A Monograph on *Artemisia annua L*: An Agroecological and Biological Study

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1.0 Introduction

Artemisia annua L., commonly known as sweet wormwood, is an annual herbaceous plant of considerable scientific and socioeconomic importance. Belonging to the Asteraceae family, this species first gained formal taxonomic recognition through the work of Carl Linnaeus in 1753. However, its global significance was firmly established centuries later when the Chinese pharmacist Tu Youyou developed artemisinin-based therapies from its leaves, revolutionizing the treatment of malaria and earning the Nobel Prize in 2015. Today, *A. annua* remains the primary natural source of artemisinin, a compound that forms the backbone of first-line antimalarial combination therapies recommended by the World Health Organization.

Beyond its medicinal value, *A. annua* presents a compelling subject for agroecological and biological study. Taxonomically classified as a diploid flowering plant (2n = 18) with a hermaphroditic, wind-pollinated reproductive system, it exhibits life history traits adapted to open, sunlit environments. Its native range spans the temperate and subtropical zones of Asia, particularly China and Vietnam, though human activity has introduced it to Europe, Africa, and the Americas. The species thrives in well-drained, neutral-to-slightly acidic loamy soils and performs optimally under full sunlight at moderate temperatures (20-26 °C). From germination to senescence, completed within a single growing season, its phenology is tightly regulated by photoperiod, with artemisinin accumulation peaking at early flowering.

Given the persistent global burden of malaria and the corresponding demand for artemisinin, understanding the ecology, biology, and cultivation requirements of *A. annua* is both scientifically relevant and practically urgent. This chapter provides a comprehensive overview of the species, covering its taxonomic hierarchy, fossil record and origin, current distribution, ecoregion preference, climate and soil requirements, water and light regimens, reproductive biology, propagation methods, pest management, growth stages, harvesting practices, and market dynamics. By synthesizing existing knowledge, this review aims to support research, growers, and policymakers in optimizing the sustainable production and utilization of this invaluable medicinal plant.

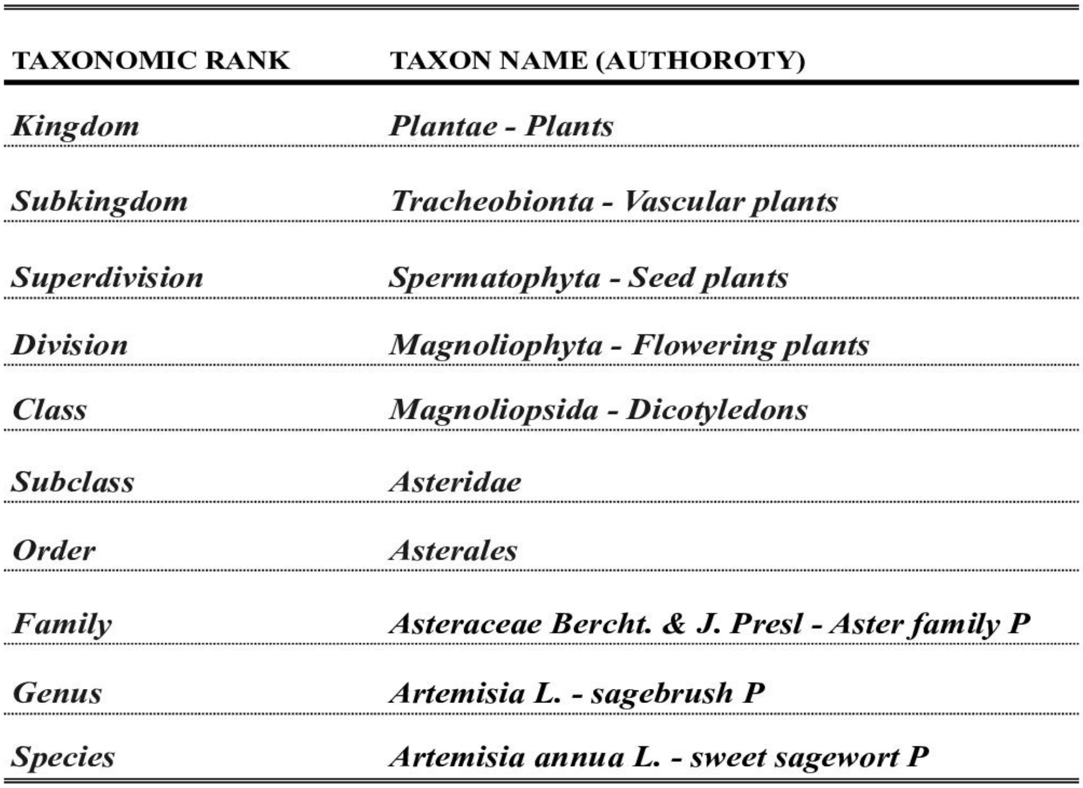
2.0 Agroecology

2.1 Taxonomy

The first person to find *A. annua* was Carl Linnaeus, the Swedish botanist credited for the original scientific description and naming of the species, in Species Plantarum, first published in 1753 (Royal Botanic Gardens Kew, 1753). The complete taxonomic hierarchy is given in Table 1. Years later, a Chinese pharmacist called Youyou delved more in depth into the medical component of the *A. annua* and developed a powerful antimalarial drug, Royen (2025).

Table 1

Taxonomic Hierarchy



TAXONOMIC RANK	TAXON NAME (AUTHOROTY)
Kingdom	***Plantae - Plants***
Subkingdom	***Tracheobionta - Vascular plants***
Superdivision	***Spermatophyta - Seed plants***
Division	***Magnoliophyta - Flowering plants***
Class	***Magnoliopsida - Dicotyledons***
Subclass	***Asteridae***
Order	***Asterales***
Family	***Asteraceae Bercht. & J. Presl - Aster family P***
Genus	***Artemisia L. - sagebrush P***
Species	***Artemisia annua L. - sweet sagewort P***

Note: Table amended from USDA Plant Database (USDA, 2025). It represents the taxonomic hierarchy of *Artemisia annua L*.

Scientists like to classify living things in order to understand their connections to each other better. One way was through taxonomy (Plant Taxonomy, 2020). Living things are separated into six kingdoms. *A. annua* is in the Plantae or Plant Kingdom. Its subkingdom is classified as Tracheobionta or Vascular plant, which means that *A. annua* is a plant that has veins or conductors that transfer water or nutrients throughout the plant.

The superdivision is Spermatophyta or seed plants; these are plants that produce seeds for reproduction. According to Sundberg (2023), this process of reproduction gives various advantages like "protection from environmental stressors, dormancy capabilities, and efficient dispersal mechanisms."(Sundberg, M. D, 2023). But this has three other divisions; in this case, *A. annua* is Magnoliophyta or flowering plants; these plants make up 90% of the plantae kingdom. They have a special term that is angiosperm. Following this, "Angiosperms are seed-producing plants with flowers and fruits that enclose the seeds. Angiosperms are part of the phylum Magnoliophyta."(Plant Taxonomy, 2020). Flowers also help plants adapt to different temperature changes by decreasing the amount of Ultraviolet (UV) pigment in their petals.

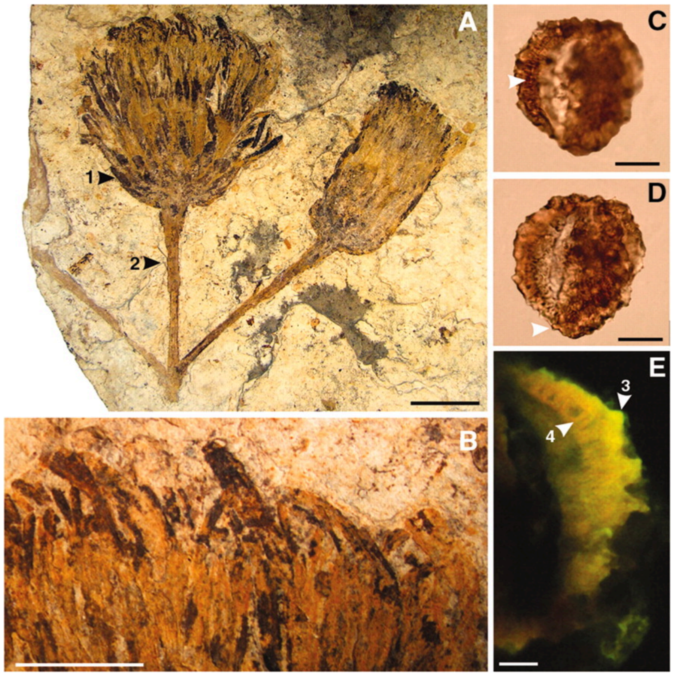
The Class of *A. annua* is *Magnoliopsida - dicotyledon*s. One of the key factors of this class is that the plant has two embryonic leaves, known as *cotyledons*, in its seeds. This class has about 175,000 species of plants with important crops like tomatoes, beans, and potatoes. Another characteristic is that they have broad leaves with a network of branching veins. (Bullard, E, 2023). The Subclass is *Asteridea*, according to the IBERS, the key characteristics are "petals fused into a tube, small numbers of stamens alternating with petals (IBERS, nd). It includes the largest family of dicots, the *Asteraceae* or Compositae (sunflowers, daisies, etc.). An economically important family is the *Solanaceae* (potato, tomato, tobacco, red peppers)." The order - *Arterales*, recognized for their compound flowers made up of small flowers called florets (BioDiversity4All, 2025). The family - *Asteraceae*. The plants are characterized by composite flower heads and one-seeded achene fruits. *Asteraceae* is important for its many garden ornamentals, such as asters, chrysanthemums, cosmos, dahlias, marigolds, and zinnias. Several members of *Asteraceae* have economic importance as food crops." (Britannica, 2025). The *Genus Artemisia L.*, according to "one of the largest and most widely distributed genera of the family *Astraceae*" (Bora & Sharma, 2010)

2.2 Fossil Record and Origin

The family of *Asteraceae*, which includes *A. annua*, is one of the largest and most diverse families of flowering plants (Figure 1 illustrates early evolutionary morphology, including the capitulum and fossilized pollen grains). Fossil evidence of this family dates back to the late Cretaceous and early Paleogene periods, approximately 50 million years ago. Fossilized pollen grains from the genus Artemisia have been found in Miocene sediments (about 5-32 million years old) in regions such as Central Asia and Europe (Graham, 1996). Although no direct fossils of *A. annua* have been identified, this evidence indicates that the genus itself has ancient roots and evolved in temperate areas of the Northern Hemisphere. The long fossil record of Artemisia suggests that the species we see today are descendants of plants that adapted to dry and open environments during the Miocene

Figure 1

Fossil Evidence



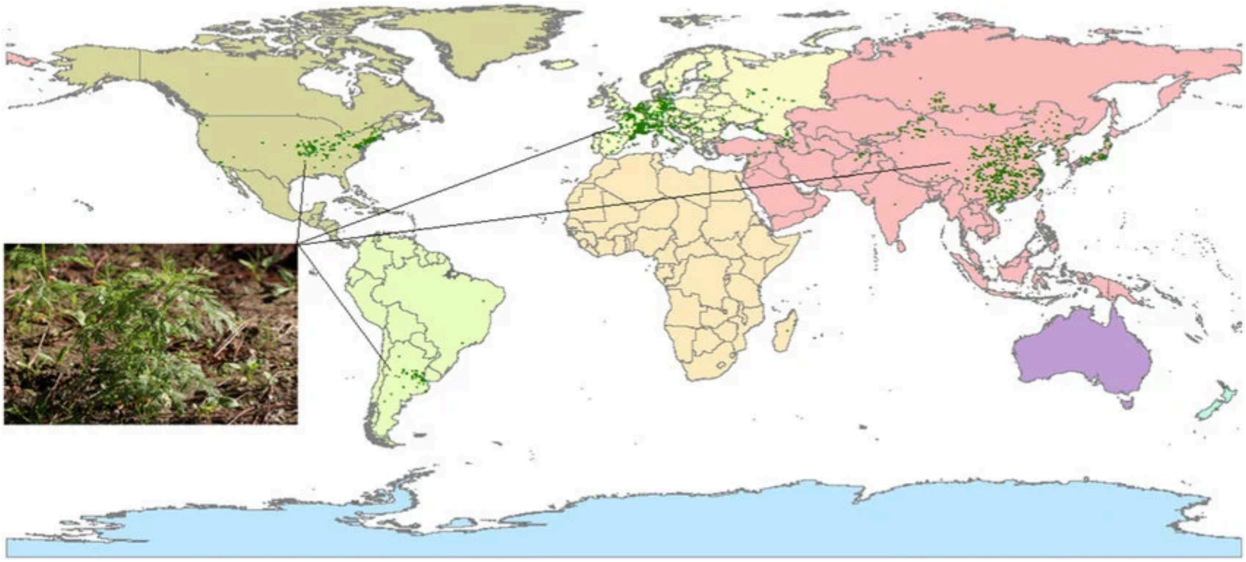
Note: Fossil plate from Barreda et al. (2010). It illustrates the early evolutionary morphology of the Asteraceae family; the capitulum (A-B) and fossilized pollen grains (C-E).

2.3 Current Distribution

The center of origin for *A. annua* is believed to be temperate Asia, particularly China, where the species has been used for medicinal purposes for over 2,000 years (Figure 2 shows its global distribution, with green shading indicating native range and purple indicating introduced or naturalized regions). Ancient Chinese texts, such as the Zhouhou Beji Fang written by Ge Hong in the 4th century CE, mention the use of this plant to treat fevers and malaria-like symptoms (Tu, 2011). From its Asian origin, *A. annua* spread to Europe and later to Africa and the Americas through human trade and medicinal interest. The plant's adaptability to diverse climates has helped it establish itself in many parts of the world. Today, *A. annua* grows in temperate and tropical regions worldwide. It thrives in well-drained soils and sunny environments. Major producing countries include China, Vietnam, India, Kenya, Tanzania, Madagascar, and Ethiopia, where it is cultivated primarily for its artemisinin content; the key compound used in modern antimalarial drugs(FAO, 2020). While it is not a major food crop, data from the Food and Agriculture Organization (FAO) and regional agricultural reports show its importance in the pharmaceutical industry. In many countries, both wild and cultivated populations exist, making *A. annua* a species with wide ecological and economic significance.

Figure 2

Global distribution of *Artemisia annua L.*



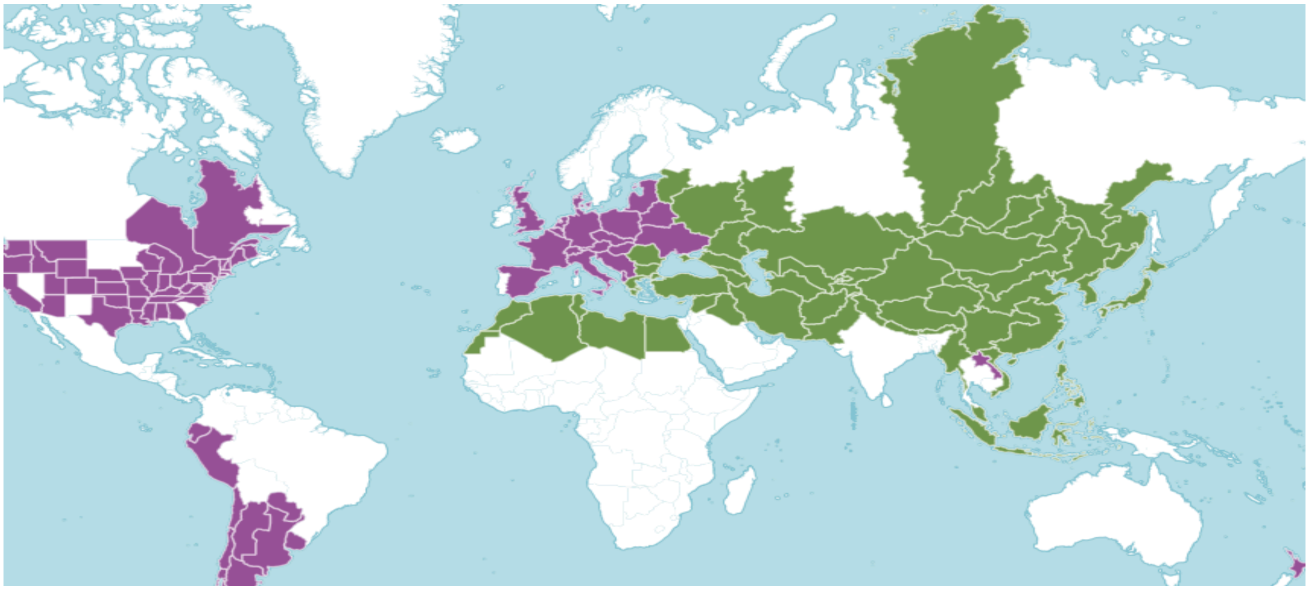
Note: Map adapted from Wang et al. (2022). It represents the distribution and occurrence points of the species; green shading typically indicates native range while purple indicates introduced or naturalized regions.

2.4 Ecoregion

Artemisia annua L. is native to the temperate and subtropical zones of Asia, particularly China, Vietnam, and parts of the Himalayas (Kew Science, n.d). As shown in Figure 3, green indicates the native range and purple indicates the introduced regions. Naturally, it grows in the temperate plains and hilly regions, favoring well-drained, open habitats rather than dense forests. It is often found along riverbanks, roadsides, grasslands, and distributed soils, where sunlight exposure is high, and competition with taller vegetation is limited. The plant typically thrives in warm temperate to subtropical climates, with moderate rainfall and seasonal variation.

Figure 3

Global distribution of *Artemisia annua L.*



Note: Map amended from Plants of the World Online | Kew Science. (n.d.). It represents where you can find *A. Annue* in the world; green is native, and purple is introduced.

2.5 Climate

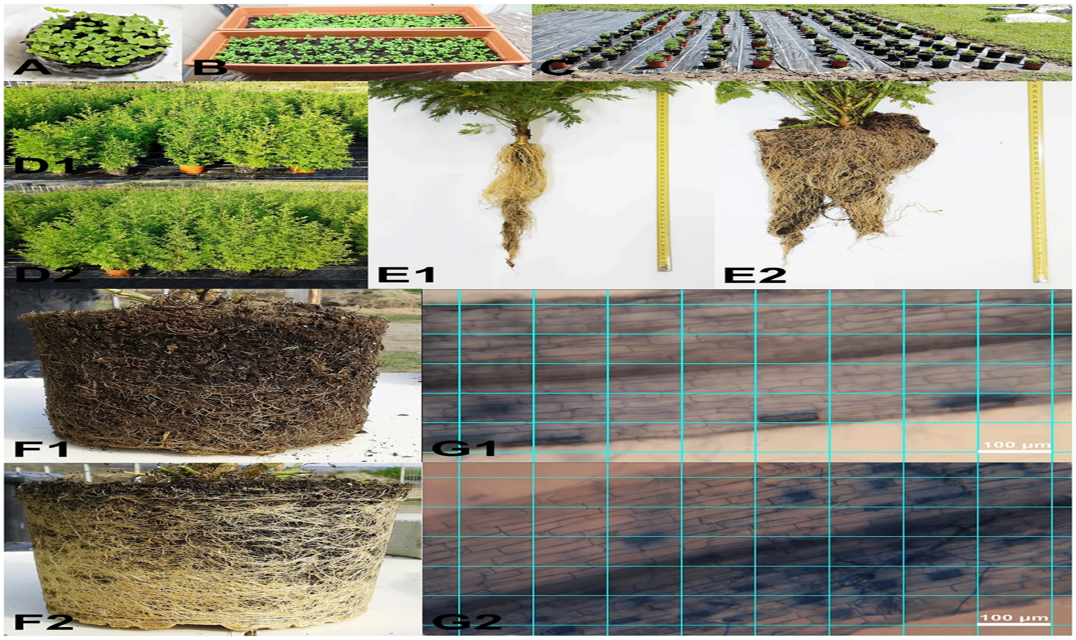
These ecoregions experience average annual temperatures between 20°C and 30°C, and *A. annua* grows during the warm months before dying back in winter (World Agroforestry Centre, 2022). Its ability to tolerate dry periods allows it to grow in semi-arid or savanna-like regions, but it does not naturally occur in desert or tropical rainforests, as it requires both sunlight and moderate soil moisture. In its native range, *A annua* commonly grows in flat plains and low mid-altitude hills, rather than mountainous regions. The plant's distribution shows that it prefers open, sunlit areas rather than shaded understorey environments. This adaptation to full sunlight enhances its photosynthetic rate and supports the production of artemisinin, its key medicinal compound (Lommen et al., 2006)

2.6 Geology and Soil Requirements

Artemisia annua L. prefers well-drained loamy soils with moderate organic matter and a neutral to slightly acidic pH (6.0-7.0). As illustrated in Figure 4, the image shows *A. annua* growth stages and root colonization by the fungus R. irregularis (Domokos et al., 2018). These conditions balance nutrient availability and water retention, preventing root stress. Fertile soils composed of sand, silt, and clay offer ideal porosity that promotes healthy root development and oxygen diffusion. The plant does not tolerate waterlogged soils, as excess moisture restricts oxygen flow to roots and encourages fungal growth, leading to writing or root rot. On the other hand, sandy loams enhance drainage while retaining enough moisture to sustain transpiration and nutrient uptake (Abdulelah & Zainal, 2022). *A. annua* also benefits from soils with moderate salinity tolerance. Slightly saline soils can enhance secondary metabolite synthesis by inducing mild physiological stress, which increases artemisinin concentration (Ferreira & Janick, 1995). However, excessive salinity disrupts ion balance and reduces growth efficiency.

Figure 4

Cultivation and root morphology of *Artemisia annua L*.



Note: Image adapted from Domokos et al. (2018). It shows *A. annua* growth stages and root colonization by the fungus R. irregularis.

The growth of *A. annua* depends on the availability of sixteen essential plant nutrients, including macronutrients like nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients such as iron (Fe) and zinc (Zn). Nitrogen supports leaf development, phosphorus aids in root growth and energy transfer, and potassium enhances stress resistance. Deficiency of any of these nutrients can lead to visible anatomical anomalies like chlorosis from nitrogen deficiency or stunted growth from phosphorus deficiency (Mengel & Krikby, 2001). The plant's optimal growth occurs when soil nutrient content is balanced through organic matter decomposition and microbial activity, both of which improve cation exchange capacity and nutrient retention. Soil derived from limestone or granite-based geology tends to have higher calcium and magnesium concentrations, contributing to neutral pH levels, and is ideal for *A. annua.*

The geology of an area determines the mineral composition of its soil, which directly affects nutrient availability. In a region where *A. annua* grows naturally in areas such as China and parts of East Africa, where the soil is often derived from sedimentary and metamorphic rocks that contribute to moderate fertility and pH stability. Weathered parent materials release minerals like potassium and calcium into the soil, essential for enzymatic and structural function in plant tissues. Furthermore, the depth of soil, generally around 30 to 50 cm, provides sufficient space for the plant's deep root system to anchor and absorb water efficiently, especially during dry seasons. The geological those plays a vital role in ensuring a nutrient-rich and aerated medium for continuous growth.

2.7 Water Management

Artemisia annua L. grows best in well-drained soils with moderate water availability during its early growth stages. Consistent watering supports leaf expansion and photosynthesis, but overwatering can reduce root oxygenation and lower artemisinin yields (Delabays et al., 2001). The plant's deep taproot system allows it to access water from lower soil layers, providing resilience against short dry periods. However, under high light and temperature, its transpiration rate increases significantly, raising water demand. Wilting can occur as a temporary survival mechanism to reduce water loss, aligning with typical C3 plants' responses to drought (Taiz et al., 2015). Proper irrigation management, especially during flowering and biomass accumulation, is essential for maximizing yield and maintaining plant health.

2.8 Light and Temperature Regimes

Artemisia annua L. is a C3 photosynthetic plant, meaning it performs best in moderate temperature conditions typical of many temperate and subtropical regions. The species grows optimally between 20°C and 26 °C, with daytime temperatures promoting active photosynthesis and nighttime temperatures aiding respiration and carbohydrate accumulation (Ferreira & Janick, 1996; Laughlin, 2002). When temperatures rise above 30°C in the Astereae family, *A. annua* does not require a cold period to flower. However, moderate temperature variation between day and night can improve artemisinin content and overall essential oil yield (Ferreira & Janick, 1996; Delabays et al., 2002). In cooler climates, germination and establishment occur best under frost-free periods, which directly influence respiration, transpiration, and photosynthesis, making temperature a key factor in its agroecological success.

Light plays a central role in the growth and secondary metabolism of *A. annua*. The plant thrives under full sunlight, where high light intensity supports maximum photosynthetic rates and higher artemisinin concentrations (Ferreira & Janick, 1996). *A. annua* performs best under long-day photoperiods of 12 to 14 hours, which stimulate vegetative growth before flowering. The quality of light also affects productivity. Blue and red wavelengths enhance photosynthetic activity, while far-red light triggers flowering responses (Taiz et al., 2015). Because *A. annua* contains abundant chlorophyll a and b, it efficiently converts light energy, carbon dioxide, and water into glucose and oxygen, supporting rapid biomass production and the synthesis of secondary metabolites.

3.0 Biology

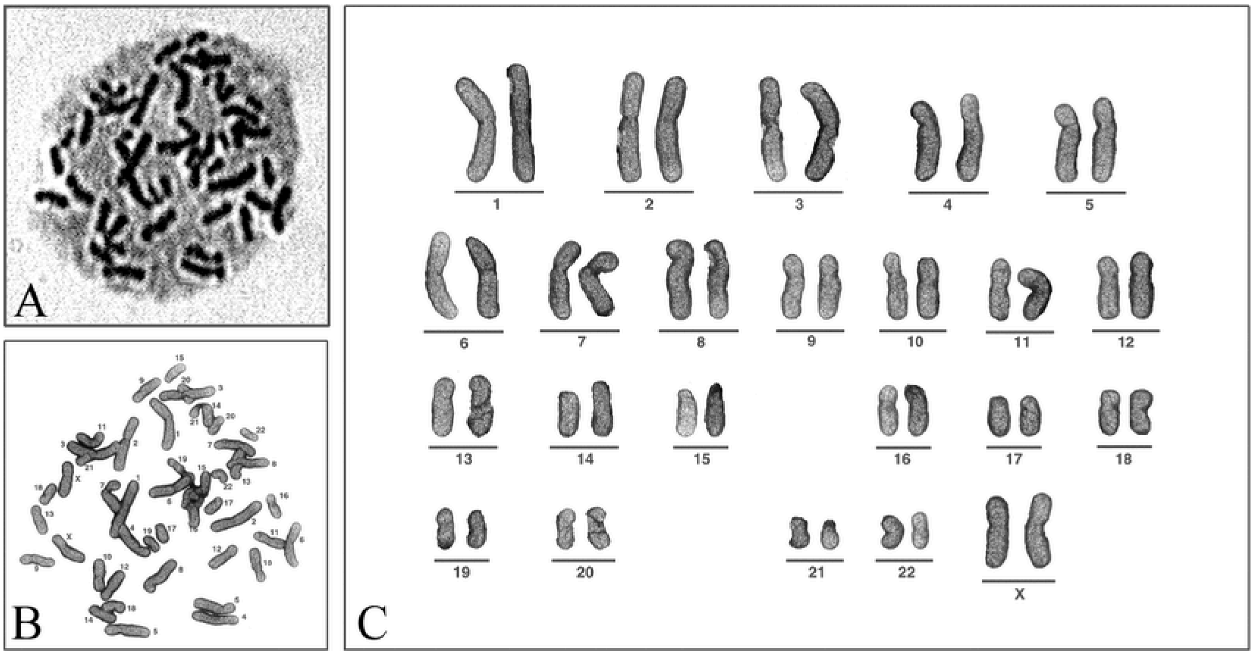
3.1 Chromosomes Complement

Artemisia annua L. is a diploid species (organisms that have somatic cells that contain two sets of complete chromosomes, meaning one set comes from each parent) with a somatic chromosome number of 2n = 18, corresponding to the basic number of chromosomes, meaning that each x = 9. As shown in Figure 5, a novel imaging technique reveals the internal ultrastructure of chromosomes (Ghazizadeh, n.d.). This configuration is mostly seen in the genus Artemisia and the Asteraceae family. Cytogenetic analyses (examine the structure and number of chromosomes) have shown relatively small and morphologically uniform chromosomes, which tells us that limited structural rearrangements have occurred during evolution (Kreistchitz & Vallès, 2007).

The diploid nature of *A. annua* is important for breeding and also domestication. Stable chromosome pairing during meiosis results in high fertility and reliable seed production, traits that facilitate genetic improvement programs. Although polyploidy is common in the genus Artemisia, *A. annua* remains predominantly diploid, which may partly explain its relatively narrow structure variation compared to other congeners (Torrel et a., 2010).

Figure 5

Internal ultrastructure of chromosomes observed using a novel image technique



Note. From a novel technique for observing the internal ultrastructure of human chromosomes with a known karyotype, by Mohammad Ghazizadeh

3.2 Life Cycle and Phenology

Artemisia annua L. is an annual plant, which means that it has a life cycle of one year, progressing through distinct vegetative, reproductive, and senescent stages. Germination generally occurs in early spring, followed by fast vegetative growth characterized by extensive leaf development and branching.

Phenological development (study of recurring plant and animal life cycle) is strongly regulated by photoperiod, with flowering induced under short-day conditions. Plants grown under long-day conditions tend to remain in the vegetative stage for extended periods, accumulating biomass but delaying reproductive development. Flowering typically begins in late summer and continues into early autumn, varying with latitude, altitude, and climatic conditions (Laughlin, 1993). The timing of flowering is essential since artemisinin concentration (an antimalarial compound) is closely linked to phenological stage, reaching its maximum shortly before or at the onset of flowering. Following seed maturation, plants undergo senescence (aging of cells), marked by leaf yellowing and reduced metabolic activity(Ferreira et al.,1997).

3.3 Reproductive Biology

3.3.1 Sexuality

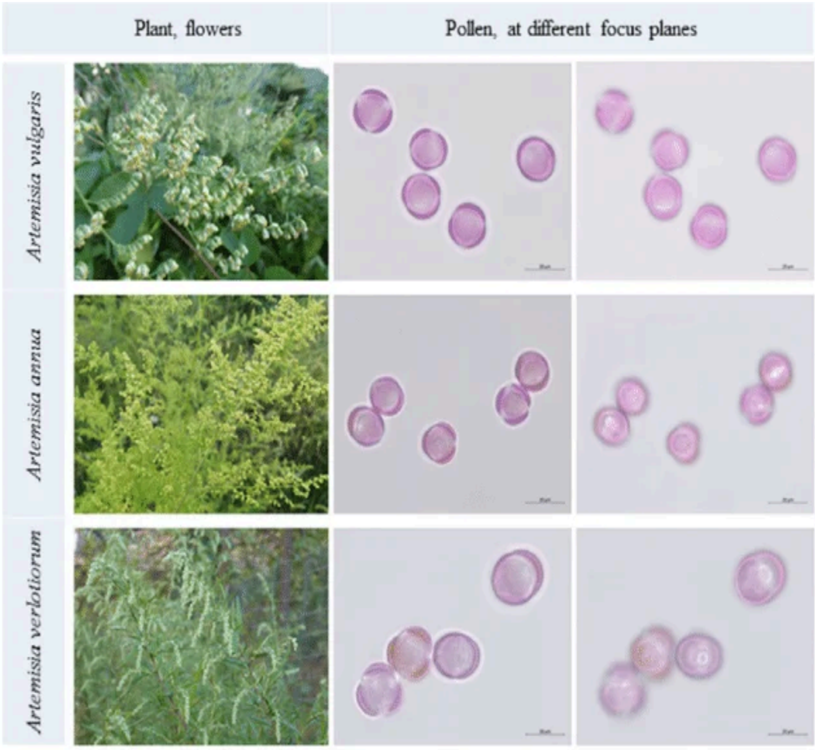
The species shows a hermaphroditic reproductive system (an organism that has both male and female reproductive organs), with flowers containing both stamens and pistils. This bisexual organisim structure allows *A. annua* to reproduce through both self-fertilization and cross-fertilization. However, genetic studies indicate that outcrossing predominates in natural populations, contributing to relatively high genetic diversity (Vallès et al., 2001)

3.3.2 Pollen and Anthesis

Anthesis is *A. annua,* which occurs gradually across the inflorescence, extending the period during which pollen is released. As shown in Figure 6, pollen concentration trends for Artemisia species, including *A. annua*, show an increase in autumn allergenic pollen due to late flowering invasive species in northern Italy (Cristofori et al., 2020). This staggered flowering pattern increases the likelihood of successful fertilization. The pollen grains are spherical to slightly ellipsoidal, with a smooth to weakly ornamented exine (variation in the structure of the pollen wall). Pollen production is abundant, compensating for the low efficiency typically associated with wind pollination. Pollen viability is highest during dry, warm conditions, which favor dispersal through air currents. Environmental stress, such as excessive humidity or low temperatures, can reduce pollen longevity and fertilization success (Torrel et al., 2010)

Figure 6

Trend of Artemisia pollen concentrations



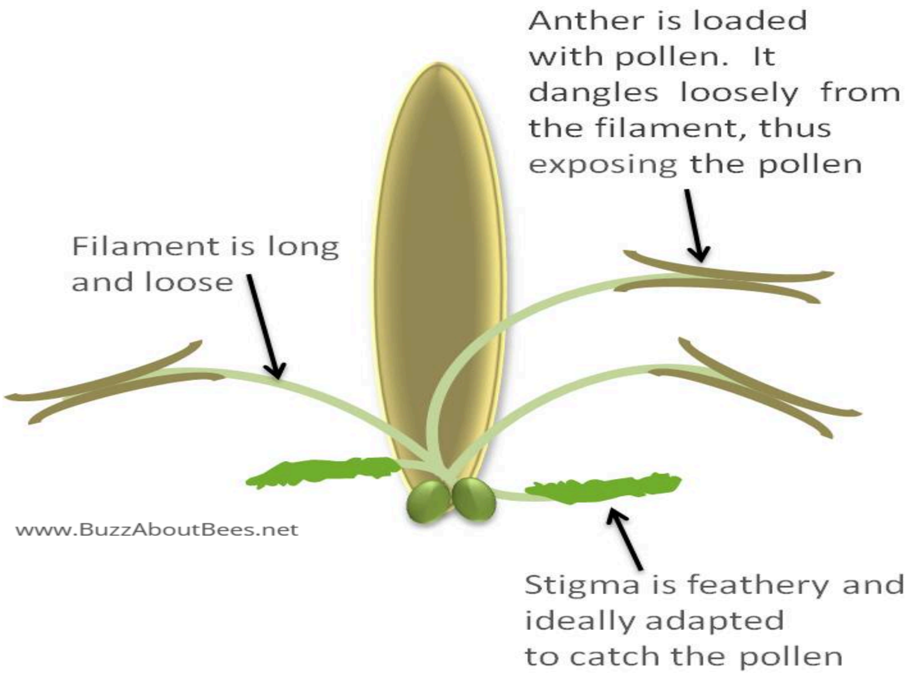
Note: Graph adapted from Cristofori et al. (2020). It shows the increase in autumn allergenic pollen due to late-flowering invasive species in Northern Italy

3.3.3 Pollination and Potential Pollinators

Pollination in *A. annua* is predominantly anemophilous (plants pollinated by wind), as evidenced by its reduced floral structures, lack of nectar, and high pollen output. As illustrated in Figure 7, specialized anatomical adaptations for wind pollination include an anther loaded with pollen that dangles loosely from a long filament, and a feathery stigma ideally adapted to catch pollen (BuzzAboutBees, n.d.). Wind-mediated pollen dispersal allows gene flow over considerable distances, reducing inbreeding and increasing genetic mixing between populations. Although wind is the principal pollination mechanism, occasional insect visits have been documented. Small insects such as flies and bees may act as secondary pollinators, especially in dense populations. However, their contribution to overall pollination success is considered minimal compared to wind dispersal (Vallès at al., 2001)

Figure 7

Anatomical adaptations for wind pollination



Note: Diagram adapted from BuzzAboutBees (n.d.). It displays the specialized structure of the anther, filament, and feathery stigma used to facilitate pollen dispersal and capture.

3.3.4 Fruit Development and Seed Set

After fertilization, the ovary develops into a single-seeded achene, the characteristic fruit type of the *Astereceae*. Fruit development is rapid, and mature seeds are produced within a few weeks after flowering. Seed set is influenced by environmental factors such as nutrient availability, water supply, and temperature. The seeds are extremely small, lacking specialized dispersal structures, but their low mass enables passive dispersal by wind and surface water. High seed production ensures successful regeneration, even under unfavorable conditions, contributing to the species' ability to establish in disturbed or marginal environments (Ferreira & Janick, 1995)

3.4 Ecophysiology

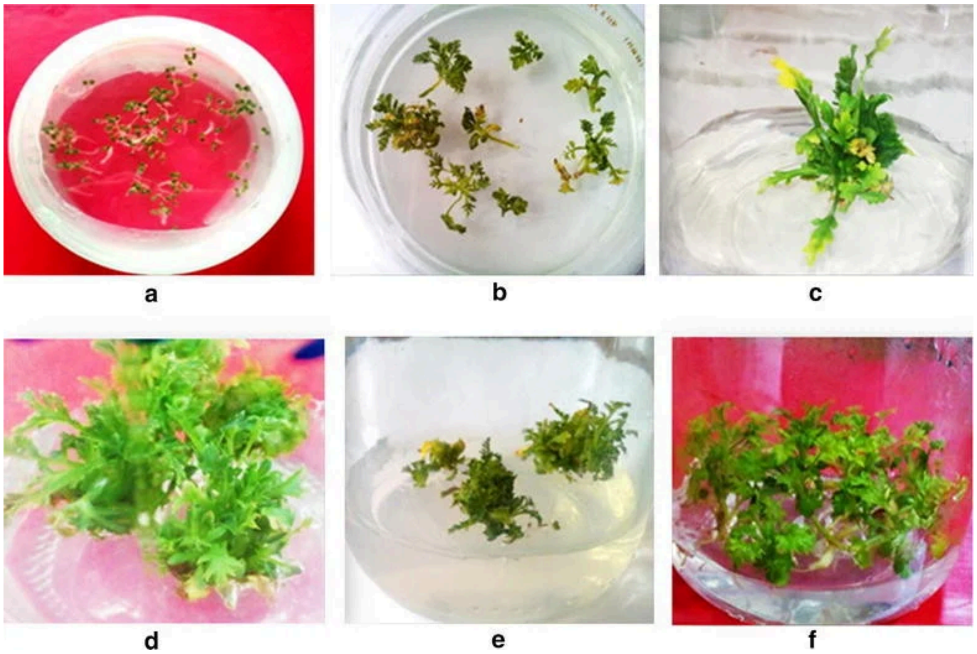
Artemisia annua L. demonstrates high ecophysiological adaptability (organism's ability to adjust its internal, functional processes), allowing it to thrive across a wide range of climatic and edaphic conditions. It grows best under full sunlight, where photosynthesis rates and biomass accumulation are maximized. Shaded environments result in reduced growth and delayed flowering. The species reveals moderated drought tolerance, achieved through efficient water use strategies and reduced leaf surface area during stress. Temperature plays a central role in metabolic regulation, influencing growth rate, flowering time, and secondary metabolite production. Optimal growth occurs in warm temperate climates, while extreme temperatures can limit physiological performance(Ferreira et al., 1997)

3.4.1 Germination

Germination in *A. annu*a is strongly influenced by light, temperature, and moisture availability. Seeds are positively photoblastic, requiring light exposure to initiate germination. This trait prevents germination at excessive soil depths, ensuring seedling emergence near the soil surface. Optimal germination temperatures range from 20 to 25 °C, although germination may still occur at slightly lower temperatures. Adequate soil moisture is essential, as desiccation during early stages can severely reduce seedling survival. Under optimal conditions, germination occurs within 7 to 14 days, followed by fast early growth (Laughlin, 1993). As shown in Figure 8, genetic transformation can increase artemisinin production through the expression of rol genes in *A. annua* tissues (Dilshad et al., 2015).

Figure 8

Effect of genetic transformation on artemisinin production.



Note: Image adapted from Dilshad et al. (2015). It illustrates the increased yield of artemisinin achieved through the expression of rol genes in *A. annua* tissues.

4.0 Propagation and Management

4.1 Propagation

4.1.1 Natural Regeneration

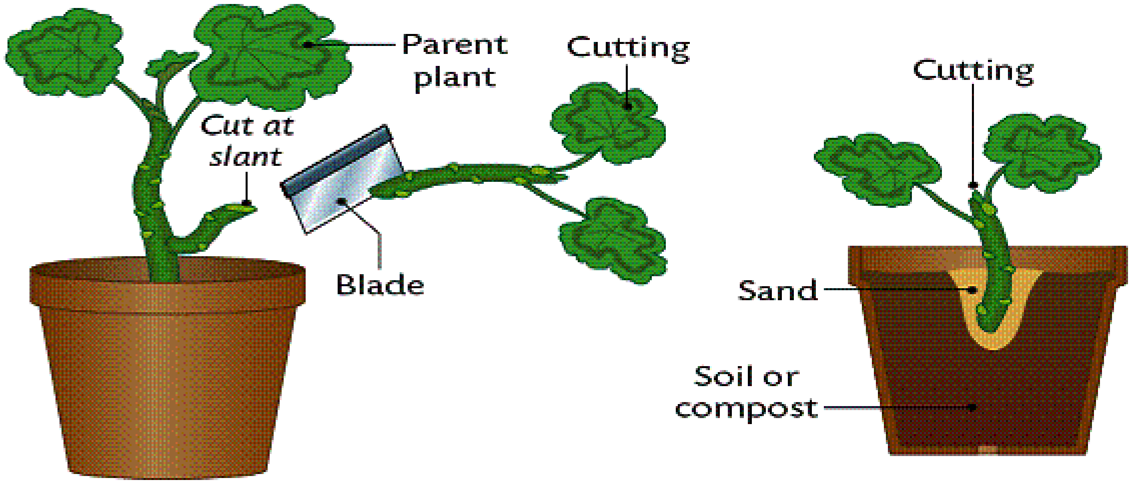
Natural regeneration of *A. annua* occurs primarily through the creation and spread of seeds by mature plants. The species produces very small seeds called achenes (a small, dry, one-seeded fruit), which can easily be dispersed by wind or water and germinate under acceptable environmental conditions. Germination generally happens within 4 to 10 days when adequate moisture, light, and temperature are available (World Health Organization, 2006). Because the seeds need light to germinate, they typically establish on the soil surface or in lightly disturbed soils. In natural ecosystems, A. annua commonly grows in open, sunny places with well drained soilds, which favor its fast growth and establishment (Ferreira & Janick, 1995).

4.1.2 Vegerative Propagation

Vegetative propagation involves producing new plants from vegetative plant parts such as stems or cuttings, as shown in Figure 9. In *A. annua,* stem cuttings taken from healthy parent plants can be placed in moist soil or another rooting medium until roots develop. This method allows farmers to maintain the genetic characteristics of selected plants, particularly those with high artemisia content, the compound used in malaria treatment. Vegetative propagation can also be advantageous because it produces uniform plants and can establish crops faster than seed propagation. Although *A. annua* is most commonly propagated by seeds, vegetative propagation is sometimes preferred in controlled cultivation systems because it preserves the desirable genetic traits of the parent plant (biovision infonet, 2024)

Figure 9

Methods of vegetative propagation in plants



Note: Diagram adapted from Murphy (n.d.). It illustrates the various natural and artificial methods used for vegetative propagation, ensuring genetic consistency in offspring.

Nursery propagation is commonly used for the large-scale cultivation of *A. annua*. Because the seeds are extremely small, they are typically first sown in seedbeds or nursery trays under controlled conditions. Once the seeds are sown on the soil surface, they are lightly pressed into the substrate to allow light exposure, which is necessary for germination. After germination, seedlings develop gradually and can be transplanted into the field when they reach around 10 centimeters in height and have 2 or 4 leaves (Artemisiaannua.net, 2024). Nursery propagation helps increase seedling survival rates and allows farmers to select the healthiest plants before transplanting them into the main cultivation field.

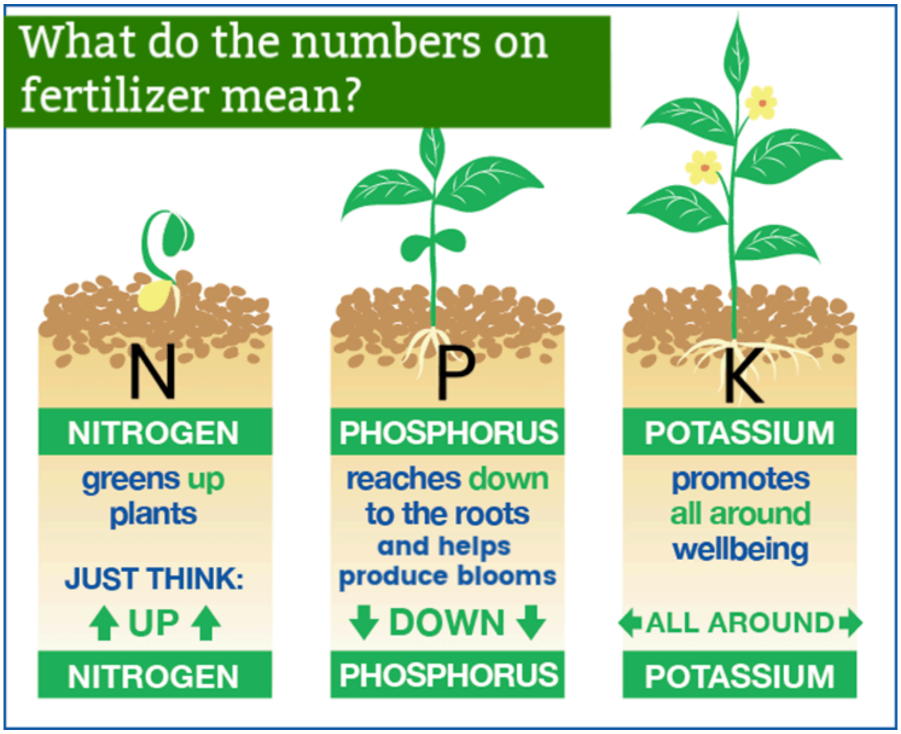
4.2 Cultivation and Care

4.2.1 Planting

Planting of *A. annua* generally occurs after seedlings have been grown in nurseries or seedbeds. The plant grows best in well-drained soils and locations with a lot of sunlight, which supports optimal growth and biomass production (Artemisiaannua.net, 2024). As explained in Figure 10, NPK ratios in plant fertilizers are significant: Nitrogen (N) supports foliage, Phosphorus (P) supports roots and flowers, and Potassium (K) supports overall plant health (Zaradmin, 2022). When seedlings reach about 10 centimeters in height, they are transplanted into the field with appropriate spacing to allow good air circulation and plant development. A planting density of about six plants per square meter has been suggested as a balance between plant growth and production of the active compound artemisinin (Artemisiaannua.net, 2024). Adequate irrigation during the early stages of growth is important, but excessive water should be avoided because the plant does not tolerate waterlogged soils.

Figure 10

The significance of NPK ratios in plant fertilizers



Note: Diagram adapted from zaradmin (2022). It explains the primary macronutrients required for plant growth: Nitrogen (N) for foliage, Phosphorus (P) for roots/flowers, and Potassium (K) for overall plant health.

4.2.2 Fertilizing

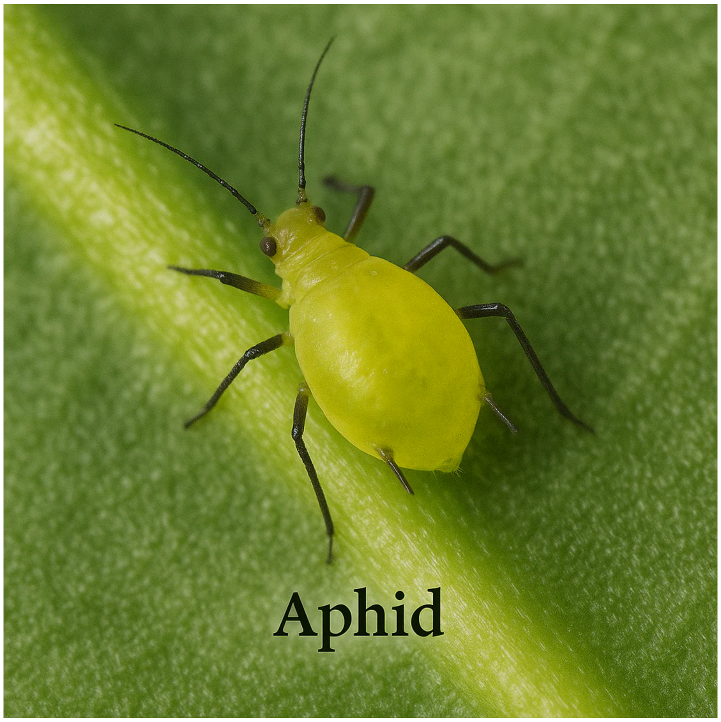
Artemisia annua L. has relatively moderate nutrient requirements but benefits from balanced soil fertility. The addition of organic matter such as compost or manure can improve soil structure, water retention, and nutrient availability (Biovision Infonet, 2024). Nitrogen is particularly important during the vegetative growth stage because it promotes leaf development and branching. However, excessive nitrogen may reduce the concentration of artemisinin in the plant. Phosphorus and potassium also play important roles in plant growth and productivity, helping improve plant health and overall yield (Artemisiaannua.net, 2024). Proper fertilization practices, therefore, contribute to higher biomass production and improved medicinal compound concentration.

4.3 Pest and disease Management

Artemisia annua L. is generally considered a relatively resistant plant and is not frequently affected by severe pest infestations. However, some pests such as aphids, mites, or leaf-feeding insects may occasionally attack the crop and damage leaves by feeding on plant sap. As illustrated in Figure 11 (Happy Houseplants, 2022), aphids (Aphidoidea) have distinct physical characteristics, and their feeding causes typical damage to plant stems and foliage. Additionally, under high humidity conditions, fungal disease management includes maintaining good soil drainage, ensuring adequate spacing between plants, and removing infected material to prevent the spread of pathogens. Crop monitoring and proper field sanitation practices are important preventive measures that help maintain a healthy plant population (Artemisiaannua.net, 2024)

Figure 11

Identification and management of Aphids (Aphidoidea) on plants



Note: Image adapted from Happy Houseplants (2022). It illustrates the physical characteristics of aphids and the typical damage caused by their feeding on plant stems and foliage.

4.4 Growth and Production

4.4.1 Growth Stages

The life cycle of *A. annua* includes several stages, such as germination, seedling establishment, vegetative growth, branching, flowering, and seed production. Germination usually lasts about 4 to 10 days after sowing, followed by the development of young seedlings that gradually grow into mature plants (World Health Organization, 2006). During the vegetative stage, the plant develops multiple branches and produces significant leaf biomass. Flowering typically occurs several months after planting and is influenced by environmental factors such as temperature and daylight length (Ferreira & Janick, 1995). These development stages are important because the concentration of artemisinin varies during the plant's life cycle.

4.4.2 Harvesting

Harvesting of *A. annua* is generally carried out at the early flowering stages, when the concentration of artemisinin in the leaves is at its highest. At this stage, plants are usually cut close to the base of the stem and collected for processing. As shown in Figure 12, specialized drying techniques are required to preserve the artemisinin content and medicinal quality of the leaves (Maison Artemisia, 2020). After harvesting, the plant material is dried in shaded and well-ventilated conditions to preserve its chemical compounds. Once dried, the leaves are separated from the stems and stored for further extraction or medicinal use (World Health Organization, 2006). Proper harvesting timing and drying conditions are essential to maintain the quality and medicinal value of the plant material.

Figure 12

Drying and post-harvest processing of *Artemisia annua L.*

Note: Diagram adapted from Maison Artemisia (2020). It outlines the specialized drying techniques required to preserve the artemisinin content and medicinal quality of the leaves.

5.0 Importance, markets, and uses

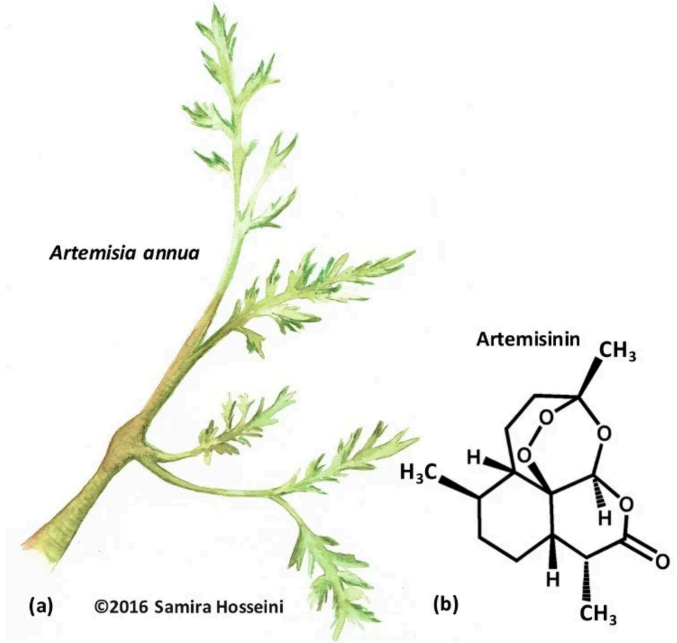
5.1 Global Importance

5.1.1 Key Source of Artemisinin Used to Treat Malaria

Artemisia annua L. is the primary natural source of artemisinin, a compound that forms the basis of the most effective treatments for a disease called malaria. As illustrated in Figure 13, the pharmacological mechanisms of terpenoids (including artemisinin) show multi-target activities interacting with various biological pathways (Hosseini et al., 2017). Artemisinin-based combination therapies are widely recommended as the first-line treatment for this disease, particularly in regions where malaria is endemic. Because malaria continues to affect millions of people every year, especially in tropical and developing countries, the plant plays a critical role in reducing mortality rates and improving global health outcomes (World Health Organization, 2023).

Figure 13

Pharmacological mechanisms of alkaloids and terpenoids



Note: Diagram adapted from Hosseini et al. (2017). It illustrates the multi-target activities of plant-derived compounds, highlighting how terpenoids interact with various biological pathways.

5.2 Production and Main Producers

5.2.1 Where it is Grown and the Top Producers

Artemisia annua L. is cultivated mainly in regions with suitable environmental conditions, including warm temperatures, adequate rainfall, and well-drained soils. The largest producers include China, which has historically led production, as well as Vietnam and several african nations such as Kenya. In these regions, both large-scale farms and smallholder farmers contribute to production, supplying raw materials to pharmaceutical companies and supporting local economies through agriculture and export activities (FAO, 2022).

5.3 Economic Value and Trade

5.3.1 Role as a Valuable Medicinal Export Crop

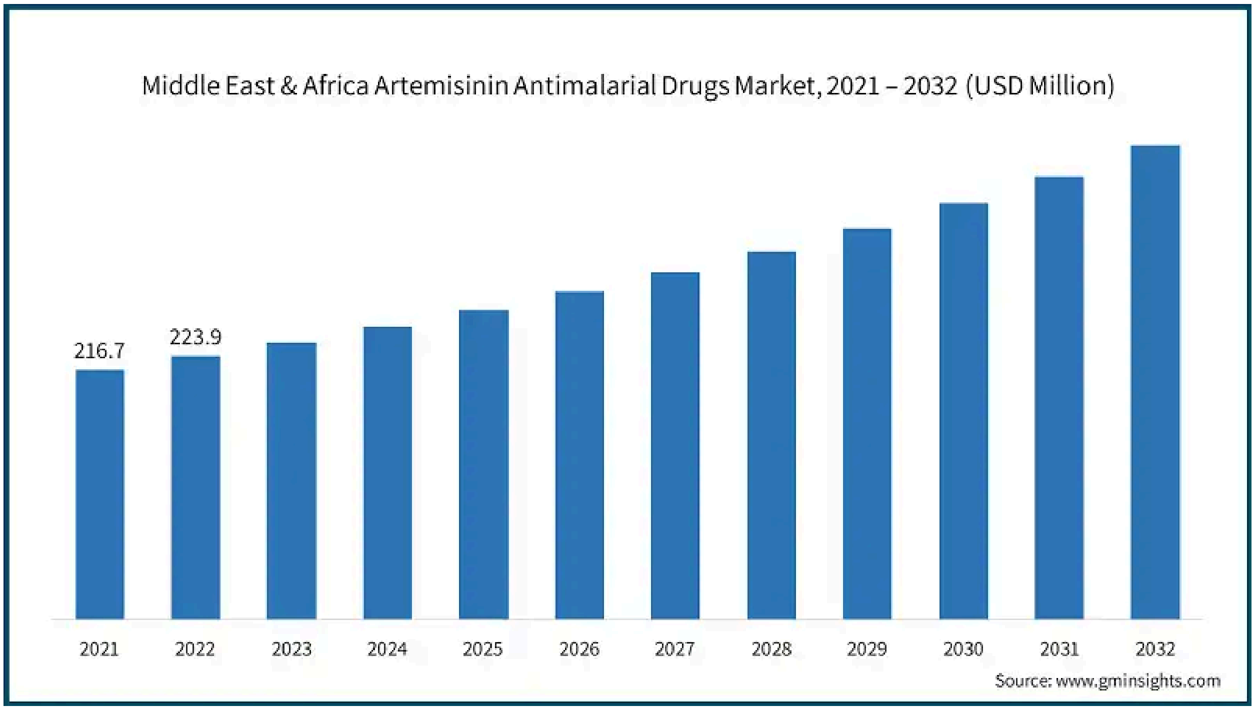
Artemisia annua L. is considered a highly valuable medicinal export crop due to its essential role in the production of life-saving drugs. Many producing countries export the plant or its extracts to international pharmaceutical companies, generating significant income. This Trade not only supports national economies but also benefits rural communities by providing employment opportunities and a stable source of revenue for farmers involved in its cultivation (van Agtmael et al., 1999).

5.3.2 Demand from Global Pharmaceutical Industries

The global pharmaceutical industry relies heavily on artemisinin as a key ingredient in antimalaria drugs. As shown in Figure 14, global market analysis of artemisinin-based antimalarial drugs shows projected growth from 2021 to 2032, highlighting the increasing demand for combination therapies in malaria treatment (Faizullahboy, 2024). As a result, there is a continuous demand for *A. annua* to ensure a steady supply of this compound. This demand is driven not only by existing malaria cases but also by ongoing public health efforts to control and eliminate the disease, making the plant an essential component of the global healthcare system (Towler & Weathers, 2015).

Figure 14

Global market analysis of artemisinin-based antimalarial drugs



Note: Chart adapted from Faizullabhoy (2024). It represents market projections by product type and parasite species, highlighting the growth of combination therapies for malaria treatment.

5.4 Market Characteristics

5.4.1 Demand Depends on Malaria Cases Worldwide

The demand for *A. annua* is closely linked to the global incidence of malaria. When malaria cases increase, especially in regions such as sub-Saharan Africa and parts of Asia, the need for artemisinin-based treatments rises significantly. Additionally, international health campaigns and funding programs aimed at reducing malaria also influence demand, as they require large quantities of effective medication to reach affected populations (World Health Organization, 2023).

5.4.2 Limited Production Compared to Demand

Despite its importance, the production of *A. annua* is relatively limited due to its dependence on specific growing conditions and agricultural cycles. Factors such as climate variability, farming practices, and the time required for cultivation can restrict supply. As a result, periods of high demand may lead to shortages, creating fluctuations in market prices and highlighting the challenges of maintaining a stable supply chain (FAO, 2022).

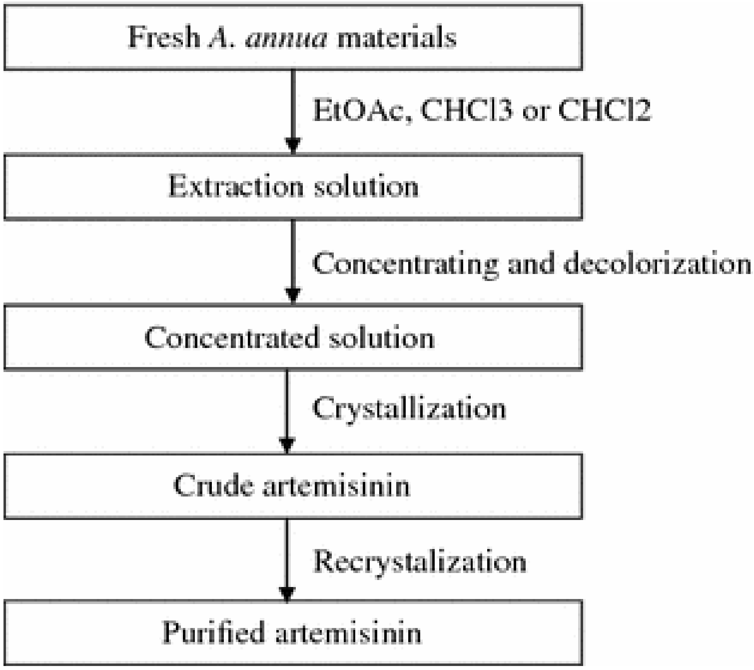
5.5 Value addition and processing

5.5.1 How it is Turned Into Artemisinin

After harvesting, *A. annu*a undergoes a series of processing steps to extract artemisinin from its leaves. As outlined in Figure 14, the extraction and purification process involves fresh plant materials, solvent extraction (using EtOAc, $CHCl_3$, or CH_2Cl_2), concentration and decolorization, crystallization, and recrystallization to obtain purified artemisinin (Liu et al., 2014). This involves drying the plant material, using chemical solvents to isolate the compound, and then purifying it to meet pharmaceutical standards. The extracted artemisinin is then used as the active ingredient in antimalarial drugs, which are manufactured and distributed globally to treat patients (Towler & Weathers, 2015).

Figure 14

Extraction and purification process of artemisinin and its analogs



Note: Diagram adapted from Liu et al. (2014). It outlines the laboratory procedures for extracting, purifying, and quantifying artemisinin and its chemical derivatives from *A. annua* plant material.

5.5.2 Why does processing increase its global value

Processing significantly increases the economic value of *A. annua* because the raw plant itself has relatively low market value compared to the refined pharmaceutical products derived from it. By converting the plant into artemisinin, additional technological, industrial, and scientific inputs are added, which greatly enhance its worth. This value addition not only increases profitability but also supports the global pharmaceutical industry and contributes to economic development in producing regions (Towler & Weathers, 2015).

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