50} = 0.38 mg/mL	[122]
	Shell	Ethanol extract	ABTS	IC_{50} = 8.23 mM trolox equivalent/mL)	
	Shell	Ethanol extract	Reducing power (mg/mL)	IC_{50} = 0.16 mg/mL	
	Shell	Ethanol extract	β-Carotene	IC_{50} = 0.79 mg/mL	
Antibacterial	Kernel	Argan oil	Microdilution broth	*Cutibacterium acnes*: MIC = 500 µg/mL)	[125]
	Kernel	Argan oil	Microdilution broth	*Prevotella intermedia*: MIC > 12,500 µg/mL	
	Kernel	Crude saponin extract	Microdilution broth	*Cutibacterium acnes*: MIC = 500 µg/mL)	
	Kernel	Crude saponin extract	Microdilution broth	*Prevotella intermedia*: MIC > 12,500 µg/mL	
	Pulp	Methanolic extract	*P. aeruginosa*	MIC = 12.5 mg/mL	[120]
	Pulp	Methanolic extract	*E. coli*	MIC = 50 mg/mL	
	Pulp	Methanolic extract	*S. aureus*	MIC = 50 mg/mL	
	Pulp	Methanolic extract	*S. typhi*	MIC = 50 mg/mL	
	Pulp	Methanolic extract	*E. faecalis*	MIC = 50 mg/mL	
	Pulp	n-Butanol fraction	*P. aeruginosa*	MIC = 12.5 mg/mL	
	Pulp	n-Butanol fraction	*E. coli*	MIC = 25 mg/mL	
	Pulp	n-Butanol fraction	*S. aureus*	MIC = 25 mg/mL	
	Pulp	n-Butanol fraction	*S. typhi*	MIC = 50 mg/mL	
	Pulp	n-Butanol fraction	*E. faecalis*	MIC = 25 mg/mL	
	Leaves	Lipophilic extract	*S. aureus ATCC 25923*	MIC_{50} = 250 µg/mL	[126]
	Leaves	Lipophilic extract	*S. epidermidis ATCC 12228*	MIC_{50} = 2000 µg/mL	
	Leaves	Lipophilic extract	*E. faecalis ATCC 29212*	MIC_{50} = 1000 µg/mL	
	Leaves	Lipophilic extract	*E. coli ATCC 25922*	MIC_{50} = >2000 µg/mL	
	Leaves	Lipophilic extract	*K. pneumoniae ATCC 9591*	MIC_{50} = 2000 µg/mL	
	Leaves	Lipophilic extract	*P. aeruginosa ATCC 27853*	MIC_{50} = 1000 µg/mL	
	Leaves	Aqueous extract	*S. aureus ATCC 25923*	MIC_{50} = 250 µg/mL	
	Leaves	Aqueous extract	*S. epidermidis ATCC 12228*	MIC_{50} = 250 µg/mL	

Table 4. *Cont.*

Pharmacological Assay	Plant Part Used	Extracts	Methods	Results	Reference
	Leaves	Aqueous extract	*E. faecalis ATCC 29212*	MIC_{50} = 500 µg/mL	[126]
	Leaves	Aqueous extract	*E. coli ATCC 25922*	MIC_{50} > 2000 µg/mL	
	Leaves	Aqueous extract	*K. pneumoniae ATCC 9591*	MIC_{50} = 2000 µg/mL	
	Leaves	Aqueous extract	*P. aeruginosa ATCC 27853*	MIC_{50} = 500 µg/mL	
	Kernel	Argan oil	*P. aeruginosa*	MIC = 0.3 mg/mL MBC = 0.4 mg/mL	[127]
	Kernel	Argan oil	*S. aureus*	MIC = 0.5 mg/mL MBC = 0.7 mg/mL	[127]
Antidiabetic	Pulp	Methanolic extract	α-amylase	EC_{50} = 0.68 mg/mL	[120]
	Pulp	Methanolic extract	α-glucosidase	EC_{50} = 0.15 mg/mL	
	Pulp	n-Butanol fraction	α-amylase	EC_{50} = 0.49 mg/mL	
	Pulp	n-Butanol fraction	α-glucosidase	EC_{50} = 0.23 mg/mL	
		Ethanolic extract	α-amylase	α-amylase-inhibition = 22.8–46.00 mg AE/g DW	[130]
	Kernel	Argan oil	α-amylase	α-amylase-inhibition = 3.4–5.7 mg AE/g DW	[130]
		Methanolic extract	α-amylase	4.5–8.4 mgAE/gDW	[130]
	Kernel	Argan oil	α-amylase	IC_{50} = 0.78–2.17 mg/mL	[131]
	Kernel	Argan oil	a-glucosidase	IC_{50} = 0.081–0.117 mg/mL	[131]
	Kernel	Methanolic extract	α-amylase	IC_{50} = 868.16 µg/mL	[133]
	Kernel	Methanolic extract	α-Glucosidase	IC_{50} = 51.67 µg/mL	[133]
	Kernel	Argan oil	α-amylase	IC_{50} = 310.21 µg/mL	[132]
	Kernel	Argan oil	α-Glucosidase	IC_{50} = 1310.97 µg/mL	[132]
Anticholinesterase activities	Leaves	Methanolic extract	Acetylcholinesterase (AChE) assay	IC_{50} = 74.90 µg/mL	[133]
	Leaves	Methanolic extract	Butyrylcholinesterase (BChE) assay	IC_{50} = 15.96 µg/mL	[133]
	Kernel	Argan oil	AChE assay	IC_{50} = 12.97 µg/mL	[132]
	Kernel	Argan oil	BChE assay	IC_{50} = 26.36 µg/mL	[122]

Table 4. *Cont.*

Pharmacological Assay	Plant Part Used	Extracts	Methods	Results	Reference
Antifungal	Leaves	Ethanolic extract	disc diffusion method	*Fusarium oxysporum*: 1.92 ± 0.02 mm	[109]
	Kernel	Aqueous	*A. fumigatus*	MIC = 0.146 g/mL	[128]
	Kernel	Aqueous	*P. brasilianum*	MIC = 0.136 g/mL	
	Kernel	Aqueous	*F. dimerum*	MIC = 0.133 g/mL	
	Kernel	Aqueous	*A. niger*	MIC = 0.223 g/mL	
	Kernel	Ethyl acetate	*A. fumigatus*	MIC = 0.146 g/mL	
	Kernel	Ethyl acetate	*P. brasilianum*	MIC = 0.136 g/mL	
	Kernel	Ethyl acetate	*F. dimerum*	MIC = 0.133 g/mL	
	Kernel	Ethyl acetate	*A. niger*	MIC = 0.133 g/mL	
Anticancer	Kernel	24 h Soaking (ethyl acetate), decoction	cytotoxic activity (cancer cells (MCF7) responsible for breast cancer)	IC_{50} = 42 µg/mL	[84]
	Kernel	24 h Soaking (petroleum ether), decoction	cytotoxic activity (cancer cells (MCF7) responsible for breast cancer)	IC_{50} > 100 µg/mL	[84]
	Leaves	Methanolic extract	Cytotoxicity assay (PC-3 human prostate cancer)	600–1000 µg/mL kills PC3.	[123]
	Kernel	Sterols extracted from argan oil	Cytotoxicity assay (DU145, LNCaP and PC3)	DU145, IC_{50} = 25.07 mg/mL LNCaP, IC_{50} = 75.03 mg/mL PC3, IC_{50} = 69.77 mg/mL	[124]
	Kernel	Polyphenols extracted from argan oil	Cytotoxicity assay (DU145, LNCaP and PC3)	DU145, IC_{50} = 75.23 mg/mL LNCaP, IC_{50} = 99.98 mg/mL PC3, IC_{50} = 50.14 mg/mL	[124]

10. Clinical Studies

Regarding experimental findings, Berrada et al. [134] were among the first to report that argan oil (*Argania spinosa*) could exert both antihypertensive and cholesterol-lowering effects under laboratory conditions, pointing to a possible role in cardiovascular protection. Later animal studies in hypertensive rats supported this idea, showing that the intake of argan oil helped bring elevated blood pressure closer to normal values while also improving lipid profiles. Comparable observations were made in gerbils (Meriones shawi) maintained on a high-calorie diet combined with limited physical activity, a setup that led to hyper-

tension, dyslipidemia, and increased insulin levels. After two months of supplementation (5 mg/kg/day), clear metabolic changes were observed: reductions in blood glucose, total cholesterol, LDL-cholesterol, and insulin, along with a decrease in both systolic and diastolic blood pressure. At the same time, HDL-cholesterol and triglycerides rose slightly, whereas body weight did not change significantly. These outcomes are generally linked to the richness of argan oil in unsaturated fatty acids and various bioactive constituents [134]. Additional experimental work using a higher dose of argan oil (10 mL/kg over five weeks) also reported a reduction in systolic blood pressure in both hypertensive and normotensive rats, together with improved vascular reactivity. In isolated vessels, this was reflected by stronger endothelium-dependent relaxation responses, involving nitric oxide signaling as well as cyclooxygenase-derived pathways, as confirmed through pharmacological inhibition approaches. Even though these preclinical results are encouraging, they still need to be validated in well-controlled human clinical trials, particularly to clarify appropriate dosing, long-term safety, and possible effects on metabolic regulation and gut microbiota [135].

From a clinical perspective, Drissi et al. [62] explored the relationship between regular consumption of virgin argan oil and metabolic health markers in a Moroccan population. The study involved 96 healthy individuals, split into habitual consumers and non-consumers. Overall, those who regularly consumed argan oil tended to show a more favorable lipid profile, with higher intake of polyunsaturated fatty acids, lower LDL-cholesterol, reduced markers of lipid oxidation, and higher α-tocopherol levels. That said, the relatively small sample size and absence of long-term follow-up limit how far these results can be generalized. In another clinical trial, Jirabundansuk et al. [136] compared a plant-based moisturizer containing argan kernel oil (*A. spinosa*), shea butter extract (*Butyrospermum parkii*), and spent grain wax with a standard 1% hydrocortisone cream in children suffering from mild to moderate atopic dermatitis. Twenty-nine patients used both treatments on opposite sides of the body over four weeks. Clinical scores (SCORAD) improved significantly in both groups after two weeks, and this improvement continued at week four, without any meaningful statistical difference between treatments. The plant-based formulation showed a slightly higher remission rate, but this did not reach significance. In the end, the authors suggested that the natural cream could be considered a valid alternative to hydrocortisone for mild to moderate cases. Still, the limited sample size and short duration of the trial make it difficult to draw firm conclusions, and larger, longer studies would be necessary to confirm these findings and better evaluate safety and efficacy [136].

11. *A. spinosa* Extract-Based Green Nanotechnology

Green synthesis of nanoparticles has attracted increasing attention as an eco-friendly alternative to conventional chemical methods for the development of bioactive nanomaterials. This approach relies on natural compounds present in plant extracts, which can act as reducing, stabilizing, and capping agents during nanoparticle formation. Consequently, plant-based resources, including agro-industrial by-products, are increasingly explored as sustainable precursors for the production of functional nanomaterials [137–139]. The effectiveness of this strategy has been widely demonstrated in the literature, with consistent formation of stable nanoparticles and reproducible biological activities [140].

Recently, Drissi et al. [141] reported the green synthesis of silver nanoparticles (AgNPs) using the previously unexploited pulp extract of *A. spinosa* (L.) as a natural reducing and stabilizing agent. Rich in bioactive compounds such as squalene (44.95%), (Z)-9-octadecenamide (13.32%), and oleic acid (5.33%), the extract enabled the efficient formation of stable, crystalline, and spherical argan-derived AgNPs with good colloidal stability. Beyond their physicochemical properties, the *A. spinosa*-based AgNPs exhibited promising biological activities, including antioxidant, enzyme inhibitory, and antibacterial effects.

In particular, they showed strong radical scavenging and reducing power, significant inhibition of acetylcholinesterase, tyrosinase, and α-glucosidase, as well as antibacterial activity against both Gram-positive and Gram-negative bacteria.

More specifically, the nanoparticles demonstrated strong antioxidant activity with IC_{50} values of 112.52 μg/mL (DPPH) and 15.60 μg/mL (ferric reducing power). They also exhibited enzyme inhibition of 76.20% for acetylcholinesterase, 64.70% for tyrosinase, and 73.45% for α-glucosidase. Their antibacterial effect was more pronounced against *S. aureus* (12.51 ± 0.18 mm inhibition zone) compared to *E. cloacae* (8.24 ± 0.24 mm) [141]. Overall, these findings highlight the dual valorization potential of *A. spinosa* pulp, both as a renewable agro-industrial by-product and as a bioactive source for the sustainable synthesis of multifunctional nanomaterials. This approach reinforces its relevance in the development of green nanotechnology platforms with promising applications in biomedicine, pharmacology, and environmental remediation. Future research should further explore optimization of synthesis conditions, scale-up feasibility, and extension of this green strategy to other underutilized parts of *A. spinosa* for a more integrated and sustainable valorization approach.

12. Toxicological Studies

Toxicological investigations on *A. spinosa* remain limited, with only a small number of experimental studies available, mainly focusing on isolated saponins and ethanolic extracts from argan kernels and fruit by-products. This scarcity of data can be partly explained by the long-established safe consumption of argan oil as a food product, as well as the traditional medicinal use of several vegetative parts such as leaves, flowers, and twigs. Experimental studies on purified argan saponins administered orally have reported moderate acute toxicity, with an LD_{50} value of approximately 1.3 g/kg body weight. Under subchronic exposure conditions, oral administration of saponins at doses of 0.1 and 0.2 g/kg body weight was associated with a reduction in blood glucose levels and suggested potential renal effects after three months of exposure [102].

Makbal et al. [122] evaluated the safety profile of ethanol extract derived from argan fruit shells through both acute and subacute oral toxicity studies in mice. In the acute toxicity assessment, single oral administrations were carried out within a dose range of approximately 2 to 5 g/kg body weight over a 14-day observation period. No mortality, behavioral disturbances, or notable variations in body weight, food consumption, or organ mass were observed. In the subacute 28-day study, conducted in accordance with OECD guidelines, animals received daily doses ranging from 0.25 to 2 g/kg body weight. Continuous monitoring revealed no significant adverse effects on physiological or behavioral parameters across all treated groups, thereby supporting a wide safety margin for this extract under the tested conditions [122].

In parallel, recent pharmacological studies on argan leaves and by-product extracts, including saponin-rich fractions, have reported no cytotoxic effects at low concentrations (around 10 μg/mL in cell-based models) and no acute toxicity in experimental systems. However, these studies also emphasize that biological activities such as antioxidant effects and enzyme modulation are strongly concentration-dependent, confirming a dose-dependent safety–efficacy relationship typical of saponin-containing plant materials. Despite these encouraging findings, the overall toxicological evidence remains limited, and further comprehensive in vivo and long-term studies are still required to fully establish the safety profile of argan-derived compounds for potential human use [142].

13. Conclusions and Future Perspectives

Argania spinosa (L.) Skeels represents a valuable Moroccan endemic species with remarkable nutritional, pharmacological, and industrial potential. This review highlights

that the biological properties of argan-derived products are mainly associated with their rich phytochemical composition, including unsaturated fatty acids, tocopherols, phytosterols, polyphenols, proteins, amino acids, saponins, and other bioactive metabolites. These compounds contribute to the diverse biological activities reported for *A. spinosa*, including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, cardioprotective, and metabolic-regulating effects. Among the different argan-derived products, argan oil remains the most extensively studied due to its high content of bioactive molecules and its recognized nutritional and functional properties, supporting its potential as a functional food and nutraceutical ingredient. In addition, other plant parts and by-products, such as leaves, pulp, shells, and press cake, contain valuable compounds with promising applications in nutraceutical, cosmetic, pharmaceutical, and biotechnological fields, emphasizing the importance of whole-plant valorization. However, despite the significant biological potential reported, current evidence remains largely based on in vitro assays and preclinical studies, while variations related to geographical origin, plant part, and extraction procedures may influence the chemical composition and biological performance of argan-derived products. Therefore, future research should focus on establishing standardized extraction protocols, strengthening quality control strategies, and conducting well-designed clinical studies to confirm efficacy, safety, and optimal applications in humans. Further investigations should also elucidate the molecular mechanisms underlying the reported bioactivities through advanced analytical and omics approaches, while innovative delivery systems, including nano-based formulations, could enhance the stability, bioavailability, and targeted application of argan bioactive compounds. Overall, the sustainable valorization of *A. spinosa* offers a promising pathway for developing evidence-based nutraceutical and health-oriented products.

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Abbreviations

Tradi*	Traditional
Mech*	Mechanical
AChE	Acetylcholinesterase
BChE	Butyrylcholinesterase
mg AE/g DW	mg acarbose equivalents per g of dry weight
mg GAE/g DW	mg gallic-acid equivalents per g of dry weight
HDL	High-Density Lipoprotein

DPPH	2 2-diphenyl-1-picrylhydrazylfree radical scavenging assays
FRAP	Ferric reducing antioxidant power
ABTS	2,2′-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid radical scavenging assay
MIC	Minimum inhibitory concentration
MBC	Minimum bactericidal concentration
EC_{50}	Half maximal effective concentration
LD_{50}	Lethal Dose 50
LDL	Low-Density Lipoprotein
IC_{50}	Inhibitory Concentration 50

References

1. Chakhchar, A.; Ben Salah, I.; El Kharrassi, Y.; Filali-Maltouf, A.; El Modafar, C.; Lamaoui, M. Agro-fruit-forest systems based on argan tree in Morocco: A review of recent results. *Front. Plant Sci.* **2022**, *12*, 783615. [CrossRef] [PubMed]
2. Msanda, F.; Mayad, E.H.; Furze, J.N. Floristic biodiversity, biogeographical significance, and importance of Morocco's Arganeraie Biosphere Reserve. *Environ. Sci. Pollut. Res.* **2021**, *28*, 64156–64165. [CrossRef] [PubMed]
3. Ezaidi, S.; Ait Haddou, M.; Kabbachi, B.; Ezaidi, A.; Aichi, A.; Das, P.; Abioui, M. Forest degradation susceptibility and sustainability: Case study of arganeraie biosphere reserve, Atlantic high atlas, Morocco. In *Geospatial Practices in Natural Re-Sources Management*; Springer International Publishing: Cham, Switzerland, 2024; pp. 507–526. [CrossRef]
4. Charrouf, Z.; Guillaume, D. Argan oil: Occurrence, composition and impact on human health. *Eur. J. Lipid Sci. Technol.* **2008**, *110*, 632–636. [CrossRef]
5. El Monfalouti, H.; Guillaume, D.; Denhez, C.; Charrouf, Z. Therapeutic potential of argan oil: A review. *J. Pharm. Pharmacol.* **2010**, *62*, 1669–1675. [CrossRef] [PubMed]
6. Allan Degen, A. Indigenous women in North Africa: Amazigh women and argan oil. In *Environments for Women Entrepreneurship in North Africa*; World Scientific: Singapore, 2023; pp. 1–35. [CrossRef]
7. Montanari, B.; Handaine, M.; Id Bourrous, J. Argan oil trade and access to benefit sharing: A matter of economic survival for rural women of the Souss Massa, Morocco. *Hum. Ecol.* **2023**, *51*, 995–1007. [CrossRef]
8. Charrouf, Z.; Guillaume, D. Ethnoeconomical, ethnomedical, and phytochemical study of *Argania spinosa* (L.) Skeels. *J. Ethnopharmacol.* **1999**, *67*, 7–14. [CrossRef] [PubMed]
9. Kirchhoff, M.; Marzolff, I.; Stephan, R.; Seeger, M.; Aït Hssaine, A.; Ries, J.B. Monitoring dryland trees with remote sensing. Part B: Combining tree cover and plant architecture data to assess degradation and recovery of *Argania spinosa* woodlands of South Morocco. *Front. Environ. Sci.* **2022**, *10*, 896703. [CrossRef]
10. Yalbeiry Labarca-Rojas, J.; Hernández-Bermejo, J.E.; Herrera-Molina, F.; Hernández-Clemente, M.; Quero, J.L. Assessing argan tree (*Argania spinosa* (L.) Skeels) ex-situ collections as a complementary tool to in-situ conservation and crop introduction in the Mediterranean basin. *Trees* **2022**, *37*, 567–581. [CrossRef]
11. Ezaidi, S.; Aydda, A.; Kabbachi, B.; Althuwaynee, O.F.; Ezaidi, A.; Ait Haddou, M.; Idoumskine, I.; Thorpe, J.; Park, H.-J.; Kim, S.-W. Multi-temporal Landsat-derived NDVI for vegetation cover degradation for the period 1984–2018 in part of the Arganeraie Biosphere Reserve (Morocco). *Remote Sens. Appl. Soc. Environ.* **2022**, *27*, 100800. [CrossRef]
12. Mouafik, M.; Chakhchar, A.; Fouad, M.; El Aboudi, A. Remote Sensing Technologies for Monitoring Argane Forest Stands: A Comprehensive Review. *Geographies* **2024**, *4*, 441–461. [CrossRef]
13. Labarca-Rojas, Y.; Hernández-Bermejo, J.E.; Quero, J.L.; Herrera-Molina, F. Bioclimatic habitat limitations for argan trees (*Argania spinosa* (L.) Skeels) in Northern Africa and Spain. *Reg. Environ. Change* **2022**, *22*, 14. [CrossRef]
14. Paul, T.; Drakpa, D.; Mukherjee, P.; Chakrabarty, S.; Jigdrel, K.; Gupta, J. Pharmacological Potential of Argan Oil (*Argania spinosa*) with a Special Focus on its Chemical Composition and Nanoformulations-based Applications. *Curr. Nanosci.* **2025**, *21*, 457–469. [CrossRef]
15. Khallouki, F.; Younos, C.; Soulimani, R.; Oster, T.; Charrouf, Z.; Spiegelhalder, B.; Bartsch, H.; Owen, R.W. Consumption of argan oil (Morocco) with its unique profile of fatty acids, tocopherols, squalene, sterols and phenolic compounds should confer valuable cancer chemopreventive effects. *Eur. J. Cancer Prev.* **2003**, *12*, 67–75. [CrossRef] [PubMed]
16. Amssayef, A.; Elbouny, H.; Soulaimani, B.; Abdessadak, O.; Chihab, H.; El Hilaly, J.; Eddouks, M. The protective effect of argan oil and its main constituents against xenobiotics-induced toxicities. *Fitoterapia* **2025**, *180*, 106325. [CrossRef] [PubMed]
17. Rabbaa, S.; Bouchab, H.; Laaziouez, Y.; Limami, Y.; Nasser, B.; Andreoletti, P.; El Midaoui, A.; Cherkaoui-Malki, M.; El Kebbaj, R. Argan oil: A natural bioactive lipid modulating oxidative stress and inflammation. *Antioxidants* **2025**, *14*, 515. [CrossRef] [PubMed]

18. Mechqoq, H.; El Yaagoubi, M.; El Hamdaoui, A.; Momchilova, S.; Guedes da Silva Almeida, J.R.; Msanda, F.; El Aouad, N. Ethnobotany, phytochemistry and biological properties of Argan tree (*Argania spinosa* (L.) Skeels) (Sapotaceae): A review. *J. Ethnopharmacol.* **2021**, *281*, 114528. [CrossRef] [PubMed]
19. Hilali, M.; Charrouf, Z.; Aziz Soulhi, A.E.; Hachimi, L.; Guillaume, D. Influence of origin and extraction method on argan oil physico-chemical characteristics and composition. *J. Agric. Food Chem.* **2005**, *53*, 2081–2087. [CrossRef] [PubMed]
20. Ganoudi, M.; Manan, N.; El Malahi, S.; Driss, I. The argan tree and argan oil: Ecological keystone, socioeconomic resource, nutritional treasure, and medicinal heritage. *Int. J. Agric. Environ. Res.* **2025**, *11*, 1302–1324. [CrossRef]
21. Barkaoui, M.; Msanda, F.; Boubaker, H.; El Boullani, R.; El Asri, O.; Chokri, A.; El Yaagoubi, M.; Koutaya, A.; Eloirdi, A.; Arifi, K.; et al. Ethnobotany, traditional knowledge, and nutritional value of argan (*Argania spinosa* (L.) Skeels) in western Anti-Atlas of Morocco. *Braz. J. Biol.* **2022**, *84*, e260477. [CrossRef] [PubMed]
22. Mehany, T.; Bahmid, N.A. Unveiling the health benefits of argan oil: Bioactive molecules and phytochemical insights for food applications. *J. Food Compos. Anal.* **2025**, *143*, 107542. [CrossRef]
23. Serrafi, A.; Chegdani, F.; Bennis, F.; Kepińska, M. The importance of argan oil in medicine and cosmetology. *Nutrients* **2024**, *16*, 3573. [CrossRef] [PubMed]
24. El Maouardi, M.; Kharbach, M.; Cherrah, Y.; De Braekeleer, K.; Bouklouze, A.; Vander Heyden, Y. Quality control and authentication of Argan oils: Application of advanced analytical techniques. *Molecules* **2023**, *28*, 1818. [CrossRef] [PubMed]
25. Charrouf, Z.; Guillaume, D. Argan oil: The 35-years-of-research product. *Eur. J. Lipid Sci. Technol.* **2014**, *116*, 1316–1321. [CrossRef]
26. Mourjane, A.; Hanine, H.; El Adnany, E.M.; Ouhammou, M.; Hidar, N.; Nabil, B.; El Mahi, B.; Boukroute, A.; Mahrouz, M. Energetic bio-activation of some organic molecules and their antioxidant activity in the pulp of the Moroccan argan tree (*Argania spinosa* L.). *Molecules* **2022**, *27*, 3329. [CrossRef] [PubMed]
27. Moukal, A. L'arganier, *Argania spinosa* L. (skeels), usage thérapeutique, cosmétique et alimentaire. *Phytothérapie* **2004**, *2*, 135–141. [CrossRef]
28. El Yamani, M.; Ijjouk, R.; Kahime, K.; Rharrabti, Y. Ethnopharmacological knowledge and antioxidant propensities of *Argania spinosa* L. from Morocco. *Adv. Pharmacol. Pharm. Sci.* **2024**, *2024*, 6795451. [CrossRef] [PubMed]
29. Katiri, A.; Barkaoui, M.; Msanda, F.; Boubaker, H. Ethnobotanical survey of medicinal plants used for the treatment of diabetes in the Tizi n'Test region (Taroudant Province, Morocco). *J. Pharmacogn. Nat. Prod.* **2017**, *3*, 1000130. [CrossRef]
30. Khallouki, F.; Eddouks, M.; Mourad, A.; Breuer, A.; Owen, R.W. Ethnobotanic, ethnopharmacologic aspects and new phytochemical insights into Moroccan argan fruits. *Int. J. Mol. Sci.* **2017**, *18*, 2277. [CrossRef] [PubMed]
31. El Hafian, M.; Benlandini, N.; Elyacoubi, H.; Zidane, L.; Rochdi, A. Étude floristique et ethnobotanique des plantes médicinales utilisées au niveau de la préfecture d'Agadir-Ida-Outanane (Maroc). *J. Appl. Biosci.* **2014**, *81*, 7198–7213. [CrossRef]
32. Barkaoui, M.; Katiri, A.; Boubaker, H.; Msanda, F. Ethnobotanical survey of medicinal plants used in the traditional treatment of diabetes in Chtouka Ait Baha and Tiznit (Western Anti-Atlas), Morocco. *J. Ethnopharmacol.* **2017**, *198*, 338–350. [CrossRef] [PubMed]
33. Ouhaddou, H.; Boubaker, H.; Msanda, F.; El Mousadik, A. An ethnobotanical study of medicinal plants of the Agadir Ida Ou Tanane province (southwest Morocco). *J. Appl. Biosci.* **2015**, *84*, 7707–7722. [CrossRef]
34. Abouri, M.; El Mousadik, A.; Msanda, F.; Boubaker, H.; Saadi, B.; Cherifi, K. An ethnobotanical survey of medicinal plants used in the Tata Province, Morocco. *Int. J. Med. Plants Res.* **2012**, *1*, 99–123.
35. Benhsain, W. Labellisation de l'UNESCO dans la Réserve de Biosphère d'Arganeraie au Maroc et l'inclusion de la culture amazighe. In *Littérature et Histoire, Langue et Société au Maghreb.-(Tracce)*; Torrossa Online Digital Bookstore: Florence, Italy, 2025; pp. 111–121.
36. Lybbert, T.J.; Aboudrare, A.; Chaloud, D.; Magnan, N.; Nash, M. Booming markets for Moroccan argan oil appear to benefit some rural households while threatening the endemic argan forest. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 13963–13968. [CrossRef] [PubMed]
37. Benhsain, W.; Boujrouf, S. Innovation of UNESCO-MAB: An opportunity for the territorial and sustainable development of the Arganeraie Biosphere Reserve. *J. Adv. Res. Soc. Sci. Humanit.* **2023**, *8*, 9–15. [CrossRef]
38. Benhsain, W.; Salhi, S. UNESCO biosphere reserves and agroecological initiatives: What convergence for what sustainable development? The case of the 'Arganeraie' biosphere reserve in Morocco. *Territ. Environ. Dév.* **2023**, *2*, 36358. [CrossRef]
39. UNESCO. Biosphere Reserve Information/Morocco/ARGANERAIE. Available online: http://www.unesco.org/mabdb/br/brdir/directory/biores.asp?mode=all&code=MOR+01 (accessed on 19 October 2017).
40. Ait Aabd, N.; El Asbahani, A.; El Alem, Y.; El Finti, A.; Msanda, F.; El Mousadik, A. Variation in oil content and fatty acid composition in preselected argan trees with morphological characters and geographical localization. *Mediterr. J. Nutr. Metab.* **2013**, *6*, 217–225. [CrossRef]
41. Ait Aabd, N.; Msanda, F.; El Mousadik, A. Evaluation of variability in argan oil content through different environments and preselection of elite genotypes. *Euphytica* **2014**, *195*, 157–167. [CrossRef]

42. Ramos-e-Silva, M.; Camargo, C.; Cavalcante, R.; Carneiro, S. Vitamin E in dermatology. *Clin. Dermatol.* **2026**, *44*, 257–263. [CrossRef] [PubMed]
43. Calder, P.C. Functional roles of fatty acids and their effects on human health. *JPEN J. Parenter. Enteral. Nutr.* **2015**, *39*, 18S–32S. [CrossRef] [PubMed]
44. Goik, U.; Goik, T.; Załęska, I. The properties and application of argan oil in cosmetology. *Eur. J. Lipid Sci. Technol.* **2019**, *121*, 1800313. [CrossRef]
45. Zarrouk, A.; Martine, L.; Grégoire, S.; Nury, T.; Meddeb, W.; Camus, E.; Badreddine, A.; Durand, P.; Namsi, A.; Yammine, A.; et al. Profile of fatty acids, tocopherols, phytosterols and polyphenols in Mediterranean oils (argan oils, olive oils, milk thistle seed oils and nigella seed oil) and evaluation of their antioxidant and cytoprotective activities. *Curr. Pharm. Des.* **2019**, *25*, 1791–1805. [CrossRef] [PubMed]
46. Abdalla, S.; Aroua, M.K.; Gew, L.T. A comprehensive review of plant-based cosmetic oils (virgin coconut oil, olive oil, argan oil, and jojoba oil): Chemical and biological properties and their cosmeceutical applications. *ACS Omega* **2024**, *9*, 44019–44032. [CrossRef] [PubMed]
47. El Kebbaj, R.; Bouchab, H.; Tahri-Joutey, M.; Rabbaa, S.; Limami, Y.; Nasser, B.; Egbujor, M.C.; Tucci, P.; Andreoletti, P.; Saso, L.; et al. The potential role of major argan oil compounds as Nrf2 regulators and their antioxidant effects. *Antioxidants* **2024**, *13*, 344. [CrossRef] [PubMed]
48. Kikuzaki, H.; Hisamoto, M.; Hirose, K.; Akiyama, K.; Taniguchi, H. Antioxidant properties of ferulic acid and its related compounds. *J. Agric. Food Chem.* **2002**, *50*, 2161–2168. [CrossRef] [PubMed]
49. Kaur, J.; Kaur, R. *p*-Coumaric acid: A naturally occurring chemical with potential therapeutic applications. *Curr. Org. Chem.* **2022**, *26*, 1333–1349. [CrossRef]
50. Kakkar, S.; Bais, S. A review on protocatechuic acid and its pharmacological potential. *Int. Sch. Res. Not.* **2014**, *2014*, 952943. [CrossRef] [PubMed]
51. Zhang, Y.; Wang, Y.; Sun, S. Tyrosol Modifications for Improved Functionality: A Review of Hydrophilic and Lipophilic Pathways and Their Potential Applications. *J. Agric. Food Chem.* **2025**, *73*, 30628–30645. [CrossRef] [PubMed]
52. Trinh, X.T.; Long, N.V.; Van Anh, L.T.; Nga, P.T.; Giang, N.N.; Chien, P.N.; Trung, N.T.; Hoa, N.T.; Thao, D.T.P.; Heo, C.Y. A comprehensive review of natural compounds for wound healing: Targeting bioactivity perspective. *Int. J. Mol. Sci.* **2022**, *23*, 9573. [CrossRef] [PubMed]
53. Khallouki, F.; Haubner, R.; Ricarte, I.; Erben, G.; Klika, K.; Ulrich, C.M.; Owen, R.W. Identification of polyphenolic compounds in the flesh of Argan (Morocco) fruits. *Food Chem.* **2015**, *179*, 191–198. [CrossRef] [PubMed]
54. Qu, Z.; Liu, A.; Li, P.; Liu, C.; Xiao, W.; Huang, J.; Liu, Z.; Zhang, S. Advances in physiological functions and mechanisms of (−)-epicatechin. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 211–233. [CrossRef] [PubMed]
55. Abd El-Aziz, T.A.; Mohamed, R.H.; Pasha, H.F.; Abdel-Aziz, H.R. Catechin protects against oxidative stress and inflammatory-mediated cardiotoxicity in adriamycin-treated rats. *Clin. Exp. Med.* **2012**, *12*, 233–240. [CrossRef] [PubMed]
56. Noui, A.; Cheurfa, M.; Merouane, A.; Kouidri, M.; Saadi, A.; Mariod, A.A. Investigations on two Algerian argan oils: Phenolic composition and antioxidant activity. *Phytothérapie* **2024**, *22*, 50–56. [CrossRef]
57. Marfil, R.; Giménez, R.; Martínez, O.; Bouzas, P.R.; Rufián-Henares, J.A.; Mesías, M.; Cabrera-Vique, C. Determination of polyphenols, tocopherols, and antioxidant capacity in virgin argan oil (*Argania spinosa* L. Skeels). *Eur. J. Lipid Sci. Technol.* **2011**, *113*, 886–893. [CrossRef]
58. Turcov, D.; Zbranca-Toporas, A.; Suteu, D. Bioactive Compounds for Combating Oxidative Stress in Dermatology. *Int. J. Mol. Sci.* **2023**, *24*, 17517. [CrossRef] [PubMed]
59. Krol, E.S.; Kramer-Stickland, K.A.; Liebler, D.C. Photoprotective actions of topically applied vitamin E. *Drug Metab. Rev.* **2000**, *32*, 413–420. [CrossRef] [PubMed]
60. Es-Sai, B.; Wahnou, H.; Benayad, S.; Rabbaa, S.; Laaziouez, Y.; El Kebbaj, R.; Limami, Y.; Duval, R.E. Gamma-tocopherol: A comprehensive review of its antioxidant, anti-inflammatory, and anticancer properties. *Molecules* **2025**, *30*, 653. [CrossRef] [PubMed]
61. Cherki, M.; Berrougui, H.; Drissi, A.; Adlouni, A.; Khalil, A. Argan oil: Which benefits on cardiovascular diseases? *Pharmacol. Res.* **2006**, *54*, 1–5. [CrossRef] [PubMed]
62. Drissi, A.; Girona, J.; Cherki, M.; Godàs, G.; Derouiche, A.; El Messal, M.; Saile, R.; Kettani, A.; Solà, R.; Masana, L.; et al. Evidence of hypolipemiant and antioxidant properties of argan oil derived from the argan tree (*Argania spinosa*). *Clin. Nutr.* **2004**, *23*, 1159–1166. [CrossRef] [PubMed]
63. Barkas, F.; Bathrellou, E.; Nomikos, T.; Panagiotakos, D.; Liberopoulos, E.; Kontogianni, M.D. Plant Sterols and Plant Stanols in Cholesterol Management and Cardiovascular Prevention. *Nutrients* **2023**, *15*, 2845. [CrossRef] [PubMed]
64. Ursoniu, S.; Sahebkar, A.; Serban, M.C.; Banach, M. The impact of argan oil on plasma lipids in humans: Systematic review and meta-analysis of randomized controlled trials. *Phytother. Res.* **2018**, *32*, 377–383. [CrossRef] [PubMed]

65. Makran, M.; Garcia-Llatas, G.; Cilla, A. Effect of plant sterols on intestinal health: A comprehensive review of biological activity in targeting cancer and inflammation pathways. *Crit. Rev. Food Sci. Nutr.* **2026**, 1–18. [CrossRef] [PubMed]
66. Ould Mohamedou, M.M.; Zouirech, K.; El Messal, M.; El Kebbaj, M.S.; Chraibi, A.; Adlouni, A. Argan oil exerts an antiatherogenic effect by improving lipids and susceptibility of LDL to oxidation in type 2 diabetes patients. *Int. J. Endocrinol.* **2011**, *2011*, 747835. [CrossRef] [PubMed]
67. Kopylov, A.T.; Malsagova, K.A.; Stepanov, A.A.; Kaysheva, A.L. Diversity of Plant Sterols Metabolism: The Impact on Human Health, Sport, and Accumulation of Contaminating Sterols. *Nutrients* **2021**, *13*, 1623. [CrossRef] [PubMed]
68. Wu, G. Dietary protein intake and human health. *Food Funct.* **2016**, *7*, 1251–1265. [CrossRef] [PubMed]
69. Rueda, A.; Samaniego-Sánchez, C.; Olalla, M.; Giménez, R.; Cabrera-Vique, C.; Seiquer, I.; Lara, L. Combination of Analytical and Chemometric Methods as a Useful Tool for the Characterization of Extra Virgin Argan Oil and Other Edible Virgin Oils. Role of Polyphenols and Tocopherols. *J. AOAC Int.* **2016**, *99*, 489–494. [CrossRef] [PubMed]
70. Kamal, R.; Kharbach, M.; Vander Heyden, Y.; Doukkali, Z.; Ghchime, R.; Bouklouze, A.; Cherrah, Y.; Alaoui, K. In Vivo Anti-Inflammatory Response and Bioactive Compounds' Profile of Polyphenolic Extracts from Edible Argan Oil (*Argania spinosa* L.), Obtained by Two Extraction Methods. *J. Food Biochem.* **2019**, *43*, e13066. [CrossRef] [PubMed]
71. de Carvalho, C.; Caramujo, M. The Various Roles of Fatty Acids. *Molecules* **2018**, *23*, 2583. [CrossRef] [PubMed]
72. Guillaume, D.; Pioch, D.; Charrouf, Z. Argan [*Argania spinosa* (L.) Skeels] Oil. In *Fruit Oils: Chemistry and Functionality*; Ramadan, M.F., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 317–352. [CrossRef]
73. Arribas-López, E.; Zand, N.; Ojo, O.; Snowden, M.J.; Kochhar, T. The Effect of Amino Acids on Wound Healing: A Systematic Review and Meta-Analysis on Arginine and Glutamine. *Nutrients* **2021**, *13*, 2498. [CrossRef] [PubMed]
74. Karna, E.; Szoka, L.; Huynh, T.Y.L.; Palka, J.A. Proline-dependent regulation of collagen metabolism. *Cell. Mol. Life Sci.* **2019**, *77*, 1911–1918. [CrossRef] [PubMed]
75. Gebashe, F.C.; Naidoo, D.; Amoo, S.O.; Masondo, N.A. Cosmeceuticals: A Newly Expanding Industry in South Africa. *Cosmetics* **2022**, *9*, 77. [CrossRef]
76. Sharifi, N.; Hamedeyazdan, S.; Shokri, J.; Monajjemzadeh, F. Argan oil as a pretreatment of human hair before exposure to oxidative damage: Attenuated total reflectance and protein loss studies. *J. Cosmet. Dermatol.* **2022**, *21*, 5010–5017. [CrossRef] [PubMed]
77. Choi, J.Y.; Lee, W.J.; Boo, Y.C. Therapeutic Potential of Cysteine and Its Derivatives in Dermatology. *Molecules* **2026**, *31*, 1277. [CrossRef] [PubMed]
78. Clemente Plaza, N.; Reig García-Galbis, M.; Martínez-Espinosa, R.M. Effects of the Usage of l-Cysteine (l-Cys) on Human Health. *Molecules* **2018**, *23*, 575. [CrossRef] [PubMed]
79. Taarji, N.; Lyamlouli, K.; Barakat, A.; Tominaga, K.; Isoda, H.; Nakajima, M. Biochemical and techno-functional investigation of argan press-cake proteins foreseeing food application. *Lwt-Food Sci. Technol.* **2024**, *192*, 115734. [CrossRef]
80. Solano, F. Metabolism and functions of amino acids in the skin. In *Amino Acids in Nutrition and Health: Amino Acids in Systems Function and Health*; Springer International Publishing: Cham, Switzerland, 2020; pp. 187–199. [CrossRef] [PubMed]
81. Sá, A.G.A.; Moreno, Y.M.F.; Carciofi, B.A.M. Plant proteins as high-quality nutritional source for human diet. *Trends Food Sci. Technol.* **2020**, *97*, 170–184. [CrossRef]
82. Sharma, M.; Saini, C.S. Amino acid composition, nutritional profiling, mineral content and physicochemical properties of protein isolate from flaxseeds (*Linum usitatissimum*). *J. Food Meas. Charact.* **2022**, *16*, 829–839. [CrossRef]
83. Bejaoui, M.; Taarji, N.; Saito, M.; Nakajima, M.; Isoda, H. Argan (*Argania spinosa*) press cake extract enhances cell proliferation and prevents oxidative stress and inflammation of human dermal papilla cells. *J. Dermatol. Sci.* **2021**, *103*, 33–40. [CrossRef] [PubMed]
84. El Babili, F.; Bouajila, J.; Fouraste, I.; Valentin, A.; Mauret, S.; Moulis, C. Chemical study, antimalarial and antioxidant activities, and cytotoxicity to human breast cancer cells (MCF7) of *Argania spinosa*. *Phytomedicine* **2010**, *17*, 157–160. [CrossRef] [PubMed]
85. Zaaboul, F.; Raza, H.; Lazraq, A.; Deng, B.; Cao, C.; Liu, Y.F. Chemical composition, physical properties, and the oxidative stability of oil bodies extracted from Argania spinosa. *J. Am. Oil Chem. Soc.* **2018**, *95*, 485–495. [CrossRef]
86. Menni, H.B.; Belarbi, M.; Menni, D.B.; Bendiab, H.; Kherraf, Y.; Ksouri, R.; Djebli, N.; Visioli, F. Anti-inflammatory activity of argan oil and its minor components. *Int. J. Food. Sci. Nutr.* **2020**, *71*, 307–314. [CrossRef] [PubMed]
87. Olojo, F.O.; Akinrinde, A.S.; Ogundairo, S.A.; Ubochi, V.C. *Argania spinosa* essential oil ameliorates colonic damage and extraintestinal alterations in a rat model of acetic acid-induced colitis by suppressing oxidative stress and inflammation. *Adv. Tradit. Med.* **2024**, *24*, 459–474. [CrossRef]
88. Alaoui, K.; Lagorce, J.F.; Cherrah, Y.; Hassar, M.; Amarouch, H.; Roquebert, J. Analgesic and anti-inflammatory activity of saponins of *Argania spinoza*. *Ann. Pharm. Françaises* **1998**, *56*, 220–228.
89. Sevindik, O.; Amanpour, A.; Tsouli Sarhir, S.; Kelebek, H.; Selli, S. Characterization of key odorants in Moroccan argan oil by aroma extract dilution analysis. *Eur. J. Lipid Sci. Technol.* **2019**, *121*, 1800437. [CrossRef]
90. Matthäus, B.; Bonte, A.; Sinning, B.; Charrouf, Z. Aroma-Relevant Volatile Compounds as Markers for the Sensory Quality of Argan Oil. *Eur. J. Lipid Sci. Technol.* **2019**, *121*, 1900279. [CrossRef]

91. Nafis, A.; Hassani, L.; Marraiki, N.; Al-Rashed, S.; Elgorban, A.M.; Syed, A.; Iriti, M. Antimicrobial and synergistic effect of Moroccan native *Argania spinosa* essential oil for modulating of antibiotics resistance. *Nat. Prod. Res.* **2021**, *35*, 6078–6082. [CrossRef] [PubMed]
92. Benabdesslem, Y.; Ghomari, S.; Adli, D.E.H.; Mébarki, M.; Hachem, K. Chemical composition and antibacterial activity of essential oil derived from the leaves of *Argania spinosa* (L.) grown in Northwestern Algeria. *J. Essent. Oil Bear. Plants* **2022**, *25*, 103–110. [CrossRef]
93. Kharbach, M.; Viaene, J.; Yu, H.; Kamal, R.; Marmouzi, I.; Bouklouze, A.; Vander Heyden, Y. Secondary-metabolites fingerprinting of *Argania spinosa* kernels using liquid chromatography–mass spectrometry and chemometrics, for metabolite identification and quantification as well as for geographic classification. *J. Chromatogr. A* **2022**, *1670*, 462972. [CrossRef] [PubMed]
94. Owen, R.W.; Giacosa, A.; Hull, W.E.; Haubner, R.; Würtele, G.; Spiegelhalder, B.; Bartsch, H. Olive-oil consumption and health: The possible role of antioxidants. *Lancet Oncol.* **2000**, *1*, 107–112. [CrossRef] [PubMed]
95. Huang, Z.R.; Lin, Y.K.; Fang, J.Y. Biological and Pharmacological Activities of Squalene and Related Compounds: Potential Uses in Cosmetic Dermatology. *Molecules* **2009**, *14*, 540–554. [CrossRef] [PubMed]
96. Smith, T.J. Squalene: Potential chemopreventive agent. *Expert Opin. Investig. Drugs* **2000**, *9*, 1841–1848. [CrossRef] [PubMed]
97. Azizi, S.E.; Dalli, M.; Roubi, M.; Moon, S.; Berrichi, A.; Maleb, A.; Gseyra, N.; Kim, B. Insights on phytochemistry and pharmacological properties of *Argania spinosa* L. Skeels: A comprehensive review. *ACS Omega* **2024**, *9*, 36043–36065. [CrossRef] [PubMed]
98. Henry, M.; Kowalczyk, M.; Maldini, M.; Piacente, S.; Stochmal, A.; Oleszek, W. Saponin inventory from *Argania spinosa* kernel cakes by liquid chromatography and mass spectrometry. *Phytochem. Anal.* **2013**, *24*, 616–622. [CrossRef] [PubMed]
99. Alaoui, A.; Charrouf, Z.; Soufiaoui, M.; Carbone, V.; Malorni, A.; Pizza, C.; Piacente, S. Triterpenoid saponins from the shells of *Argania spinosa* seeds. *J. Agric. Food Chem.* **2002**, *50*, 4600–4603. [CrossRef] [PubMed]
100. Charrouf, Z.; Wieruszeski, J.M.; Fkih-Tetouani, S.; Charrouf, M.; Fournet, B. Triterpenoid saponins from *Argania spinosa*. *Phytochemistry* **1992**, *31*, 2079–2086. [CrossRef] [PubMed]
101. Guillaume, D.; Charrouf, Z. Saponines et métabolites secondaires de l'arganier (*Argania spinosa*). *Cah. Agric.* **2005**, *14*, 509–516.
102. Alaoui, K.; Belabbes, M.; Cherrah, Y.; Hassar, M.; Charrouf, Z.; Amarouch, H.; Roquebert, J. Acute and chronic toxicity of saponins from *Argania spinosa*. *Ann. Pharm. Françaises* **1998**, *56*, 213–219.
103. Badague, A.; Bounouira, H.; Chakir, E.M.; Didi, A.; Amsil, H.; Aarab, I.; Said, S.; Zefti, H. Chemical composition analysis of argan kernel, leaves and shell from the Oujda region using neutron activation analysis technique at CNESTEN-Morocco. *Int. J. Nucl. Energy Sci. Technol.* **2025**, *18*, 58–75. [CrossRef]
104. Ennoukh, F.E.; Bchitou, R.; Mohammed, F.; Guillaume, D.; Harhar, H.; Bouhaouss, A. Study of the effects of extraction methods on Argan oil quality through its metal content. *Ind. Crops Prod.* **2017**, *109*, 182–184. [CrossRef]
105. Marfil, R.; Cabrera-Vique, C.; Giménez, R.; Bouzas, P.R.; Martínez, O.; Sánchez, J.A. Metal content and physicochemical parameters used as quality criteria in virgin argan oil: Influence of the extraction method. *J. Agric. Food Chem.* **2008**, *56*, 7279–7284. [CrossRef] [PubMed]
106. El Abbassi, A.; Khalid, N.; Zbakh, H.; Ahmad, A. Physicochemical characteristics, nutritional properties, and health benefits of argan oil: A review. *Crit. Rev. Food Sci. Nutr.* **2014**, *54*, 1401–1414. [CrossRef] [PubMed]
107. Cerulli, A.; Badalamenti, N.; Sottile, F.; Bruno, M.; Piacente, S.; Ilardi, V.; Tundis, R.; Pino, R.; Loizzo, M.R. Phytochemical profile and functional properties of the husk of *Argania spinosa* (L.) Skeel. *Plants* **2025**, *14*, 2288. [CrossRef] [PubMed]
108. Hilali, M.; El Monfalouti, H.; Kartah, B.E. Evaluation of the chemical composition of Argan (*Argania spinosa* L.) oil according to its extraction method. *Online J. Anim. Feed Res.* **2020**, *10*, 111–118. [CrossRef]
109. El Idrissi, Y.; El Moudden, H.; El-Guezzane, C.; Bouayoun, T.; Dahrouch, A.; Chahboun, N.; Zarrouk, A.; Tabyaoui, M. The influence of the forms on the quality, chemical composition and antioxidant activity of argan oil grown in Morocco. *J. Microbiol. Biotechnol. Food Sci.* **2023**, *12*, e5794. [CrossRef]
110. Kamal, R.; Kharbach, M.; Heyden, Y.V.; Yu, H.; Bouklouze, A.; Cherrah, Y.; Alaoui, K. In Vitro In Vivo Anti-Hyperglycemic Potential of Saponins Cake and Argan Oil from *Argania spinosa*. *Foods* **2021**, *10*, 1078. [CrossRef] [PubMed]
111. Koufan, M.; Belkoura, I.; Mazri, M.A.; Amarraque, A.; Essatte, A.; Elhorri, H.; Zaddoug, F.; Alaoui, T. Determination of antioxidant activity, total phenolics and fatty acids in essential oils and other extracts from callus culture, seeds and leaves of *Argania spinosa* (L.) Skeels. *Plant Cell Tissue Organ Cult.* **2020**, *141*, 217–227. [CrossRef]
112. Hanana, M.; Mezghenni, H.; Ben Ayed, R.; Ben Dhiab, A.; Jarradi, S.; Jamoussi, B.; Hamrouni, L. Nutraceutical potentialities of Tunisian Argan oil based on its physicochemical properties and fatty acid content as assessed through Bayesian network analyses. *Lipids Health Dis.* **2018**, *17*, 138. [CrossRef] [PubMed]
113. Dakiche, H.; Khali, M.; Boutoumi, H. Phytochemical Characterization and in vivo Anti-inflammatory and Wound-healing Activities of *Argania spinosa* (L.) Skeels Seed Oil. *Rec. Nat. Prod.* **2017**, *11*, 171–184.

114. Drouche, I.; José Maria, C.; Saidi, F.; Maria Del Carmen, P.C. Valorisation de l'huile d'argan de Tindouf et étude de l'influence de l'originedes fruits (Arganiers/Caprins) et de la torréfaction sur sa qualité et sa composition chimique. *AGROBIOLOGIA* **2021**, *11*, 2617–2627.
115. Ben Mansour, R.; Ben Slema, H.; Falleh, H.; Tounsi, M.; Kechebar, M.S.A.; Ksouri, R.; Megdiche-Ksouri, W. Phytochemical characteristics, antioxidant, and health properties of roasted and unroasted Algerian argan (*Argania spinosa*) oil. *J. Food Biochem.* **2018**, *42*, e12562. [CrossRef]
116. El Kharrassi, Y.; Maata, N.; Mazri, M.A.; El Kamouni, S.; Talbi, M.; El Kebbaj, R.; Moustaid, K.; Essamadi, A.K.; Andreoletti, P.; El Mzouri, E.H.; et al. Chemical and phytochemical characterizations of argan oil (*Argania spinosa* L. skeels), olive oil (*Olea europaea* L. cv. *Moroccan picholine*), cactus pear (*Opuntia megacantha Salm-Dyck*) seed oil and cactus cladode essential oil. *J. Food Meas. Charact.* **2018**, *12*, 747–754. [CrossRef]
117. Benaouf, Z.; Kechairi, R.; Djorf, O.; Kies, M.L. Fruiting and productivity of the Argan (*Argania spinosa*) tree and evaluation of the nutritional value of its early and late fruits from Western Algeria. *Int. J. Fruit Sci.* **2023**, *23*, 151–164. [CrossRef]
118. Badreddine, A.; Zarrouk, A.; Karym, E.M.; Debbabi, M.; Nury, T.; Meddeb, W.; Sghaier, R.; Bezine, M.; Vejux, A.; Martine, L.; et al. Argan Oil-Mediated Attenuation of Organelle Dysfunction, Oxidative Stress and Cell Death Induced by 7-Ketocholesterol in Murine Oligodendrocytes 158N. *Int. J. Mol. Sci.* **2017**, *18*, 2220. [CrossRef] [PubMed]
119. Zhar, N.; Naamani, K.; Dihazi, A.; Jaiti, F.; El Keroumi, A. Comparative analysis of some biochemical parameters of argan pulp morphotypes (*Argania spinosa* (L) Skeels) during maturity and according to the continentality in Essaouira region (Morocco). *Physiol. Mol. Biol. Plants* **2016**, *22*, 361–370. [CrossRef] [PubMed]
120. Alaoui, A.; Sahri, N.; Mahdi, I.; Fahsi, N.; Sobeh, M. Argan: Phytochemical profiling and evaluation of the antioxidant, hypoglycemic, and antibacterial properties of its fruit pulp extracts. *Heliyon* **2024**, *10*, e23612. [CrossRef] [PubMed]
121. Bakrim, H.; El Galiou, O.; Lamhamdi, M.; El Moudden, H.; Zerrouk, M.H.; Arakrak, A.; Bouslamti, R.; El Atki, Y.; Zahir, H.; Laglaoui, A. Smen and argan oil as a source of bioactive natural products: An insight into their fatty acid profile, antioxidant and antimicrobial activities. *J. Microbiol. Biotechnol. Food Sci.* **2025**, *14*, e11347. [CrossRef]
122. Makbal, R.; Idrissi, F.E.J.; Ouchbani, T.; Tastift, M.A.; Kiai, H.; Hafidi, A.; Gadhi, C. Anti-Inflammatory, Antioxidant, Chemical Characterization, and Safety Assessment of *Argania spinosa* Fruit Shell Extract from South-Western Morocco. *BioMed Res. Int.* **2021**, *2021*, 5536030. [CrossRef] [PubMed]
123. Dakiche, H.; Khali, M.; Abu-el-Haija, A.K.; Al-Maaytah, A.; Al-Balas, Q.A. Biological activities and phenolic contents of *Argania spinosa* L. (Sapotaceae) leaf extract. *Trop. J. Pharm. Res.* **2016**, *15*, 2563–2570. [CrossRef]
124. Bennani, H.; Drissi, A.; Giton, F.; Kheuang, L.; Fiet, J.; Adlouni, A. Antiproliferative effect of polyphenols and sterols of virgin argan oil on human prostate cancer cell lines. *Cancer Detect. Prev.* **2007**, *31*, 64–69. [CrossRef] [PubMed]
125. Lall, N.; Canha, M.D.; Szuman, K.; Charrouf, Z.; Davids, L.M.; Rademan, S. The Anti-proliferative and Anti-bacterial Activity of Argan oil and Crude Saponin Extract from *Argania spinosa* (L.) Skeels. *Pharmacogn. J.* **2019**, *11*, 26–31. [CrossRef]
126. Bonvicini, F.; Antognoni, F.; Mandrone, M.; Protti, M.; Mercolini, L.; Lianza, M.; Gentilomi, G.A.; Poli, F. Phytochemical analysis and antibacterial activity towards methicillin-resistant *Staphylococcus aureus* of leaf extracts from *Argania spinosa* (L.) Skeels. *Plant Biosyst.* **2017**, *151*, 649–656. [CrossRef]
127. Almuhayawi, M.S.; Alruhaili, M.H.; Gattan, H.S.; Alharbi, M.T.; Nagshabandi, M.K.; Hagagy, N.; Almuhayawi, S.M.; Al Jaouni, S.K.; Selim, S.; Mostafa, E.M.; et al. In vitro and in silico biopotentials of phytochemical compositions and antistaphylococcal and antipseudomonal activities of volatile compounds of *Argania spinosa* (L.) seed oil. *Front. Bioeng. Biotechnol.* **2024**, *12*, 1348344. [CrossRef] [PubMed]
128. Lfitat, A.; Ed-Dahmani, I.; Bousraf, F.Z.; Belhaj, A.; Ainane, T.; Taleb, M.; Gourch, A.; Abdellaoui, A. Comprehensive evaluation of antifungal activity of *Argania spinosa* (L.) Skeels kernels of the hot and cold extraction and the effect of solvents varying polarities and the heat treatment on yield and activity variance. *Indones. Food Nutr. Prog.* **2023**, *20*, 10–23. [CrossRef]
129. Charrouf, Z.; Guillaume, D. Phenols and polyphenols from *Argania spinosa*. *Am. J. Food Technol.* **2007**, *2*, 679–683. [CrossRef]
130. El Adib, S.; Aissi, O.; Charrouf, Z.; Ben Jeddi, F.; Messaoud, C. *Argania spinosa* var. mutica and var. apiculata: Variation of Fatty-Acid Composition, Phenolic Content, and Antioxidant and a-AmylaseInhibitory Activities among Varieties, Organs, and Development Stages. *Chem. Biodivers.* **2015**, *12*, 1322–1338. [CrossRef] [PubMed]
131. Daoudi, N.E.; Bouhrim, M.; Ouassou, H.; Legssyer, A.; Mekhfi, H.; Ziyyat, A.; Aziz, M.; Bnouham, M. Inhibitory effect of roasted/unroasted *Argania spinosa* seeds oil on α-glucosidase, α-amylase and intestinal glucose absorption activities. *S. Afr. J. Bot.* **2020**, *135*, 413–420. [CrossRef]
132. Khammassi, M.; Amato, G.; Caputo, L.; Nazzaro, F.; Fratianni, F.; Kouki, H.; Amri, I.; Hamrouni, L.; De Feo, V. Fatty Acid Profiles and Biological Activities of the Vegetable Oils of *Argania spinosa*, *Pinus halepensis* and *Pistacia atlantica* Grown in Tunisia: A Preliminary Study. *Molecules* **2024**, *29*, 160. [CrossRef] [PubMed]
133. Haouame, I.; Semcheddine, N.; Bendif, H.; Çam, D.; Öztürk, M.; Acquaticci, L.; Boufahja, F.; Garzoli, S. Bioactive compounds from *Argania spinosa* (L.) Skeel: Extraction, phytocomplex characterization, and biological activities. *J. Food Qual.* **2025**, *2025*, 8016160. [CrossRef]

134. Berrada, Y.; Settaf, A.; Baddouri, K.; Cherrah, A.; Hassar, M. Experimental evidence of an antihypertensive and hypocholesterolemic effect of argan oil (*Argania sideroxylon*). *Thérapie* **2000**, *55*, 375–378. [PubMed]
135. Berrougui, H.; de Sotomayor, M.A.; Pérez-Guerrero, C.; Ettaib, A.; Hmamouchi, M.; Marhuenda, E.; Herrera, M.D. Argan (*Argania spinosa*) oil lowers blood pressure and improves endothelial dysfunction in spontaneously hypertensive rats. *Br. J. Nutr.* **2004**, *92*, 921–929. [CrossRef] [PubMed]
136. Jirabundansuk, P.; Ophaswongse, S.; Udompataikul, M. Comparative trial of moisturizer containing spent grain wax, Butyrospermum parkii extract, *Argania spinosa* kernel oil vs. 1% hydrocortisone cream in the treatment of childhood atopic dermatitis. *J. Med. Assoc. Thai.* **2014**, *97*, 820–826. [PubMed]
137. Al Moudani, N.; Aarab, L. Valorization of Moroccan flora in green nanotechnology. *Int. J. Environ. Health Res.* **2026**, 1–24. [CrossRef] [PubMed]
138. Ouassil, M.; Msairi, S.; Ainane, T. Medicinal and aromatic plants (MAP) based metal nanoparticles and their potential as nanopesticides in Morocco: A review study. *Not. Sci. Biol.* **2024**, *16*, 12043. [CrossRef]
139. Nguyen, N.T.T.; Nguyen, L.M.; Nguyen, T.T.T.; Nguyen, T.T.; Nguyen, D.T.C.; Tran, T.V. Formation, antimicrobial activity, and biomedical performance of plant-based nanoparticles: A review. *Environ. Chem. Lett.* **2022**, *20*, 2531–2571. [CrossRef] [PubMed]
140. Mejía-Méndez, J.L.; Reza-Zaldívar, E.E.; Sánchez-Martínez, A.; Ceballos-Sánchez, O.; Navarro-López, D.E.; Marcelo Lozano, L.; Armendáriz-Borunda, J.; Tiwari, N.; Jacobo-Velázquez, D.A.; Sánchez-Ante, G.; et al. Exploring the cytotoxic and antioxidant properties of lanthanide-doped ZnO nanoparticles: A study with machine learning interpretation. *J. Nanobiotechnol.* **2024**, *22*, 687. [CrossRef] [PubMed]
141. Drissi, O.; Ghazi, S.; Daoudi, B.; Hsissou, R.; Ouknin, M.; Oubihi, A.; Azogagh, M.; Rafiq, M.; El Harfaoui, N.; Nouneh, K. An Innovative Method for the Green Synthesis of Silver Nanoparticles Using Argan Pulp Extract as Bioreductant for Efficient Enzyme Inhibition, Antioxidant, and Antibacterial Activities. *Waste Biomass. Valor.* **2026**, *17*, 4085–4107. [CrossRef]
142. Villareal, M.O.; Chaochaiphat, T.; Makbal, R.; Gadhi, C.; Isoda, H. Molecular Analysis of the Melanogenesis Inhibitory Effect of Saponins-Rich Fraction of *Argania spinosa* Leaves Extract. *Molecules* **2022**, *27*, 6762. [CrossRef] [PubMed]

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