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Review

Rock Samphire, a Candidate Crop for Saline Agriculture: Cropping Practices, Chemical Composition and Health Effects

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Featured Application: The present literature review aims to present the most recent advances in the study of *Crithmum maritimum*, focusing on presenting new data regarding the cultivation practices that will help to domesticate this important species. Moreover, information regarding the health effects and the bioactive compounds of the species will help to further valorize it and increase its added value in sustainable cropping systems.

Abstract: The recent market trends for functional healthy foods have rekindled the interest in wild edible species and created a market niche for high added value products. The current supply, mainly supported by plants collected from the wild, cannot meet increasing market needs; therefore, it is of major importance to establish cropping protocols and further valorize wild plants for culinary and industrial applications. Sea fennel is a wild edible halophyte that is an important ingredient in local cuisines and is also used in folk medicine for its beneficial health effects. Its valorization has not been commercially explored on a great scale and more efforts are needed to integrate the species in farming systems. The present review compiles the most recent reports regarding the farming practices that could allow for the establishment of cultivation protocols for farmers, while the main constraints that hinder the further exploitation of the species are also presented. Moreover, this review presents the most up-to-date information regarding the chemical composition (e.g., chemical composition of the aerial parts and volatile compounds in essential oils) and the health-related effects of various plant parts (e.g., antimicrobial, insecticidal and anticholinesterase activities) aiming to reveal possible alternative uses that will increase the added value of the species and will contribute to its commercial exploitation. Finally, the future remarks and the guidelines that have to be followed are also discussed.

Keywords: sea fennel; rock samphire; saline agriculture; wild edible plants; halophyte; bioactive compounds; health effects

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1. Introduction

Rock samphire or sea fennel (*Crithmum maritimum* L.) is a perennial halophyte that belongs to the family Apiaceae and is naturally grown in coastal areas of the Mediterranean region and the Atlantic Ocean [1–3]. It is highly appreciated for its edible tender leaves (Figure 1), although, apart from culinary uses, several other applications have been recorded such as medicinal, cosmetic and essential oil production [4–8]. Moreover, sea fennel used to be a basic ingredient in folk medicine for scurvy prevention, against parasites or as a diuretic [9]. Nowadays, these practices still exist and, in several regions, sea fennel leaves are used to improve digestion or as diuretic agents [10], against liver and genito-urinary tract diseases [11] or as remedies of coughs and colds [12]. Moreover, in specific regions of Italy, the juices of the leaves and fruit infusions are used against disorders of the gastrointestinal system, or as depuratives and diuretics [13]. The most common use is the consumption of fresh, pickled or fermented leaves and tender stems in mixed salads and cooked dishes and soups [9,14,15], while Renna and Gonnella [16] suggested the use of dried leaves as a spice colorant in various dishes. Except for the leaves, the seeds and the flowering aerial parts are equally important, since they contain important bioactive compounds and are commonly used for their essential oils [17–19].

Figure 1. Plant parts of sea fennel: (**A**). Seeds; (**B**). Seedling in seeding tray at the stage of two true leaves; (**C**). Seedling transplanted in pot filled with peat; (**D**). Young leaves of wild plants; (**E**). Aerial parts of fully grown wild plants; (**F**). Stem of fully grown plant; (**G**). Mature leaves; (**H**). Immature inflorescences (umbels); (**I**). Inflorescences after seed maturation and dispersion.

In addition to the above properties, sea fennel exhibits a considerable insecticidal activity against serious pests of crops and insects of health importance such as the red flour beetle (*Tribolium castaneum* Herbst.), the cotton leafworm (*Spodoptera litura* F.), the yellow fever mosquito (*Aedes aegypti* L.) and the southern house mosquito (*Culex quinquefasciatus* Say) [18,20,21]. In particular, Mustapha et al. [21] observed that the essential oil obtained from the fresh leaves of sea fennel exhibited both repellent and toxic effects against the adults of the red flour beetle. Specifically, the essential oil at a concentration of 10% exhibited 50% mortality against adults within 24 h, while its repellent activity varied between 83 and 93%, depending on the exposure time, with the highest values recorded after exposure for 120 h. Suresh et al. [20] also reported that sea fennel essential oil decreased the longevity of the cotton leafworm male and female adults by 5 to 60%, depending on the essential oil dose, while the fecundity of the same insect declined by 77.8% at an essential oil dose of 250 $\mu L\ L^{-1}$. The same authors suggested that the encapsulation of essential oil in silica nanoparticles improved its insecticidal activity [20]. Moreover, the microemulsion formulation of sea fennel essential oil provided high mortality on the third instar larvae of the southern house mosquito [18] or increased the antimicrobial effects against *Microsporum* *canis* and *Candida albicans* (fungal isolates) and *Escherichia coli* and *Staphylococcus aureus* (bacterial isolates) [22]. Koutsaviti et al. [23] also suggested the use of sea fennel essential oils as fumigants against the rice weevil (*Sitophylus oryzae*). Moreover, processing techniques such as the freeze-drying of leaves may help to retain the volatile compounds content and the antioxidant efficacy of essential oils after harvesting [24].

Sea fennel is also examined and recommended for use on green roofs in the context of urban horticulture [25,26]. According to Martini et al. [25], sea fennel plants were satisfactorily grown on a soilless substrate, a mixture of grape marc compost, perlite and pumice, with a shallow depth of 15 cm. The better growth of sea fennel plants on a substrate consisting of pumice, perlite, compost, peat and zeolite, with a depth of 15 cm compared to a depth of 7.5 cm is also reported by Nectarios et al. [26], while the same researchers found that the growth of plants was greater in the deficit irrigation treatment of 60% evapotranspiration (ETc) compared to the irrigation treatment of 30% ETc. When a different substrate composed of clay tiles and organic material (10.6%) was implemented, the above-ground dry biomass of sea fennel plants under severe drought conditions decreased significantly compared to well-watered plants [27,28]. In substrates consisting of mixtures of green compost with expanded clay or crushed bricks, the species showed good growth, but its fresh aboveground biomass and height were lower by 28–40.4 and 47–75.2%, respectively, compared to *Silene secundiflora*, another annual halophyte belonging to Caryophyllaceae family [29]. In contrast, the fresh biomass of sea fennel roots was greater by 55.8 to 86.1% compared to that of *S. secundiflora.* Due to their drought tolerance and low water requirements, sea fennel plants can be grown satisfactorily on substrates with a low water holding capacity and, thus, this species is suitable for use on green roofs. This ability of sea fennel plants to withstand severe drought conditions could be attributed to the internal storage of water in the leaves [30].

Therefore, sea fennel is a plant with multiple uses since it can be grown as a vegetable or ornamental species, while its essential oil can be used in various industry sectors, e.g., the production of bio-pesticides that can be applied for insect control in organic cropping systems or the production of biogas [31]. Thus, the aim of this review is to compile the recent information about the chemical composition and the active constituents of the various plant parts of *C. maritimum*. Moreover, the health-related effects of sea fennel are presented, as well as the cultivation techniques that have been studied and reported thus far and that could be applied to improve the quality and yield of this crop. Moreover, the information presented in this review will help the growers to facilitate the commercial cultivation of the species, which is essential for its valorization, especially in small-scale and sustainable farming systems, within the context of saline agriculture. For this purpose, the information presented was sourced in databases such as Scopus, ScienceDirect, PubMed, Google Scholar and ResearchGate using the terms of *Crithmum maritimum*, sea fennel and rock samphire.

2. Sustainable Farming and Saline Agriculture

The ongoing climate change or climate crisis combined with land degradation and the ever-increasing world population necessitate the adoption of novel farming approaches within the concept of sustainability [32]. Considering that the available agricultural land is expected to decrease due to anthropogenic activities, marginal lands should be exploited with novel crops that could be profitable under unfavorable conditions while, at the same time, contributing to food security [33–35]. Other important issues for the Mediterranean farming are land fragmentation and labor shortages, which minimize the profit margins of crops and eventually lead to land abandonment [36,37]. In most European and North Africa countries and several other parts of the world, small-scale and family farming are the backbone of crop production and are expected to be a pivotal driving force for securing food availability in the future [38]. Therefore, the introduction of novel and resilient-to-environmental-adversities species offers a viable option to farmers, while, at the same time, providing food products of high added value and improved quality [32]. In this context, saline agriculture may increase the available agricultural land through the exploitation of salinized soils and groundwater aquifers that are not appropriate for conventional crops [39].

The Mediterranean basin is abounding with wild plants that have a great potential as complementary/novelty crops, especially in arid and semi-arid regions where the cultivation of conventional crops is unviable [40]. Several studies have evaluated the introduction of wild edible species in commercial cropping systems, including purslane [41,42], spiny chicory [43–45], *Silene vulgaris* [46], *Salicornia* and *Sacrocornia* [47,48]. Sea fennel is a wild species that can be grown in saline soils as an alternative vegetable crop since its tender leaves are edible and have aromatic properties [8,49]. Being a halophyte, sea fennel has various adaptive mechanisms for high salinity conditions. It is considered a halophyte, meaning it has developed a tolerance mechanism that allows it to overcome high salinity through the accumulation of Na^+ and Cl^+ in leaf vacuoles [9]. Jiménez-Becker et al. [50] observed that the chloride (Cl^-) concentration in the leaves of the species was lower than other halophytes (*Asteriscus maritimus* and *Halimione portulacoides*) due to the reduction in Cl^- uptake and the capacity of plants to excrete these anions from their leaves. Moreover, at the highest salinity level tested (300 mM NaCl), the same authors recorded a greater concentration of soluble sugars and proline in the leaves compared to the lowest salinity level (100 mM NaCl). An increase in the concentration of osmolytes such as proline, glycine betaine and soluble sugars due to salt stress was also observed by Hamdani et al. [51] and Boestfleisch and Papenbrock [52]. However, Hamdani et al. [51] reported that the concentration of the above-mentioned osmolytes was greater in the leaves compared to the roots. Another mechanism related to the salt tolerance of the species is associated with the spongy coat of seeds that accumulates 8–11 times more Na and Cl ions than seeds and probably protects the young seedlings from the adverse effects of salts, while they also allow for the dispersal of seeds in natural environments [53,54]. Moreover, the succulent texture of the leaves, as well as the small density of leaf stomata and the high thickness of the cuticle, altogether contribute to the overall tolerance of the species against high salinity [9]. According to Ben Amor [55], the tolerance of the species under saline conditions is associated with the activity of antioxidant enzymes, which is gradually decreased with increasing salinity levels. Similarly, Gil et al. [56] highlighted the effectiveness of plant antioxidant mechanisms against lipid peroxidation, while they also identified differences in the antioxidant defense machinery between different populations of *C. maritimum.* Gómez-Bellot et al. [57] reported that the water status and photosynthetic activity was not impaired in *Crithmum maritimum* plants irrigated with brine, while the leaf content in Ca and B and 1-aminocyclopropane-1- carboxylic acid and trans-zeatin-glucoside increased under saline conditions. Moreover, according to Ciccarelli [30], sea fennel exhibits high resistance to drought stress due to the high water capacity of leaves, which is an important feature considering the impact of climate change on irrigation water availability. Another aspect related to the adaptation mechanisms of sea fennel is the presence of endophytic bacteria that may provide protection against abiotic and biotic stressors [58]. Finally, a study by Labidi et al. [59] highlighted the importance of the insensitiveness of the species to changes in P availability under moderate salinity, a feature that is essential for plant growth under harsh conditions and allows the colonization of specific areas.

3. Cultivation Practices in Sea Fennel Crop

3.1. Soil and Tillage

Sea fennel can either be grown in the field or in pots (Figure 2) with different growth substrates such as a mixture of peat with perlite or vermiculite and a pH of up to 8.1 [50,60–62]. When grown in the wild, plants prefer alkaline soils with a pH of up to 9.5 [63]. Under commercial cultivation conditions, the soil should be prepared in the fall with the main tillage where the field is plowed with a multiple moldboard plow at a depth of 40 cm, while the secondary tillage is carried out for seed-bed preparation and is performed with harrows [62].

Figure 2. Pot cultivation of sea fennel under greenhouse conditions at the experimental farm of University of Thessaly.

3.2. Transplanting-Sowing

Several attempts have been made to produce sea fennel in commercial farms. The species is sexually propagated and is usually transplanted in the field when the seedlings are in the stage of three or four leaves [62]. Sea fennel can be planted in rows with a spacing of 45 cm and a total density of 98.000 plants ha^{-1} [62]. The preparation of seedlings takes a long time due to its slow growth, especially at the early stages and after the seeds' germination. In the Mediterranean region, the sowing of sea fennel seeds in commercial farms usually occurs in the period of May to June [62]. The untreated seeds have a germination rate of 80% when sown at temperatures of 18 °C, whereas the priming with 50 mM NaCl or distilled water and the application of different concentrations of NaCl (50–150 mM NaCl) during germination significantly reduced the germination rates (down to 2% in the case of seeds primed with 50 mM NaCl and subjected to 150 mM NaCl) [64]. In another study, Kostoula et al. [61] reported that sea fennel seeds exhibited a germination rate greater than 90% at a temperature of 21 °C and a photoperiod of 11/13 h light/dark, while the germination process was completed at 21 days. Moreover, alternate temperatures were shown to be more effective in improving the seed germination rates than constant temperatures [65]. In order to optimize the germination rate in soil conditions, seeds should be sown to a depth of between 0.5 and 1 cm since they need light to germinate [66]. According to the same authors [66], the germination rate was less than 10% in seeds sown under dark conditions, whereas the white light increased the germination rate (>80%). Additionally, at salinity levels higher than 15 dS m^{-1}, the germination rate is reduced, especially when whole fruits are used [3]. A germination rate less than 40% at a salinity level of 200 mM NaCl was reported by Atia et al. [67]. A significant improvement in the seed germination rate at various salinity levels (100, 150 and 200 mM NaCl) was also recorded after the exogenous application of nitrates (20 mM KNO_3) [68]. Strumia et al. [69], who evaluated seed germination at different solutions containing distilled water and sea water, suggested that *C. maritimum* seeds retained their ability to germinate after exposure to 100% sea water although the germination percentage decreased from 80 to 65% in the recovery phase. The same authors reported that storage for 4 months did not affect the germination rate, whereas prolonged storage for 12 months resulted in a significant decrease (50% germination rate) [69]. Moreover, Pistelli et al. (2013) [70] reported that the species is responsive to micropropagation. This practice could be proven very useful in the commercial exploitation of the species as well as in breeding efforts for the production of elite genotypes.

3.3. Crop Inoculation

Inoculation of sea fennel plants with symbiotic microorganisms can improve plant growth. In particular, in a greenhouse experiment conducted by Kostoula et al. [71], it was found that the symbiosis of sea fennel with arbuscular mycorrhizal fungus *Glomus intraradices* or the plant growth promoting bacterium *Bacillus amyloliquefaciens* improved plant growth, while the co-inoculation with both microorganisms gave the best results. Moreover, Kostoula et al. [61] reported that the height of plants inoculated with the bacterium *Bacillus amyloliquefaciens* FZB42 was greater than that in the control treatment, while this bacterium increased the phosphorus content by 46.9%. The same authors also suggested that the inoculation of plants with *G. intraradices* caused a considerable reduction (27.8%) in Na content, which is very important from a nutritional point of view [61]. In contrast, inoculation with the fungus *Glomus mosseae* did not affect the shoot biomass of the sea fennel plants grown in soil polluted with heavy metals, while a synergistic effect on mycorrhiza colonization was recorded under drought conditions when microbial inoculation was combined with an organic amendment with sugar beet residue [60]. The reported experimental results [60,61,71] clearly show that the inoculation of sea fennel plants with beneficial symbiotic microorganisms such as arbuscular mycorrhizal fungi or plant growth promoting bacteria could be a useful cultivation practice that can increase the biomass yield of this crop while improving soil microbial communities at the same time.

3.4. Breeding Genotypes

The most important problem that farmers face in cropping sea fennel is the lack of sufficient amounts of propagating material (seeds). In addition, there is a need to develop varieties with stable characteristics, since thus far, the farmers usually use material collected from wild ecotypes with significant variability among plants. To our knowledge, limited research has been carried out on this topic and is essential to initiate breeding programs that will allow the valorization of the species. In a recent study conducted in France, Latron et al. [72] examined the genetic diversity of four wild populations of *C. maritimum* and they recorded a high divergence among the tested genotypes. In another study conducted in Israel, it was found that sea fennel genotypes may differ in salt tolerance [73]. In particular, the genotype FR originating from France produced greater dry biomass (>6 g per pot) at moderate salinity levels of 50 or 100 mM NaCl compared to genotypes HB, IS (origin: Israel) and PO (origin: Portugal) [73]. Moreover, significant differences in plant morphology and phenology were recorded, especially in regard to the flowering time, leaf morphology and growth habits [73]. Apart from the morphological features, the use of genetic tools such as the polymorphic nuclear markers is also very useful for the identification of genetic differentiation in wild populations [74]. These studies indicate that various native populations and ecotypes should be included in intensive breeding programs to develop varieties with uniform characteristics.

3.5. Weed Management

Weeds are an important limiting factor in a sea fennel crop. To our knowledge, there are no studies on this topic, while there are no registered herbicides for this crop. Sea fennel is characterized as a species with low competitiveness against weeds because it has a small height and narrow leaves (Figure 3), while it exhibits slow growth. Moreover, it is a heliophile, meaning that adequate distances between plants should be implemented to allow the exposure of the plant canopy to sunlight [9]. For these reasons, timely weed control is very important, while the farmers should carry out hand hoeing every two or three weeks to control the weeds. Moreover, for the successive exploitation of the species, chemical herbicides should be tested and registered for the cultivation of sea fennel. In a recent study conducted in Italy, it was reported that the weed management during the first two months after transplanting seedlings was very efficient and significantly reduced the competition from the weeds that had no impact on crop biomass yield [62]. However, the agronomic practice of mulching applied in this study may also contribute to the lack of weed competition, since it is well documented in other studies that mulching reduced both the density and biomass of weeds in several crops [75–77]. An alternative weed control method usually applied in row crops is mechanical weeding with various tillage tools [78–80]. Thus, the planting of sea fennel in rows could be very important for controlling weeds and reducing cost production, since the lack of registered herbicides for this specific crop may significantly increase the production cost due to increased man labor for hand hoeing.

Figure 3. Sea fennel plants at different growth stages (**left** picture: fully grown plants; **right** picture: plants at flowering stage).

3.6. Other Cultural Practices

The experimental data about the effects of fertilization and irrigation on the growth and yield of sea fennel are limited, since it is a species barely commercialized thus far. Although this species is drought tolerant, irrigation enhances the plants' growth and increases the biomass yield of this crop. In a field experiment, irrigation via a drip system at 65% of the total available water increased the dry biomass yield by 33.3% (up to 1.8 t ha^{-1}) compared to rainfed control treatment, while the fertigation with a liquid fertilizer (25 kg N ha^{-1}) also had a positive impact on the biomass yield (2.0 t ha^{-1}) [62]. Moreover, in an experiment conducted in pots, both the phosphorus content and shoot biomass of sea fennel plants increased by the application of an organic amendment (sugar beet residue) in well-watered plants, although the same trend was not confirmed when plants were subjected to water stress conditions [60].

Apart from soil or pot cultivation, recently, Sarrou et al. [81] suggested the hydroponic cultivation of the species in floating systems at a density of 230 plants m^{-2}. Such practices may facilitate an improvement in the nutritional value of the species through the adjustment of the nutrient solution composition.

4. Chemical Composition

The aerial parts of the species contain a great diversity of volatile compounds, including sabinene, α-Terpinene, γ-Terpinene, limonene, terpinen-4-ol, thymyl methyl oxide, p-Cymene, α-Pinene, Z-β-Ocimene, β-Phellandrene, dillapiole and myrcene [1,7,21,23,82–86].

Fruits and seeds (mericarps) also contain essential oils and lipids that are located in the canals of the outer secretory envelope that covers the seeds and the endosperm, respectively [87,88], as well as tocopherols [89]. The growing conditions may affect the composition of essential oils by altering the content of its constituents. For example, Pasias et al. [6] reported that the essential oils of sea fennel cultivated in Greece contained sabinene (49.45%), gamma-terpinene (31.35%), followed by pinene (9.57%), limonene (2.73%) and terpinen-4-ol (1.50%). In contrast, Alves-Silva et al. [85] suggested sabinene and γ-terpinene as the major compounds (32.0 and 33.6%, respectively) in wild plants collected in Portugal, followed by terpin-4-ol (3.4%) and limonene (2,73%). Similar results were reported by Flamini et al. [82], who also identified sabinene and γ-terpineol as the major compounds, while Barroso et al. [90] reported that sabinene, γ-terpinene and methylthymol accounted for more than 80% of the total identified compounds. The genotype also has an important effect on essential oil composition. According to Pateira et al. [91], two distinct chemotypes of Portuguese populations of *C. maritimum* were identified based on their dillapiole content, while the same authors reported a variable essential oil composition in plant parts at different growth stages (e.g., vegetative stage, anthesis and fruit formation) [91]. Similarly, Marongiu et al. [92] identified two chemotypes based on dillapiole content, with its greatest content being recorded in samples from Sardinia. Flamini et al. [82] suggested that the essential oil composition of plant parts is susceptible to seasonal variation and dillapiole may increase its content in December (up to 10%), while the sabinene content was the highest during fruit ripening (up to 30%). According to Beeby et al. [93], the oil yield of the aerial parts was 0.36%, while Pateira et al. [91], who determined the oil yield of the aerial biomass and distinct plant parts (leaves, stems and inflorescences), suggested oil yields between 0.2 and 0.5% for aerial biomass and 0.3 and 0.9%, 0.3 and 0.6% and 0.6 and 2.4% for leaves, stems and inflorescences, respectively. Moreover, Burczyk et al. [94] highlighted the importance of growing conditions (location) and genotype on the essential oil yield and reported a varied oil content among the *C. maritimum* plant material (aerial parts) collected from six natural sites (Greece, Cyprus, Spain, Malta, France and Poland), while similar results were reported by Özcan et al. [95] for the essential oil of plants collected from different sites in Turkey. The same authors suggested that the application of Tytanit, a mineral biostimulant, significantly increased the total oil yield as well as the individual terpenes content [94]. Therefore, it is important to determine the appropriate harvesting time of the crop in each area in order to optimize the quality of the final product.

Apart from volatile compounds, several secondary metabolites have been identified in plant parts of the species thus far. According to Boestfleisch and Papenbrock [52], mild saline conditions may induce the biosynthesis of secondary metabolites, although reduced biomass production should be expected. The same authors suggested that *C. maritimum* showed a slow (long-term) response since it accumulated proline several days after the exposure to saline conditions, followed by a significant increase in the oxygen radical absorbance capacity (ORAC), total phenols and total flavonoids values [52]. Moreover, the optimization of agronomic practices such as the use of brackish water or seawater for irrigation purposes could allow for an increase the bioactive compounds content in commercially grown plants and improve the added value of the final product through the design of functional food products or the incorporation of bioactive compounds in nutraceuticals [96].

The total phenolic and flavonoid contents in the aerial part of sea fennel naturally grown in Spain were up to 8.3 mg GAE (gallic acid equivalents) g^{-1} dw (dry weight) and 5.6 mg CE (catechin equivalents) g^{-1} dw, respectively [97], while the phenolic (31.7 mg GAE g^{-1} dw) and flavonoid (25.61 mg CE g^{-1} dw) contents were greater in the leaves of the sea fennel collected in France [2]. Moreover, Souid et al. [2], who tested the hydro-ethanolic extracts of sea fennel leaves, identified eighteen compounds that belong to the groups of hydroxycinnamic acids, flavonoids and flavanols. Chlorogenic acid was the most abundant hydroxycinnamic acid (7.25 mg g^{-1} DW), while rutin (1.75 mg g^{-1} dw) and cirsiliol (1.31 mg g^{-1} dw) were the main flavonoids detected [2]. In addition, Sarrou et al. [81]

reported that the content of chlorogenic, 1.5-dicaffeoylquinic acid, cryptochlorogenic and neochlorogenic acid were greater in the leaves compared to that in the stems. Moreover, the same authors suggested that quercetin 3-*O*-rutinoside was only detected in leaves, while the harvesting season may affect the phenolic compounds content and composition [81]. Similarly, Generalić Mekinić et al. [98] suggested a great variation in the profile of bioactive compounds throughout the growing period, a finding that highlights the importance of the harvesting stage on the quality of the final product. Other compounds that were present in considerable amounts were kaempferol, hyperoside, quercetrin and neochlorogenic acid [2]. In contrast, Martins-Noguerol et al. [99] reported rutin and 5-caffeoyl quinic acid as the major compounds in the methanolic extracts of sea fennel leaves. In a recent study by Chen et al. [100], the partitioning of the methanolic extracts of sea fennel aerial parts allowed the identification of eight new flavonoids (various methoxyflavones). Moreover, the aerial parts of sea fennel are a source of fatty acids. Ventura et al. [73] observed that the total fatty acids content in leaves ranged between 1.9 and 2.7%. Regarding the fatty acids profile, Labiad et al. [101] reported that the most abundant fatty acids were linoleic (C18:2 n6, 45.04–49.46%) and linolenic acid (C18:3 n3, 36.0–38.61%). Similarly, Sánchez-Faure et al. [102] identified linoleic (7.2 mg g^{-1} dw) and linolenic acid (6.39 mg g^{-1} dw) as the main fatty acids, followed by palmitic acid (3.5 mg g^{-1} dw). The leaves of sea fennel are also a good source of amino acids. In a recent study, Martins-Noguerol et al. [99] identified eleven amino acids in the leaves of the species, with leucine, lysine, valine, phenylalanine and threonine being detected in the highest amounts. The chemical structures of the major bioactive compounds are presented in Figure 4.

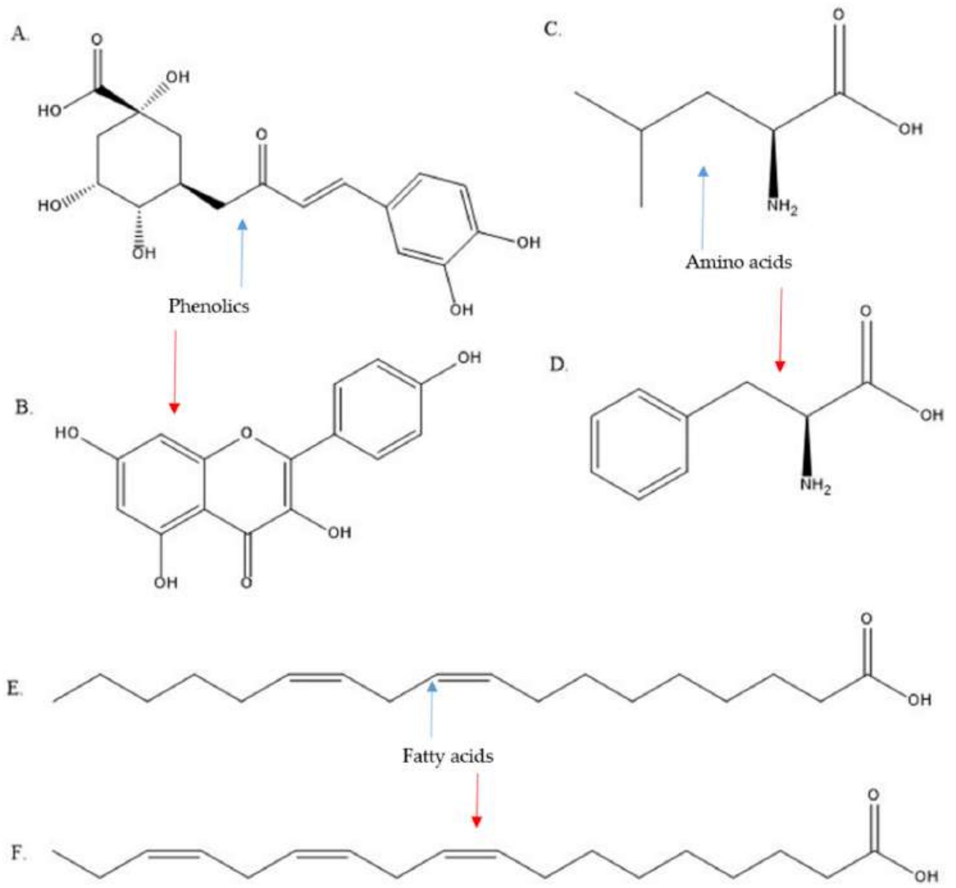

Figure 4. Chemical structure of major bioactive compounds contained in the aerial parts of sea fennel: (**A**). chlorogenic acid ($C_{16}H_{18}O_9$), (**B**). kaempferol ($C_{15}H_{10}O_6$), (**C**). leucine ($C_6H_{13}NO_2$), (**D**). phenylalanine ($C_9H_{11}NO_2$), (**E**). linoleic acid ($C_{18}H_{32}O_2$) and (**F**). linolenic acid or a-linolenic acid ($C_{18}H_{30}O_2$).

Sea fennel is also a valuable source of minerals [99,103], especially Na and Fe, which were the main minerals (14.7 and 8.5 g kg^{-1} WW (wet weight), respectively) in the wild plants collected from a coastal area in Spain, followed by Ca (5.9 g kg^{-1} WW) and K (4.2 g kg^{-1} WW) [102]. In another study, Labiad et al. [101] determined the content of Mg, K, Na and Ca in sea fennel leaves and recorded the greatest values for K and Na. Moreover, in four wild populations of sea fennel collected from Spain, the greatest content recorded was of Fe (58.4–191.7 mg kg^{-1} dw), followed by Mn and Zn [99].

It is also important to point out that the content of oxalic acid in the leaves of sea fennel varied between 16 and 77 mg 100 g^{-1} FW and was lower than that in leaves of goosefoot (*Chenopodium album* L.) (361–2027 mg 100 g^{-1} FW) and slender amaranth (*Amarranthus viridis* L.) (810–1353 mg 100 g^{-1} FW) [104]. Other wild species contain greater amounts of oxalic acid in edible tissues compared to sea fennel. For example, Petropoulos et al. [105] determined high amounts of oxalic acid in the stems and leaves of common purslane (*Portulaca olearacea* L.), 371–753 (mg 100 g^{-1} FW), while the content of this compound in the leaves of *Cichorium spinosum* L. varied between 432 and 740 mg 100 g^{-1} FW [44]. However, considering the antinutritional properties of oxalic acid, further studies are needed to evaluate the effects of commercial cropping practices on its content, since several studies have reported significant differences in the chemical composition of cultivated and wild plants [106,107].

5. Health Effects

Sea fennel exhibits several bioactive effects (see Table 1). Recently, Souid et al. [108] reported that the hydro-methanolic extracts from leaves of this species showed significant in vitro (DPPH and ORAC assays) antioxidant activity, while the same extracts exhibited in vivo protective effects in the liver of rats against carbon-tetrachloride-induced toxicity. In the same study, it was found that the administration of a sea fennel leaves water suspension to rats with liver toxicity reduced the activities of the enzymes used as markers of liver damage, e.g., alanine aminotransferase (ALT) and aspartate aminotransferase (AST) (reduction of 8.1 and 9.3%, respectively), as well the levels of creatinine (reduction of 41.3%) [108]. Moreover, Najjaa et al. [109] reported that the antioxidant activity of ethanolic and aqueous extracts from aerial parts of sea fennel were 89.35 mg GAE dw^{-1} and 82.35 mg GAE dw^{-1}, respectively, while the total phenolic, total flavonoid and total condensed tannins contents were lower in the ethanolic extracts (62.47 mg GAE dw^{-1}, 6.05 mg CE g dw^{-1} and 16.62 mg CE g dw^{-1}, respectively) compared to the aqueous ones (116.13 mg GAE dw^{-1}, 21.26 mg CE g dw^{-1} and 58.31 mg CE g dw^{-1}, respectively). The main constituents of sea fennel identified in this study were epigallocatechin, vanillic acid and chlorogenic acid [109].

Table 1. Main biological activities of essential oil or extracts from aerial parts of sea fennel (*Crithmum maritimum* L.).

Plant Part Used	Extract or Essential Oil	Biological Activity	References
Leaves	Extract	Antioxidant, hepatoprotective	[108]
Aerial parts		Antioxidant	[109]
Whole plant		Anticancer (mechanisms: cell death, apoptosis, and proliferation)	[110–112]
Leaves		Antioxidant, antimicrobial, antimutagenic	[2]
Leaves		Anti-stress	[120]
Flowers		Anti-parasitic	[119]
Aerial parts at flowering stage	Essential oil	Anti-inflammatory	[85]
-		Antioxidant, antimicrobial	[122]
Aerial parts		Antifungal	[92]

The extracts from sea fennel plants exhibited notable anticancer properties [110]. In particular, Gnocchi et al. [111] reported that the ethyl acetate extracts from sea fennel plants collected on the Apulian coast, Italy at a concentration of 0.5 μM showed anticancer activity against hepatocellular carcinoma cell lines (Huh7 and HepG2) by causing cell necrosis and apoptosis on the one hand and by reducing cancel cell growth on the other hand. Moreover, in vitro studies with sea fennel extracts showed that the combined application of ethyl acetate extracts with a half IC_{50} dose of sorafenib treatment (a common anticancer drug against hepatocellular carcinoma) caused a reduction in the cell proliferation of two hepatocellular carcinoma lines (Huh7 and HepG2) compared to the full IC_{50} dose of the drug, without increasing cell toxicity [112]. Other anticancer effects, include the inhibition of proliferation in the human skin cancer cell line A375, which was attributed to the presence of specific flavonoids (5-hydroxy-7,4′-dimethoxyflavone; 5-hydroxy-7,3′,4′-trimethoxyflavone; 5,3′-dihydroxy-7,4′-dimethoxyflavone; 5,4′-dihydroxy-7,3′-dimethoxyflavone; 5,4′-dihydroxy-7-methoxyflavone; 3,5-dihydroxy-7,3′,4′,5′- tetramethoxyflavone; 5,8-dihydroxy-7,3′,4′-trimethoxyflavone; and 5,8-dihydroxy-7,4′-dimethoxyflavone) [100]. Therefore, plant extracts could be used in integrative strategies in cancer therapy where conventional drugs could be combined with natural matrices that will increase the effectiveness of drugs and ameliorate their toxic and adverse effects.

In contrast, the essential oil of sea fennel's aerial parts did not show significant cytotoxic effects against colorectal (RKO) or breast cancer (MCF7) cell lines [93], while, according to Özcan [113], the essential oils exert significant antioxidant activity. Apart from the essential oil, the residual water of hydro-distillation may contain significant amounts of bioactive compounds. According to Alves-Silva et al. [85], the residual water from hydro-distillation contains chlorogenic acid and quercetin, which are responsible for antioxidant properties, while the essential oil of the species at a concentration of 3.125 μg mL^{-1} reduced the nitric oxide levels in lipopolysaccharide (LPS)-induced macrophages. In other studies, it is well documented that some active constituents identified in sea fennel may exhibit biological properties. For example, Zeng et al. [114] reported that chlorogenic acid, which is one of the main constituents of sea fennel essential oil, exhibited an antitumor capacity against breast cancer by inhibiting the proliferation of tumor cells, while it also triggered the apoptosis and inhibited the metastasis of cancer cells. Moreover, the same compound was associated with the reduction in the cell proliferation of the human lung cancer cell line A549 [115]. In a study by Wang et al. [116], DPPH and ABTS assays revealed that kaempferol exhibited significant antioxidant activity (IC_{50} values of 47.93 μM and 0.337 μM for DPPH and ABTS radical scavenging, respectively), while it also increased apoptosis in the human hepatoma cell line HepG2.

In another study, Souid et al. [2] reported that *C. maritimum* hydro-ethanolic leaf extracts at a concentration of 1 mg mL^{-1} exerted considerable antimicrobial activity against various Gram-positive or Gram-negative bacteria such as *Enterococcus faecalis* ATCC 29212 and *Enterobacter aerogenes* ATCC, as well as anti-mutagenic effects against hydrogen peroxide and menadione induced mutagenesis in the yeast of *Saccharomyces cerevisiae* (D7 strain). In particular, it was reported that the leaf extracts reduced the mitotic gene conversion values in treated yeast cells compared to that in cells treated only with hydrogen peroxide and menadione [2].

In a study by Marongiu et al. [92], it was reported that the essential oil of aerial parts of *C. maritimum* exhibited antifungal activity against dermatophyte fungi such as *Microsporum canis* (strain FF1), *Trichophyton rubrum* (strain CECT 2794) and yeasts. The same authors suggested that the lowest MIC (minimal inhibitory concentration) values (0.08 μL mL^{-1}) were recorded for the essential oil from samples collected in Sardinia and attributed this effect to the highest dillapiole content [92], since, according to Ferreira et al. [117], essential oils rich in dillapiole are very effective against dermatophytes. Other constituents of sea fennel essential oil, such as sabinene and β-phellandrene, can also contribute to its antifungal capacity. In a recent study, Ma et al. [118] reported that both sabinene and β-phellandrene may exhibit antifungal activity against *Candida* strains. In addition to the above biological properties, sea fennel exerts notable anti-parasitic activity. Pereira et al. [119] reported that the decoctions, tinctures and essential oils of sea fennel's aerial parts collected from wild plants in Portugal exhibited activity against the protozoan *Trypanosoma cruzi* (strain Y), which is responsible for Chagas disease, while falcarindiol was the main constituent identified in the extracts. The same authors found that the latter compound showed anti-trypanosomal activity and caused a reduction in *Trypanosoma cruzi* infection [119]. In another study, Ben Othman et al. [120] performed in vitro assays to determine the anti-stress effects of extracts from leaves of five plant species at the cellular level and found that the extracts of sea fennel were capable of reversing the heat stress induced in cells. Recently, Tabari et al. [121] reported the moderate efficacy of *C. maritimum* essential oils against *Dermanyssus gallinae*, an ectoparasite that affects the aviary system of laying hens and further suggested its use as biopesticides.

Moreover, the bioactive properties of sea fennel extracts could be further valorized through their incorporation in food products. For this purpose, Alemán et al. [123] suggested the use of soy phosphatidylcholine liposomes for the encapsulation of aqueous and ethanolic extracts obtained from the leaves and stems of sea fennel. The same authors reported a significant increase in the antioxidant activity of the encapsulated extracts compared to the untreated ones [123].

6. Conclusions and Future Remarks

The dramatic changes in climate conditions have severely affected several crops, making their cultivation unviable due to yield losses and the increased cost of agrochemical inputs. Therefore, new alternatives have to be invented, allowing farmers to deviate from conventional farming systems and crops. Two new promising strategies consist of the introduction of wild edible species in sustainable farming systems on the one hand and the reclamation of abandoned or degraded agricultural land on the other hand. The cultivation of halophytes as cash crops integrates these strategies and allows the cultivation of salinized soils or the use of salinized underground water in coastal areas for the production of high added value products. Sea fennel is an important halophyte with special features that fits this context. Recent case studies have shown its potential for commercial cultivation in conventional cropping systems, while the application of tailor-made agronomic practices could increase its quality and yield (Figure 5).

However, despite the promising results, further studies are needed to establish cultivation protocols for different cultivation systems (e.g., soil or soilless systems) that will enable growers to adopt this new species. Moreover, breeding efforts are needed to valorize the great genetic variability present in the various ecotypes of the species through the selection of elite genotypes with improved quality and agronomic features. The propagation of the species is also an issue, since commercial cultivation requires high numbers of plants with uniform size and morphological traits. Therefore, in vitro propagation protocols have to be further studied and established, thus allowing for the easy production of seedlings. More studies related to the health effects of the various plant parts focusing on unraveling those mechanisms involved in bioactive effects as well as revealing the chemical compounds that are responsible for these effects are also needed. This approach will help to further improve the quality of the final product through the application of fine-tuned cultivation practices as well as through the selection of specific ecotypes. Finally, considering the current trends in the food industry and the well-established consumer needs for convenient and easy-to-cook or ready-to-cook products, the whole food chain has to be reinvented. The consumers, especially the younger ones, have to be trained to prefer healthy and functional foods, even food products with peculiar and unusual taste, while the concepts of eating locally and seasonally, which are fully in line with the introduction of wild edible species in the everyday diet, should be promoted within the context of climate crisis mitigation.

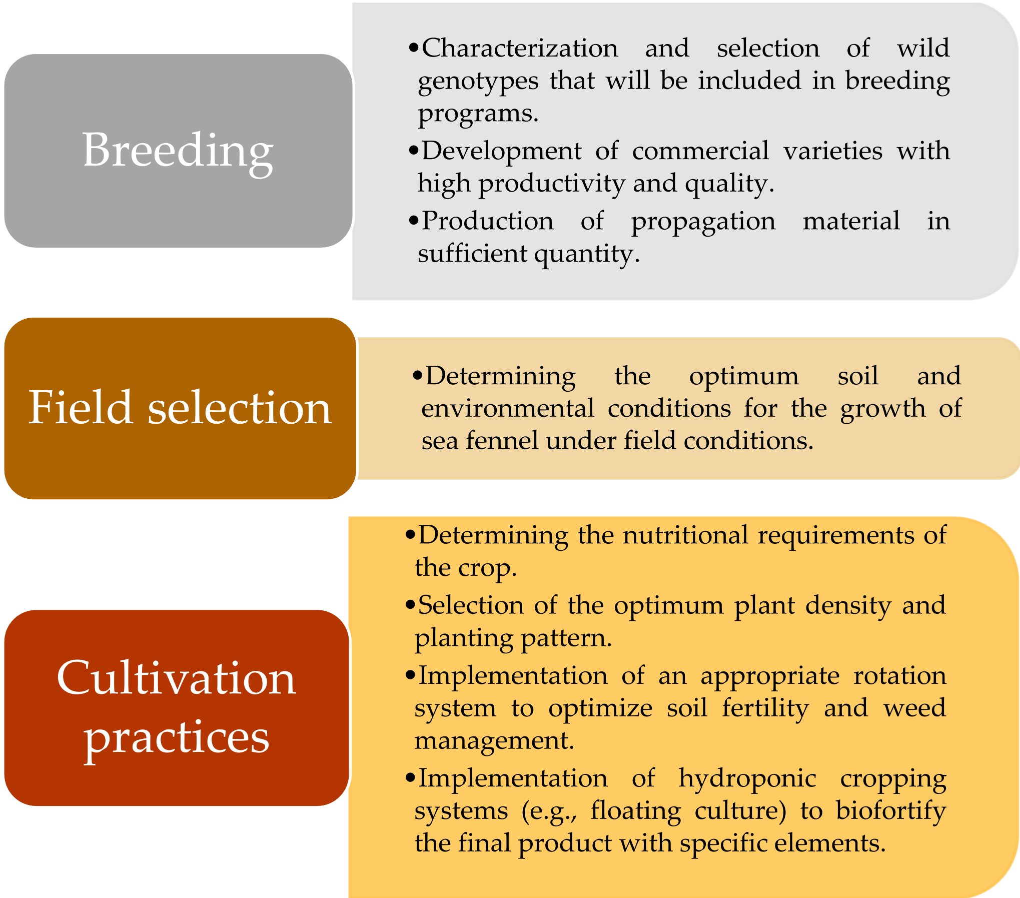

Figure 5. Optimization of biomass yield and quality of sea fennel under field and soilless conditions: Priorities and challenges.

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