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Comprehensive Review of the Phytochemistry, Biological Activities, and Ecological Relevance of *Artemisia herba-alba*

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Abstract: Artemisia herba-alba is a perennial aromatic plant common in arid and semi-arid regions and known for its medicinal, ecological, and industrial importance. This review presents updated insights into its phytochemical profile, essential oils, biological activities, and adaptive physiology. The essential oils are rich in monoterpenes such as 1,8-cineole, camphor, thujone, and borneol, showing strong antimicrobial, antioxidant, and anticancer properties. Phenolic compounds enhance antioxidant and allelopathic functions, influencing seed germination and enzymatic regulation. Recent studies have revealed eco-friendly uses, including corrosion inhibition and natural insecticidal effects. Physiological and biochemical assessments confirm drought tolerance through osmoprotective accumulation of sugars and proline and activation of antioxidant enzymes. Molecular analyses using ISSR, RAPD, and DNA barcoding show high genetic diversity linked to ecological and geographical variations. Further integration of omics technologies and applied studies will advance the pharmacological, ecological, and economic utilization of this species.

Keywords: Artemisia herba-alba, essential oils, phenolic compounds, antioxidant activity, allelopathy, ecological adaptation.

المراجعة الشاملة للكيمياء النباتية والأنشطة الحيوية والأهمية البيئية لنبات الشيح الأبيض

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المستخلص :يُعد نبات الشيح الأبيض من النباتات العطرية المعمرة المنتشرة في المناطق الجافة وشبه الجافة، ويُعرف بأهميته الطبية والبيئية والصناعية . تتناول هذه المراجعة أحدث النتائج حول تركيبه الكيميائي وزيوته الطيّارة وأنشطته الحيوية وخصائصه الفسيولوجية التكيفية .أظهرت الزيوت الطيّارة احتواءها على مركبات مونوتربينية مثل-1,8 سينول، الكافور، الثوجون، والبورنيول، ذات نشاط قوي مضاد للميكروبات والأكسدة والسرطان . تسهم المركبات الفينولية في تعزيز الأنشطة المضادة للأكسدة والتأثيرات الأليلوباثية من خلال تنظيم الإنبات ومسارات الإنزيمات .كما أشارت الدراسات الحديثة إلى تطبيقاته البيئية الصديقة مثل مقاومة التآكل وفعاليته كمبيد حشري طبيعي .كشفت التقييمات الفسيولوجية والجزيئية عن قدرة النبات العالية على التكيّف مع الجفاف من خلال تراكم السكريات والبروتينات والأحماض الأمينية وتنشيط الإنزيمات المضادة للأكسدة، إضافة إلى تنوعه الوراثي المرتبط بالعوامل البيئية والجغرافية .إن دمج التقنيات الحيوية الحديثة مع الدراسات التطبيقية يعزّز من القيمة الدوائية والبيئية والاقتصادية للنبات.

الكلمات المفتاحية :الشيح الأبيض، الزيوت الطيّارة، المركبات الفينولية، النشاط المضاد للأكسدة، التأثيرات الأليلوباثية، التكيّف البيئي.

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1.Introduction

The Asteraceae Martinov (Compositae Giseke), often referred to as the Aster or Compositae family, is one of the largest families of flowering plants, encompassing over 23,000 species and 1,535 genera of trees, shrubs, and herbaceous plants (Judd et al., 2002). Within this family, the genus Artemisia which includes species such as wormwood and tarragon holds particular ecological and commercial importance, comprising around 400 widely distributed species.

Among these, Artemisia herba-alba Asso [Artemisia aragonensis Lam., Seriphidium herba-alba (Asso) Soják] is a small, greyish, highly aromatic perennial shrub commonly known as white wormwood or desert wormwood (Arabic name: chih). This species is native to the Mediterranean Basin, the Arabian Peninsula, Western Asia, Southwestern Europe, and North Africa. In Algeria alone, eleven spontaneous species of Artemisia have been documented (Belhattab et al., 2014).

The taxonomic complexity of A. herba-alba in North Africa has been emphasized by Dobignard (1977), who highlighted the need for a comprehensive taxonomic review of this group. Accordingly, the current investigation adopts a conventional species delimitation approach. Recent reviews, such as that by Mohamed et al. (2010), have examined in detail the plant’s taxonomy, morphology, phytochemistry, distribution, and diverse biological activities.

From an ecological standpoint, Artemisia herba-alba typically thrives in arid and semi-arid climates, particularly in the dry regions of the Mediterranean basin and the northwest Himalayas. It is commonly found on nitrophilous and gypsum-rich substrates. A significant population of this species has been documented in the Iberian Peninsula, especially across eastern, southeastern, and southern Spain (Salido et al., 2004). Due to its medicinal and aromatic properties, in addition to increasing ecological threats such as overgrazing and over-harvesting, this species is receiving growing scientific attention both for conservation and pharmaceutical development.

Taxonomy of Artemisia herba-alba

The taxonomic classification of Artemisia herba-alba places it within the following hierarchical structure: Kingdom Plantae, Subkingdom Tracheobionta, Superdivision Spermatophyta, Division Magnoliophyta, Class Magnoliopsida, Subclass Asteridae, Order Asterales, and Family Asteraceae. It belongs to the subfamily Asteroideae, Subtribe Artemisinin, Tribe Anthemideae, Genus Artemisia L., and Subgenus Seriphidium, with its specific classification as Artemisia herba-alba Asso.

2.Methodology

This review utilized a structured approach centered on literature to gather, assess, and summarize scientific research on the chemical composition, biological activities, and possible uses of Artemisia herba-alba. Information was sourced from credible scientific databases such as PubMed, Scopus, ScienceDirect, and Google Scholar, emphasizing studies released between 1990 and 2024. To identify relevant materials, keywords including “Artemisia herba-alba,” “chemical composition,” “biological activities,” “essential oils,” “pharmacological effects,” and “toxicology” were applied.

Studies were selected based on specific criteria: they had to (1) explore the phytochemical aspects of A. herba-alba, (2) examine its biological or medicinal effects, (3) be peer-reviewed, and (4) offer clear experimental data. Any duplicates or non-scientific materials were eliminated. The selected studies were organized into thematic categories, focusing on properties such as antimicrobial, antioxidant, anticancer, insecticidal, allelopathic, and anticorrosive actions, with a spotlight on essential oils and phenolic compounds.

he analysis followed a narrative synthesis method, drawing comparisons across various studies, identifying commonalities, distinctions, and existing research gaps. References were formatted using APA style and grouped according to their thematic relevance. All findings and interpretations aimed to reflect the current understanding of Artemisia herba-alba while offering thoughtful insights into its practical uses and limitations.

3. Results and Discussion

3.1 Chemical Composition and Essential Oils

Essential oils of A. herba-alba are chemically diverse, with major constituents such as 1,8-cineole, camphor, thujone, borneol, α- and β-pinene (Zeggwagh et al., 2008). Geographical origin, harvest time, and extraction methods produce distinct chemotypes with varying bioactivities. Oxygenated monoterpenes are correlated with strong antimicrobial and antioxidant activities. Recent studies confirm variability and enhanced bioactivities among different populations (Belhattab et al., 2014; Mahgoub et al., 2025).

3.2 Antimicrobial Activity

Artemisia herba-alba has demonstrated broad-spectrum antimicrobial activity against a wide range of pathogens, including both Gram-positive and Gram-negative bacteria, as well as various fungal species. Extracts obtained using ethanol or methanol as solvents generally exhibit greater antimicrobial potency compared to aqueous extracts (Benbott et al., 2012). The essential oil of A. herba-alba has shown significant inhibitory effects against Staphylococcus aureus, Escherichia coli, and Candida albicans. These antimicrobial properties are primarily attributed to the presence of phenolic constituents and monoterpenes, which are known to disrupt microbial cell membranes and impair their function.

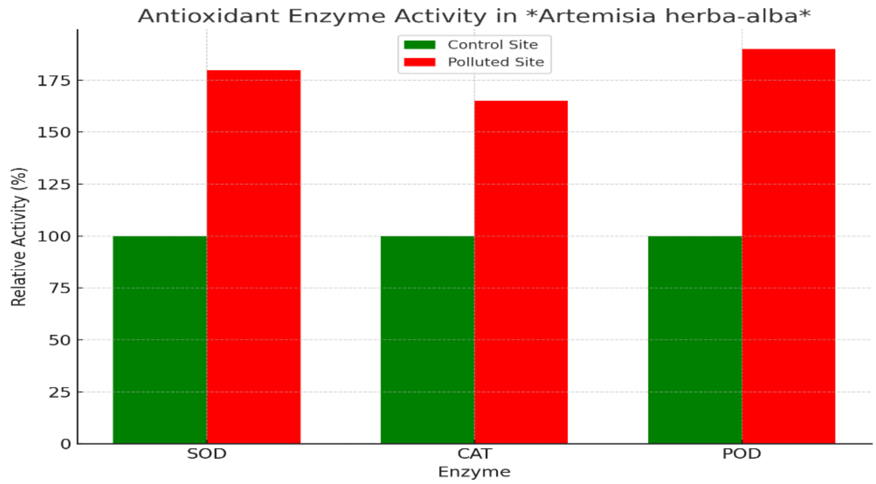
Recent research also indicates larvicidal activity against mosquitoes, expanding eco-friendly applications (Alami et al., 2025).

3.3 Antioxidant and Cytotoxic Properties

Phenolic compounds, particularly flavonoids, play a crucial role in the antioxidant potential of Artemisia herba-alba. Investigations employing DPPH radical scavenging assays have demonstrated notable antioxidant activity, which shows a positive correlation with total phenolic content (Bendif et al., 2017). Additionally, certain extracts have exhibited cytotoxic effects against cancer cell lines such as HepG2 and MCF-7, indicating their potential as candidates for anticancer drug development. However, further in vivo studies are required to validate these findings and determine their clinical relevance.

Figure 1 presents the comparative activity levels of antioxidant enzymes—superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD)—in A. herba-alba specimens collected from polluted and non-polluted (control) environments. The marked increase in enzymatic activity under pollution stress suggests an adaptive physiological response to airborne contaminants.

Figure 1: Antioxidant enzyme activity comparison between control and polluted sites.



3.4 Anticorrosion Properties of Essential Oils

Benabdellah et al. (2014) evaluated the anticorrosive activity of Artemisia herba-alba essential oil on steel in acidic environments, specifically 2 M phosphoric acid (H_3PO_4) and 0.5 M sulfuric acid (H_2SO_4). The oil exhibited significant inhibition efficiencies, reaching up to 79% at a concentration of 6 g/L in phosphoric acid and 74% at 1 g/L in sulfuric acid. The inhibition mechanism was identified as cathodic inhibition. Notably, in phosphoric acid, the inhibition efficiency decreased with increasing temperature, whereas in sulfuric acid, it increased with rising temperature. The adsorption behavior of the oil followed the Langmuir isotherm model, indicating that the oil forms a monolayer adsorption on the metal surface.

3.5 Role of Phenolic Compounds in Seed Germination

Phenolic compounds in Artemisia herba-alba extracts have been shown to exhibit phytotoxic effects, such as inhibiting seed germination and photosynthesis. Al-Quadan and Al-Charchafchi (2008) investigated the regulatory role of esculetin, a phenolic compound, on the enzymes of the pentose phosphate pathway during seed germination. They found that the activities of glucose-6-phosphate dehydrogenase (G6PDH) and 6-phosphogluconate dehydrogenase (6PGDH) were reduced in the presence of esculetin. Notably, enzyme activity was higher under dark conditions compared to light. Furthermore, additional isoenzymes were identified when 0.4 mM concentrations of chlorogenic or caffeic acids were present, highlighting the complexity of enzymatic responses under various germination conditions and phenolic concentrations.

3.6 Allelopathic and Insecticidal Effects

The allelopathic potential of Artemisia herba-alba has been extensively documented, with aqueous extracts shown to inhibit seed germination and seedling growth in several plant species. These inhibitory effects are primarily attributed to the presence of phenolic acids and terpenoids, which interfere with enzymatic and hormonal processes during germination. Moreover, essential oils derived from A. herba-alba exhibit strong insecticidal activity against agricultural pests such as Callosobruchus maculatus, emphasizing its promise as a sustainable and eco-friendly alternative to synthetic pesticides (Alami et al., 2025).

3.7 Physiological, Biochemical, and Thermodynamic Characteristics of Artemisia herba-alba

The physiological and biochemical responses of Artemisia herba-alba to water deficit stress were comprehensively evaluated by Guenaoui et al. (2008), aiming to understand the plant's adaptability to drought conditions. Plants were exposed to two levels of water stress, 70% and 40% of field capacity (CC), for 36 days, followed by a recovery phase under full irrigation (100% CC) for 40 days. Several physiological and biochemical markers were monitored, including biomass production, water content, chlorophyll concentration, sugar and proline levels, and osmotic potential.

The results revealed that water stress at both 70% and 40% CC led to significant reductions in biomass accumulation, plant water content, and chlorophyll levels. In contrast, the accumulation of sugars and proline increased proportionally with the intensity of water deficit, indicating an osmoprotective response. Well-watered control plants showed higher biomass production but lower concentrations of osmolytes. A substantial decline in osmotic potential ($P < 0.05$) was also observed under both stress levels, confirming the impact of water scarcity on plant water relations. Notably, rewatering facilitated a gradual restoration of these parameters toward pre-stress levels, suggesting a strong recovery capacity and adaptive resilience of A. herba-alba under arid environmental conditions.

In parallel, the thermodynamic properties and moisture sorption behavior of A. herba-alba were investigated using isotherms generated at three different temperatures (30°C, 40°C, and 50°C) and across a wide range of water activity (0.0572 to 0.898). A clear hysteresis effect was observed between adsorption and desorption processes. Experimental data were fitted to five mathematical sorption models. The Guggenheim–Anderson–de Boer (GAB) model best described the desorption data, while the modified Halsey model provided the best fit for adsorption behavior. Using the Clausius–Clapeyron equation, thermodynamic parameters such as differential enthalpy and entropy were calculated. The observed sorption patterns supported the enthalpy–entropy compensation theory, indicating a consistent thermodynamic response in moisture interactions of A. herba-alba.

3.8 A. herba-alba Genetic Polymorphism Analysis

A genetic variability analysis was conducted on Artemisia herba-alba to investigate the morphological and chemical variation observed in this species. Inter-simple sequence repeats (ISSR) markers were used to examine DNA-level polymorphism, revealing no clear correlation between morphological characteristics, geographic distance, and genetic distance among the 60 polymorphic loci scored (Guenaoui et al., 2008). Recent advances have expanded this approach through RAPD and DNA barcoding analyses, which further confirmed a high degree of genetic variability influenced primarily by environmental and geographical factors rather than morphological traits (Mahgoub et al., 2025).

3.9 Corrosion Inhibition and Phenolic Activity of Artemisia herba-alba Extracts

The essential oil of Artemisia herba-alba, extracted via hydrodistillation and analyzed by GC and GC/MS, exhibits notable anti-corrosive properties when applied to steel in acidic media. In studies conducted by Benabdellah, the oil demonstrated a concentration-dependent inhibition efficiency in 2 M H_3PO_4, reaching up to 79% at 6 g/L, primarily through a cathodic inhibition mechanism. However, the efficiency decreased with increasing temperature, indicating a physical adsorption process that weakens under thermal stress.

Interestingly, in a separate system using 0.5 M H_2SO_4, the same oil exhibited a different thermodynamic behavior—its inhibition efficiency improved with rising temperature, peaking at 74% at a lower concentration of 1 g/L. This trend suggests a chemisorption-dominated mechanism in sulfuric acid, contrasting with the physisorption observed in phosphoric acid. These findings highlight the complex interaction between extract composition, temperature, and the corrosive medium.

Adsorption isotherm modeling further supported the interaction between the oil's bioactive components and the steel surface. The presence of phenolic compounds in the oil is particularly relevant, as these constituents not only influence corrosion behavior but also play a key role in plant metabolic processes. From a physiological perspective, phenolic compounds extracted from A. herba-alba have demonstrated phytotoxic effects, including suppression of photosynthesis and inhibition of seed germination. Their biosynthesis involves key pathways such as the pentose phosphate and shikimate routes, in which enzymes like glucose-6-phosphate dehydrogenase (G6PDH) and 6-phosphogluconate dehydrogenase (6PGDH) play central roles.

Al-Quadan and Al-Charchafchi (2008) investigated the regulatory effect of esculetin—a phenolic compound—on these enzymatic pathways during seed germination. Their findings revealed that esculetin treatment significantly reduced G6PDH and 6PGDH activity. Moreover, enzyme activity levels were generally higher under dark conditions than light, with both enzymes showing increased expression from day one to day five. The presence of chlorogenic and caffeic acids (0.4 mM) also triggered early expression of a secondary G6PDH isoenzyme, indicating concentration- and light-dependent modulation of metabolic responses.

Collectively, these findings emphasize the multifunctional role of A. herba-alba extracts: not only do they exhibit potential as eco-friendly corrosion inhibitors, but they also modulate fundamental physiological pathways, indicating their broader applicability in both industrial and biological contexts. Furthermore, recent research has highlighted the scalability potential of A. herba-alba essential oils in industrial corrosion control, although long-term performance and cost-effectiveness still require further applied investigation (Beniaich et al., 2023). Phenolic compounds thus remain central to both biochemical and industrial functionality, influencing enzymatic regulation, photosynthetic activity, and seed germination.

5. Research Gaps and Future Directions

The current body of literature on Artemisia herba-alba reveals several critical gaps that merit further exploration to support its scientific, pharmacological, and industrial development.

Firstly, there is a notable lack of methodological standardization across studies, particularly concerning environmental conditions, extraction techniques, and stress induction protocols. Establishing unified experimental frameworks is essential to ensure reproducibility and allow for robust cross-study comparisons.

Secondly, while physiological and phytochemical investigations are relatively well-documented, genomic and transcriptomic data remain scarce. Future research should leverage advanced omics approaches to elucidate gene networks associated with secondary metabolite production and stress adaptation mechanisms.

Thirdly, although some findings suggest that ecological and geographical variability affects phytochemical composition, comprehensive multi-regional studies are lacking. Integrated analyses incorporating soil characteristics, climatic variables, and ecological parameters are necessary to better understand chemical polymorphism and local adaptation.

Fourthly, with increasing demand for A. herba-alba in medicinal applications, there is an urgent need for sustainable cultivation methods and conservation strategies, particularly under the pressures of climate change in arid and semi-arid ecosystems. Future work should adopt a holistic approach that balances ex-situ and in-situ conservation with ecological resilience.

Fifthly, while the essential oils of A. herba-alba have demonstrated antimicrobial and corrosion-inhibitory properties, there is limited research addressing industrial scalability, cost-effectiveness, and long-term performance. Applied studies in collaboration with industrial sectors are needed to assess commercial viability and application potential.

Lastly, the role of specific phenolic compounds in seed germination and abiotic stress response remains insufficiently understood. Mechanistic studies focusing on enzyme activity modulation and metabolite profiling under varying light and stress conditions are recommended to elucidate their functional roles.

Addressing these interrelated gaps will significantly enhance the scientific basis for the utilization and conservation of A. herba-alba, while promoting its integration into sustainable industrial and pharmacological frameworks.

Conclusion

Artemisia herba-alba is a widely distributed plant with significant therapeutic and medicinal properties, used in both traditional and modern medicine. Extensive studies confirm its chemical diversity and biological activities, particularly antimicrobial, antioxidant, anticancer, allelopathic, and corrosion-inhibitory effects. The integration of recent omics studies and applied research highlights its potential in pharmacology, agriculture, and eco-friendly industrial applications. Despite progress, research gaps in standardization, genomic insights, multi-regional variability, and industrial scalability persist. Future work focusing on these areas will support sustainable exploitation and conservation strategies, ensuring the continued value of this versatile species. Emerging studies also indicate potential applications in larvicidal control and genetic-assisted breeding for stress resilience.

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