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Review

Potential exploitation of Mediterranean wild halophyte species: four case studies for a sustainable horticulture

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Abstract: The Mediterranean Basin hosts a rich diversity of wild halophyte species that have evolved remarkable adaptations to saline and arid environments. This narrative review explores the potential exploitation of four Mediterranean halophytes - *Crithmum maritimum*, *Cakile maritima, Atriplex halimus*, and *Suaeda maritima* - with applications ranging from high-quality vegetable and spice production to ornamental use. Each species is described in terms of botanical traits, environmental adaptability, chemical composition, and current or potential food or non-food uses. Particular attention is given to the challenges and opportunities associated with seed germination and propagation techniques as agronomic development. Their ability to thrive under salinity, drought, and nutrient-poor soil conditions highlights their suitability for cultivation in marginal areas increasingly affected by climate change. The multifunctional role of these plants - spanning nutritional value, phytochemical richness, soil fertility improvement - makes them promising candidates for sustainable cropping systems aimed at biodiversity conservation and rural development. Further research is encouraged to develop effective agronomic protocols and value chains that support their transition from wild species to economically viable crops. This review underlines the relevance of integrating halophyte species into diversified and resilient agricultural models, particularly in Mediterranean regions and other salt-affected environments.

Keywords: *Crithmum maritimum* L.; *Cakile maritima* Scop.; *Atriplex halimus* L.; *Suaeda maritima* (L.) Dumort; food use; ornamental use.

1. Introduction

The Mediterranean Basin biodiversity hotspot is the second largest in the world and the largest among the world's five Mediterranean-climate regions, spanning over 2 million square kilometers. It is also the third richest hotspot globally in terms of plant diversity, according to Mittermeier et al. (2004). The region hosts approximately 30,000 plant species, with over 13,000 endemic species found nowhere else worldwide (Derneği, 2010). This massive abundance of biodiversity can be attributed to the region's varied climatic conditions and diverse terrain morphology and traits, resulting in numerous species and ecotypes across the countries surrounding the Mediterranean Sea (Sánchez-Mata et al., 2012). The climate features cool, wet winters and hot, dry summers, with rainfall ranging from 100 to 3,000 millimeters. These factors collectively contribute to an exceptionally high level of plant endemism and diversity (Derneği, 2010).

Much of this biodiversity exists in marginal areas, which are lands with various limitations, such as those affected by degradation processes like erosion, salinization, drought, and low organic content. These issues are often exacerbated by human activities (Derneği, 2010). Some marginal areas of the Mediterranean Basin are exceptionally rich in wild herbaceous species that have been used for centuries as both food and medicine, particularly during times of famine or food scarcity. Many wild species are edible and can be used as leafy greens in place of cultivated vegetables. They are often essential ingredients in various traditional dishes among Mediterranean populations, forming an integral part of the Mediterranean diet (Renna et al., 2015).

Similarly, the Mediterranean Basin represents a rich reservoir of plant species potentially suitable for ornamental purposes, which integrate well into their native environment from both an ecological and landscape viewpoint. These species offer undeniable advantages due to their low nutritional and maintenance requirements, as well as their resilience to the abiotic stressors typical of Mediterranean environments, to which these plants have adapted their evolutionary patterns (primarily aridity, salinity, and high temperatures) (Cervelli, 2009).

Considering increasing global climate change and its severe effects widespread throughout the world, cultivation of conventional crops is facing various limitations related to scarcity of good quality water, temperature increase, salinization and degradation of soil properties, especially in salt-affected agricultural soils and marginal areas of the Mediterranean basin where these limitations are predominant (Slama et al., 2015).

Halophytes are salt-tolerant plants that can complete their life cycle in high-salt conditions where glycophytes cannot survive. They have developed multiple mechanisms (ion compartmentalization and/or exclusion/excretion, osmotic adjustment, succulence, antioxidant response) contributing to salt adaptation. These adaptations make halophytes promising candidates for emerging cash crops and for restoring non-arable or marginal lands in the Mediterranean area (Panta et al., 2014; Ben Hamed et al., 2021).

A significant number of halophyte species that thrive along the Mediterranean shoreline and inland are edible plants traditionally used for their interesting organoleptic traits (Petropoulos et al., 2018). Several of these wild edible species show a suitable nutritional profile for human consumption, being a good source of minerals and other healthy bioactive compounds (Renna, 2017). Further, the chemical diversity of halophytes provides a wealth of natural products with significant value across various commercial sectors, including veterinary and pharmaceutical industries (Ben Hamed et al., 2021).

From an ornamental perspective, Mediterranean halophytes have significant potential to enhance the aesthetic appeal of degraded landscapes and improve overall environmental quality (De Pascale and Romano, 2019). Additionally, within a landscaping and xeriscaping approach, these species could be employed in innovative green infrastructures where salt and/or drought stresses are particularly pronounced, such as rooftop gardens and living walls (Zizzo and Aprile, 2009; De Pascale and Romano, 2019). A study by Cassaniti and Romano (2011) identified 172 halophyte species in the Mediterranean region with potential ornamental value. These species belong to 30 families and 86 genera, with Chenopodiaceae being the most represented family (34 species), followed by Poaceae (18 species) and Plumbaginaceae (17 species).

The profitable introduction of these wild halophyte species into the vegetable, officinal/medicinal, and other non-food production circuits implies complex and well-structured processes. This involves a thorough understanding of both propagation techniques, such as seed production and germination, and cultivation methods that optimize plant growth according to specific soil and climatic conditions (Ben Hamed et al., 2021).

In this narrative review, we focus on four Mediterranean halophyte species, namely *Crithmum maritimum* L., *Cakile maritima* Scop., *Atriplex halimus* L. and *Suaeda maritima* (L.) Dumort. (Table 1), selected based on three complementary criteria: (i) ecological adaptability to marginal coastal and saline habitats; (ii) documented multifunctional potential; and (iii) limited current commercialization despite evidence of agronomic interest. *C. maritimum* and *C. maritima* were chosen mainly for their potential food use, while *A. halimus* and *S. maritima* were chosen mainly for their potential non-food uses (Table 1). These four species offer a diverse set of physiological strategies relevant to biosaline agriculture and marginal lands valorization. Although many other halophytes exist in the Mediterranean flora, each of the four chosen species is presented as a single, practical case study for agronomic development and pre-domestication evaluation.

Table 1. Main characteristics and proposed use of the species presented in this review.

Scientific name	Common name	Botanical family	Growth habit	Response to salinity	Photosynthetic pathway	Main proposed use
Crithmum maritimum L.	Sea fennel	Apiaceae	Perennial herb	Facultative halophyte	C3	Food
Cakile maritima Scop.	Sea rocket	Brassicaceae	Annual succulent	Facultative/ obligate halophyte	C3	Food
Atriplex halimus L.		Amaranthaceae	Evergreen shrub	Euhalophyte	C4	Non-food
Suaeda maritima (L.) Dumort.	Herbaceous seepweed	Amaranthaceae	Annual herb	Obligate halophyte	C3	Non-food

2. *Crithmum maritimum* L.

2.1. Plant features and biological traits

Sea fennel (*Crithmum maritimum* L.) is the only species of the genus *Crithmum* within the Apiaceae family. It is a perennial halophyte also known as samphire, crest marine, marine fennel, and rock samphire, naturally grows on sandy beaches, maritime rocks, breakwaters, and piers along coastlines worldwide (Figure 1), with particular abundance in Mediterranean regions (Renna, 2018).

Figure 1. Plant of *Crithmum maritimum* L. in its natural coastal habitat (sandy beach), showing succulent foliage and vigorous growth despite saline conditions unsuitable for most non-halophytic species.

The plant features a robust rhizomatous root system that can extend up to five meters, along with a branched stem that is often woody at the base. Its leaves are persistent, glabrous, and have a triangular shape, typically bi- or tri-pinnate with fleshy, keeled lanceolate segments. The leaves alternate along the stem, each with a long petiole that broadens into a sheath, wrapping around the stem's base. The pale-yellow, five-petaled flowers are arranged in umbels with 10–30 rays, further divided into umbellets surrounded by bracts. The flowering period usually lasts from June to September. After flowering, the plant produces ovoid, glabrous achenes, 3–6 mm in diameter, with 10 ridges (Kraouia et al., 2023).

Sea fennel produces a large quantity of viable fruits. However, despite its typical growth near seawater, seed germination percentage significantly decreased when salinity levels exceeded 50 mM NaCl (Atia et al., 2006). Sodium salts primarily hinder seed germination through osmotic effects; the significant recovery in germination after transferring seeds to distilled water clearly demonstrates this. Sea fennel seeds remain viable under high salinity conditions and likely start germinating in early spring, once winter precipitation leaches the salts (Atia et al., 2011). Researchers widely recognize that temperature, salinity, and light conditions strongly influence the germination and seedling development of sea fennel. Marchioni-Ortau and Bocchieri (1984) demonstrated that the optimal conditions for germinating seeds of a Mediterranean Sea fennel population were a temperature of 20 °C and darkness, using either deionized water or a solution with very low salt concentrations. It is important to note that the optimal germination conditions for seed populations from the Atlantic coast appear to differ significantly from those of sea fennel populations in the Mediterranean basin (Marchioni-Ortau and Bocchieri, 1984). To enhance sea fennel seed germination and improve seedling production, valuable insights can be found in the literature. For instance, Atia et al. (2009) reported that red light exposure and nitrogen-based compounds can significantly boost and speed up germination. Additionally, pretreating seeds with L-ascorbic acid or ethanol has been shown to improve germination rates by 30% (Meot-Duros and Magné, 2008). Moreover, seed priming can be employed to accelerate germination and promote greater uniformity by encouraging early seedling growth (Renna, 2018).

Accogli et al. (2024) found that seeds collected from various locations in the Salento area (Southern Italy) exhibited a high germination rate, averaging around 78%, with no significant dormancy under controlled conditions, consistent with findings by Nimac et al. (2018). However, differences in germination rates between seeds from different sites indicate intraspecific variability, as observed in *C. maritimum* seeds from the Atlantic coast of England (Accogli et al., 2024). These findings emphasize a key characteristic of specific accessions, which could support the large-scale cultivation of sea fennel.

Some studies have classified sea fennel as a facultative halophyte during the vegetative stage (Hamed et al., 2004; Ben Amor et al., 2005). Effectively, when salinity levels are altered during this stage, different eco-physiological responses are observed. For instance, Hamed et al. (2004) cultivated this halophyte using nutrient solutions with varying NaCl concentrations (0, 50, 100, 150, 200, and 300 mM). Plants were harvested 13 weeks after transplanting, with NaCl treatments starting 8 weeks post-transplant. The authors reported a biomass production of 1 g DW per plant with 300 mM NaCl, compared to 13 g DW per plant with no NaCl. Similarly, leaf area increased from 100 to over 600 cm^2 per plant under the same salinity levels, indicating that sea fennel is moderately salt-tolerant. Moreover, Ben Hamed et al. (2007) found that plant growth was greater with a nutrient solution containing 50 mM NaCl compared to one with 300 mM NaCl, though no toxicity symptoms were noted in either case. At higher salinity, the activity of the antioxidant system decreased (Ben Amor et al., 2005; Ben Hamed et al. 2007), while the accumulation of toxic ions increased (Hamed et al., 2004). However, photosynthetic activity remained stable under both low and high salinity conditions (Hamed et al., 2004). Sea fennel's halophytic nature seems to be linked to its ability to maintain tissue hydration and prevent oxidative stress (Hamed et al., 2004; Ben Amor et al., 2005).

2.2. Plant composition and utilization

Sea fennel is distinctive for the presence of essential oils (about 0.8% in fruits and 0.15–0.3% in leaves) containing volatile compounds like limonene, α-pinene, sabinene, p-cimene, β-terpinene, β-myrcene, thymol, γ-terpinene, carvacrol, p-cymol, β-ionone, dillapiole, anisaldehyde, β-caryophyllene, carvone and myristicine (Guil-Guerrero et al., 1999), contributing to aromas similar to celery, fennel, and citrus peel (Renna and Gonnella, 2012). The composition of these oils varies significantly with plant origin, allowing for chemotype differentiation (e.g., aromatic monoterpenes-type and phenylpropanoids ones) and can also be influenced by the plant's growth stage and harvest year (Özcan et al., 2001; Pateira et al., 1999). For instance, diallopil content differs by stage (vegetative, flowering, fruiting) and year (Pateira et al., 1999). Sea fennel essential oil content is about 0.8% in fruits and 0.15–0.3% in leaves (Renna, 2018). The oils derived from sea fennel (Guil-Guerrero et al., 1999) leaves are notable for their ω-3 and ω-6 fatty acids, comprising 2.02% of neutral lipids, 0.57% of glycolipids, and 0.26% of phospholipids (on a dry weight basis, DW) (Guil-Guerrero and Rodríguez-García, 1999). Sea fennel seeds contain around 44% oil (DW), primarily oleic (78.6%), linoleic (15.4%), and palmitic acids (4.8%), making their composition comparable to high-quality oils like olive and canola (Burczyk et al., 2002). Additionally, sea fennel leaves are rich in compounds such as ascorbic acid, carotenoids, tannins, and flavonoids, with high phenolic content, notably chlorogenic and phenolic acids, which vary by vegetation period (Guil-Guerrero et al., 1999).

In many parts of the world, sea fennel is used as a key ingredient in traditional recipes, valued for its pleasant sensory qualities, largely due to its high essential oil content. In many Mediterranean countries, tender leaves and stems have traditionally been eaten in salads, either raw or briefly blanched in boiling water to soften them. They are also commonly preserved as pickles in olive oil, vinegar, or brine, and served as appetizers with various foods, paired with bread and olive oil, or prepared with capers. Additionally, there are reports of its use in making sauces, soups, fish seasonings, and even an herbal liqueur (Kraouia et al., 2023). Currently, a niche market exists for fresh-cut sea fennel, offering it for a wide range of culinary applications. In addition to being sold fresh, sea fennel can also be used in its dried form. Effectively, some authors (Renna and Gonnella, 2012; Renna et al., 2017) highlighted its potential culinary use as a novel spice-colorant for some gastronomic products. Sea fennel is also prized for its nutritional and medicinal benefits, as its leaves contain numerous health-promoting compounds, and its seeds are rich in essential fatty acids (Renna, 2018).

Despite its potential as a sustainable and promising crop, particularly on saline soils, sea fennel remains underutilized in commercial cultivation (Renna, 2018). In this regard, it is important to note that the indiscriminate harvesting of sea fennel from the wild has caused its disappearance from certain European habitats. As a result, this species is now protected in some areas, such as England and the Mt. Conero Natural Park in Italy's Marche Region, where the collection of wild plants is prohibited (Parco del Conero, 2023). For all these reasons, sea fennel can be considered an excellent candidate for promoting halophyte agriculture in the Mediterranean basin. Its proven adaptation to the Mediterranean climate, resilience to climate change-related risks (such as seawater intrusion, soil salinization, and short-term droughts), and versatility in both food and non-food applications make it a valuable alternative source of employment in rural areas (Kraouia et al., 2023). However, further research is necessary, as there is currently a lack of information in the literature regarding the open-field cultivation of sea fennel, particularly concerning the effects of soil composition and salinity.

3. *Cakile maritima* subsp. *maritima* Scop.

3.1. Plant features and biological traits

Sea rocket (*Cakile maritima* subsp. *maritima* Scop.) is an annual succulent halophyte belonging to the Brassicaceae family. It thrives in abundance along the sandy coasts of the Atlantic and Mediterranean regions. This plant has a bushy appearance with branched, prostrate, or ascending stems (Figure 2). Its dense inflorescences feature numerous flowered racemes terminating the main stem and branches, adorned with lilac or purple petals. The distinctive, indehiscent fruits are two-jointed siliquas that transition from green and fleshy to brown, tough, and corky. The upper segment of the fruit is deciduous and possesses adaptive features like buoyancy, enabling long-distance dispersal via sea currents. In contrast, the lower segment remains attached, facilitating local dispersal. Each segment typically contains a single seed (Conversa et al., 2024a). Its deep root system with numerous lateral roots makes this species important for soil fixation in the coastal dunes (Gallego-Fernández et al., 2011).

Figure 2. Plant of *Cakile maritima* L. growing in its typical coastal habitat. The species thrives on saline shorelines, where few non-halophytic plants can survive. Its fleshy, bright-green leaves and vigorous growth illustrate remarkable adaptation to salt spray and nutrient-poor conditions characteristic of maritime environments.

C. maritima is a highly adaptable species capable of growing in a wide range of climates, from semi-desertic to arctic zones. It exhibits remarkable tolerance to both extreme heat and drought, as well as low temperatures and frost. This species can thrive in relatively poor soil conditions, including those with low water and nutrient availability, and can tolerate exposure to salt spray and occasional seawater inundation (Arbelet-Bonnin et al., 2019). Although it survives harsh conditions, the plant significantly benefits from available nitrogen (Davy et al., 2006). This behavior can explain its invasive spread into nearby vegetable crops (Conversa et al., 2024a).

The low self-pollination rate of *C. maritima*, combined with its ability to cross-pollinate with *Cakile edentula* (Rodman, 1974), promotes genetic diversity. Additionally, the high dispersal rate of seeds by sea currents (Gandour et al., 2008) facilitates gene flow among populations across different regions in Europe. These factors likely contribute to the observed genetic distances among *C. maritima* individuals and explain the plasticity and adaptability of this species to diverse environments.

Specifically, populations from different climate regions exhibit morphological variation in leaf shape (entire or pinnatifid) (Davy et al., 2006; Ceccarelli et al., 2010; Conversa et al., 2024a). Pinnatifid leaves, with adaptations like dorsiventral rolling, larger epidermal cells, and increased essential oil content, exhibit greater tolerance to high temperatures, solar radiation, and drought than entire leaves (Ciccarelli et al., 2010). Comparative studies of two *C. maritima* morphotypes have revealed distinct physiological and biochemical characteristics. In particular, the pinnatifid morphotype exhibits higher photoprotective pigments (carotenoids and anthocyanins) and net photosynthetic rate (An) compared to the entire one. This increased photosynthetic efficiency suggests a greater tolerance of this genotype to environmental stresses such as high light intensity and temperatures (Conversa et al., 2024a).

C. maritima exhibits tolerance to high salinity, showing enhanced growth at moderate salinity levels (50-100 mM of NaCl) and no adverse effects even up to 200 mM NaCl (Debez et al., 2004, 2012, 2018; Arbelet-Bonnin et al., 2019; Conversa et al., 2025). However, the extent of its salinity tolerance is influenced by water availability. Arid-adapted accessions of *C. maritima* exhibit obligate halophytic behavior, requiring saline conditions for optimal growth. In contrast, accessions adapted to humid environments display facultative halophytic characteristics with lower tolerance to salinity (Mir et al., 2024).

While halophytes develop salinity tolerance during vegetative growth, their seeds are sensitive to high salinity. *C. maritima* seed germination is inhibited by NaCl concentrations above 200 mM, despite this, salinity exposure during germination does not compromise embryo viability but rather delays the germination process (Debez et al., 2004).

A major challenge in domesticating wild species is seed propagation, often hindered by low and erratic germination rates associated with seed dormancy (Corrêa et al., 2020; Castañeda-Loaiza et al., 2024; Khan et al., 2006; Gul et al., 1013). Under non-saline conditions, *C. maritima* seeds exhibit high germination rates (75-100%) when the pericarp is removed (Debez et al., 2004, 2012, 2018; Ghars et al., 2009; Del Vecchio et al., 2018). In contrast, seeds within the indehiscent fruit remain dormant due to the testa and the mechanical constraints imposed by the pericarp (Debez et al., 2006).

Given the time-consuming nature of seed extraction, studying seed germination in intact fruits is essential for developing effective propagation techniques for sea rocket, making it more accessible and appealing to growers. Recent research has revealed that seeds from southern Italian populations of *C. maritima* exhibit a range of physiological dormancy levels, from intermediate to non-deep, with a small proportion of seeds lacking dormancy. To overcome this dormancy and enhance germination, strategies such as fruit dry storage and moist stratification under Mediterranean autumn–spring temperatures (7-18 °C mean minimum and maximum, respectively) have proven effective, resulting in high emergence rates of 70-80% (Conversa et al., 2024b). Optimal germination temperatures for non-dormant seeds range from 10-15 °C under saline conditions (at least 200 mM NaCl) to 20-25 °C in non-saline conditions (Del Vecchio et al., 2018).

3.2. Plant composition and utilization

C. maritima is a highly valuable species due to its wide geographical and ecological range as well as its potential economic importance (Arbelet-Bonnin et al., 2019; Agudelo et al., 2021). Sea rocket is a versatile edible species with almost all organs suitable for consumption. Young leaves and stems are ideal for fresh salads, while the mature leaves, having a bitter taste, are usually preferred for soups, cooked dishes, or flavor extracts (Mir et al., 2024). The flowers add a delicate bitterness to salads and soups, and the roots can be ground into flour. Both immature and mature fruits are edible, with the former eaten raw, while the latter is usable as a source of oil (Ríos et al., 2020). In addition to culinary uses, the powdered roots of *C. maritima* have been incorporated into bread-making (Guil-Guerrero et al., 1999; Merchaoui et al., 2016; Agudelo et al., 2021).

The stressful conditions of its habitat trigger *C. maritima* to produce a variety of secondary metabolites, including phenols, glucosinolates, sterols, and vitamin C, as adaptive responses (Qasim et al., 2017; Corrêa et al., 2020). These secondary metabolites, identified in sea rocket (Mansour et al., 2018; Arbelet-Bonnin et al., 2019; Conversa et al., 2025), exhibit potent biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties (Fuochi et al., 2019; Meot-Duros et al., 2008a; Placines et al., 2020). These beneficial properties suggest that *C. maritima* could serve as a valuable source for developing innovative nutritional and functional products, addressing the increasing demand for healthier food and supplement options (Petropoulos et al., 2018; Stanković et al., 2019; Ríos et al., 2020; Lombardi et al., 2022).

Sea rocket is renowned for its high vitamin C content, rivaling that of many Italian leafy greens and fruits (INRAN-CREA -Centro di Ricerca per l'Agricoltura e l'Analisi dell'Economia Agraria, 2024). Many studies have shown that sea rocket can contain significant amounts of this essential nutrient, making it a valuable addition to a healthy diet. For a Tunisian ecotype vitamin C was found to be close to 400-445 mg 100 g^{-1} fresh weight (FW) in non-salt-stressed and salt-stressed plants (Mansour et al., 2018). Spanish ecotypes exhibited a vitamin C level of 178 mg 100 g^{-1} FW (Guil-Guerrero et al., 1999), comparable to the entire-leaf morphotype from the Apulia region in Southern Italy (Conversa et al., 2024a) and high or higher than other halophytes (Hulkko et al., 2022). In contrast, studies on wild and cultivated sea rocket in Egypt reported a lower average vitamin C content (61.2 mg 100 g^{-1} FW) (Azim and Yaecob, 2009), aligning with the value observed in the Apulian pinnatifid morphotype (Conversa et al., 2024a).

The phenolic content of *C. maritima* is variable according to the ecotypes and growing conditions. The Apulian populations showed higher levels (209 mg 100 g^{-1} FW; 1855 mg 100 g^{-1} DW) (Conversa et al., 2024a) than the Tunisian ecotypes grown in greenhouse conditions, both saline and non-saline, at vegetative and flowering stages (average of 605 mg 100 g^{-1} DW) (Mansour et al., 2018) and Spanish ecotype cultivated in a controlled environment (517 100 g^{-1} DW) (Agudelo et al., 2021). Conversely, higher phenolic levels were reported in other Tunisian ecotypes, whether grown in natural habitats (500-700 mg 100 g^{-1} FW) (Ksouri et al., 2008) or controlled environments (nearly 4302 mg 100 g^{-1} DW) (Ksouri et al., 2007) and for ecotypes from Brittany (France) (2224 mg g^{-1} DW) (Meot-Duros et al., 2008). Glucosinolates (GLS) are abundant in the Brassicaceae family and contribute significantly to human nutrition. While numerous studies have explored GLS content in various *Brassica* species, research on *Cakile maritima* (sea rocket) remains limited. Previous studies have identified 11 (Davy et al., 2006) and 4 (Radwan and Soliman, 2008) GLS compounds, respectively, in sea rocket seeds and shoots. More recently, a comprehensive analysis of Apulian Sea rocket morphotypes revealed a total GLS content of 1877 μmol kg^{-1} FW, surpassing that of other Brassica crops cultivated in the region (Conversa et al., 2024a).

As concerns iodine (I), a trace mineral essential for human health, no published data are reported for *C. maritima* except for Apulian ecotypes. They showed approximately 42 times higher than the I concentration reported for leafy vegetables (84 vs 2.3 μg 100 g^{-1} FW) (Conversa et al., 2024a). Sea rocket exhibits I levels close to several halophytes (*Atriplex halimus, Inula crithmoides, Sarcocornia fruticosa*) collected from saline areas (Duarte et al., 2022).

Due to the diverse bioactive compounds produced by various plant parts, *C. maritima* holds significant potential for medicinal applications. These secondary metabolites exhibit potent biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties, which may offer benefits for various human diseases. Furthermore, *C. maritima* is recognized as a promising oilseed crop, with seeds containing 30-40% oil (rich in erucic acid) and it is considered an energy crop and has potential applications in the desalination of salinized land and phytoremediation of heavy metal-contaminated soils (reviewed in Mir et al., 2024).

4. *Atriplex halimus* L.

4.1. Plant features and biological traits

Atriplex halimus L., commonly known as Mediterranean saltbush, sea orache, shrubby orache, or silvery orache, is an evergreen perennial shrub in the family Amaranthaceae. Native to the arid and coastal regions of the Mediterranean area, it is characterized by an upright, bushy growth habit with branching from the base and can reach a height of up to 2.5 m (Figure 3).

A. halimus is an interesting evergreen species, known for its remarkable adaptations to diverse, harsh environments. As a C4 photosynthetic plant, it demonstrates efficient carbon fixation under high temperatures, with an optimal photosynthesis range around 35 °C (Le Houérou, 1992; Walker et al., 2014). This salt-handling capability, along with its ability to store these ions in vacuoles, enables *A. halimus* to tolerate saline soils, qualifying it as a “euhalophyte” that thrives in conditions with electrical

Figure 3. *Atriplex halimus* showing its erect, branched habit characteristic of this halophytic shrub thriving in saline, arid xeric environments.

conductivities in the range of 25-30 dS m^{-1} (Le Houérou, 1992). Moderate salinity levels (<200 mM NaCl) even enhance its growth, with populations from coastal regions demonstrating higher salt tolerance (Walker et al., 2014). Adapted to xeric environments, the species efficiently utilizes water through a deep-rooting system, extending as far as 5 m to access groundwater, complemented by fine, surface roots that absorb moisture after rainfall (Guerrero-Campo et al., 2006). It also demonstrates moderate cold tolerance, with field studies indicating enhanced tolerance to -18 °C linked to leaf accumulation of Na^+, K^+, amino acids, and soluble sugars (Walker et al., 2008). The plant features dense, silvery-green foliage with a bluish sheen. The leaves are slightly fleshy and leathery, measuring 10-40 mm in length and 5-20 mm in width. They are ovate to rhomboid or lanceolate in shape, with entire or occasionally slightly toothed and wavy margins. The bark is greyish-white, complementing the plant’s distinctive silvery appearance. The inflorescence is a tapered, compact panicle. Female flowers predominate towards the base, while male flowers are concentrated towards the tip, giving the stems a pale greenish-brown hue during flowering, typically between May and December, depending on location. *A. halimus* was previously considered monoecious, bearing small, yellowish flowers in clusters of about 3 mm. Male flowers are apetalous, with a simple perianth of 5 sepals and 5 stamens. Female flowers are also apetalous but enclosed within two ovate-orbicular or reniform bracts. The numerous fruits are 6-8 mm long, reniform to sub-orbicular dicleses, entire or toothed, obtuse or acute, with a smooth dorsal surface, often arranged horizontally. The exocarp of the dicleses develops from the enlargement of the bracts. Fruit maturation occurs in autumn-winter. The 100-seed weight is variable, ranging from 1 to 4 g, with individual seeds measuring 0.8-1.2 mm in diameter, being orbicular, laterally compressed, and brown. Previous studies suggested that fruit bracts inhibit seed germination through the presence of saponins (Askham and Cornelius, 1971) and salt (Walker et al., 2014). Indeed, Osman and Ghassali (1997) demonstrated a significant increase in germination rates upon bract removal. However, they failed to identify any specific water-soluble germination inhibitors, leading them to conclude that the primary inhibitory effect of the bracts is likely mechanical rather than chemical. *A. halimus* seeds exhibit a wide tolerance to salinity levels; however, Shaygan et al. (2017) observed the highest germination rate - approximately 71% - under conditions equivalent to 0 MPa, which corresponds to fully saturated soil or non-saline environments. The same study reported that when seeds were subjected to an osmotic potential of -1.5 MPa, germination rates dropped to 31% with PEG treatment and just 3% with NaCl solution. These findings suggest that *A. halimus* seeds show strong resilience to water deficit, their tolerance to salinity is comparatively lower. In another study (Kheloufi and Mansouri, 2024), *A. halimus* seeds exhibited a germination rate of approximately 90% in distilled water. However, germination percentages gradually declined with increasing salinity, although seeds maintained the ability to germinate at salt concentrations up to around 400 mM. Notably, the same study reported that when ungerminated seeds were transferred from a 600 mM salt solution to distilled water, their germination capacity was restored, depending on the type of salt used.

Le Houérou (1992) categorized *A. halimus* into two subspecies based on morphological differences: *halimus* (var. *typica* Aellen, var. *genuina* Maire et Weill) and *schweinfurthii* (Boiss.) (var. *glaucoidea* L. Chevall, var. *ramosissima* L. Chevall, var. *argutidens* Bornm). The *halimus* subspecies is characterized by a shorter stature, an upright growth form, and shorter fruiting branches, with slightly twisted upper branches. In contrast, the *schweinfurthii* subspecies features leafless, reddish-hued fruiting branches. *A. halimus* is native to a broad range of regions, including Macaronesia, the Mediterranean basin, northeastern Africa, and the Arabian Peninsula. Its natural distribution extends across southern Europe, North Africa, and western Asia, encompassing countries like Portugal, Spain (including the Canary Islands), France, Italy, Greece, Turkey, and Israel, among others. Beyond its native range, the species has been widely introduced to regions such as the Middle East, South Asia, parts of Africa, and the Americas, owing to its utility as livestock forage. However, in equatorial regions like Kenya and Ethiopia, where seasonal changes in photoperiod are minimal, it does not typically flower (Walker et al., 2014).

4.2. Potential utilization

A. halimus, owing to its nature as a densely branched evergreen shrub, unique foliar chromatic traits, and its ability to tolerate a wide range of abiotic stressors (primarily salinity, aridity, and high temperatures), exhibits significant ornamental potential for the restoration of degraded areas, especially along Mediterranean coastal areas, as it stands out for its bright, silvery foliage, creating a luminous contrast and adding texture and brightness to landscape designs (Dessena and Mulas, 2012). Its airy inflorescences, though subtle and characterized by predominantly yellow and orange perianth colors, sometimes with pale red hues, produce chromatic variations during the flowering period, which lasts from summer to autumn, that are highly appreciated for ornamental purposes (Dessena and Mulas, 2012; Abbad et al., 2003). Moreover, the species is well-suited for the creation of hedges of varying lengths and widths, and a wide range of environmental applications (naturalistic engineering, etc.), beyond merely aesthetic purposes (Zizzo and Aprile, 2009). Moreover, given its ability to develop on immature soils (rocky substrates, sandy soils), *A. halimus* is considered a pioneer species able to facilitate the soil preparation for more demanding plant species, thus allowing for a more rapid plant repopulation of the degraded areas (Zizzo and Aprile, 2009). In this regard, the species propagates naturally through reproduction, although asexual propagation is also relatively easy to achieve (Dessena and Mulas, 2012). While the species has not yet been extensively targeted by genetic improvement programs, this aspect, combined with its high polymorphism, is particularly relevant for the potential selection of clones with traits such as higher biomass production, adaptability to water stress, and seasonal low temperatures, which can sometimes be limiting factors for the species' spread in Mediterranean regions (Ortiz-Dorda et al., 2005). Regarding this aspect, both the plant's growth habit and phenology make it well-suited for various ornamental uses. Indeed, the plant canopy exhibits considerable variability depending on the genotype used, ranging from upright to prostrate, making this plant commonly used for hedges and in xerophytic gardens (De Lucia and Cervelli, 2004). Moreover, its low susceptibility to pests and diseases generates the need for low inputs (Dessena and Mulas, 2012). Research conducted in Italy has demonstrated that *A. halimus*, when intercropped with *Hedysarum coronarium* L., exhibits significant potential for soil remediation. This combination improved soil porosity enhanced the formation of soil aggregates and significantly reduced soil loss through runoff (Chisci et al., 2001). Furthermore, this species can successfully colonize polluted soils, including those contaminated with As, Cd, Zn, Pb, and Cu, making it a promising candidate for phytoextraction applications (Lutts et al., 2004; Lotmani et al., 2011; Tapia et al., 2013).

A. halimus is also a highly versatile species with a wide range of applications that highlight its multifunctionality. In Southern Italy, its young shoots are consumed in traditional vegetable mixtures (Guarrera and Savo, 2016). Like other species belonging to the *Atriplex* genus, this species is rich in saponins, betaines, proteins, amino acids, mineral salts, and phytoecdysteroids. Notably, quercetin, kaempferol, isorhamnetin, spinacetin (6-methoxyisorhamnetin), patuletin (6-methoxyquercetin), and other 6-methoxyflavonols have been isolated from *Atriplex* species. Other derivatives, including patuletin glycosides, quercetin and kaempferol glycosides, tricin, and isoorientin, have also been identified (Clauser et al., 2013). Ethnobotanical studies further reveal its extensive use across various Mediterranean Countries, including Morocco, Algeria, Tunisia, Lebanon, Jordan, and Palestine, where its roots and leaves are utilized in numerous forms, such as infusions, decoctions, powders, dried preparations, and salads (Roubi et al., 2024). In many Mediterranean countries, it is employed in traditional remedies to prevent or treat conditions like cystitis, stomach and intestinal pain, diabetes, renal pain, hypertension, rheumatism, intoxication, hypercholesterolemia, and genito-urinary diseases. It is also used for thyroid disorders, eczema, scabies, cancer (including breast and cervical cancer), intestinal inflammations, and hydatid cysts (Roubi et al., 2024). Moreover, since the 1960s, *A. halimus* has been cultivated in arid Mediterranean zones as a valuable source of forage for livestock, including sheep, goats, cattle, and camels, providing brows, silage, and standing feed (Walker et al., 2014). Additionally, this species has potential for marginal land valorization as an energy crop, with its biomass being suitable for gasification, pyrolysis, or combustion (McKendry, 2002).

5. *Suaeda maritima* (L.) Dumort.

5.1. Plant features and biological traits

Suaeda maritima (L.) Dumort., commonly known as herbaceous seepweed or annual seablite, is an annual flowering plant in the family Amaranthaceae. It is primarily found along coastal areas and saline regions of Eurasia, North Africa, and North America (Chapman, 1947). This halophyte species is typically found in salt marshes and coastal habitats, reaching heights of 20-80 cm. The plant features an erect or prostrate stem that is striated and often becomes reddish as it matures, with pendulous branches near the apex. The foliage of *S. maritima* is yellow-green, fleshy, and succulent, showing remarkable adaptations to saline environments. The leaves are linear in shape, measuring 1 - 2 mm in width and 10 - 25 mm in length, with a cylindrical or slightly flattened cross-section and smooth margins (Figure 4)

The leaves undergo a striking transformation to a red-violet hue in autumn when intracellular salt concentrations become excessively high, creating vivid patches of coloration that can enhance the visual interest in naturalistic or coastal garden designs (Savona, 2009; Zizzo and Aprile, 2009). This seasonal chromatic shift, combined with the rusticity and the compact growth habit of the plant, makes *S. maritima* a promising ornamental halophyte for landscape applications, particularly in low-maintenance conditions. These characteristics enable *S. maritima* to thrive in high-salinity habitats, such as salt marshes and coastal regions. *S. maritima* is a typical obligatory euhalophyte thriving in highly saline habitats such as the coast of the Mediterranean and Arabian seas, often coexisting with species such as *Atriplex portulacoides* L., but where organic matter accumulates (Anoè et al., 1984; Lombardi et al., 2023). Under salinity stress, this species maintains high turgor and relative water content, a capability attributed to its prominent osmotic adjustment. Na^+ ions and glycine betaine serve as the primary osmotics, and the expression of the betaine aldehyde dehydrogenase gene in this species has been observed to increase with increasing salt stress (Todorović et al., 2022).

Figure 4. *Suaeda maritima* showing its fleshy yellow-green foliage and slender, striated stems that may turn reddish with age - typical morphological adaptations of this halophytic species to saline coastal environments.

The plant produces small inflorescences, typically solitary or arranged in clusters of 2–5, located in the axils of the upper leaves and are integral to the plant's identification and survival in saline environments. These inflorescences may form dense, spike-like, or paniculate structures at the tips of the stems, optimizing pollination by grouping the flowers closely together. The flowers (appearing between July and September) are tiny, often less than 1 mm in diameter, are hermaphroditic, display either radial (actinomorphic) or bilateral symmetry and consist of five greenish-red tepals, five stamens, and a superior ovary with two styles. The fruit of *S. maritima* is a small, dry, one-seeded achene. Oval, compressed, and typically less than 2 mm in diameter, the achene is surrounded by persistent tepals that offer additional protection. Its surface is often finely reticulate, displaying a network of small ridges or veins, and its coloration ranges from reddish-brown to black. The achene has a hard external layer that enhances its resilience in harsh saline environments. Inside the achene lies a single seed that is smooth, rounded, and dark-colored. This seed is firmly attached to the inner wall of the fruit and features a durable, protective seed coat that shields the embryo from extreme environmental conditions. Adapted for dispersal by wind or water, the seed is compact and dormant, awaiting favorable conditions such as adequate moisture and warmth to germinate. In this regard, Wetson et al. (2008) observed that the germination of *S. maritima* seeds is influenced by the conditions in which they are stored. While temperatures ranging from 4 to 17 °C had a minimal impact on the timing of germination, these authors found that freezing seeds for just two weeks, after eight weeks into the dormancy period, led to a significant increase in germination percentage. Similarly, brief submersion of seeds in cold seawater after 12 weeks of dormancy also enhanced germination. These results suggest that in dry-stored seeds, both low temperatures and exposure to seawater help reduce dormancy duration and promote germination. The authors emphasize that the germination responses observed under laboratory conditions - designed to mimic natural environmental factors such as hypoxia, moisture availability, and temperature - correlate strongly with the environment to which the seeds are exposed under field conditions.

5.2. Potential utilizations

The species is considered a pioneer, as it can thrive on highly sandy soil, classifying it as both a psammophilous and halophilous plant (Zizzo and Aprile, 2009). Indeed, its well-developed root system enables *S. maritima* to anchor to extremely loose and incoherent soils. Its ability to grow under extreme conditions (such as saline, loose, or arid soils) facilitates the preparation of the soil for more demanding species, thereby accelerating the vegetative repopulation of degraded lands. Moreover, *S. maritima*, a characteristic element of psammophilous plant communities, could play a crucial role in the restoration of green areas along coastal strips. Specifically, it can contribute to the formation of vegetative strips that protect the plant communities located just behind the shores. By acting as a barrier, it mitigates the impact of chemical and physical stresses, such as reducing the amount of salt and wind-driven sand reaching more sensitive plants. This protective effect creates better internal conditions for these species, allowing them to thrive in less hostile environments (Savona, 2009). Consequently, it promotes higher organic matter turnover and accumulation, ultimately enhancing the area's ecological resilience. It is worth noting that recent research conducted in France (Sordes et al., 2023) has demonstrated the usefulness of *S. maritima* for phytoremediation in chloride-rich substrates, such as marine dredged sediments. This species exhibited a remarkable ability for chloride phytoextraction, with chloride concentrations in its aerial biomass reaching up to 160 mg kg^{-1} DW. These levels are higher than those observed in other halophytic species, including *Suaeda vera* J.F. Gmel., *Glaucium flavum* Crantz, *Melica ciliata* L., and *Polypogon maritimus* Willd.

S. maritima is a species with significant potential for diverse applications too, both edible and non-edible (Dzhoglova et al., 2024). Its leaves are highly valued and widely consumed as vegetables in certain countries, particularly in Asia (Certain et al., 2021). The phytochemical composition of *S. maritima* includes minerals (mainly Na, Ca, K, Mg and P), pigments (mostly lutein and β-carotene), and vitamins (mainly A, E, C and B_6). Moreover, the extracts of the plant have strong antioxidant and anti-inflammatory activities, because of their high contents of flavonoids (among which quercetin, kaempferol and epicatechin), phenolic acids, (among which vanillic, syringic and ellagic acids), and hydroxycinnamic acids (neochlorogenic, chlorogenic, caffeic and coumaric acids), while the oil extracted from the plant is rich in cirtonellyl propionate, cirtonellyl acetate, 2-hexyl-1-octanol, citronellal and aciphyllene (Dzhoglova et al., 2024). For this reason, the species holds a prominent place in traditional medicine across many Asian countries, where the whole plant or specific parts, such as the roots, are used to treat conditions like hepatitis, various skin disorders, allergies, and as antibacterial preparations (Dzhoglova et al., 2024, Wang et al., 2024). *S. maritima* also shows promise as a source for developing eco-friendly insecticides, as its extracts exhibit larvicidal, ovicidal, and pupicidal properties (Suresh et al., 2018). Beyond insect protection, *S. maritima* has demonstrated antibacterial activity too, suggesting it could play a valuable role in protecting crops against specific pathogens (Beulah et al., 2021).

6. Prospects

The agronomic valorization of the four species discussed in this review should involve a practical approach to seed production and commercialization.

In this regard, it is important to note that none of the four species are listed in Section C, Annex II of Italian Legislative Decree 20/2021 (adaptation of national legislation to EU Regulation 2016/2031 and EU Regulation 2017/625). This provides the opportunity to commercialize the seeds without the requirement for registration in the national variety register. However, it is important to consider that seeds intended for commercialization must still meet specific quality and labeling requirements, such as the indication of germinability. To this end, some studies highlight specific challenges related to seed germination. For example, *C. maritimum*, *C. maritima* and *A. halimus* exhibit germination inhibition under moderate or high salt concentration (Atia et al., 2009; Debez et al., 2004; Shaygan et al., 2017). In addition, some authors suggest that the seeds of *A. halimus* (Osman and Ghassali, 1997) and *C. maritima* (Conversa et al., 2024b) experience physical dormancy. This is primarily caused by the bracts, which act as a physical barrier preventing germination. At the same time, Wetson et al. (2008) reported that short freezing seeds can help to reduce dormancy duration and promote germination.

In this context, it is hypothesized that germination of these species could be supported through innovative and environmental-friendly approaches involving the application of plant biostimulants (PBs) to the seed via priming treatment. PBs are natural substances and beneficial microorganisms that enhance flowering, plant growth, fruit set, crop productivity and quality, nutrient use efficiency, and tolerance against a wide range of abiotic stresses (Rouphael and Colla, 2020). These categories include humic and fulvic acids, animal and vegetal protein hydrolysates, seaweed extracts, silicon, as well as beneficial microorganisms as arbuscular mycorrhizal fungi and N-fixing bacteria (*Rhizobium, Azotobacter, Azospirillum*) (Regulation EU 2019/1009) (https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng). Regardless of the categories mentioned above, many other bioactive molecules are studied for their biostimulant effect. Even for *Trichoderma*, although it is a biocontrol agent fungus, there is a wide literature attesting to its biostimulant effect on plants. Foliar or soil applications of PBs have been investigated on a range of horticultural crops, while little research has been conducted on seed priming applications.

Priming is a pre-sowing treatment that makes active seeds for radical protrusion and reduces physical resistance during imbibition of endosperm (Khan et al., 2009; Kubala et al., 2015). There are many metabolic processes involved: development of immature embryos is improved, respiratory pathways are more efficient (Afzal et al., 2008; Jatana et al., 2024), cell division is accelerated, synthesis of enzymes for degradation of reserve substances is increased, nucleic acids are repaired and built-up of, membranes are repaired thus reducing lipid peroxidation, improves development of immature embryos, osmotic regulatory mechanisms are activated, and phytohormonal balance is altered (El-Araby etal., 2006). Moreover, priming generates moderate levels of abiotic stress during both soaking and dehydration phases that can improve the activities of anti-oxidative metabolites, so enhancing tolerance to subsequent abiotic stress during post-priming germination and seedling establishment. In addition, reactive oxygen species (ROS), which are formed due to abiotic stresses, can participate in endosperm weakening during germination through cell wall loosening, as reported in lettuce (Zhang et al., 2014b). Many authors emphasize the beneficial effect of priming on germination, and in the case of sea fennel, it could accelerate germination and promote early and uniform growth of seedlings (Renna et al., 2018).

As for biopriming with natural substances, however, there is evidence about their effectiveness in promoting germination, even under stressful conditions. Di Filippo-Herrera et al. (2019) observed an increased germination of mung bean (*Vigna radiata* L.) seeds bio-primed with seaweeds derived by *Gelidium robustum* (N.L.Gardner) Hollenberg & I.A.Abbott (among red seaweeds), *Macrocystis pyrifera* (L.) C. Agardh and *Ecklonia arborea* (Areschoug) M.D.Rothman, Mattio & J.J.Bolton (both brown seaweeds); *E. arborea* also promoted the shoot length, with an increase of 39%, compared to the control (Di Filippo-Herrera et al., 2019). Seaweed-based biostimulant (*Ascophyllum nodosum* (L.) Le Jolis) affects germination and early seedling growth of primed bean seeds (González-Pérez et al., 2020), ornamental sunflower (Ferreira dos Santos et al., 2019) and kale (*Brassica oleracea* L.) (Mendes et al., 2022). Under salinity-stressed conditions, seaweed (*Sargassum angustifolium* C. Agardh) and microalga (*Spirulina platensis* (Nordstedt) Gomont) extracts enhanced milkweed (*Calotropis procera* Ait) salinity tolerance; at certain doses, both seed priming treatments improved germination, seed vigor index, root and shoot length (Bahmani Jafarlou et al., 2021).

Moringa oleifera Lam. leaf extract (MLE) favored germination of pepper (*Capsicum annuum* L.) (Hala et al., 2017) and cocks comb (*Celosia cristata* L.), in the last case, even under salt stress conditions (Noor et al., 2024). Seed priming with pig blood protein hydrolysate (PHs) improved tomato seed germination and seedling growth under drought conditions (Wang et al., 2022); the authors verified improved seed reserve mobilization, and enzymatic and non-enzymatic antioxidant activities in priming-derived seedlings. Shaffique et al. (2023) determined the enhancement to drought tolerance of biopriming treatment on wheat (*Triticum aestivum* L.) seeds by using a novel strain (99.9% similar to *Klebsiella aerogenes* Tindall et al.); according to results, drought tolerance was increased by up to 20% and germination percentage was 60% higher compared with the control. Moreover, the novel strain increased plant biomass, plant endogenous phytohormone content and antioxidants (i.e., SOD, APX, and CAT), minimizing the effects of ROS. Kim et al. (2023) also verified that dip-treatment of soybean (*Glycine max* L.) seeds in *Bacillus butanolivorans* and *B. siamensis* enhanced the seeds' resistance to osmotic stress during germination, and ameliorated cellular damage caused by secondary oxidative stress.

Apart from propagation, the adoption of specific cultivation techniques can play an important role in the agronomic valorization of these halophytic species.

Sea fennel has recently emerged as a promising cash crop due to its potential economic importance. However, this potential is undermined by unsustainable practices, such as indiscriminate wild harvesting, which have led to the species disappearing in some European habitats and have prompted legal protections and harvest bans (Kraouia et al., 2023). As a result, cultivation becomes essential to meet future market demand. Soilless cultivation of this halophytic species is feasible using a renewable seaweed-based growing material (Montesano et al., 2018), without any negative effects on its growth compared to a commercial peat substrate. Nevertheless, the literature offers limited information on the open-field cultivation of sea fennel. Duca et al. (2024) conducted a Life Cycle Assessment (LCA) of its open-field production in central Italy, revealing that despite its status as a minor crop, sea fennel possesses an attractive environmental profile. Notably, its cultivation involves low external inputs, particularly due to the absence of agrochemicals, which help reduce emissions typically associated with conventional agricultural practices. Additionally, the low water requirements of sea fennel lead to minimal water consumption, a significant advantage in water-scarce regions. Moreover, the plant's ability to thrive in marginal soils with high salinity and arid conditions allows it to be grown on less valuable lands, thereby alleviating competition with more productive crops and contributing to the mitigation of desertification in arid and semi-arid areas. However, it is important to note that, despite these environmental benefits, sea fennel exhibits a relatively low yield (approximately 8 tons per hectare), resulting in a higher impact in terms of land use. Therefore, future research activities could focus on verifying potential increases in yield per unit area by using different types and doses of fertilizer.

Cakile maritima, due to its short life cycle (approximately three months from seed to seed), small diploid genome, and high seed yield (up to 10,000 seeds per plant), is considered both a model species for studying salinity tolerance and a promising "minor crop" for sustainable saline agriculture (Conversa et al., 2025; Mir et al., 2024). Various perspectives for its agronomic valorization can be envisioned. For instance, the production of seeds with a high lipid content (30–40% oil) offers potential for both edible oil production and renewable energy sources. At the same time, the abundance of secondary metabolites - such as glucosinolates, phenols, and carotenoids - makes this species of particular interest for applications in cosmetics and nutraceuticals (Arbelet-Bonnin et al., 2019). Nevertheless, several gaps in current knowledge suggest directions for future research aimed at establishing this species as a viable cash crop. For example, Conversa et al. (2024a) observed that morphotypes with pinnatifid leaves appear better adapted to water and nutrient limitations, as well as to the coastal climate of southern Italy, compared to those with entire leaves. However, further studies — including genetic characterization — are required to confirm these differences in stress adaptation strategies and to gain clearer insights into the species' salinity tolerance. Moreover, while most studies to date have focused on the response of *C. maritima* to salinity during vegetative growth, little is known about its behavior during flowering and reproductive stages, aside from some seed production and germination experiments (Debez et al., 2004; Debez et al., 2006). Overall, *C. maritima* shows strong potential as a halophytic crop suited to marginal lands. However, to transition from experimental settings to commercial cultivation, structured domestication programs, large-scale agronomic trials, and the development of an integrated value chain are essential.

Compared to sea fennel and *C. maritima*, *Atriplex halimus* is a species that has been much more extensively studied for its ability to improve soil properties and increase carbon sequestration, restore highly calcareous sodic soils, enhance degraded pastures, remove heavy metals and salts from contaminated soils, and support the growth of salt-sensitive companion crops (Calone et al., 2021). Calone et al. (2021) conducted a comparative study on *A. halimus* and *A. hortensis* to assess their biomass yield, carbon content, and sodium accumulation capabilities, to understand how salt tolerance influences their physiological characteristics. Despite their close genetic relationship, the two species differ significantly in their life cycles and photosynthetic mechanisms. The findings revealed that both species adapted well to saline conditions, although *A. halimus* demonstrated a slightly superior performance. This advantage is attributed to its C4 photosynthetic pathway, which allows it to sustain net photosynthesis more effectively than the C3 *A. hortensis*, even under reduced stomatal conductance and transpiration rates caused by salinity. Moreover, *A. halimus* showed a more substantial reduction in leaf water potential under stress, enabling it to preserve higher relative water content. Overall, the outcomes suggest that both *Atriplex* species are viable candidates for cultivation on saline, degraded, or abandoned lands, promoting carbon sequestration in the soil - a key step toward the agricultural rehabilitation of such areas. Nevertheless, as a perennial species, *A. halimus* offers more enduring soil cover and stability over time due to its greater physiological resilience to saline environments. In this context, future studies could aim to assess these potential effects on areas that have become marginal due to climate change or biotic factors, such as the territories of Southern Italy affected by the spread of *Xylella fastidiosa* (Valente et al., 2024). In these areas, the cultivation of *A. halimus* could represent an option for replacing dried-out olive groves, both in terms of biomass production and ecosystem services (Luković et al., 2021).

Suaeda maritima is an obligate euhalophyte that has been extensively studied for its phytoremediation capacity of both heavy metals (Cd, Pb, Ni) in saline environments and saline ions (e.g. Na^+ and Cl^-) in soil. The combination of high salt tolerance and selective accumulation mechanisms makes this species an ideal candidate for the reclamation of contaminated soils in coastal and brackish-wetland areas (Fatnami and Parida, 2024). Numerous recent studies have characterized *S. maritima*'s potential to accumulate and stabilize heavy metals in soils and sediments. For example, Fatnami and Parida (2024) showed that, under Cd and Pb stress, *S. maritima* accumulates significant amounts of these metals in its roots (translocation factors, Tf < 1), indicating strong phytostabilization in the root system. Baharvand et al. (2023) reported mean concentrations in roots of Cd = 0.160 mg kg^{-1} and Pb = 1.22 mg kg^{-1}, and in leaves of Cd = 0.157 mg kg^{-1} and Pb = 2.23 mg kg^{-1}, with both bioconcentration factors (BCF) and TF>1 for Cd and Pb, suggesting good phytoextraction potential for Pb and continued phytostabilization of Cd. The same study found that Ni accumulated up to 3.34 mg kg^{-1} in leaves (TF > 1), demonstrating *S. maritima*'s ability to extract Ni from saline sediments. Studies on *S. maritima*'s role in removing saline ions from soil also report promising results. Sordes et al. (2023) observed in chlorine-rich dredged sediments an accumulation of 160 g Cl^- per kg of dry biomass, with a translocation factor of 4.5, enabling soil remediation within 2–9 years through natural recolonization. Moreover, Sabreena et al. (2022) report that *S. maritima* can remove up to 504 kg of NaCl per hectare in a four-month growth cycle, confirming its high Na^+ and Cl^- extraction potential from saline soils. In summary, *S. maritima* emerges as a halophytic species of great interest for the remediation of both heavy metals and salinity, yet it requires multidisciplinary studies and pilot-scale applications to translate experimental results into real-world solutions. Future research could include large-scale field trials across diverse coastal and brackish-wetland sites, with medium- to long-term monitoring to assess agronomic and ecological sustainability. Another possible research option could be the valorization of heavy-metal-contaminated biomass via treatment or reuse strategies (e.g., commercial metal recovery, bioenergy production) to minimize environmental risks and foster a circular economy.

7. Conclusions

The four Mediterranean halophyte species analyzed in this review demonstrate significant potential for agronomic valorization in marginal environments. Their tolerance to abiotic stressors, such as salinity and drought, alongside their nutritional, ornamental, phytoremediation, and phytochemical properties, supports their inclusion in sustainable production systems aimed at crop diversification and land rehabilitation. Although each species shows promising features, further research is needed to optimize propagation techniques, particularly regarding seed germination and dormancy-breaking methods. Moreover, advances in seed priming technologies and the use of biostimulants could play a pivotal role in enhancing their establishment and early growth under stress conditions. In addition to propagation, the development of specific cultivation protocols tailored to each species is essential to support their transition from wild resources to cultivated crops. This is particularly relevant for *Crithmum maritimum* and *Cakile maritima*, which are still underutilized despite their high agronomic and nutraceutical value. Overall, the integration of these species into cropping systems represents a valuable strategy to promote agricultural resilience, biodiversity conservation, and economic opportunities in marginal and coastal areas of the Mediterranean basin.

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