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gece
kitaplığı

**International
Research and
Evaluations
in the Field of
Field Crops
Cultivation and
Breeding**

**October
2025**

Genel Yayın Yönetmeni / Editor in Chief • Eda Altunel

Kapak & İç Tasarım / Cover & Interior Design • Gece Kitaplığı

Birinci Basım / First Edition • © Ekim 2025

ISBN • 978-625-388-792-6

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Baskı & Cilt / Printing & Volume

Sertifika / Certificate No: 42488

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Chapter 1

**THE THERAPEUTIC POTENTIAL OF
OTANTHUS MARITIMUS (L.) HOFFMANS.
& LINK: FROM TRADITIONAL USE
TO MODERN PHARMACEUTICAL
APPLICATIONS**

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INTRODUCTION

On the Mediterranean windy coast, there is the glow of silver that goes against the hard dunes. *Otanthus maritimus* (in Turkey called cotton grass, child's grass, yogurt grass, Otanthus grass, or sea daisy) is an unusual representative of *Asteraceae* (daisy). This plant is locally a native plant in Egypt, either called *Hashet El Rih* (Wind Herb) or *Gaadeh*. Not only is it a dune ornament but a therapeutic agent that has high pharmacological potential (Tutin, 1964). On top of other pioneer species, cotton grass serves a major ecologic purpose in sand dune communities since it helps stabilize against wind and wave erosion (Charbonneau et al., 2016). The pharmacological and ecological aspect of the plant has placed the plant in a better position by its secondary metabolite profile (Tsoukatou et al., 2000).

The species' name comes from its very hairy trichomes, which make it look like cotton during flowering. It looks simple on the outside, but it contains many beneficial chemicals that have been used for a long time in traditional medicine and are now being studied by scientists (Tsoukatou et al., 2000). Maun (1998) stated that *O. maritimus* can live in harsh coastal circumstances. The trichomes on a plant's leaves help it keep water and protect it from harsh sun and salt air (Waisel, 2012). It blooms in the summer with small, round, yellow flowers that make dune areas look better. Still, the phytochemical makeup of this species is the most important thing about it. Researchers have found that the oral chemicals and essential oils that are taken from this plant may be good for people's health (Romeo et al., 2007). Human-induced exploitation and associated habitat degradation causes significant issues to the populations of this species in the coastal areas (Benabdelkader et al., 2025). Besides environmental advantages, child grass has also been discovered to possess rather numerous health-related advantages (Fattahi et al., 2014). Sun and Shahrajabian (2023) had it that such distinct properties could be utilized to develop products that are in the interest of the planet.

The intent of the present book chapter is to offer a thorough discussion of the multifarious nature of *O. maritimus*. This review encompasses the botanical and ecological aspects of this species, its geographical distribution and conservation issues of the species in its natural ambience. Later, the abundant phytochemical composition of the plant is discussed in detail and geographic disparity (chemotypes) of the essential oil components, the alkylamides which generate the insecticidal effect, and the nutritionally beneficial fatty acids are emphasized. The pharmacological properties revealed through the scientific investigations of the present time, from antimicrobial to antifungal, anti-inflammatory to insecticidal,

and the potential anticancer properties, which are increasingly being recognized, are discussed in separate sections. The historical lineage of the species and the ethnobotanical use in traditional medicine of the plant is evaluated in the context of these empirical results. Finally, the potential for biotechnological application of *O. maritimus* into the pharmaceutical, cosmetic and nutraceutical sectors, as well as prospective researches directions are considered.

1. BOTANY, ECOLOGY, AND DISTRIBUTION

1.1. Botanical Characteristics and Taxonomy

The *O. maritimus* is a species that lives in the dunes and is confined to the Mediterranean and Atlantic coast. The plant reaches a height of between 15 and 50 cm and is mainly shrubby (Romeo *et al.*, 2007). One morphological difference between this taxon and others is the existence of a white woolly indumentum of trichomes on the stems and leaves. Not only does such an indumentum give a silvery-white look, but it is also an important adaptation on how to survive in the tough coastal habitat. The layer of wool minimizes transpiration and alleviates physiological stress as a protection barrier to high salinity, intense sunlight radiation and desiccation. *O. maritimus* is covered with oval and oblong, succulent foliage that is placed alternately around the stem. Margins are usually entire or slightly serrated, and each blade is 5-17mm². This succulence allows the storage of water in leaves tissues, therefore, increases the resistance to arid conditions and salinity stress (Basile *et al.*, 2013).

O. maritimus begins flowering in summer and continues flowering until autumn. The flowers are clustered in small, spherical heads (capitula), forming a dense, umbrella-like (corymbose) cluster. The capitula are spherical, with involucre bracts 4-5 mm long, numerous, oval, outer ones lanate, and inner ones glabrous and lanate at the tip. Each capitulum consists of numerous small tubulars, bright yellow flowers (florets). These dense flower clusters create a striking contrast to white leaves (Cabral *et al.*, 2013). After flowering, the plants produce small dry fruits.

Taxonomically, *O. maritimus* is classified within the tribe *Anthemideae* of the family *Asteraceae*. The genus name *Otanthus* is derived from the Greek words “otos” meaning “ear” and “anthos” meaning “flower,” and probably refers to the ear-like structure at the base of the flower heads. The species name ‘*maritimus*’ comes from the Latin word meaning “belonging to the sea” and directly describes the plant’s habitat (Christodoulou *et al.*, 2005). For many years considered the only species of the genus *Otanthus*, this plant has been shown to be closely related to the genus *Achillea* through molecular phylogenetic studies and is also referred

to as *Achillea maritima* (L.) Ehrend. & Y. P. Guo in some modern classifications (Benabdelkader et al., 2025; Taç & Özcan, 2019). Therefore, both names can be found in the scientific literature. This taxonomic change reflects the shared evolutionary heritage of the chemical and genetic characteristics of the plant with members of the *Achillea* (yarrow) genus.

1.2. Habitat and Ecological Adaptations

O. maritimus is an ecologically specialized perennial plant confined to coastal dunes (Ciccarelli, 2015). These dynamic and stressful environments create significant abiotic stress for plants owing to a series of challenging conditions, such as high salinity, constant wind, mechanical wear, high temperatures, and nutrient deficiency (Flowers & Colmer, 2008). *O. maritimus* has developed remarkable adaptation mechanisms to survive under extreme conditions. These adaptations have enabled their classification as halophytes (salt-tolerant plants) and psammophytes (sand-tolerant plants) (Flowers & Colmer, 2008; Sapiña-Solano et al., 2024).

O. maritimus is a halophyte that tolerates high salt concentrations (Flowers & Colmer, 2008). Salt in the soil and sea breeze is toxic to most plants and inhibits water uptake by inducing osmotic stress in plants. Plants adapt to saline conditions by physiologically adjusting their intracellular osmotic pressures (Grigore et al., 2014). Plants are morphologically adapted to these environmental conditions. Its fleshy leaves increase its water storage capacity, helping it survive during dry periods and under high osmotic stress conditions. Additionally, the dense layer of hair (trichomes) covering the leaf surface creates an extra protective layer by preventing salt crystals from coming into direct contact with the leaf surface and reducing evaporation (Maun, 1998).

As a psammophyte, this plant is adapted to sandy and loose soils. Its strong and spreading root system allows the plant to anchor itself in loose sand and access scarce water and nutrients in the soil. The root system also plays an important role in sand dune stabilization (Maun, 1998). Sand grains carried by wind can continuously erode plant stems and leaves. The dense woolly layer of hair on *O. maritimus* acts as an effective buffer against mechanical erosion. These hairs also create a layer of still air on the leaf surface, reducing the drying effect of the wind and minimizing water loss from the leaf.

1.3. Geographic Distribution

O. maritimus has a wide geographic distribution and is primarily endemic to the Mediterranean Basin (Davis, 1970; Tutin, 1964). Its distribution extends along the coastline of all Mediterranean countries (Italy,

Greece, Croatia, Turkey, and North African countries), starting from the eastern shores of the Atlantic Ocean (Portugal, Spain, and France). It is also present along the western shores of the Black Sea (Davis, 1970).

O. maritimus is a widespread sand dune plant in Turkey (Davis, 1970). It is wild growing on the beaches of the whole coast of Aegean and Mediterranean areas, beginning with sandy beaches in the north of Istanbul, for example, Terkos and Kilyos (Taç & Özcan, 2019). This broad distribution suggests the capacity of the plant to carry out and steer under varying climatic and microhabitats within the area. However, geographical diversity has resulted in tremendous variations in the chemical composition of flora. The observation that the volatile oil compositions of *O. maritimus* specimens growing in various regions significantly differed has indicated the presence of chemical races referred to as chemotypes (Cabral et al., 2013; Halim et al., 1993; Lum & Barton, 2020; Romeo et al., 2007). The following section describes this issue in detail.

1.4. Conservation Status and Threats

Despite the wide distribution of *O. maritimus*, its natural habitat and coastal dunes are threatened by human activity (Lum & Barton, 2020; Trotta et al., 2024). Murray and Jackson (2022) reported that sea yarrow (*Achillea maritima*), once widespread along the coasts of Ireland and Britain, is now found only at Lady's Island Lake in Wexford, and that the population of this once-abundant species has declined significantly (Ciccarelli, 2015). The development of beaches for recreational purposes, clearing of dune vegetation, and introduction of alien species (especially invasive plants) into the area places significant pressure on *O. maritimus* populations (Trotta et al., 2024). Marine pollution and solid waste have negative effects on these ecosystems. The increased awareness of the pharmacological and cosmetic value of such plant species has simultaneously left the destruction of uncontrolled and unregulated harvesting (Nazish et al., 2025). In this regard, conservation of *O. maritimus* and other species that are related to dune ecosystems becomes of utmost importance.

Since dune ecosystems cannot be overstated in terms of their importance in reducing shoreline erosion, any conservation strategy that should be taken should not only be concerned with protecting each single species, but also the integrity of the entire ecosystem (Maun, 1998). It is therefore necessary to take steps like restoration of habitats, sensitization of the people, formulation of sustainable harvesting policies and consolidation of legal protection status.

2. PHYTOCHEMICAL PROFILE: THE CHEMICAL BASIS OF BIOACTIVITY

The ability to develop under unfavorable environmental conditions into a distinct and extensive secondary metabolite repertoire gives *O. maritimus* the opportunity to become an excellent pharmaceutical agent (Custodio *et al.*, 2022; Lopes *et al.*, 2023). These secondary chemical compounds provide protection against herbivores, pathogens and abiotic stress-inducing factors. Based on this, the current paper critically analyzes the phytochemical profile of the target species, especially on its essential oils, chemotypic geographic variation, bioactive alkylamides, essential fatty acids and other relevant metabolites.

2.1. Essential Oil Composition and Chemotypes

The primary characteristic of the last is that it produces highly characteristic aromatic flowers and leaves (Romeo *et al.*, 2007). It is a volatile compound that is formed from essential oil constituents in the glandular trichomes in the plant and can be extracted through hydrodistillation. Analytical investigations of the composition of the essential oil have revealed that there exist significant variations in their composition, according to the geographical origin, climate, timing of harvest, and the section of the plant utilized (Muselli *et al.*, 2007). Mostly, the *O. maritimus* essential oil comprises of monoterpenes and oxygenated monoterpenes. These data contribute to the idea of chemotypes which are specialized clusterings of the individual species and have particular chemical profiles. A chemotype is a subspecific rank whereby the plant produces a distinct chemical content as a result of genetic or environmental variation. The bioactivity of the plant material itself and its possible application in industrial contexts are directly and strongly influenced by such chemotypic differentiation. The Table 1 below attests to the high profile chemotypes recorded in different geographical locations and their main components.

This table demonstrates the high chemical plasticity of *O. maritimus*. For example, whereas oxygenated monoterpenes, such as camphor and its derivatives, are dominant in the Egyptian and Greek populations, non-head-to-tail irregular monoterpenes, such as santolin triene, are prominent in the Italian population (Romeo *et al.*, 2007). The first report of irregular monoterpenoids in the genus *Otanthus* is of great significance (Halim *et al.*, 1993). The dominant chemotype of crisanthenone reported in Portugal has a completely different chemical profile, highlighting the adaptability of this plant and its regional genetic differentiation from the Brazilian populations.

Table 1. Relevant major chemotypes documented in various geographical locations and their preponderant constituents

Geographical Region	Dominant Essential Oil Components	Researcher(s) and Year
Egypt	Camphor, Yomogi Alcohol, Artemisia Alcohol	(Halim et al., 1993)
Italy	Santolina Trien, Camphor, Artemisia Acetate	(Romeo et al., 2007)
Italy (Sicily)	Yomogi Alcohol, Artemisinin Acetate, Camphor	(Basile et al., 2013)
Portugal	Chrysanthenone, Filifolone, cis-Chrysanthenyl Acetate	(Cabral et al., 2013)
Greece	cis-Chrysanthenyl acetate, 1,8-Cineole, Camphor	(Christodouloupoulou et al., 2005)
Algeria	(α/β)-Isocomen, α -epi-Bisabolol	(Benabdelkader et al., 2025)

In the same study, chrysanthenone (40.4–57.2%), filifolone (12.2–15.5%), cis-chrysanthenyl acetate (10.1–12.2%), and α -pinene (6.7–7.2%) were identified as the main components (Cabral et al., 2013). Essential oil of both aerial and subterranean parts of this plant, which were harvested in Corsica, consisted of yomogi alcohol (24.4–34.7%), artemisia alcohol (11.5–19.2%), and artemisyl acetate (4.9–12.6%) as the primary components (Muselli et al., 2007). Similar studies on specimens gathered in Sicily showed that the most significant constituents were yomogi alcohol (20.8%), camphor (15.8%), artemisia acetate (15.3%), and artemisia alcohol (13.7%) (Basile et al., 2013). The key oil, in material of Algiers origin, was enriched in α -isocorenenol (15.75%), β -isocorenenol (7.92%), artemisin acetate (6.63%), and α -epi-bisabolol (6.16%) (Benabdelkader et al., 2025). The strong chemical heterogeneity of this species indicates that it has developed region-specific defense responses against a range of biotic and abiotic stresses. As a result, it provides a competitive edge for industrial exploitation, allowing the selection of plant populations with a chemical signature idealized for a specific bioactivity, including antifungal or anti-inflammatory effects.

2.2. Alkylamides: Nature's Powerful Insecticides

The pharmacological effect of alkylamides on insect nervous system is mainly due to the blockades of voltage-gated sodium channels, which ultimately result in paralysis. While some parallels in mode-of-action to classical synthetic insecticides still exist, their intrinsic naturality and swift biodegradability is very favourable for the development of environmentally benign pesticides (Zeni et al., 2021). Scientific studies in search of the specific phytochemical constituents that endow the insect repellent extracted from *O. maritimus* with its insecticidal activity have been fueled by its age-long traditional use (Christodouloupoulou et al., 2005; Elufioye et al., 2020).

The plant contains alkylamides in both the subterranean and aerial tissues and it has a high level of insecticidal activity. Two new piperidine amides, N-[(2E,4E,8Z)-tetradecatrienoyl] piperidine and N-[(2E,4E,8Z,11Z)-tetradecatrienoyl] piperidine, were isolated from the plant *Otanthus maritimus* growing on the coast of Greece by Christodouloupoulou et al. (2005) As shown by Christodouloupoulou et al. (2005), the effects of the use of the piperidinyl amides are harmful to the ant species, *Crematogaster scutellaris*, and the termites one, *Reticulitermes balkanensis*. Ruiu et al. (2013) also demonstrated that the N-alkyl dien- and trien-amide constituents recovered after extracting roots appear to bind to opioid and cannabinoid receptors and therefore have neuropharmacological effects on top of being insecticides.

Alkylamides are a significant part of the chemical defense of the plant profile. Their ability to affect herbivores like ants and termites is due to blocking of voltage-gated sodium channels, and, consequently, disrupt neuronal transmission signals and cause paralysis (Christodouloupoulou et al., 2005; Divekar et al., 2022). Besides, compared to synthetic analogues, alkylamides are more degradable, which makes them more eco-friendly (Walkowiak-Nowicka et al., 2023; Zeni et al., 2021). Along with insecticidal effects, alkylamides have been reported to have analgesic, anti-inflammatory, and neuroprotective effects (Divekar et al., 2022). Therefore, alkylamides of plant origin can be used as a potential environmentally friendly pesticide and lead compound in pharmaceutical design (Najmi et al., 2022; Rios, 2012).

2.3. Other Important Secondary Metabolites

The chemical richness of *O. maritimus* is not limited to essential oils, alkylamides, and fatty acids. It is also a plant that should be evaluated in terms of other secondary metabolites that contribute to various biological activities such as flavonoids, sesquiterpene lactones, polyines and thio-

phenes (Lopes et al., 2023).

2.3.1. Flavonoids

Flavonoids are a vast family of various polyphenolics which are distributed throughout plants and have significant functions in numerous body processes. Their powerful antioxidant properties are of great interest to researchers, particularly those who research nutrition, pharmacology, and medicine (Lopes et al., 2023). The chemical composition of flavonoids of numerous species has been extensively studied, but little of the marine herb *O. maritimus*, despite some intriguing botanical characteristics.

The existing body of literature on the flavonoids of *O. maritimus* is limited with the available information that mainly originates as a result of studies conducted by El-Sayed et al. (1992) that identified a range of flavonols and flavone glycosides in foliage and floral tissues. This initial data demonstrates that further studies should be done on the complete profile of flavonoids of *O. maritimus*. As flavonoids are a broad group of bioactive agents with well-characterised anti-inflammatory, antimicrobial, and cardioprotective effects, systematic study of the composition of these in this species can provide novel compounds with distinct therapeutic potential. Such discoveries are of enormous potential to further develop new pharmacological agents and nutraceuticals from this largely neglected marine plant. Thus, there is the possibility of adding new biologically active molecules to the existing repertoire for clinical and nutritional uses.

2.3.2. Sesquiterpene Lactones

Sesquiterpene lactones are common secondary metabolites in the *Asteraceae* family. They are usually bitter in taste and provide protection to herbivores (Demetrio & de Freitas Coelho, 2023). The aerial parts of *O. maritimus* have been isolated to obtain complex guaianolide-type sesquiterpene lactones (Jakupovic et al., 1988; Sabri et al., 1983). These compounds have a wide pharmacological profile, including anti-inflammatory, antimicrobial, and cytotoxic effects. However, there is limited clinical research on their effectiveness in humans.

2.3.3. Polynes and Thiophenes

Asteraceae (*Compositae*) species, including cotton, are reported to have over 700 isolatable pollen grains (Bohlmann et al., 1974). The biological activities of these pollen-based compounds have not been fully understood; however, experimental evidence indicates that some of them are phototoxic to bacteria, fungi, inorganic-matter-based viruses, nematodes, and insects when subjected to long-wave UV light (UVA 320–400

nm) (Hudson & Towers, 1988).

Thiophenes are heterocyclic aromatic compounds with one carbon atom and four sulfur atoms in a five-membered ring. Thiophene nucleus is a highly studied scaffold and it has been used widely in chemical studies. Naturally occurring thiophenes are a group of secondary metabolites that are common in *Asteraceae*, including *Tagetes*, *Echinops*, *Artemisia*, *Balsamorhiza*, *Blumea*, *Pluchea*, *Porophyllum*, and *Eclipta* (Ibrahim et al., 2016).

Thiophenes and thiophenyl derivatives are produced as part of the chemical defense arsenal of many plants, both synthetically and stored in various tissues. These chemicals can also be used as repellents, toxins, or have anti-nutritional effects on herbivores (Gil et al., 2002).

The naturally occurring thiophenes are either stored in the tissues of plants or emitted to the soil around them, where they are produced by polyacetylenic precursors (Tang et al., 1987). A wide range of bioactivity is exemplified by thiamine-parameterized thiophene-based compounds which include antimicrobial, antiviral, HIV-1 protease, antileishmanial, nematocidal, insecticidal, phototoxic, and anticancer activities. These sulfur-based molecules and unsaturated acetyl enough structures (especially in the roots of cotton plants) are found to have a strong antimicrobial and antifungal effect (Bohlmann et al., 1974). They are, therefore, an important element of the plant defense armoury against on-land pathogens. The phytochemical structure of *O. maritimus* is in general complex and diverse; it is often referred to as a phytochemical factory, which supports a plethora of biological activity.

3. PHARMACOLOGY AND BIOLOGICAL ACTIVITIES.

The rich phytochemical profile of *O. maritimus* encompasses a wide range of pharmacological and biological activities (Beeby et al., 2020; Lopes et al., 2023). Its uses in traditional medicine are increasingly being validated by modern scientific research, shedding light on the plant's therapeutic potential. This section addresses the main proven biological activities of the plant.

3.1. Antimicrobial and Antifungal Effects

The ability of the plant to generate potent antimicrobial and antifungal effects is one of the most repeated and most significant impacts of pharmacological studies of *O. maritimus* (Cabral et al., 2013; Muselli et al., 2007; Romeo et al., 2007). The key oil and other forms of extracts of the species have a broad-spectral activity against bacterial and fungal taxa.

As part of several confirmations, it is established that the essential oil is particularly effective against Gram-positive bacterial species, including one of the major etiologic agents of nosocomial infections (*Staphylococcus aureus*) (De Pascual Teresa et al., 1981; Muselli et al., 2007). This antibacterial property has been attributed to camphor, 1,8-cineole and other oxygenated monoterpenes that are found in the oil (Romeo et al., 2007).

The highest antimicrobial activity observed is that of antifungal action of *O. maritimus*. It is an essential oil, which contains chrysanthenone, which has demonstrated a powerful antifungal effect on the dermatophytes causing nail infection, skin and hair infection (Cabral et al., 2013). Likewise, Basile et al. (2013) reported that a sample of Sicilian essential oil was effective in the prevention of growth of both yeasts, including, but not limited to *Candida albicans*, as well as growth of mold fungi including, but not limited to *Aspergillus spp.* These results place the production of antifungal compounds of natural origin through the use of the antifungal agent, *O. maritimus*, in promising perspectives to manage the recalcitrant fungal infections and support the historical therapeutic use of the antifungal agent, in the management of inflammatory dermatological pathologies, that are often complicated with secondary colonies of fungi.

3.2. Insecticidal and Repellent Activity

The most widely recorded and ethnically vested ethnobotanical use of *Otanthus maritimus* is that of repellence and insecticidal. The dried herb is also commonly used in Mediterranean cultures to keep moths and other undesirable insects out of the home. This tradition has been given a strong scientific ground by the seminal study by Christodouloupoulou et al. (2005). Their study showed that the piperidiny l amides produced by the species are strongly toxic to the ant species, e.g., *Crematogaster scutellaris*, and the termite, e.g., *Reticulitermes balkanensis*. The further studies showed that these natural products affect the insect nervous system, triggering a quick death (Elufioye et al., 2020). This has resulted in the potential of using this biodegradable, environmentally benign insecticide, developed using *O. maritimus* as a promising alternative to synthetic pesticidal agents in development (Zeni et al., 2021). This inherent characteristic of the plant implies its possible usefulness in both pest control in agriculture, as well as in the domestic and overall health care situations.

3.3. Anti-inflammatory Activity

O. maritimus has been used traditionally by the Bedouins to treat various conditions such as asthmatic bronchitis, dysentery, and inflammation of the bladder and this indicates that this plant may have some anti-inflammatory effects (Tackholm & Boulos, 1974). Subsequent studies

have supported such a classical use. As an example, a single research study showed that the necessary oil of *O. maritimus* significantly decreased the release of nitric oxide - a pivotal role in the immune responses - in macrophage (immune) cells stimulated with lipopolysaccharide. Critically, this inhibition was observed at non-cytotoxic concentrations (0.16-0.32 g mL⁻¹) which do not affect cell viability and this indicates that the plant can inhibit inflammation, without any adverse effects on normal cells. This preferential anti-inflammatory effect renders *O. maritimus* an almost ideal option to use in topical preparations in the treatment of chronic inflammatory diseases, including rheumatoid arthritis, inflammatory bowel disease and dermatologic pathologies, such as acne (Cabral et al., 2013).

3.4. Anticancer and Cytotoxic Potential of the Extract

Over the last few years there has been a growing focus in scholarly research on the role of naturally sourced compounds used in oncological therapeutics (Custodio et al., 2022; Ribas-Taberner et al., 2025). Microorganisms that inhabit inadaptive environments, like dune systems, are highly favourable sources of secondary metabolites. In this direction *O. maritimus* has been paid attention. Beeby et al. (2020) have made the basis of its anticancer activity by performing a thorough screening. The cytotoxicity of essential oils from different Portuguese dune species was assessed using several human cancer cell lines, and *O. maritimus* showed the lowest IC₅₀ values compared to the other samples, demonstrating the strongest cytotoxic activity. These results imply that not only is there an ethnomedical value of the species, but that the species contains strong potential lead compounds to be utilized in the next-generation anticancer drug development. Despite the fact that this sphere is still in its system, the initial evidence is promising and should be followed by further in vivo studies and clinical trials.

4. ETHNOBOTANY AND TRADITIONAL USE

It's worth has been passed down through generations of local communities long before modern science discovered the power of this taxon and is still here today (Ksouri et al., 2012). Cultures of the Mediterranean Basin have been cognizant of the particular properties of this plant and have used it in their day-to-day activities in a variety of ways. The scientific field of ethnobotany, which studies the customary human use of plants, provides information about the rich cultural heritage of *O. maritimus* and its ancient history, which remains current in contemporary science.

4.1. *O. maritimus* in Mediterranean Culture

The traditional utilisation of *O. maritimus* has been mainly due to its medicinal and practical applications. Ethnobotanical, in general, most frequently, the effects attributed to *O. maritimus* include the following; *O. maritimus* was reported to be used by Bedouin tribes of North Africa to treat asthmatic bronchitis (Tackholm & Boulos, 1974). It is widely assumed that the steam or smoke of the brewed tea has a calming effect on the respiratory tract, which is consistent with the already known anti-inflammatory effect of this plant, as demonstrated in the existing pharmacological literature (Cabral et al., 2013).

The plant has also been utilized in medicine against severe diarrheal diseases such as dysentery and in infections of the bladder such as cystitis (Christodoulopoulou et al., 2005). This is owed to the high antimicrobial and anti-inflammatory properties of this substance (Basile et al., 2013; Cabral et al., 2013). Besides, its capacity to kill pathogenic microorganisms and to slow down the inflammatory processes can be used to diminish the impact of such infections. In application, the most common application is the insect repellent. Since they repel moths, mosquitoes and other nuisance insects, large bundles of dried *O. maritimus* are frequently hung in wardrobes and rooms in Mediterranean areas. Empirical studies have shown that the plant's characteristic sharp aromatic odour can repel insects (Christodoulopoulou et al., 2005), because of the presence of insecticidal alkylamides in the plant. Morphologically, *O. maritimus* is silvery colored and does not lose its shape after drying which has been the basis for its use as an ornamental plant. It is often used with dried flower arrangements and as a decorative material.

4.2. Integration of Traditional Knowledge into Modern Science

Ethnobotany, rather than being just a repository of cultural heritage, is also an essential jumping-off point for investigating pharmaceuticals today (Ksouri et al., 2012). The usefulness of such an interdisciplinary synthesis may be illustrated by the case of the species *O. maritimus* whose pharmacological properties have been carefully documented (Christodoulopoulou et al., 2005; Rios, 2012). A good example of how the folk knowledge of centuries past can be supported by the empirical data of the latest testing methods is a plant commonly used to improve inflammatory disorders; *in vitro* tests have been done, confirming its ability to inhibit nitric oxide production (Cabral et al., 2013). Another example is the production of potent insecticidal compounds by a species considered an insect repellent (Christodoulopoulou et al., 2005). This is the basis of the study of ethnopharmacology, which investigates the pharmacological

effects of natural substances traditionally used (Ksouri et al., 2012).

Traditional knowledge will significantly accelerate the drug discovery process and save money by providing scientists with a strategic guide on which plants to screen to obtain a given bioactivity. Completely novel and unrelated to traditional uses, such as the discovery of the anticancer properties of *O. maritimus* (Beeby et al., 2020), demonstrate the chemical richness of this species and its broad exploration potential in the future.

5. BIOTECHNOLOGICAL AND INDUSTRIAL APPLICATIONS

The phytochemical abundance and established biological properties of *O. maritimus* suggest its potential as a raw material in various industries (Jazeel et al., 2025; Surówka et al., 2025). In the field of pharmaceutical, cosmetology and nutraceuticals, this species provides natural and efficacious solutions that could benefit product development considerably.

5.1. Pharmaceutical Industry

More and more, synthetic pesticides are hurting people and the environment, so it is more important than ever to find naturally biodegradable options (Zeni et al., 2021). It looks like piperidinyl amides from *O. maritimus* could be very useful in this area (Christodouloupoulou et al., 2005; Elufioye et al., 2020). These chemicals could be used as starting points to make next-generation botanical insecticides that can be used to get rid of bugs in farms or safe-for-the-environment topical insecticides that people can use at home. Additionally, this plant's anti-inflammatories could lead to new ways of treating long-term inflammation diseases (Cabral et al., 2013). It is already known that topical preparations can help treat inflammatory skin diseases like acne, eczema, and psoriasis. However, more pharmacological and clinical research is needed to find out how they can be used in other parts of the body. The ability of *O. maritimus* to kill cells has also opened up new and interesting study areas in oncology. Beeby et al. (2020) thought that pure chemicals or essential oils that come from plants might help scientists find new ways to fight cancer. But even though the studies that have been done in this area are still in their early stages, they are expected to be very useful for future cancer research.

5.2. Cosmetics and Perfumery

O. maritimus is a perfect multipurpose ingredient in the cosmetic market (Cabral et al., 2013). The compound, fine, and long-lasting odor of the essential oil of the plant makes it a useful raw material for perfumery (Romeo et al., 2007). The chrysanthenone-enriched nature of the Portuguese chemotype (with its fresh and woody attributes) is why it can be

applied to niche perfumes and male grooming products. Its antimicrobial and anti-inflammatory effects also make it a good choice for functional skin care (Cabral et al., 2013). It can be successfully added to the preparation of sensitive and problematic skin formulations, such as redness-reducing serums, acne-prone cleansers, and smooth creams. In addition, it has antioxidant properties that may protect the skin against environmental stress factors and suppress the effects of early aging (Lopes et al., 2023).

5.3. Functional Foods and Nutraceuticals

Nutraceuticals, as defined by Barba-Espín et al. (2025), as well as Sun et al. (2025), are a new class of supplements that are defined by having a nutritional component as well as a (therapeutic) component. The marine herb *O. maritimus* has a number of characteristics that indicate its sustainability in this sphere. It has a high oleic content, more than 66% linoleic acid (Omega-6) and consequently, it assumes the status of an effective nutritional supplement (Taç & Özcan, 2019). Because of this, this oil is sold in capsules, functional foods, salad dressings, and snack foods that are high in nutrients to help people get more important fatty acids. It is interesting that the plant leaves produce an essential oil that is blue in color, smells like wood, and has different scent notes based on the weather. This shows that the plant has a lot of potential for making useful products. As for using the extract as a food supplement, El-Sayed et al. (1992) and Lopes et al. (2023) found that it has a high concentration of antioxidant compounds, mostly flavonoids. This means that it can be used in food supplements to help keep you healthy by getting rid of reactive oxygen species.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

6.1. Summary and Evaluation

O. maritimus, a relatively small native of the Mediterranean coast, has an exceptional phytochemicals repertoire and extraordinary bioactive versatility (Custodio et al., 2022; Lopes et al., 2023). Its chemical composition includes different chemotypes that differ significantly based on geographical provenance thus forming the basis of the significant chemical and pharmacological diversity observed (Benabdelkader et al., 2025; Halim et al., 1993; Romeo et al., 2007). Scientific investigations of our times have supported the centuries old use of such taxa in traditional medicinal systems (Tackholm & Boulos, 1974).

The species has showed strong antimicrobial and antifungal activity which makes them a potential natural candidate for solving recalcitrant infections (Cabral et al., 2013), and the alkylamides present in the species,

which target the nervous system, have potential for environmentally benign insecticidal formulations (Christodouloupoulou et al., 2005; Elufioye et al., 2020). Its established anti-inflammatory effect offers new treatment options for chronic inflammatory diseases (Cabral et al., 2013), and its newly discovered anticancer effect provides new perspectives for research in the field of oncology (Beeby et al., 2020). These pharmacological characteristics are a clear depiction of the usefulness of this plant as an indicator in the pharmaceutical, cosmetic, and nutraceutical industries.

6.2. Future Research Directions

It is critical that future research focuses on specific areas to fully realize the potential of *O. maritimus*. To date, most studies have been conducted in vitro (laboratory) or in vivo (animal testing) (Beeby et al., 2020; Cabral et al., 2013). There is an urgent need for well-designed randomized controlled clinical trials to evaluate the safety and efficacy of plant extracts and isolated compounds in humans. The distinct chemotypic variations in this plant pose a challenge for its industrial use (Benabdelkader et al., 2025; Halim et al., 1993). The extracts used for specific activities must be standardized in terms of their active ingredient contents. As the different environments in which the plant grows directly affect its chemical composition, which in turn affects the products to be produced, standardization is essential for the development of consistent and reliable products. A comparative analysis of the biological activities of different chemotypes will help identify the most valuable populations. Increasing industrial demand may exert pressure on natural populations (Nazish et al., 2025; Trotta et al., 2024). Almost all studies on this plant have indicated that there is pressure on its distribution areas, causing it to be confined to very small specific areas, which has brought the issue of its cultivation to the forefront of research. Further studies should be conducted on the cultivation of this plant under field conditions. The effects of different cultivation conditions (soil type, irrigation, and fertilization) on secondary metabolite production should be investigated, and optimal agricultural protocols should be developed to obtain high-yield, high-quality raw materials. Plants synthesize valuable and structurally interesting compounds, such as chrysanthenone, santolin triene, and piperidinium amides, are synthesized by plants (biosynthetic pathways) which have the potential to increase the production of these compounds through metabolic engineering and synthetic biology methods (Gupta et al., 2024).

In conclusion, *O. maritimus* is a treasure trove of secrets that must be discovered at the intersection of traditional wisdom and modern science. This resilient coastal dune plant has the potential to significantly contribute to human health and well-being when used sustainably (Barba-Espín

et al., 2025; Lombardi et al., 2025; Sun et al., 2025).

Disclosure statement

The article was written by a single author. There are no conflicts of interest with any individuals or organizations.

Funding

No financial support was received from any organization for the preparation of this manuscript.

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Chapter 2

ALTERNATIVE PATHWAYS FOR SUSTAINABLE AGRICULTURE BEYOND TRADITIONAL AND MODERN AGRICULTURE

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1. INTRODUCTION

Agricultural systems have long been the backbone of human civilization, yet the intensive expansion of conventional and modern agriculture since the mid-20th century has produced both opportunities and challenges. While the Green Revolution and subsequent technological advances contributed to significant yield gains, they have also led to soil degradation, biodiversity loss, and escalating greenhouse gas emissions (Pingali, 2012; Foley et al., 2011). In the face of global climate change, resource scarcity, and rapid population growth, there is an urgent need to rethink agricultural practices and identify alternative pathways for sustainable food production. These pathways are not intended to replace conventional methods entirely, but rather to complement and, in some cases, correct their shortcomings.

Among the most promising approaches are permaculture, hydroponic agriculture, aquaponic farming, regenerative agriculture, and agroforestry. Each of these systems integrates ecological principles with food production, offering novel strategies to enhance resilience while reducing environmental impacts.

Permaculture is based on the design of agricultural landscapes that mimic natural ecosystems, emphasizing diversity, resilience, and long-term sustainability (Ferguson and Lovell, 2014). It seeks to create self-sufficient systems by integrating crops, animals, soil, and water management in ways that minimize external inputs and maximize ecological balance. Hydroponic agriculture, a soilless cultivation system, allows plants to grow in nutrient-rich water solutions, making efficient use of water and land resources. By eliminating the need for fertile soil, hydroponics provides opportunities for food production in urban areas and regions with poor soil conditions (Resh, 2013). Aquaponic farming combines hydroponics with aquaculture, creating a closed-loop system in which fish waste is biologically converted into nutrients for plants, while plants purify the water for fish (Vasdravanidis et al., 2022). This symbiotic relationship improves resource efficiency and reduces dependence on chemical fertilizers, making it a promising model for sustainable intensification.

Regenerative agriculture seeks to restore soil health, biodiversity, and ecosystem function through practices such as reduced tillage, organic amendments, crop diversification, and integrated livestock management (Lal, 2020; Schreefel et al., 2020). Unlike conventional farming, which often depletes soil organic matter, regenerative systems aim to sequester carbon, thereby contributing directly to climate change mitigation. Agroforestry, the intentional integration of trees with crops or livestock, offers

multiple ecological and socioeconomic benefits. Trees provide shade, improve soil fertility, reduce erosion, and support biodiversity while simultaneously producing timber, fruits, or fodder (Jose, 2009). Agroforestry systems are increasingly recognized as climate-smart solutions that combine productivity with ecosystem restoration.

Taken together, these approaches highlight a transformative shift toward farming systems that work with, rather than against, natural processes. While challenges such as initial costs, technical expertise, and scalability remain, these alternative pathways represent vital strategies to ensure food security and ecological resilience in the Anthropocene. By integrating ecological design, resource efficiency, and carbon-conscious management, they collectively offer a roadmap for sustainable agriculture beyond traditional and modern systems.

This review will explore contemporary agricultural production models that offer alternative pathways to traditional and modern systems, with the potential to ensure reliable food production in both the near and distant future.

2. TRADITIONAL AGRICULTURE

Traditional agricultural practices, developed over centuries through experiential knowledge, rely on natural inputs rather than modern machinery and synthetic fertilizers. In such systems, organic amendments including animal manure and crop residues (green manuring) are commonly applied, alongside the use of traditional seeds and cultivation techniques (Altieri, 2004; Gliessman, 2015). Irrigation is typically carried out through surface flooding or furrow methods instead of modern sprinkler or drip irrigation technologies. Furthermore, biological control plays a central role, with natural predators such as mantises, lady beetles, and birds acting against pests like aphids and grasshoppers, thereby reducing dependence on chemical pesticides (Nicholls and Altieri, 2018). These methods collectively represent ecologically grounded farming approaches that contribute to soil health, biodiversity conservation, and the sustainability of agroecosystems.

☛ **Fallowing:** Refers to the practice of leaving land uncultivated for a certain period, allowing the soil to regenerate naturally (Lal, 2015). This method enhances soil structure, restores nutrient balance, and contributes to long-term agricultural sustainability.

☛ **Crop rotation:** involves the sequential cultivation of different crop species in the same field across years. This practice prevents

soil exhaustion caused by monocropping and reduces the prevalence of pests and weeds (Karlen et al., 1994). In field crop systems, rotations that integrate legumes with cereals are particularly recommended, as legumes contribute to nitrogen fixation and thus improve soil fertility and productivity (Drinkwater et al., 1998).

☛ **Polyculture farming:** Polyculture farming, defined as the simultaneous cultivation of multiple crop species within the same area, has been identified as an effective strategy to enhance resilience against the impacts of global warming. By increasing biodiversity, polyculture systems improve soil fertility, reduce pest and disease outbreaks, and enhance water-use efficiency, thereby contributing to greater ecological stability compared to monocultures (Altieri, 1999; Vandermeer, 2011). Empirical studies have demonstrated that polyculture not only improves yield stability under climate-induced stresses such as drought and heat but also supports ecosystem services including pollination and carbon sequestration (Tilman et al., 2006; Lin, 2011). Consequently, polyculture is increasingly recognized as a key component of climate-smart agriculture, offering both adaptive and mitigative benefits in the face of global warming.



Figure 1. An example of polyculture farming in Mardin, Turkey (mixed cultivation of wheat and vetch)

2.1 Advantages of Traditional Agriculture

☛ Since chemical fertilizers and pesticides are not used, soil productivity improves in the long term, while exposure to pesticide and nitrate pollution is avoided (Altieri, 2004; Gliessman, 2015).

☛ The use of local seeds and intercropping practices enriches the ecosystem and enhances biodiversity (Frison et al., 2011).

- ☛ It requires fewer natural resources and causes minimal environmental harm.

- ☛ Over the long term, it improves the natural cycles of soil, ensuring that fertile and healthy land is preserved for future generations (Nicholls and Altieri, 2018).

- ☛ It contributes to the preservation and intergenerational transfer of ancestral knowledge while maintaining local culture and practices.

2.2 Disadvantages of Traditional Agriculture

- ☛ Yields per unit area may be lower compared to modern agricultural methods (FAO, 2018).

- ☛ It requires significant labor, time, and effort.

- ☛ Due to limited access to modern supports such as greenhouses or advanced irrigation systems, traditional farming is more vulnerable to abiotic stress factors, including drought and extreme temperatures (Lal, 2015).

- ☛ It is more suitable for small-scale production rather than large-scale commercial farming, making its application in industrial agriculture economically less viable.

- ☛ In years when pests, diseases, or weeds reach epidemic levels, biological and traditional methods may prove insufficient. The absence of pesticide use makes pest and disease management more demanding and costly (Pretty et al., 2006).

3. MODERN AGRICULTURE

Modern agriculture integrates technological and scientific advancements to enhance productivity, optimize resource utilization, and promote environmental sustainability. Key methodologies include drip irrigation, controlled environment agriculture (CEA), agricultural biotechnology, smart/digital farming, and precision agriculture (Abbasi et al., 2022; Morante et al., 2023).

3.1. Drip Irrigation

Drip irrigation delivers water directly to plant roots, minimizing evaporation and runoff.

3.1.1 Advantages

Efficient water use, reducing consumption by up to 95% in some cases (Kushwaha et al., 2024).

Enhanced crop yields in arid regions (Mgendi, 2024).

Reduced weed growth due to targeted watering (Bahmutsky et al., 2024).

3.1.2 Disadvantages

High initial setup costs (GAO, 2024).

Requires regular maintenance to prevent clogging (Morante et al., 2023).

Limited effectiveness on uneven terrains (Kushwaha et al., 2024).

3.2 Controlled Environment Agriculture (CEA)

CEA encompasses methods like greenhouses and vertical farming, where environmental factors are regulated to optimize plant growth.

3.2.1 Advantages

Year-round production independent of external weather conditions (Abbasi et al., 2022).

Efficient use of space, suitable for urban settings (Morante et al., 2023).

Reduced pesticide use, leading to safer food products (Soussi et al., 2024).

3.2.2 Disadvantages

Significant energy consumption, especially for lighting and climate control (GAO, 2024).

High capital investment for infrastructure (Bahmutsky et al., 2024).

Potential for increased labor requirements for system management (Mgendi, 2024).

3.3 Agricultural Biotechnology

This involves genetic modification and other biotechnological techniques to enhance crop traits.

3.3.1 Advantages

Development of pest-resistant and drought-tolerant crop varieties (Morante et al., 2023).

Potential for increased nutritional content in food (Abbasi et al., 2022).

Reduction in the need for chemical pesticides (Kushwaha et al., 2024).

3.3.2 Disadvantages

Ethical concerns regarding genetic modifications (Mgendi, 2024).

Potential for reduced biodiversity (Morante et al., 2023).

Regulatory challenges and public resistance in certain regions (Abbasi et al., 2022).

3.4. Smart/Digital Farming

Utilizes IoT devices, drones, and data analytics to monitor and manage agricultural operations.

3.4.1 Advantages

Real-time monitoring of crop health and soil conditions (Soussi et al., 2024).

Optimization of input usage, leading to cost savings (Abbasi et al., 2022).

Enhanced decision-making through data-driven insights (Bahmutsky et al., 2024).

3.4.2 Disadvantages

High upfront costs for technology acquisition (GAO, 2024).

Dependence on reliable internet connectivity (Mgendi, 2024).

Data privacy and cybersecurity concerns (Abbasi et al., 2022).

3.5 Precision Agriculture

Involves the use of GPS, sensors, and variable rate technology to apply inputs precisely where needed.

3.5.1 Advantages

Reduction in input costs (water, fertilizers, pesticides) (Kushwaha et al., 2024).

Increased crop yields through targeted interventions (Mgendi, 2024).

Minimization of environmental impact due to efficient resource use (Bahmutsky et al., 2024).

3.5.2 Disadvantages

Requires specialized knowledge and training (Morante et al., 2023).

High initial investment in equipment and software (GAO, 2024).

Potential for technological obsolescence (Abbasi et al., 2022).

Modern agricultural methods hold significant potential for addressing global food security and environmental challenges. However, their long-term success depends on proper implementation, equitable access, and supportive institutional frameworks, and reduction of high upfront costs

4. CURRENT APPROACHES IN AGRICULTURAL PRODUCTION

4.1 Permaculture

4.1.1 What is permaculture?

Permaculture is a system of agricultural and ecological design principles that mimics natural ecosystems to create sustainable, resilient food production systems. The concept was first developed by Bill Mollison and David Holmgren in the late 1970s (Janzon, 2018). It integrates land, resources, people, and the environment through mutually beneficial synergies.

4.1.2 Why is permaculture necessary?

Traditional industrial agriculture often degrades soils, reduces biodiversity, and depends heavily on external inputs (fertilizers, pesticides). Permaculture offers a regenerative alternative-emphasizing closed loops, ecological harmony, and long-term resilience. In the face of resource scarcity, ecosystem degradation, and climate stress, permaculture provides strategies to restore ecosystem services, capture carbon, and increase system stability (Reiff et al., 2024)

4.1.3 Advantages

- ✦ Permaculture techniques (composting, mulching, polycultures) enhance soil structure, fertility, microbial life, and carbon storage (Reiff et al., 2024).
- ✦ Systems are designed to recycle nutrients, reduce external fertilizer or pesticide use, and minimize waste.
- ✦ Polycultures, companion planting, integrated animals promote biodiversity and pest suppression (Mercer, 2021).
- ✦ Techniques like rainwater harvesting, swales, ponds, and microtopography conserve water and stabilize local climates.
- ✦ Permaculture fosters local self-reliance, community involvement, and reconnects people with their landscapes (Mercer, 2021).

4.1.4 Disadvantages

- ✦ Transitioning land or designing permaculture systems requires labor, design work, and investment
- ✦ Short-term yields may be lower, and benefits accrue over longer time frames.
- ✦ Mechanization and industrial scale may be difficult to adapt; scaling without losing ecological integrity is challenging.
- ✦ Success relies heavily on good design, local adaptation, and continuous observation. Poor design can lead to failure.
- ✦ Conventional agricultural policies, subsidy systems, and market forces often discourage permaculture adoption (Mercer, 2021).

4.1.5 Application domains

- ✦ Homesteads and Permaculture Farms; small to medium farms designed to be self-sufficient.
- ✦ Agroforestry & Food Forests; integration of perennial trees, shrubs, and understory crops.
- ✦ Urban Permaculture / Community Gardens; edible landscapes in urban settings-rooftops, backyards.
- ✦ Landscape Restoration & Watershed Design; using permaculture for rewilding, erosion control, watershed rehabilitation.

• Historical & Cultural Landscapes; restoration of heritage agricultural systems with permaculture principles (Öztekin and Kaya, 2025).

4.1.6 Examples Worldwide & in Turkey

• Australia is recognized as the birthplace of permaculture, where Bill Mollison and David Holmgren pioneered the first permaculture gardens, laying the foundation for a global movement.

• In Bayındır, İzmir, Turkey, the Permakamp initiative provides structured education in natural living and permaculture design. Meanwhile, the Yeryüzü Association in Istanbul has gained prominence for its urban permaculture implementations within metropolitan settings.

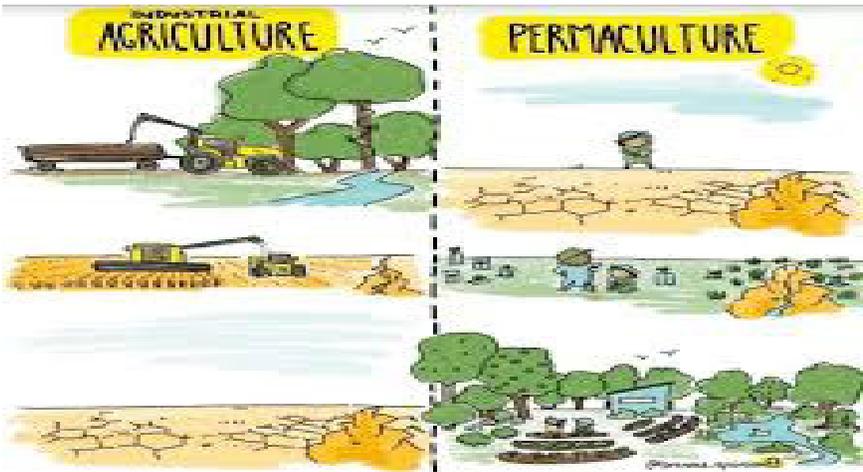


Figure 1. A sustainable design philosophy which is permaculture

4.2 Hydroponic Agriculture

4.2.1 What is hydroponic agriculture?

Hydroponics is a soilless cultivation method in which plants are grown with their roots immersed in a nutrient solution or supported by an inert medium (e.g. rockwool, perlite) and supplied directly with the essential mineral nutrients dissolved in water (A Review on Hydroponics and the Technologies Velazquez-Gonzalez et al., 2022). It is an alternative to conventional soil-based agriculture and includes techniques such as nutrient film technique (NFT), deep water culture (DWC), and media-bed systems (Çekin et al., 2024).

4.2.2 Why it should be adopted?

The adoption of hydroponics is motivated by several constraints in traditional agriculture:

- ☛ Soil degradation, salinity, drought, erosion, and urban expansion reduce the availability of fertile arable land. Soilless farming provides a solution independent of soil quality (Velazquez-Gonzalez et al., 2022).

- ☛ Water Efficiency: Hydroponic systems recirculate nutrient solutions, which can drastically reduce water consumption compared to conventional farming. (Bunyuth and Mardy, 2024).

- ☛ Controlled delivery of nutrients, optimized environmental parameters (light, pH, temperature) allow more consistent yields and faster crop cycles (Bunyuth and Mardy, 2024).

4.2.3 Advantages

- ☛ Plants grow faster because nutrients are directly available without soil constraints. Compared to conventional soil-based agriculture, it enables faster plant growth and higher yield per unit area.

- ☛ Water consumption can be dramatically reduced by up to approximately 90%. (Rajaseger et al., 2023). It offers a future-oriented projection for the world's arid and semi-arid regions.

- ☛ Vertical farming, indoor farms and small-area systems make hydroponics suitable for urban or limited-land environments. The hydroponic method can enable agricultural production even at the household level, using minimal water and inputs in a future scenario marked by extreme drought.

- ☛ Control over environment allows production in all seasons (Rajaseger et al., 2023).

- ☛ No soil means less soil-borne disease, reduced weeds, fewer pesticides required. It is possible to grow crops such as lettuce, parsley, and tomatoes continuously throughout the year.

4.2.4 Disadvantages

- ☛ Equipment (pumps, lighting, nutrient supplies), infrastructure, monitoring systems are expensive.

- ☛ Requires skill to maintain nutrient balance, pH, water quality; failures (pump, electricity) can damage or kill crops quickly. (Agustian et al.,

2022)

☛ Artificial lighting, climate control, pumping consume energy. Without renewable energy sources, carbon footprint may be higher. Attempts to mitigate global warming may unintentionally contribute to it. However, if the energy demand is met through renewable sources, this issue can be effectively resolved

☛ Waterborne pathogens can spread through recirculated water.

☛ While hydroponic systems are highly efficient for cultivating leafy greens and herbs, they pose challenges for root vegetables such as carrots, potatoes, sugar beet, and radish due to spatial and structural constraints. Moreover, crops with extensive root systems or requiring substantial mechanical support are generally unsuitable for conventional hydroponic setups.



Figure 2. Lettuce cultivation at home using a hydroponic system

4.2.5 Plant cultivation using home-based hydroponic systems

For effective home-based hydroponic farming, it is essential to utilize pH and EC meters. These parameters are critical for nutrient uptake and overall plant health. The nutrient solution must be monitored regularly, as EC (expressed in mS/cm) indicates the salt concentration of the water, while pH reflects its acidity or alkalinity. Optimal EC and pH values vary depending on the plant species. To maintain appropriate pH levels, pH-lowering agents should be applied when necessary. Below are the recommended EC and pH ranges for selected crops suitable for hydroponic cultivation at home.

Optimal pH & EC

HYDROPONIC VEGETABLES

VEGETABLE	pH	EC	VEGETABLE	pH	EC
ARTICHOKE	6.5-7.5	0.8-1.8	MARROW	6.0	1.8-2.4
ASPARAGUS	6.0-6.8	1.4-1.8	OKRA	6.5	2.0-2.4
BASIL	5.5-6.5	1.0-1.6	ONIONS	6.0-6.7	1.4-1.8
BEAN [COMMON]	6.0	2.0-4.0	PAK CHOI	7.0	1.5-2.0
BEETROOT	6.0-6.5	0.8-5.0	PARSNIP	6.0	1.4-1.8
BOK CHOI	6.0-7.0	1.5-2.5	PEA	6.0-7.0	0.8-1.8
BROAD BEAN	6.0-6.5	1.8-2.2	PEA (SUGAR)	6.0-7.0	0.8-1.8
BROCCOLI	6.0-6.5	2.8-3.5	PEPINO	6.0-6.5	2.0-5.0
BRUSSELL SPROUT	6.5-7.5	2.5-3.0	PEPPERS	5.8-6.3	2.0-3.0
CABBAGE	6.5-7.0	2.5-3.0	PEPPERS (BELL)	6.0-6.5	2.0-3.0
CAPISCUM	6.0-6.5	1.8-2.2	PEPPERS (HOT)	5.0-6.5	3.0-3.5
CARROTS	6.3	1.6-2.0	POTATO	5.0-6.0	2.0-2.5
CAULIFLOWER	6.0-7.0	0.5-2.0	PUMPKIN	5.5-7.5	1.8-2.4
CELERY	6.5	1.8-2.4	RADISH	6.0-7.0	1.6-2.2
CUCUMBER	5.8-6.0	1.7-2.5	SPINACH	6.0-7.0	1.8-2.3
EGGPLANT	5.5-6.5	2.5-3.5	SILVERBEET	6.0-7.0	1.8-2.3
ENDIVE	5.5	2.0-2.4	SWEET CORN	6.0	1.6-2.4
FODDER	6.0	1.8-2.0	SWEET POTATO	5.5-6.0	2.0-2.5
GARLIC	6.0	1.4-1.8	TARO	5.0-5.5	2.5-3.0
KALE	5.5-6.5	1.25-1.5	TOMATO	5.5-6.0	2.0-5.0
LEEK	6.5-7.0	1.4-1.8	TURNIP	6.0-6.5	1.8-2.4
LETTUCE	5.5-6.5	0.8-1.2	ZUCCHINI	6.0	1.8-2.4

These values are general guidelines for hydroponic gardening, and may be slightly different based on your climate and growing conditions.

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Figure 3. Optimal pH and EC values for selected plant species

In hydroponic farming, growers can either rely on commercially available nutrient solutions or prepare custom formulations tailored to specific crops. When developing a nutrient solution, all macro and micro nutrients must be supplied in fully water-soluble forms to ensure optimal plant uptake and growth (Resh, 2013). A balanced nutrient solution should include the essential macro nutrients which are nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) as well as critical micro nutrients such as calcium (Ca), sulfur (S), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), molybdenum (Mo), and boron (B) (Savvas and Gruda, 2018). Proper formulation and monitoring are vital, as imbalances in nutrient concentration can lead to deficiencies or toxicities that impair plant health and productivity (Sardare, 2013).

In hydroponic farming, the nutrient solution should be replaced at least once every two weeks to prevent nutrient imbalances and microbial growth. Water levels must be continuously monitored to ensure that the solution does not fall below the root zone. Adequate light is also essential for plant growth and development, as photosynthesis depends directly on light availability. Insufficient lighting often results in elongated, weak, and fragile stems, along with pale green leaves, indicating poor physiological performance. For leafy crops in particular, supplemental nighttime lighting can enhance yield. The use of red, blue, and white LED lamps has been shown to optimize photosynthetic activity and improve overall plant growth.

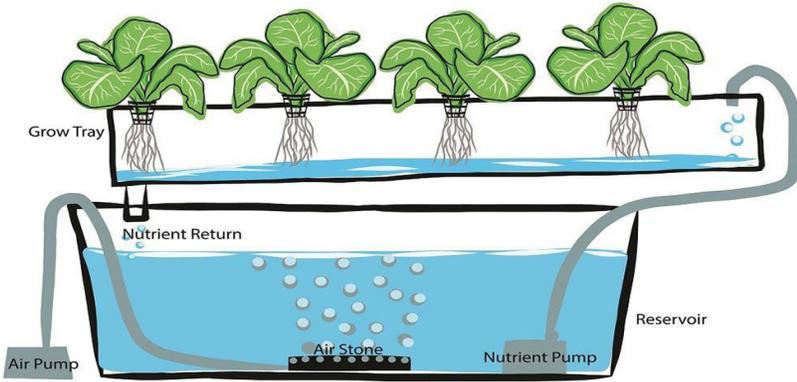


Figure 4. Home-based hydroponic farming system

4.2.6 Hydroponic farming in the World and Turkey

The Netherlands is recognized as a global leader in hydroponic farming, particularly in advanced greenhouse systems where crops such as tomatoes and peppers are widely cultivated using hydroponic techniques. In Turkey, the province of Antalya has become a prominent center for hydroponic production, with modern greenhouse facilities focusing on the cultivation of lettuce, strawberries, and tomatoes through soilless systems.



Figure 5. Hydroponic farming practices in Antalya and Amsterdam

4.3 Aquaponic Farming

4.3.1 What is aquaponics?

Aquaponics is an integrated agricultural system that combines aquaculture (fish farming) with hydroponics (soilless plant cultivation). In this closed-loop approach, nutrient-rich water from fish tanks provides essential minerals for plants, while plants and associated microorganisms

purify and recycle the water before it returns to the aquaculture unit (Vasdravanidis et al., 2022). Fish excrete ammonia and other wastes, which are biologically transformed by nitrifying bacteria into nitrites and subsequently nitrates. These compounds serve as plant-available nutrients, and in turn, the plants remove them from the water, maintaining a balanced and sustainable cycle (Rawal and Puspa, 2024).

4.3.2 Why it should be adopted?

☛ Aquaponics offers a regenerative alternative to conventional agriculture and aquaculture by combining benefits of both systems while minimizing waste and resource use (Ibrahim et al., 2023). Some key motivations include:

☛ Because the water is recirculated and reused, aquaponics systems can dramatically reduce fresh water demand compared to traditional agriculture or aquaculture (Vasdravanidis et al., 2022; Ibrahim et al., 2023). Aquaponic farming may serve as a sustainable alternative in response to the threats of global warming and climate change, particularly due to its potential for significant water conservation.

☛ Dual harvest (fish + plants) enhances food productivity per unit area and diversifies output streams (Ibrahim et al., 2023).

☛ Nutrient losses to the environment are minimized; waste from fish is recycled rather than discharged (Vasdravanidis et al., 2022).

☛ Aquaponic systems operate under controlled environments, making them less susceptible to climate extremes and less reliant on arable land (Nair et al., 2025).

4.3.3 Advantages

☛ Significant reduction in freshwater use via recirculation (Vasdravanidis et al., 2022).

☛ Simultaneous production of fish and plants enhances productivity (Ibrahim et al., 2023).

☛ Fish wastes become plant fertilizers, minimizing external nutrient inputs (Rawal and Puspa, 2024).

☛ Systems can be designed vertically or intensively, making them suitable for small areas.

☛ Less nutrient leaching and discharge into the environment compared to conventional farming (Vasdravanidis et al., 2022).

4.3.4 Disadvantages

- ✦ Infrastructure, monitoring equipment, pumps, and sensors require steep investment (Ibrahim et al., 2023).
- ✦ Maintaining the delicate balance between fish, microbes, plants, and water parameters (pH, dissolved oxygen, nitrification) is technically demanding (Rawal and Puspa, 2024).
- ✦ Running pumps, aeration, lighting (in indoor systems) can lead to substantial energy use. Utilizing renewable energy through solar panels can significantly reduce energy costs to a minimum.
- ✦ A single failure (pump, aeration, water quality crash) may harm both plants and fish.
- ✦ Scaling up without losing system stability and profitability remains a challenge (Ibrahim et al., 2023).
- ✦ Not all fish or plants pair well—choices must match system conditions and climatic constraints.

4.3.5 Examples around the World & in Turkey

- ✦ Aquaponics has been explored in controlled systems in various developed countries such as United States and Europe, often focusing on tilapia and leafy greens under recirculating systems (Ibrahim et al., 2023).
- ✦ Report on advanced aquaponic systems that incorporate climate control, sensor networks, and automation to mitigate climate change impacts in aquaculture systems (Nair et al., 2025)
- ✦ Though literature in Turkey is more limited, some experimental projects integrate aquaponics in academic or pilot greenhouses, often combining local fish species (e.g. trout or carp) with vegetables.

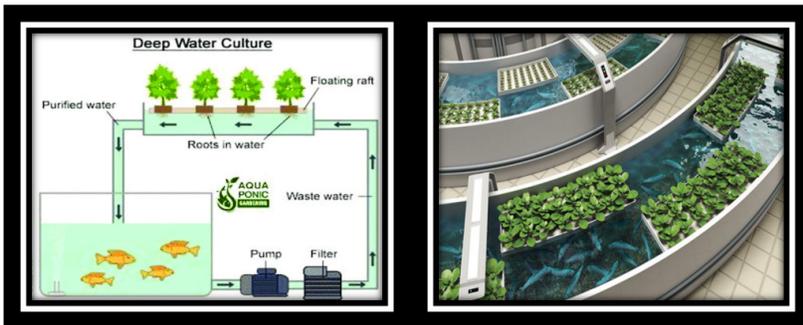


Figure 6. The working principle of aquaponic farming and an example from Turkey

4.4 Agroforestry

4.4.1 What is agroforestry?

Agroforestry refers to land-use systems that intentionally integrate woody trees or shrubs with crops and/or livestock on the same parcel, such that ecological and economic interactions among them enhance productivity, biodiversity, soil health, and sustainability (Kumar et al., 2024). These systems include silvopasture, alley cropping, forest garden, wind-breaks, riparian buffers, and home gardens.

4.4.2 Why should agroforestry be adopted?

- **Soil health and fertility:** Trees contribute organic matter such as leaf litter, root exudates, improve structure, enhance microbial activity, and fix nitrogen in some systems (Quandt et al., 2023).
- **Diversification of production and income:** Farmers obtain multiple products (timber, fruit, fodder, non-timber forest products) along with crops or livestock, reducing risk (Raihan, 2023).
- **Ecosystem services:** Agroforestry supports biodiversity, pollinators, water regulation, erosion control, and microclimatic buffering (Tebkew, 2024).
- **Sustainability and resilience:** By integrating trees, agroforestry stabilizes ecological functions and offers long-term sustainability beyond monocultures (Dophal et al., 2024).

4.4.3 Advantages

- **Improved soil quality and nutrient cycling** (Quandt et al., 2023).
- **Multiple outputs and diversified income** (Raihan, 2023).
- **Biodiversity conservation and habitat enhancement** (Dophal et al., 2024).
- **Erosion control, water regulation, and microclimate buffering** (Kumar et al., 2024).
- **Carbon storage and mitigation capacity** (Kumar et al., 2024).

4.4.4 Disadvantages

- **Trees may compete with crops for light, water, and nutrients, potentially reducing overall yields.** (Tebkew et al., 2024). In some cases, trees and crops may compete for resources. Tree roots might absorb water that

crops need, and shade from trees can lower crop yields depending on how they are arranged.

- ☛ It requires knowledge of ecology and forest management, as well as planning tailored to the specific conditions of each site.

- ☛ Agroforestry systems require long-term commitment, as trees take several years to reach maturity and the associated benefits may accumulate gradually over time.

- ☛ Initial investment and labor demands are typically high during the establishment phase.

- ☛ Adoption may be hindered by challenges such as insecure land tenure, limited technical knowledge, and financial constraints.

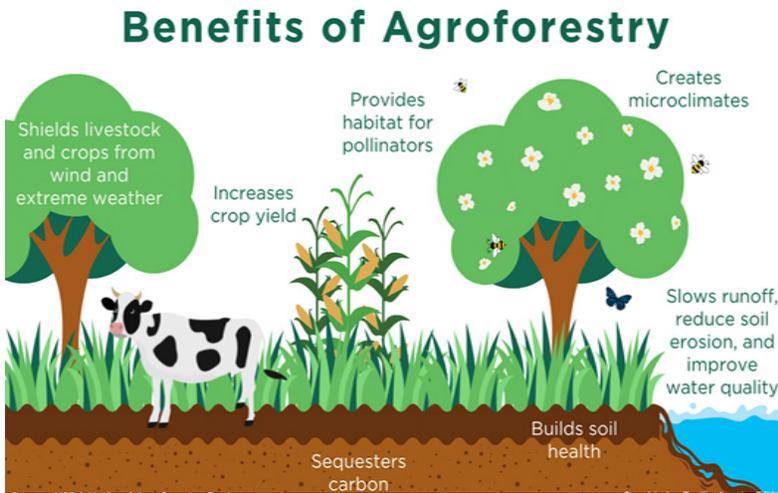


Figure 7. Some of the many benefits of agroforestry systems

4.4.5 Examples Worldwide & in Turkey

In Peru, agroforestry is commonly practiced in the Amazon region, where farmers integrate trees with crops such as coffee, cacao, and bananas. These systems help preserve biodiversity, improve soil health, and provide economic benefits to local communities. In Kenya, the Green Belt Movement is a major initiative led by women that integrates agriculture and forestry.

In Turkey's Mersin and Adana provinces, agroforestry systems combine citrus orchards with large shade-providing trees. Additionally, Steppe Regeneration Projects have been launched in Central Anatolia to restore degraded landscapes.



Figure 8. Visuals of agroforestry practices in Peru and Turkey

4.5 Regenerative Agriculture

4.5.1 What is regenerative agriculture?

Regenerative agriculture is a holistic farming approach aimed at restoring and enhancing ecosystem functions by improving soil health, biodiversity, water cycles, and carbon sequestration while maintaining agricultural productivity (Giller et al., 2021). It emphasizes practices such as minimal soil disturbance, cover cropping, crop diversification, rotational grazing, and integration of livestock and crops (Rhodes, 2017). Unlike conventional agriculture, which often depletes soil organic matter and contributes to greenhouse gas emissions, regenerative agriculture seeks to reverse degradation and regenerate ecosystems.

The foundation of soil degradation lies in the Green Revolution, which followed World War II and dramatically increased agricultural production. By the 1950s, the global population was rapidly expanding, yet food supplies were insufficient to meet demand. During this period, the invention and widespread use of chemical fertilizers (particularly nitrogen-based), pesticides, and modern agricultural machinery led to substantial increases in yield per unit area. The term conventional agriculture emerged alongside the Green Revolution. However, decades later, the heavy cost of this revolution has manifested as widespread soil degradation (Pingali, 2012).

According to United Nations projections, within the next 50 years, a

significant portion of fertile topsoil and consequently much of our food production capacity will be lost (FAO, 2018). Even today, erosion has reduced topsoil thickness to as little as 15 cm in many regions, a level at which healthy root development is no longer feasible. Carbon is the most essential component that gives vitality to the soil ecosystem. Before the rise of conventional farming, soils typically contained 25–30% carbon, whereas under intensive conventional practices, this level has declined to around 5% (Lal, 2020).

At this point, regenerative agriculture offers a powerful solution. Since approximately 55% of soil organic matter is composed of carbon, increasing organic matter means capturing carbon dioxide (CO₂) directly from the atmosphere and storing it in soils (Schreefel et al., 2020). The following methods are key to restoring soil health:

- ☛ Reducing or eliminating tillage to protect and regenerate the soil ecosystem.
- ☛ Promoting direct seeding (no-till planting) into crop residues.
- ☛ Incorporating compost and compost teas, which are rich in organic matter.
- ☛ Applying biochar, which is highly carbon-dense, to the soil.
- ☛ Integrating plant and animal production, enabling the use of livestock manure as a soil amendment.
- ☛ Adopting soilless cultivation systems, such as hydroponics or aquaponics, as complementary models.
- ☛ Practicing organic (ecological) farming, both annual and perennial, to support long-term soil recovery.
- ☛ Expanding managed grazing systems and agroforestry, which strengthen soil structure and biodiversity.

Through these practices, regenerative agriculture not only halts soil degradation but also restores ecological balance and enhances resilience against climate change (Giller et al., 2021).

4.5.2 Why should regenerative agriculture be adopted?

- ☛ Regenerative agriculture promotes soil regeneration by increasing organic matter, which in turn enhances fertility, microbial activity, and nutrient availability (Lal, 2020).

- ☛ Through diversified production and stabilized yields, Regenerative agriculture strengthens food system resilience, reducing exposure to climate and market-related shocks (Giller et al., 2021).

- ☛ by minimizing dependence on synthetic inputs, regenerative practices contribute to lower pollution levels, healthier food, and more ecologically sustainable landscapes (Rhodes, 2017).

4.5.3 Advantages

- ☛ Improved soil fertility and carbon sequestration (Lal, 2020).

- ☛ Enhanced biodiversity and ecosystem services (Paustian et al., 2019).

- ☛ Reduced dependence on synthetic fertilizers and pesticides (Rhodes, 2017).

- ☛ Greater resilience against climate variability (Giller et al., 2021).

- ☛ Products marketed as “regeneratively produced” may attract higher prices.

4.5.4 Disadvantages

- ☛ With the global population approaching 8.5 billion, one of the major challenges in transitioning from industrial agriculture to regenerative practices is the concern over maintaining high yields per unit area. This pressure for productivity often leads to hesitation toward adopting regenerative agriculture.

- ☛ Transitioning from conventional to regenerative agricultural systems requires significant investment in training, infrastructure, and technical expertise, which can pose challenges for farmers (Giller et al., 2021).

- ☛ During the early years of implementation, soil recovery processes may take several growing seasons, often resulting in temporary reductions in yield and productivity (Rhodes, 2017).

- ☛ The concept of “regeneration” remains difficult to quantify, as there is ongoing debate regarding its definition, assessment criteria, and verification mechanisms (Paustian et al., 2019).

The lack of supportive government policies and limited integration into mainstream agricultural frameworks further restrict the widespread adoption of regenerative practices.

4.5.5 Global & Turkey examples

In the U.S., regenerative ranching (rotational grazing, prairie restoration) has been promoted for carbon sequestration and biodiversity gains (Rhodes, 2017). In Australia and New Zealand, regenerative cropping integrates cover crops and rotational livestock to combat soil erosion and desertification (Paustian et al., 2019).

Regenerative agriculture practices are emerging in regions such as Central Anatolia and Aegean Turkey, where farmers experiment with cover crops, no-till systems, and organic amendments to reverse soil degradation. NGOs and local initiatives promote regenerative olive farming and vineyard management to enhance soil quality, water conservation, and resilience against climate variability. Scientific research on regenerative agriculture in Turkey remains limited but is growing, often linked with sustainable agriculture and agroecology studies.



Figure 9. Regenerative agriculture offers a pathway to revitalize soil ecosystems and mitigate climate degradation.

5. CONCLUSION

Emerging agricultural paradigms such as permaculture, hydroponic agriculture, aquaponic farming, regenerative agriculture, and agroforestry present promising alternatives to traditional and modern systems. Collectively, they demonstrate that food production can move beyond the linear extractive logic of traditional models toward circular, adaptive, and ecologically embedded practices. In the near future, in parallel with the growing population and the decline in fertile soils, these approaches may serve as complementary systems that address specific challenges—hydroponics and aquaponics providing resilient food production in urban and resource-scarce contexts, permaculture and agroforestry enhancing biodiversity and ecosystem services in rural landscapes affected by severe heat and drought stress, and regenerative agriculture restoring degraded soils and mitigating climate change.

Looking further ahead, the transformative potential of these systems lies not in isolated adoption but in their integration into broader agricultural policy frameworks, market structures, and cultural practices. Widespread implementation will require investments in research, technological innovation, and farmer training, as well as supportive governance that values ecological sustainability alongside productivity. While challenges of scalability, cost, and social acceptance remain, the convergence of these alternative pathways suggests a trajectory where agriculture is no longer defined solely by yield maximization, but by resilience, equity, and long-term planetary health.

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Chapter 3

**IMPACT OF WATER DEFICIT STRESS ON
GROWTH, METABOLISM, AND ESSENTIAL
OIL COMPOSITION OF MENTHA PIPERITA
L.**

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1. Introduction

Among various abiotic constraints, water deficit stands out as one of the most severe environmental factors affecting the productivity, physiology, and biochemical stability of medicinal and aromatic plants. Within this group, *Mentha piperita* L. (peppermint) has gained considerable attention due to its essential oil, rich in valuable monoterpenes such as menthol and menthone, which impart distinctive aroma and therapeutic functionality. These bioactive compounds possess strong antimicrobial, anti-inflammatory, and soothing properties, ensuring the plant's wide application in the pharmaceutical, cosmetic, and food sectors (Lim et al., 2018; Carretto et al., 2011; Taylan et al., 2021). The formation and accumulation of these secondary metabolites are highly dependent on environmental conditions, particularly on water availability, which modulates both enzymatic activity and carbon flux within the plant's metabolic network. In recent years, climate-driven irregularities in precipitation and the decline of freshwater resources have increased the frequency of drought episodes, posing a serious challenge to peppermint cultivation, especially in semi-arid regions with restricted irrigation capacity (Kleinwächter & Selmar, 2014; Gupta et al., 2020).

When exposed to drought, peppermint exhibits profound physiological and biochemical adjustments aimed at maintaining internal homeostasis. These include restricted stomatal conductance, reduced photosynthetic rates, and reprogramming of metabolic pathways associated with energy and carbon balance. Water deficiency leads to the excessive generation of reactive oxygen species (ROS), which can damage cellular components such as lipids and proteins. To counteract these effects, the plant enhances the activity of both enzymatic antioxidants—superoxide dismutase (SOD), catalase (CAT), peroxidase (POD)—and non-enzymatic molecules such as ascorbate, glutathione, and phenolic derivatives (Wang et al., 2019). Simultaneously, osmolytes including proline, soluble sugars, and glycine betaine accumulate to protect cellular membranes and preserve turgor pressure during dehydration (Reddy et al., 2004). These responses are further reinforced by hormonal regulation, characterized by increased abscisic acid (ABA) and reduced gibberellin levels, which together mediate stomatal closure and sustain metabolic energy allocation under water stress.

Collectively, these drought-induced adjustments not only help the plant survive water limitation but also influence the biosynthesis of essential oil constituents. Moderate stress may enhance the production of defense-related volatiles such as menthol and menthone, while prolonged or severe drought often suppresses their accumulation. A deeper under-

standing of these interconnected physiological and metabolic responses is therefore essential for improving peppermint's resilience, ensuring stable oil yield, and maintaining phytochemical quality under evolving climatic conditions.

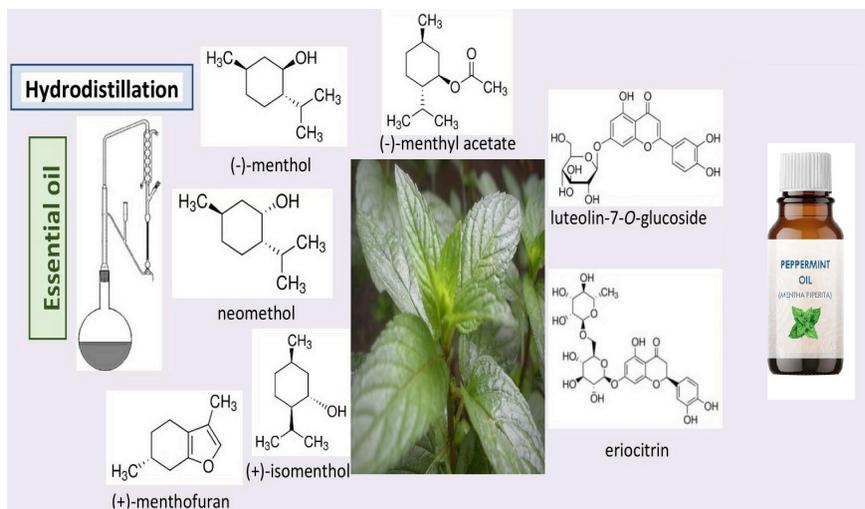


Figure 1. *Mentha piperita L.* and some of its essential oil components.

2. Botanical Description of *Mentha piperita L.* (Peppermint)

Mentha piperita L., commonly known as peppermint, is an aromatic perennial herb belonging to the *Lamiaceae* family. It is a naturally occurring hybrid ($2n = 6x = 72$) between *M. aquatica* (water mint, $2n = 96$) and *M. spicata* (spearmint, $2n = 48$), representing a taxonomically and phytochemically distinctive member of the genus *Mentha* (Heydari et al., 2018; Singureanu et al., 2015). The genus name *Mentha* derives from “Mintha,” a nymph of Greek mythology transformed into the plant, while the species epithet *piperita* originates from the Latin *piper*, meaning pepper, in reference to its characteristic pungent aroma (Pushpangadan & Tewari, 2006; Tyler et al., 1988).

Peppermint usually reaches 50–90 cm in height and exhibits a square-shaped, slightly purplish stem covered with fine hairs. The leaves are opposite, long-petiolate, and lanceolate, showing a glossy dark-green upper surface and a paler underside. Both sides bear numerous glandular trichomes, the microscopic oil-secreting structures responsible for the plant's strong aroma and pharmacological activity (Singureanu et al., 2015; Mahendran & Rahman, 2020). The flowering spikes consist of small, violet-purple blossoms with tubular calyces and corollas adapted for insect pollination. The essential oil, accumulated mainly within these

glandular trichomes, is dominated by monoterpenes such as menthol and menthone, compounds known for their cooling properties and therapeutic potential (Mogoşan et al., 2017; Meamarbashi & Rajabi, 2013; Lim et al., 2018). These metabolites confer antimicrobial, antiviral, and antifungal effects and are therapeutically valuable in treating gastrointestinal disorders, particularly irritable bowel syndrome, by reducing smooth-muscle spasms in the intestinal wall (Buleandră et al., 2016; Egan et al., 2015).

Morphologically, peppermint resembles spearmint but can be distinguished by its more compact inflorescences, ovate and sharply serrated leaves, and denser oil glands. The overall plant emits a characteristic refreshing fragrance that is emblematic of the *Mentha* genus.

3. Chemical Composition of *Mentha piperita* Essential Oil

The essential oil of *M. piperita* is typically extracted from the aerial parts during the flowering stage using hydrodistillation. This method ensures maximum recovery of volatile constituents while maintaining the integrity of thermolabile compounds (Mimica-Dukić et al., 2003; Piasecki et al., 2023). After primary extraction, the oil is often redistilled to eliminate sulfur-containing volatiles such as dimethyl sulfide that can negatively influence aroma quality (Hudz et al., 2023).

The refined peppermint oil generally appears as a colorless to pale yellow or faintly greenish liquid, exhibiting a distinctive cooling aroma and taste profile primarily attributed to the dominance of L-menthol ($\approx 39.6\%$), menthone ($\approx 8.9\%$), and menthyl acetate ($\approx 10.4\%$) (Mimica-Dukić et al., 2003; Heydari et al., 2018). Minor yet significant constituents such as α -pinene, β -pinene, myrcene, and carvone—present at approximately 3.5%—further enrich the oil's chemical complexity (Soković et al., 2009). Additional compounds, including eucalyptol (1,8-cineole), pulegone, and other oxygenated monoterpenes, contribute to its multifaceted aroma and bioactivity spectrum (Soković et al., 2009). The composition and relative proportions of these constituents can vary significantly based on cultivation conditions, plant maturity at harvest, and the extraction methods employed (Sharma et al., 2025).

4. Biological and Pharmacological Effects of Peppermint Essential Oil

Peppermint (*Mentha piperita* L.) essential oil (PEO) is a complex mixture of monoterpenes and their oxygenated derivatives, primarily menthol and menthone, which together confer its distinctive aroma and diverse bioactivities. Extensive pharmacological and biochemical studies have demonstrated that PEO exerts a wide range of biological effects,

including anti-inflammatory, antibacterial, antiviral, scolicidal, immunomodulatory, antitumor, neuroprotective, antifatigue, and antioxidant actions (Figure 2) (Hudz et al., 2023; Zhao et al., 2022).

Menthol acts as an agonist of the transient receptor potential melastatin 8 (TRPM8) channel, modulating nociceptive and inflammatory pathways by reducing the release of pro-inflammatory mediators while enhancing anti-inflammatory cytokine production. Evidence indicates that peppermint essential oil (PEO) effectively mitigates intestinal and dermal inflammation through inhibition of key signaling cascades, particularly ERK–NF- κ B and JAK2–STAT3, while also providing protection against oxidative stress-induced tissue injury (Chumpitazi et al., 2018; Zhang et al., 2023).

Furthermore, PEO is recognized for its potent antibacterial and antifungal characteristics. It disrupts microbial cell membrane integrity, inhibits biofilm formation, and interferes with quorum sensing mechanisms in Gram-negative bacteria, which supports its use in food preservation and medicinal applications (Kung et al., 2014; Lim et al., 2018; Tyagi & Malik, 2011; Sutthanont et al., 2022). The antiviral properties of PEO, particularly against viruses such as HIV-1, respiratory syncytial virus (RSV), and herpes simplex virus (HSV), are notable, likely due to its interference with viral envelope glycoproteins and replication processes, illustrating its potential as an antiviral agent (Shah, 2018; Jangi et al., 2022).

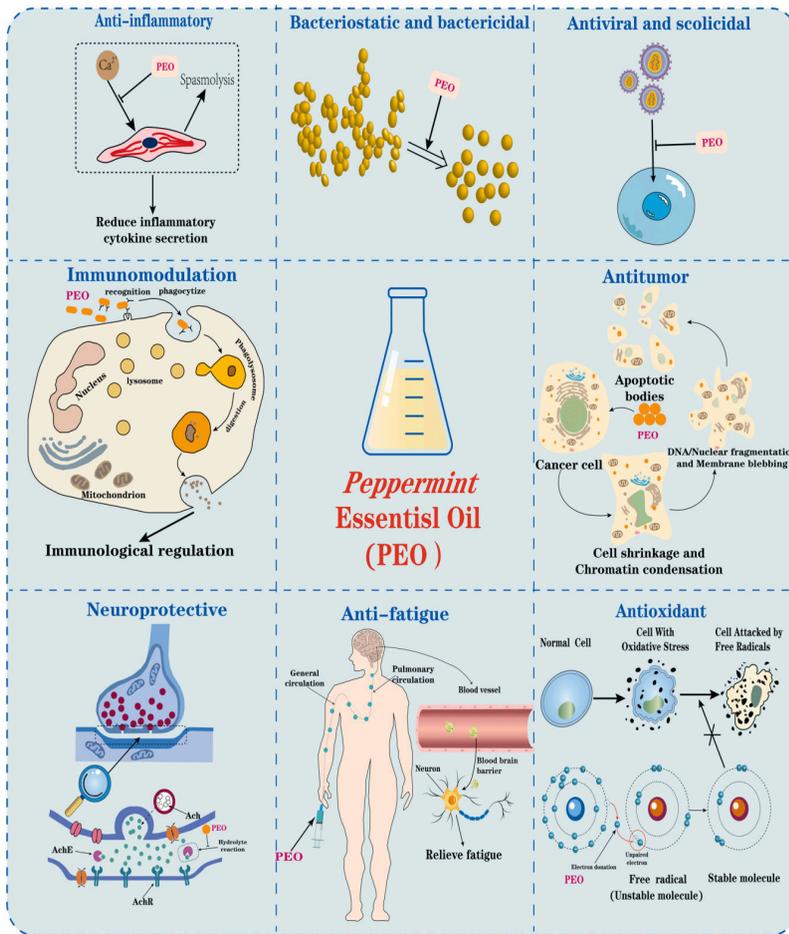


Figure 2. Biological activities of peppermint essential oil (PEO).

Reproduced from Zhao et al. (2022), *Biomedicine & Pharmacotherapy*, 154, 113559 (CC BY 4.0, Elsevier).

In addition to its antimicrobial and antiviral activities, PEO exhibits significant immunomodulatory effects, enhancing macrophage function while influencing oncogene expression in various cancer cell lines. It has been shown to induce apoptosis and cell cycle arrest, providing insight into therapeutic interventions in oncology (Kennedy et al., 2018; Mahdavi-kian et al., 2020). Furthermore, neuroscience studies suggest that PEO offers neuroprotection through its enhancement of γ -aminobutyric acid (GABA) receptor-mediated signaling, modulation of acetylcholinesterase activity, and action on nicotinic receptors, thereby promoting cognitive function and reducing mental fatigue (Chumpitazi et al., 2018; Zhang et al., 2023; Kennedy et al., 2018; Mahdavi-kian et al., 2021).

Moreover, PEO exhibits smooth muscle-relaxant properties and bronchodilatory effects through mechanisms such as calcium channel blockade and nitric oxide signaling, underpinning its therapeutic use in gastrointestinal and respiratory conditions (Sousa et al., 2010; (Shepherd & Peart, 2017; . It also demonstrates antifatigue and antioxidant capabilities, enhancing energy metabolism, reducing blood lactate levels, and neutralizing reactive oxygen species, further emphasizing its profile as a multi-functional agent with broad pharmacological applications (Shepherd & Peart, 2017; Kumar et al., 2011).

5. Impact of Drought Stress on the Essential Oil Composition and Biochemical Adaptation of *Mentha piperita* L.

Drought stress represents one of the most influential abiotic constraints affecting the physiological, biochemical, and metabolic performance of aromatic plants, including *Mentha piperita* L. (peppermint). Variations in water availability can markedly alter the biosynthesis, yield, and chemical composition of essential oils, which are key determinants of peppermint's pharmacological and industrial value. According to García-Caparrós et al. (2019), differential water regimes significantly modulate essential oil production in *M. piperita*, with prolonged drought leading to a notable reduction or alteration in volatile oil profiles. Their findings further emphasize that the genotypic variability of *Mentha* species plays a crucial role in determining drought tolerance and metabolic stability under stress conditions.

Despite this general trend, reports concerning the response of essential oil constituents to water limitation remain partly inconsistent. Some studies indicate a decline in menthol concentration under severe stress, while others suggest an increase in certain secondary metabolites that enhance plant defense and oxidative stability (Kalemba & Synowiec, 2019). Moderate drought, in particular, has been associated with a stimulatory effect on essential oil biosynthesis. For instance, Bidabadi et al. (2020) reported that mild water deficit improved essential oil yield in *Salvia* species, implying that sub-lethal stress may activate secondary metabolic pathways as part of an adaptive mechanism. Conversely, more intense water deprivation typically suppresses essential oil accumulation, reflecting a physiological burden that limits carbon allocation to secondary metabolism (Bidabadi et al., 2020). A similar trend was observed by Gordanić et al. (2021) in *Melissa officinalis*, where essential oil content increased from 0.44% under well-watered conditions to 0.59% under drought, suggesting a complex biochemical adjustment enabling metabolic resilience. Such discrepancies underscore the genotype-specific nature of drought responses and the necessity for cultivar-based evaluations to unravel the

underlying regulatory mechanisms.

The major monoterpenes of peppermint—menthol and menthone—are particularly sensitive to drought-induced alterations in plant metabolism. Sun et al. (2014) demonstrated that their concentrations fluctuate in response to soil moisture variations, highlighting a nonlinear relationship between essential oil biosynthesis and environmental stress. These dynamic changes suggest that certain stress levels can enhance the synthesis of defense-related volatiles, providing plants with an adaptive advantage against oxidative damage and pathogen invasion.

Moreover, *M. piperita*'s biochemical plasticity under drought extends beyond compositional adjustments, encompassing enhanced antioxidant capacity as a potential stress-mitigation strategy. Pagonopoulou et al. (2025) observed that peppermint essential oil exhibits substantial antioxidant and protective activity under water deficit, implying a correlation between drought-induced oxidative stress and the upregulation of defensive metabolites. The accumulation of monoterpenoids under controlled stress intensities thus reflects a fine-tuned metabolic response, reinforcing the dynamic interplay between environmental stress factors and secondary metabolite biosynthetic pathways.

6. Conclusion and Future Perspectives

Drought stress poses a major limitation to the growth, productivity, and biochemical integrity of *Mentha piperita* L., influencing both its physiological performance and essential oil profile. Water deficiency disrupts photosynthetic activity, reduces metabolic efficiency, and alters the synthesis of monoterpenes such as menthol and menthone, which are key determinants of peppermint oil quality. To counteract these challenges, the plant activates complex defense mechanisms, including osmotic regulation, antioxidant enzyme activity, and hormonal adjustments that help maintain cellular balance and delay tissue damage. Yet, prolonged or recurrent drought episodes continue to cause significant yield and compositional losses, threatening the economic sustainability of peppermint cultivation. Future research should focus on integrating molecular breeding, omics-based screening, and precision water management with eco-friendly solutions such as microbial inoculants and biostimulants. The convergence of these strategies will not only enhance drought tolerance but also secure stable essential-oil production and quality in the face of accelerating climate change.

Acknowledgements

The author gratefully acknowledges the support of the Scientific Research Projects Coordination Unit of Cankiri Karatekin University (Project No. GTM240223B07).

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