

Review

Crambe Maritima as a Promising Halophyte for Climate-Resilient Agriculture: Agronomy, Phytochemistry and Future Perspectives

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Abstract

Global agricultural productivity is increasingly threatened by climate change, soil salinization, and freshwater scarcity. In response, edible halophytes such as *Crambe maritima* L. (sea kale) are emerging as resilient, promising alternative crops for biosaline agriculture. This review comprehensively evaluates the agronomic, phytochemical, and commercial potential of *C. maritima* and related *Crambe* species. We examine current propagation protocols and highlight the application of controlled-environment agriculture (CEA) to leverage “saline eustress,” strategically enhancing secondary metabolite biosynthesis without penalizing harvestable biomass. Nutritionally, *Crambe* species exhibit a highly favorable profile, selectively accumulating essential macro- and micro-minerals alongside potent bioactive compounds, particularly characteristic glucosinolates, including sinigrin, together with diverse phenolic acids. These specific secondary metabolites confer antioxidant defense system and antimicrobial properties, positioning the genus as an unexploited resource for functional foods, nutraceuticals, and cosmeceuticals. However, successfully transitioning *C. maritima* from a wild coastal halophyte into a reliable horticultural crop necessitates overcoming critical domestication bottlenecks, including mechanical seed dormancy, polygenic salinity tolerance, and a scarcity of long-term field data. By addressing these multidisciplinary challenges through targeted breeding and advanced agronomy, *C. maritima* represents a highly promising candidate for dietary diversification and the advancement of climate-resilient agricultural systems.

Keywords: *Crambe maritima*; halophytes; biosaline agriculture; saline eustress; glucosinolates; antioxidant capacity; climate-resilient crops; domestication; functional foods



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1. Introduction

1.1. Salinity as a Global Threat to Agricultural Sustainability

Global food systems face increasing pressure from climate change, population growth, and changing dietary patterns, requiring substantial increases in agricultural production to meet future food demand by 2050 [1]. Concurrently, arable land availability is shrinking due to severe anthropogenic and environmental degradation, with soil salinisation emerging as a paramount threat to global food security [2,3]. Globally, more than 830 mil-

lion hectares of land are currently classified as salt-affected, a footprint that continues to expand annually [4].

Soil salinisation is driven by both primary (natural) and secondary (anthropogenic) regimes. Primary salinisation occurs via the geological weathering of parent rock and marine salt deposition through wind or coastal spray; this is further exacerbated in littoral zones by sea-level rise and saltwater intrusion into coastal aquifers [1]. Conversely, secondary salinisation is primarily propelled by unsustainable agronomic practices, particularly in arid and semi-arid regions where high evapotranspiration rates coupled with deficient drainage systems induce rapid salt accumulation within the crop root zone [4]. Irrigation with saline or brackish water further increases concentrations of sodium (Na^+), chloride (Cl^-), and magnesium (Mg^{2+}), leading to long-term soil degradation [1,4].

The physicochemical impacts of salinity stress on conventional crops are profound, operating via a classic two-phase model: osmotic stress followed by tissue ion toxicity [5]. Elevated rhizosphere salinity reduces the soil water potential, inflicting physiological drought that severely constrains root water uptake even under moisture-replete conditions [6,7]. Subsequently, plants experience severe ion imbalances and toxicity as systemic Na^+ and Cl^- accumulate in aerial tissues, accelerating the premature senescence of older leaves [8]. These metabolic disruptions trigger cascading secondary oxidative stress via the overproduction of reactive oxygen species (ROS), which damage vital cellular membranes, degrade photosynthetic pigments, and arrest growth [7]. Consequently, highly sensitive staple crops (glycophytes), such as rice (*Oryza sativa* L.), frequently exhibit yield collapses of 50–80% under even moderate salinity levels [2,4].

Mitigating salinity stress demands integrated, multifaceted solutions. Current agronomic interventions include breeding salt-tolerant crop cultivars, exploiting halophytic genetic reservoirs, and employing plant growth-promoting rhizobacteria (PGPR) to improve nutrient assimilation and osmotic adjustment [2,6]. In parallel, engineering advancements in micro-irrigation efficiency, real-time soil salinity monitoring technologies, and ecological landscape restoration are essential to prevent further structural land degradation and protect global crop productivity [1,9].

1.2. Halophytes as Genetic and Agronomic Resources for Saline Agriculture

While conventional glycophytic crops often suffer physiological failure at low salt concentrations, halophytes—representing approximately 1% of the global flora—possess a unique evolutionary capacity to complete their ontogeny in hypersaline environments exceeding 200–500 mM NaCl [10–12]. Halophytic resilience relies on a highly integrated suite of morphological, physiological, and biochemical adaptations. Principal among these are precise osmotic adjustments driven by the synthesis of compatible organic solutes (proline, glycine betaine) and highly efficient vacuolar ion compartmentalisation, which isolates toxic Na^+ and Cl^- away from sensitive cytosolic enzymes [12]. Furthermore, specialised halophytic structures, such as epidermal bladder cells or multicellular salt glands, allow certain species to actively excrete excess ions directly out of their foliar surfaces.

Maintaining photosynthetic integrity under concurrent salinity, thermal, and moisture stress is another hallmark of halophyte survival. While specialised C_4 halophytes utilise concentrated carbon-fixing pathways to optimise water-use efficiency [13], many C_3 halophytes rely on robust antioxidant enzyme networks (e.g., superoxide dismutase, catalase) and structural modifications, such as dense foliar trichomes or multi-layered waxy cuticles, to shelter their photosynthetic machinery from photoinhibition and desiccation.

From an agricultural perspective, halophytes offer viable pathways for marginal land utilisation and biosaline farming. Numerous edible halophytes, particularly within families such as Amaranthaceae and Brassicaceae, can be intensively cultivated using brackish or

marine water in both soil-based and aquaponic configuration matrices [11]. Beyond directly providing alternative food, forage, or industrial oil streams, halophytes improve marginal soil configurations; their extensive root architectures stabilise soil aggregates, suppress wind and water erosion, and systematically elevate soil organic carbon content through rhizosphere deposition. Consequently, they represent an indispensable genetic blueprint for identifying stress-responsive alleles and developing future climate-resilient crops via molecular and transgenic breeding frameworks [11].

1.3. *Crambe Maritima* as an Emerging Climate-Resilient Vegetable Crop

Crambe maritima L. (commonly known as sea kale) is a perennial, coastal halophyte that shows significant promise for diversifying modern saline agricultural systems. As a wild relative within the Brassicaceae family, it is closely related to economically vital cole and oilseed crops, making it excellent for expanding sustainable horticultural production into marginal coastal ecosystems [14,15].

Sea kale uniquely couples extreme ecophysiological tolerance with valuable culinary characteristics. Naturally adapted to well-drained coastal shingles, sand dunes, and strandlines, *C. maritima* easily tolerates chronic salt spray, severe macronutrient deficiencies, and harsh wind exposure. Its deep, robust taproot system anchors the plant against shifting coastal substrates and accesses deep moisture reserves to maintain perennial growth regimes. Concurrently, its prominent, glaucous, and succulent leaves feature a thick waxy cuticle that drastically restricts non-stomatary water loss and provides physical protection against osmotic shocks. Ecologically, its prolific spring blooms of fragrant white flowers provide vital resources for coastal pollinator networks, followed by the development of highly buoyant, single-seeded fruits (silicles) adapted for long-distance marine hydrochory [16].

Geographically, *C. maritima* exhibits a native distribution spanning the northern and western coastlines of Europe, with discontinuous populations extending deeply into the Baltic and Black Sea maritime regions. It typically populates microhabitats directly above the spring high-tide line, interacting within specialised plant communities that form the first line of coastal ecological defence.

From an agronomic perspective, sea kale represents a premium, underutilised vegetable crop with high market potential. Its exceptional capability to thrive in hyper-saline margins, combined with a rich nutritional profile (high in vitamin C, mineral content, and bioactive glucosinolates), positions it as a foundational candidate for climate-resilient horticultural systems. However, despite its clear potential, the specific physiological responses of *C. maritima* to prolonged, incremental soil salinity levels and its corresponding biochemical antioxidant variations during key vegetative stages remain poorly characterised (Figure 1). Despite its recognised potential as a climate-resilient crop, current knowledge on *C. maritima* remains fragmented across agronomy, plant physiology, phytochemistry, and horticultural sciences. A comprehensive synthesis of the available evidence is still lacking, particularly regarding its adaptation to saline environments, nutritional value, and potential applications in biosaline agriculture. Therefore, this review aims to critically summarise and integrate the current knowledge on *C. maritima*, with emphasis on its botanical characteristics, ecological adaptations, physiological mechanisms of salinity tolerance, agronomic management, phytochemical composition, biological activities, and potential applications as a climate-resilient crop. Furthermore, this review identifies current knowledge gaps and discusses future research priorities required to support the domestication and commercial development of this promising halophyte under sustainable agricultural systems.

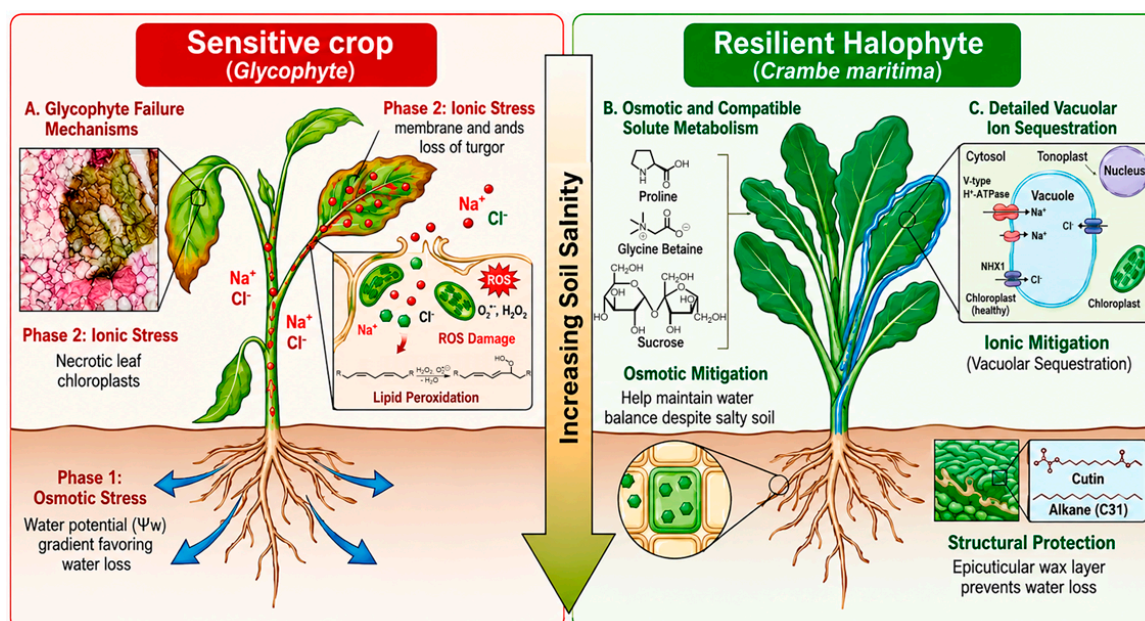


Figure 1. Comparative physiological, biochemical, and structural responses to increasing soil salinity in a sensitive glycophyte versus the resilient halophyte *C. maritima*. **(Left)** Sensitive crop (Glycophyte): Salinity exposure triggers a devastating biphasic stress response. Phase 1 (Osmotic Stress) creates a root-zone water potential (Ψ_w) gradient favouring rapid water loss. Phase 2 (Ionic Stress) is characterised by the toxic cytosolic accumulation of Na^+ and Cl^- ions. This drives the generation of reactive oxygen species (ROS, such as O_2^- and H_2O_2), leading to severe lipid peroxidation, membrane degradation, loss of cellular turgor, and visible chloroplast necrosis. **(Right)** Resilient Halophyte (*C. maritima*): Salinity tolerance is mediated through a highly coordinated suite of adaptive traits. Osmotic mitigation is achieved via the biosynthesis of compatible solutes—specifically proline, glycine betaine, and sucrose—which help maintain cellular water balance. Ionic mitigation relies on the active compartmentalisation of toxic Na^+ and Cl^- ions into the vacuole, driven by tonoplast-localised V-type H^+ -ATPases and NHX1 antiporters, thereby shielding functional chloroplasts from ionic toxicity. Further structural protection against desiccation is provided by the deposition of a thick epicuticular wax layer rich in cutin and very long-chain alkanes (e.g., C31).

Unlike previous reviews that have addressed halophytes or biosaline agriculture from a broad perspective, this review focuses specifically on *C. maritima*. It integrates current knowledge on its ecology, salinity tolerance, agronomic management, nutritional and phytochemical composition, biological activities, and potential applications as a climate-resilient crop. By consolidating the available evidence for this species and identifying key knowledge gaps, this review provides a comprehensive reference to support future research and its sustainable utilisation in saline agricultural systems.

2. Materials and Methods

A structured narrative approach was used to identify and synthesise literature on the agronomic potential, phytochemistry, and climate resilience of *C. maritima* (sea kale), drawing on established methodological guidelines for narrative literature reviews [17,18]. To strengthen the epistemological foundation of this synthesis, our analytical strategy was explicitly informed by recent advancements in systematic review methodologies, particularly rigorous mapping frameworks. By engaging with these advanced methodological paradigms, we adopted a more rigorous analytical strategy for drawing cohesive insights across highly heterogeneous sources. Specifically, these frameworks provided a critical lens for systematically mapping the intersections between peer-reviewed academic literature in plant physiology, biosaline agriculture, and phytochemistry.

Rigorous search strategies were applied to ensure traceability and reduce selection bias. A quantitative meta-analysis was deemed not feasible. Following established statistical and methodological parameters for meta-analyses [19,20], pooling data requires high uniformity across study designs, which was absent here. Specifically, a meta-analysis was precluded due to three key challenges:

- **High Heterogeneity:** Studies vary widely in cultivation environments (e.g., controlled-environment hydroponics versus open-field marginal coastal soils) and applied salinity regimes, preventing meaningful statistical pooling.
- **Incompatible Metrics:** Outcomes are not standardised (e.g., varying extraction solvents for total polyphenols or differing indices for biomass yield), which limits mathematical comparability.
- **Inapplicable Tools:** Standard risk-of-bias tools are generally designed for highly standardised clinical interventions, making them ill-suited for evaluating the complex, multi-scalar physiological responses inherent in halophyte ecology and biosaline agriculture.

This review therefore uses a thematic narrative synthesis to evaluate the data appropriately.

During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-5.5) exclusively as a graphical design assistant for the generation of conceptual scientific illustrations. All scientific concepts, figure organization, annotations, and interpretations originated from the authors. Every AI-generated output was critically reviewed, manually edited, corrected where necessary, and verified against the cited literature before inclusion. The authors assume full responsibility for the originality, accuracy, and final content of all figures.

2.1. Literature Search Strategy

A literature search was conducted across major academic databases—Scopus, Web of Science, ScienceDirect, and SpringerLink—supplemented by Google Scholar and relevant grey literature from institutional agricultural bodies (e.g., FAO). The search included studies published between 2010 and 2026, with an emphasis on recent studies. Boolean operators (AND, OR) were used to combine key constructs, including *Crambe maritima*, Halophytes, Biosaline Agriculture, Saline Eustress, Glucosinolates, Antioxidant Capacity, and Climate-Resilient Crops. Backward citation tracking was used to identify additional relevant studies by screening the reference lists of key reviews and highly relevant primary studies, capturing seminal botanical works not retrieved via initial electronic queries. Supplementary Table S1 details the results of the literature search.

2.2. Thematic Criteria and Study Selection

To ensure consistent screening, eligibility was defined using a thematic framework adapted from established literature review methodologies. This framework was adapted from systematic review methods to structure the agronomic and phytochemical research parameters:

- **Context:** Saline environments, coastal shingle habitats, marginal degraded lands, and controlled-environment agriculture (CEA) systems.
- **Strategies:** Integration of biosaline agricultural practices, propagation methods, and the targeted application of moderate saline eustress.
- **Baselines:** Conventional glycophytic crop responses, standard non-saline cultivation practices, and historical wild-foraging paradigms.

- Metrics: Quantifiable physiological tolerance, biomass allocation, antioxidant enzyme activity, and phytochemical yields (specifically glucosinolates, phenolic acids, and flavonoids).

This approach ensured consistent study selection, ensuring that all selected studies were directly aligned with the review's core objectives.

2.3. Inclusion and Exclusion Criteria

Regarding botanical and agronomic typologies, the inclusion criteria specifically targeted studies examining edible halophytes and *Crambe* species within both open-field agricultural settings and precision hydroponic systems. This focus is justified by two primary factors: first, these environments serve as the principal settings for evaluating realistic biosaline crop viability; second, they provide the most direct context for analysing the physiological trade-offs between harvestable biomass and stress-induced secondary metabolite accumulation.

Inclusion was limited to English-language publications, encompassing peer-reviewed journal articles, conference proceedings, technical reports, and comprehensive reviews. While peer-reviewed literature formed the foundational basis of this synthesis, select grey literature was incorporated to capture current macroeconomic frameworks and applied regulatory environments. Unverified industry publications and non-institutional web sources were systematically excluded. Furthermore, studies were included only if they provided methodologically sound evaluations of salt tolerance mechanisms, agronomic performance, or phytochemical profiling accompanied by quantifiable outcomes. Conversely, studies were excluded if they lacked methodological transparency, presented duplicated findings, or focused exclusively on non-edible industrial oilseed *Crambe* species without relevant horticultural metrics.

While this study is designed as a thematic narrative review, we employed a systematic search strategy adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This approach was utilised to ensure transparency, minimise selection bias, and clearly document the literature retrieval and screening process (Figure 2).

Step 1: Identification and Initial Screening. Given the highly multidisciplinary nature of halophyte agronomy and phytochemistry research, a comprehensive database search was conducted across electronic databases. The initial search targeting the primary subject yielded a total of 577 records. The breakdown of initial records retrieved per database, along with the exact Boolean search strings applied, is detailed in Supplementary Table S1. A summary of the initial distribution is as follows:

- SpringerLink: 352 records.
- ScienceDirect: 133 records.
- Scopus: 46 records.
- Web of Science: 46 records.

Following the automated removal of duplicates, the remaining records underwent rigorous title and abstract screening. Ultimately, the studies that met all strict inclusion criteria formed the empirical basis of this qualitative synthesis. This systematic filtering process ensured the inclusion of only highly relevant, contextually appropriate, and methodologically robust studies. The complete screening progression is detailed in Figure 2.

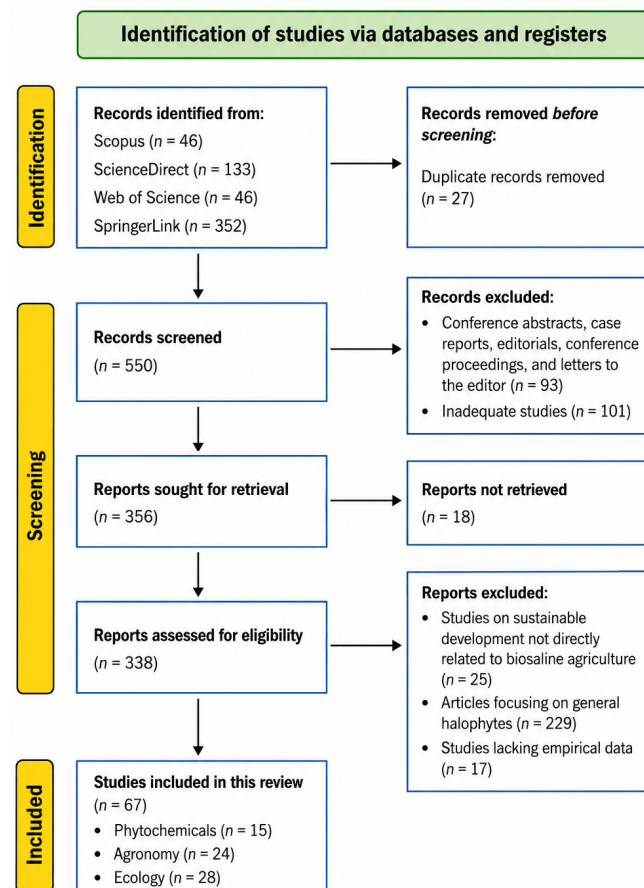


Figure 2. The research flow diagram conducted to perform this review.

2.4. Data Extraction and Synthesis

Data was extracted using a standardised matrix to ensure consistency. Variables were mapped to the thematic criteria, capturing author details, publication year, cultivation setting, baseline comparators, applied salinity thresholds, and defined physiological or biochemical outcomes. Due to methodological heterogeneity and variability in reporting metrics across the selected studies, data were synthesised narratively. Interventions were clustered by type—such as propagation strategies or salinity treatments—and cross-analysed according to their efficacy. The synthesised findings are reported as outcome ranges rather than statistical averages, providing an overview of performance and highlighting key gaps in the contemporary biosaline agricultural discourse.

2.5. Thematic Validation and Coding Protocol

To ensure analytical rigour and replicability in the absence of a quantitative meta-analysis, this review followed a structured three-stage thematic synthesis approach:

- **Coding Protocol:** Primary literature was subjected to line-by-line coding by the authors. Initial codes were derived inductively from the text of the selected studies, capturing key concepts related to osmotic adjustment, secondary metabolism, and agronomic management. These codes were then grouped into categories through an iterative process of comparison and refinement.
- **Thematic Derivation:** Through constant comparison, descriptive themes were synthesised into higher-order analytical themes (e.g., shifting from “salt tolerance” to “saline eustress optimisation”). This process was performed collaboratively to ensure inter-rater consistency in conceptual classification.

- **Thematic Saturation:** The iterative search and analysis process continued until thematic saturation was reached—a point at which no new conceptual dimensions or critical perspectives were identified within the retrieved literature. This saturation criterion served as the internal validation mechanism for the scope of the synthesis, ensuring the final thematic framework was representative of the current scholarly consensus rather than selective interpretation.

3. Botanical, Ecological, and Ethnobotanical Background

3.1. Taxonomy, Morphology, and Geographic Distribution

Integrating wild coastal species into modern agricultural systems requires a precise understanding of their taxonomic lineage, morphological traits, and natural ecological distribution. *C. maritima* (commonly known as sea kale) is a perennial halophyte of particular horticultural interest due to its extreme environmental resilience and potential for crop diversification.

Taxonomically, *C. maritima* belongs to the Brassicaceae family within the tribe Brassiceae [14]. The genus *Crambe* encompasses approximately 36 species, several of which hold significant economic and industrial value, including the oilseed crops *C. abyssinica* and *C. hispanica* [15]. First formally described by Carl Linnaeus in 1753, the species' binomial nomenclature directly reflects its ecological niche: *Crambe* derives from the Greek *krambē* (denoting cabbage-like plants), while *maritima* indicates its obligate coastal habitat (Figure 3).

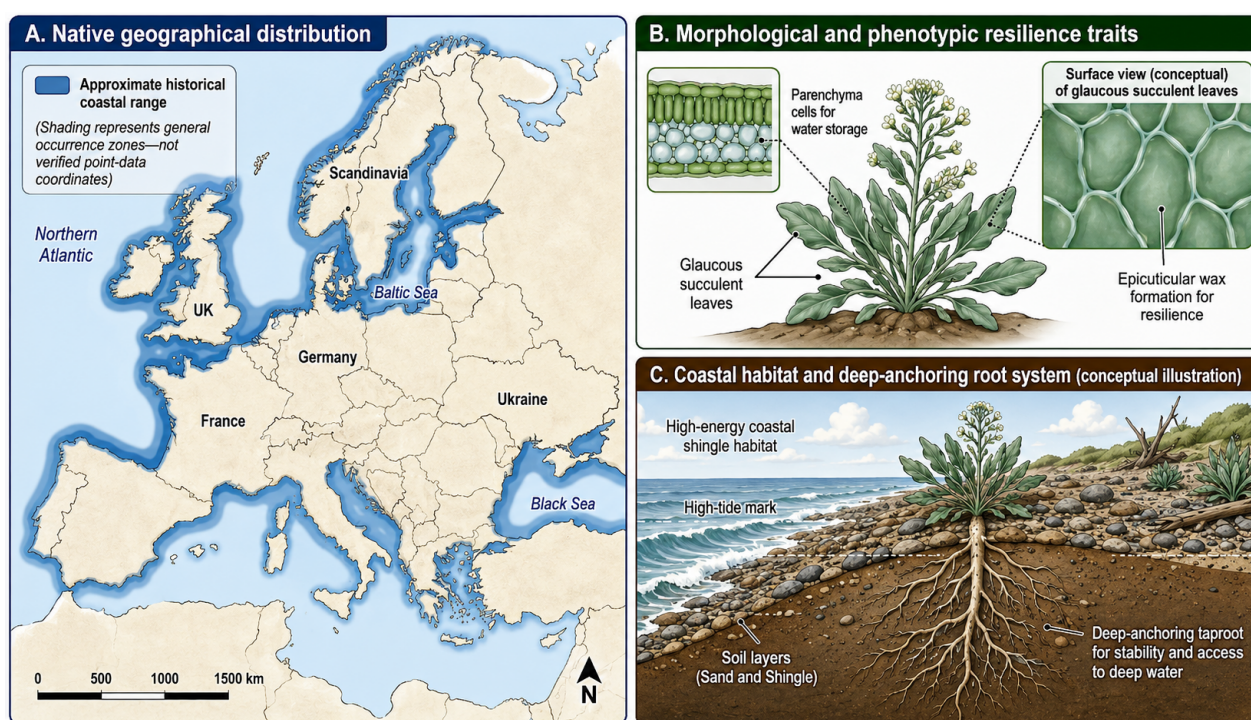


Figure 3. Approximate geographic range, structural morphology, and typical habitat of *C. maritima*. (A) Generalised schematic representing the approximate historical coastal range of the species across the Northern Atlantic, Baltic, and Black Sea regions (shading represents general occurrence zones rather than verified point-data coordinates). (B) Illustrative representation of morphological and phenotypic resilience traits. Note: Leaf surface and anatomical cross-section panels are conceptual schematics designed to highlight physiological adaptations—such as parenchyma water storage and epicuticular wax formation—and do not represent experimental microscopy. (C) Conceptual illustration of the deep-anchoring taproot system and a typical high-energy coastal shingle habitat near the high-tide mark.

Morphologically, sea kale is a robust, long-lived herbaceous perennial perfectly adapted to harsh maritime conditions. It forms a dense basal rosette that can reach up to 75 cm in both height and spread. The plant is anchored by a deep, fleshy, and highly regenerative taproot that stabilises it within shifting shingle substrates and acts as a vital carbohydrate storage organ during winter dormancy [15]. The foliage comprises large, distinctively glaucous and succulent leaves. These wavy, lobed leaves—which can exceed 30 cm in length—are heavily coated with a thick epicuticular wax that restricts non-stomatal water loss and provides a physical barrier against abrasive salt spray and high ultraviolet (UV) radiation (Figure 4).

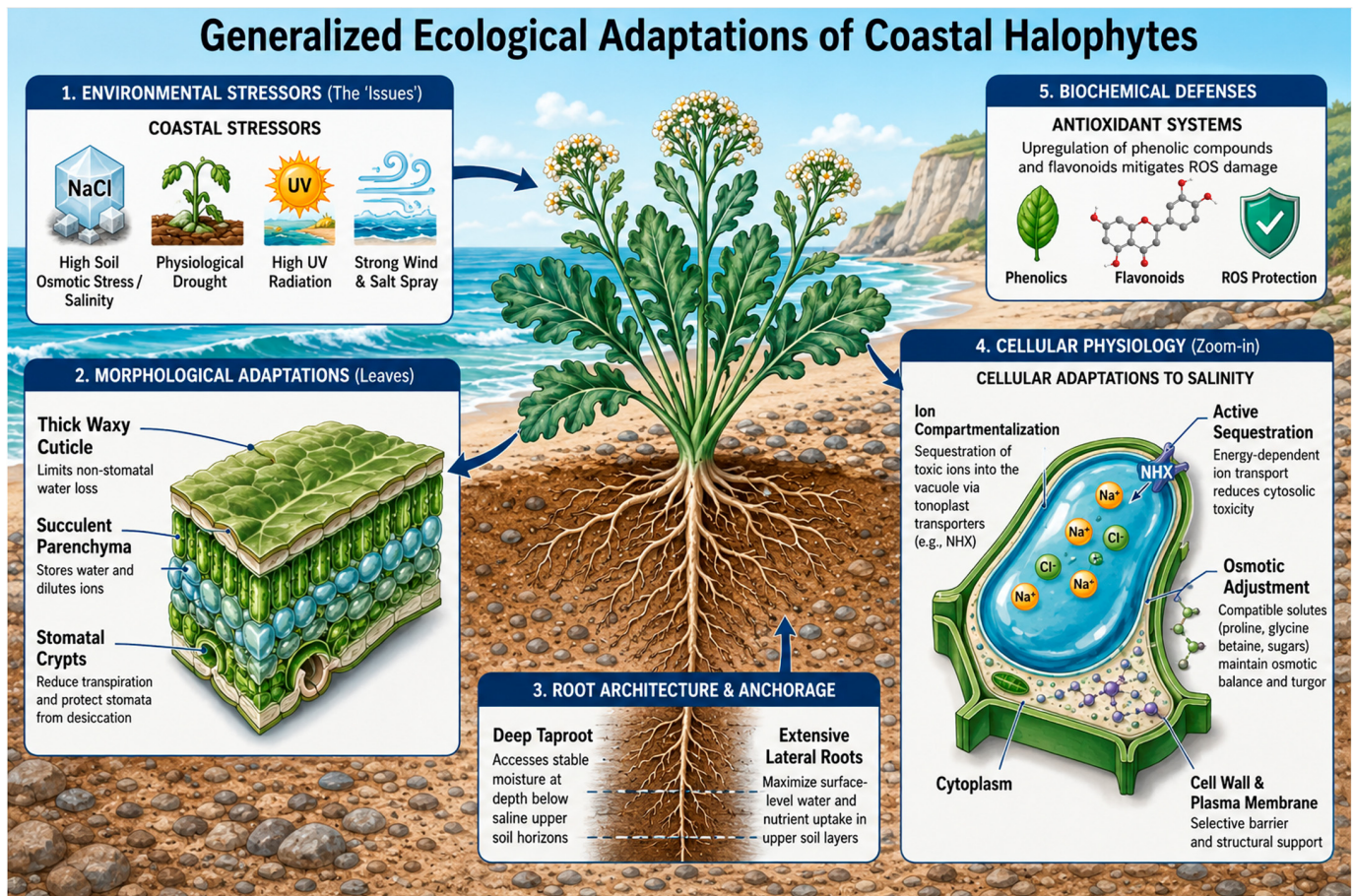


Figure 4. Generalised ecological and physiological adaptations of coastal halophytes. This schematic utilises the gross morphology of *C. maritima* as a representative archetype to illustrate widely conserved halophytic survival mechanisms in high-energy coastal environments. (1) Environmental Stressors: Coastal halophytes must navigate complex abiotic factors, including high soil salinity, physiological drought, UV radiation, and mechanical stress from wind and salt spray. (2) Morphological Adaptations (Leaves): Generalised xerophytic and halophytic leaf traits include thick waxy cuticles to limit non-stomatal water loss, succulent parenchyma for water storage and ion dilution, and stomatal crypts to minimise transpiration. (3) Root Architecture: Extensive lateral root networks maximise surface-level water acquisition, while deep taproots access stable moisture profiles beneath saline upper soil horizons. (4) Cellular Physiology: Core halophytic cellular defence mechanisms include the active sequestration of toxic Na^+ and Cl^- ions into the vacuole via tonoplast transporters (e.g., NHX), coupled with the accumulation of compatible solutes (e.g., proline, glycine betaine) in the cytosol to maintain osmotic balance and turgor. (5) Biochemical Defences: Upregulation of antioxidant systems, including phenolic compounds and flavonoids, mitigates reactive oxygen species (ROS) damage induced by compounded salinity and UV stress.

During its reproductive phase (late spring to early summer), *C. maritima* produces expansive, branched corymbose inflorescences containing numerous small, cruciferous white flowers. These highly fragrant blooms are crucial resources for coastal insect pollinators. Following fertilisation, the plant develops indehiscent, single-seeded fruits (silicles) featuring a spongy, buoyant pericarp. This specialised structure facilitates hydrochorous (water-borne) dispersal, enabling the seeds to survive prolonged immersion in seawater and colonise distant shorelines [16].

Geographically, *C. maritima* is a native European coastal species exhibiting a discontinuous distribution along the northern and eastern Atlantic shorelines, encompassing the British Isles, Scandinavia, and the Baltic region. Distinct subpopulations reappear along the coastlines of the Black Sea, though the species is notably absent from the broader Mediterranean basin, where other related halophytes occupy similar ecological niches.

3.2. Ecological Adaptations to Coastal Shingle Habitats

Coastal littoral zones impose a multi-stress environment characterised not only by soil salinity, but also by physiological drought, mechanical wind abrasion, nutrient scarcity, and tidal disturbance [17]. Rather than exhibiting the typical adaptations of marsh-dwelling halophytes (such as pneumatophores or salt glands), *C. maritima* has evolved specific morpho-ecological traits to dominate the high-energy shingle beaches and strandlines situated just above the high-tide mark.

The primary ecological challenge in shingle habitats is substrate instability and extremely poor water retention. *C. maritima* overcomes this through its specialised taproot system, which can penetrate deep into stratified sand and gravel to access subterranean freshwater lenses safely isolated from surface salt accumulation. Above ground, the high degree of foliar succulence allows the parenchyma tissue to store significant water reserves, effectively diluting internal ion concentrations during periods of osmotic stress [18].

Furthermore, because shingle beaches are highly deficient in essential macronutrients (nitrogen and phosphorus), *C. maritima* typically establishes itself in micro-niches enriched by marine drift—such as decomposing macroalgae (seaweed) and organic tidal detritus. Within these specialised communities, it acts as a pioneer species alongside co-occurring coastal flora such as *Glaucium flavum* (yellow horned poppy) and *Honkenya peploides* (sea sandwort), playing a critical ecological role in initial substrate stabilisation and the early stages of coastal dune succession [15].

3.3. Ethnobotanical Relevance and Traditional Culinary Uses

Historically, *C. maritima* has maintained a profound ethnobotanical relationship with European coastal communities. Before its formal integration into agriculture, wild sea kale served as a vital foraging staple. Coastal populations routinely harvested the emerging spring shoots and unexpanded flower heads, utilising them as a nutrient-dense food source during the “hungry gap” (late winter to early spring) when other agrarian crops were unavailable.

Because the mature leaves can develop a distinct bitterness and high levels of sulfurous glucosinolates common to the Brassicaceae family, traditional culinary practices involved boiling the foliage in multiple changes of water or pickling the shoots to improve palatability. Beyond its dietary utility, the plant was historically recognised for its anti-scorbutic properties; its high ascorbic acid (Vitamin C) content made it a valuable resource for sailors and local populations to prevent scurvy during long winters. Consequently, sea kale is deeply embedded in the culinary heritage of the British Isles and coastal France, representing a localised, place-based food system born directly out of coastal foraging traditions.

3.4. Historical Domestication and Horticultural Decline

The transition of *C. maritima* from a wild-foraged coastal plant to a domesticated horticultural crop occurred primarily in Western Europe during the 18th and 19th centuries. The true horticultural domestication of the species is widely attributed to the development of the “forcing” technique. Gardeners discovered that by burying the dormant crowns under deep sand or covering them with specialised terracotta “sea kale pots” during early spring, they could effectively etiolate (blanch) the emerging shoots. This process inhibited chlorophyll production, resulting in tender, pale shoots with a delicate, nutty flavour reminiscent of asparagus.

By the late Victorian era, forced sea kale had become a highly prized, luxury winter vegetable across Britain and France, extensively cultivated in elite kitchen gardens and commercial market gardens alike. However, the cultivation of *C. maritima* experienced a severe decline during the early to mid-20th century. The two World Wars, combined with the extreme labour intensity required for winter forcing and trenching, rendered the crop economically unviable compared to more easily mechanised vegetables.

Today, *C. maritima* is considered an underutilised and largely forgotten orphan crop. However, the current global focus on climate-resilient agriculture and saline farming systems has sparked a modern scientific and gastronomic revival, positioning sea kale as a prime candidate for sustainable re-domestication in marginal, salt-affected landscapes.

4. Salinity Tolerance and Agronomic Potential

4.1. Physiological and Biochemical Mechanisms of Salt Tolerance in *Crambe Maritima* L.

Soil salinisation constitutes a severe abiotic bottleneck that constrains global agricultural output by inflicting concurrent osmotic, ionic, and oxidative stresses. While conventional glycophytic crops undergo rapid metabolic collapse under these conditions, *C. maritima* exhibits robust tissue tolerance, successfully maintaining cellular homeostasis under elevated macronutrient salinity profiles [5]. Current knowledge of salt tolerance in *C. maritima* is derived from a combination of species-specific studies and evidence inferred from other halophytes and Brassicaceae. Where direct experimental evidence is unavailable, the mechanisms discussed below should be regarded as putative rather than experimentally confirmed for *C. maritima*.

Available evidence suggests that osmotic adjustment is likely to contribute to salt tolerance in *C. maritima*, as reported for many halophytes and Brassicaceae species. To counteract the reduced water potential of saline rhizospheres, this species synthesises and accumulates high intracellular concentrations of compatible organic osmolytes—predominantly proline, soluble sugars, and polyols [19]. These cytosolic compounds act as metabolic chaperones, stabilising tertiary protein structures, protecting cellular membranes, and maintaining the positive turgor pressure necessary for cell expansion without interfering with fundamental enzymatic processes.

Concurrently, maintaining a favourable cytosolic K^+/Na^+ ratio is essential for the survival of *C. maritima*, as excess intracellular Na^+ competitively inhibits essential K^+ -dependent enzymes. Because *C. maritima* lacks specialized excretory structures like the epidermal salt bladders found in Chenopodiaceae halophytes, it relies entirely on a highly efficient internal ion-homeostasis network. These mechanisms are well established in halophytes and are likely to operate in *C. maritima*, although direct experimental evidence remains limited [20]. This vacuolar sequestration is driven by tonoplast-bound transport proteins, including V-type H^+ -ATPases and Na^+/H^+ antiporters (NHX pathways), which successfully isolate toxic ions away from the metabolic machinery of the cytoplasm and chloroplasts.

Furthermore, the prevention of salinity-induced photoinhibition and oxidative stress in sea kale is managed by an integrated antioxidant defence network. Antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidases (POD) are known to play central roles in halophyte salt tolerance and are likely to contribute to stress responses in *C. maritima*, although species-specific studies are still scarce [21]. This complex physiological suite is coordinated by fine-tuned phytohormonal signalling cascades; localised spikes in abscisic acid (ABA) regulate stomatal conductance to balance carbon assimilation against transpirational water loss, while ethylene and jasmonates modulate downstream stress-responsive gene networks [22].

Although several physiological and biochemical mechanisms have been proposed to explain salinity tolerance in *C. maritima*, much of the current understanding is inferred from studies on other halophytes and Brassicaceae species. Consequently, the relative contribution of ion homeostasis, osmotic adjustment, antioxidant defenses, and hormonal regulation remains insufficiently validated in this species. Future studies integrating physiological, molecular, and omics approaches under both controlled and field conditions are needed to confirm these mechanisms. Therefore, *C. maritima* should currently be regarded as a promising halophyte for biosaline agriculture rather than a fully established model species, highlighting the need for further physiological, molecular and agronomic research. Future research should integrate physiological, transcriptomic and metabolomic approaches to identify which mechanisms most strongly contribute to field-level salt tolerance and productivity.

4.2. Environmental Interactions: Responses to Drought and Marginal Soils

In coastal strandlines and degraded agricultural regions, salinity rarely occurs in isolation; it frequently co-occurs with severe drought and macronutrient deficiencies [23]. The morpho-physiological architecture of *C. maritima* provides unique cross-tolerance to these compounding stresses. The earliest visible response to combined osmotic and moisture stress is a highly regulated reduction in stomatal aperture. Although this limits immediate CO₂ influx, the high photosynthetic plasticity of sea kale preserves baseline carbon fixation rates while drastically improving water-use efficiency (WUE) [24].

On marginal, alkaline, and nutrient-poor coastal soils, *C. maritima* exhibits significant subterranean adaptation. While members of the Brassicaceae family are characteristically non-mycorrhizal and cannot form symbioses with arbuscular mycorrhizal fungi, *C. maritima* effectively alters its root system architecture (RSA) by increasing deep taproot elongation and lateral branching density to tap into deeper, non-saline moisture zones [24].

Furthermore, as reported for several halophytes, associations with halotolerant plant growth-promoting rhizobacteria (PGPR) and fungal endophytes may contribute to improved nutrient acquisition and stress tolerance. These beneficial microorganisms can enhance iron mobility through siderophore production, solubilise inorganic phosphorus, and produce phytohormones such as auxins that stimulate root development. However, direct evidence for these rhizosphere interactions in *C. maritima* remains limited and warrants further investigation [24].

4.3. Propagation, Agronomic Practices, and Saline Irrigation Management

The commercialisation of *C. maritima* as a climate-resilient vegetable requires optimising its agronomic management, particularly during its highly sensitive early growth phases. Seed-based propagation of sea kale faces notable challenges due to the mechanical and chemical dormancy imposed by its thick, woody, and buoyant pericarp (silicle), which limits uniform germination under stress due to osmotic inhibition [25]. To bypass this bottleneck, agronomic systems utilise mechanical dehulling or chemical seed priming tech-

niques to accelerate uniform germination. Alternatively, vegetative propagation utilising root cuttings—commonly termed “thongs”—is highly preferred in commercial settings, as it bypasses early seedling vulnerability, guarantees genetic uniformity, and ensures rapid field establishment (Figure 5).

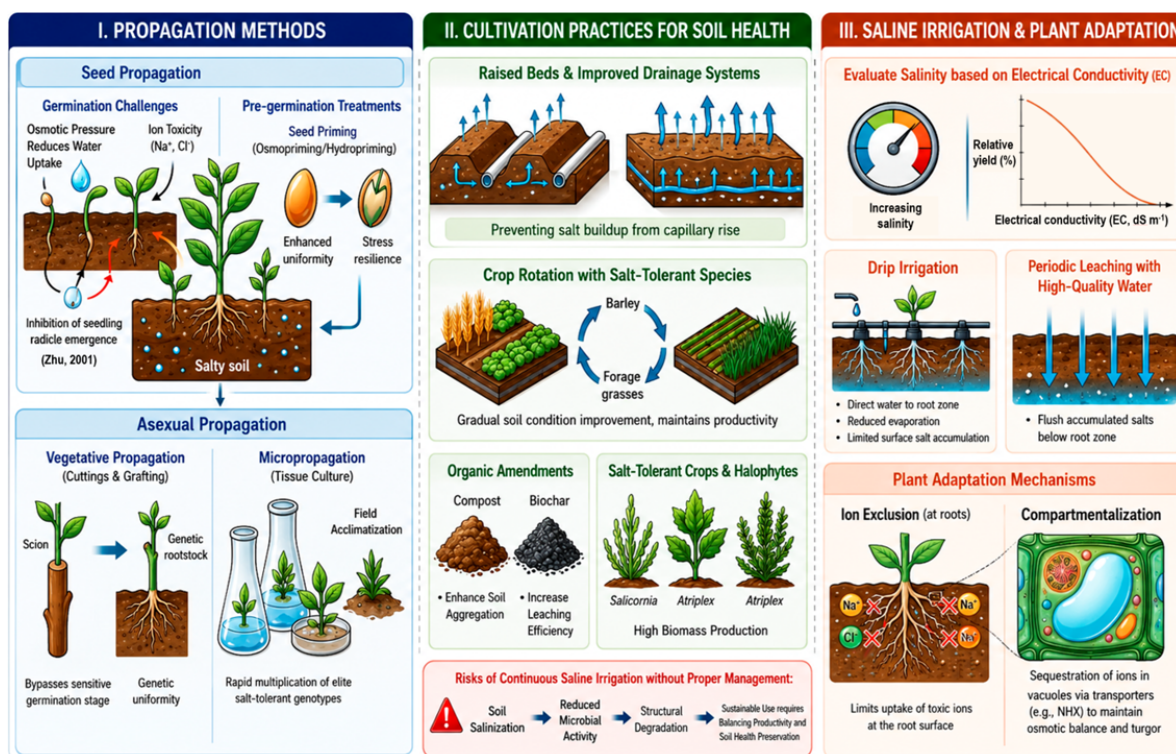


Figure 5. Agronomic management and propagation pathways for coastal halophytes in biosaline agriculture. I. Propagation Methods: Overview of generative and asexual propagation pathways. Seed propagation highlights the challenges of osmotic pressure and ion toxicity, alongside mitigation strategies such as pre-germination seed priming. Asexual strategies encompass vegetative propagation (e.g., grafting) and micropropagation to bypass vulnerable early germination stages and ensure genetic uniformity [25]. II. Cultivation Practices for Soil Health: Open-field management strategies designed to mitigate root-zone salinity and maintain soil structure. Practices include raised beds with improved drainage to prevent capillary salt rise, crop rotation, organic amendments (compost and biochar) to enhance leaching efficiency, and the integration of highly salt-tolerant indicator crops (e.g., *Salicornia*, *Atriplex*). III. Saline Irrigation and Plant Adaptation: Evaluation of irrigation suitability based on electrical conductivity (EC) thresholds, utilising drip irrigation and periodic high-quality water leaching to flush accumulated salts below the root zone. Successful cultivation relies on balancing these agronomic practices with inherent plant physiological adaptations, such as root-level ion exclusion and cellular vacuolar compartmentalisation, to prevent long-term soil salinisation and microbial degradation.

Field cultivation strategies for sea kale in salt-affected environments focus heavily on preventing excessive salt accumulation within the primary root zone. Implementing raised-bed configurations combined with managed sub-surface drainage networks enhances the downward leaching of excess salts away from emerging root systems [26]. Incorporating organic soil amendments, such as composted agricultural wastes or biochar, structurally improves marginal soil matrices, enhances cation exchange capacity, and cushions the crop against acute osmotic shocks.

When utilising saline or brackish water for irrigation, precise management of electrical conductivity (EC) thresholds is mandatory. Applying water through high-efficiency drip irrigation systems minimises evaporation rates and prevents the surface crusting of

salts [27]. Furthermore, applying strategic leaching fractions—irrigation volumes slightly exceeding crop evapotranspiration requirements—periodically flushes concentrated Na^+ and Cl^- out of the root zone, preventing long-term soil structure degradation and securing sustainable perennial yields.

4.4. Biosaline Agriculture and Controlled-Environment Cultivation (CEA) Potential

Biosaline agriculture presents a useful framework for converting marginal, salt-degraded land and brackish water resources into productive horticultural landscapes [28]. As a perennial halophyte, *C. maritima* appears to be a promising candidate for these low-freshwater agronomic systems, capable of producing high-value culinary biomass where conventional glycophytic vegetables fail [29]. Beyond direct crop production, field-scale cultivation of sea kale provides valuable ecological services, including dune stabilisation, wind erosion control, and increased carbon sequestration within marginal soils through its persistent perennial root biomass.

However, open-field biosaline farming faces persistent challenges from environmental variables, microclimate fluctuations, and the long-term risk of progressive soil salinisation. These limitations have generated substantial interest in cultivating *C. maritima* within controlled-environment agriculture (CEA) systems, such as advanced greenhouses, hydroponics, and vertical farming configurations [30]. CEA allows for the ultra-precise management of nutrient solution composition, temperature, and light quality, eliminating the risks of soil heterogeneity.

Crucially, hydroponic configurations allow growers to exploit the biological phenomenon of saline eustress. By introducing moderate, non-toxic concentrations of NaCl (50–150 mM) into the nutrient solution, growers can deliberately trigger the plant's secondary metabolic pathways without penalising total biomass yield. In *C. maritima*, this controlled saline eustress significantly upregulates the synthesis of health-promoting phytochemicals, leading to higher concentrations of sulfurous glucosinolates, total polyphenols, and ascorbic acid. Consequently, combining large-scale field biosaline systems for regional soil rehabilitation with high-precision CEA setups for premium vegetable production offers a highly effective, dual-track for integrating sea kale into modern, climate-resilient food networks.

While controlled-environment agriculture offers unique opportunities to manipulate salinity for improving phytochemical quality, the transferability of these findings to commercial production remains uncertain. Salinity thresholds that stimulate secondary metabolism without reducing yield are likely to vary with genotype, developmental stage, environmental conditions, and production system. Furthermore, the economic feasibility of hydroponic or vertical farming systems for sea kale has received little attention compared with conventional greenhouse vegetables. Therefore, future studies should combine physiological optimization with techno-economic analyses before saline eustress strategies can be widely recommended.

4.5. Comparative Agronomic and Phytochemical Potential

To adequately contextualise the agronomic and nutritional potential of *Crambe* spp. within the broader paradigm of biosaline agriculture, a comparative analysis against established glycophytic crops and highly adapted halophytes is essential (Table 1). While conventional Brassicaceae crops, such as *Brassica oleracea*, offer high commercial yields and well-characterised glucosinolate profiles, their cultivation is fundamentally constrained by low-to-moderate salinity thresholds, requiring significant freshwater inputs [31]. Conversely, obligate euhalophytes like *Salicornia europaea* demonstrate exceptional biomass

production in highly degraded, hypersaline environments; however, they lack the diverse glucosinolate-driven phytochemical profile characteristic of the Brassicaceae family [32].

Table 1. Comparative analysis of edible halophytes and Brassicaceae crops.

Species & Category	Salinity Tolerance	Nutritional Composition	Glucosinolate Profile	Agronomic Performance	Industrial Applications	References
<i>Crambe maritima</i> (Sea Kale) <i>Brassicaceae</i> , <i>Halophyte</i>	High: Adapted to coastal shingle beaches; tolerates equinoctial tides, salt spray, and highly saline soils.	Total polyphenols (up to 70.88 mg GAE g ^{−1} DW) and flavonoids (up to 29.92 mg QE g ^{−1} DW) peak during the fruiting stage. Exhibits strong free radical scavenging and molybdenum reducing power that increases with plant maturity.	Produces unique aliphatic and indole glucosinolates (e.g., epiprogoitrin, sinigrin) that contribute to its distinctive bitter/pungent flavour and stress defence.	Perennial plant with a fleshy taproot propagated via root cuttings or seeds; takes 5–8 years to flower from seed; lower overall biomass yield compared to commercial crops.	Gourmet vegetable and functional food ingredient. Extracts show consistently strong antimicrobial activity against <i>B. cereus</i> , <i>S. aureus</i> , <i>C. perfringens</i> , and <i>C. albicans</i> , peaking during the flowering and fruiting stages.	[33]
<i>Brassica oleracea</i> (Broccoli/Cabbage) <i>Brassicaceae</i> , <i>Glycophyte</i>	Low to Moderate: High salinity (>100 mM NaCl) significantly reduces biomass, osmotic potential, and root hydraulic conductance, though some cultivars adapt.	Rich in vitamins (C, K), dietary fibre, and minerals. Interestingly, moderate saline stress can improve its nutritional quality by concentrating phenolic compounds and soluble sugars.	Highly concentrated in aliphatic (glucoraphanin) and indole (glucobrassicin) glucosinolates. Salinity stress often triggers an increase in these secondary metabolites.	Highly domesticated, high-yield annual crop. Requires standardised irrigation, fertilisation, and non-saline soils for maximum commercial productivity.	Global staple food crop. Highly valued in the nutraceutical industry for the extraction of bioactive degradation products like sulforaphane.	[31]
<i>Cakile maritima</i> (Sea Rocket) <i>Brassicaceae</i> , <i>Halophyte</i>	High: Thrives in coastal sand dunes and tolerates severe salt stress, drought, and low-nutrient substrates.	Rich in dietary fibre, essential lipids, and antioxidant polyphenols. Leaves accumulate high mineral ash content due to root-level salt compartmentalisation.	Contains high levels of specific defensive glucosinolates, such as glucocapparin and sinigrin, which aid in environmental adaptation.	Wild-foraged or in the early stages of domestication. Exhibits a rapid, annual growth cycle adapted to sandy, well-drained coastal soils.	Niche culinary market (spicy edible leaves used in salads), potential alternative sources of industrial seed oil, and natural antioxidants.	[34]
<i>Salicornia europaea</i> (Glasswort/Sea Asparagus) <i>Amaranthaceae</i> , <i>Obligate Halophyte</i>	Extreme: Obligate halophyte that actively requires salt for optimal growth (typically 200–500 mM NaCl).	Exceptionally high mineral/ash content (Na, K, Mg). Valuable source of proteins and features a highly favourable lipid profile rich in polyunsaturated fatty acids (Omega-3).	None: Does not belong to the Brassicaceae family and therefore does not synthesize glucosinolates.	Excellent biomass production in severely salinised soils. Highly effective when used in monoculture or intercropping systems.	Gourmet food (“sea asparagus”), green salt substitute, biofuel production, and widely utilised for the phytoremediation of degraded, salt-affected lands.	[32,35]

C. maritima occupies a unique and highly advantageous intermediate niche. As outlined in Table 1, it exhibits robust salinity tolerance characteristic of coastal pioneer species, while simultaneously maintaining a complex, high-value secondary metabolome. Notably, the ontogenetic accumulation of bioactive compounds in *Crambe* spp.—specifically the peaking of total polyphenols, flavonoids, and antimicrobial activity during the fruiting stage [33]—highlights its dual utility. It serves not only as a resilient crop for marginal lands but also as a concentrated source of novel functional ingredients. Compared to the wild-foraged *Cakile maritima*, *C. maritima* presents a more established pathway for

domestication as a perennial gourmet vegetable, though intensive, field-scale agronomic optimisation remains a critical prerequisite for its commercial upscaling.

5. Nutritional and Phytochemical Composition

5.1. Nutritional Profile and Mineral Composition

Halophytes have attracted increasing attention as alternative crops for saline agriculture due to their exceptional nutritional value and their unique biological capacity to thrive under conditions unsuitable for conventional agricultural cultivation. Many edible halophytes are densely packed with dietary fibre, vital vitamins, essential minerals, and health-promoting phytochemicals, making them highly promising candidates for integrating into sustainable, climate-resilient food systems [29,36].

One of the most distinctive physiological characteristics of halophytes is their complex mineral composition. Their evolutionary adaptation to saline environments enables these plants to selectively accumulate and compartmentalise substantial quantities of vital inorganic ions—predominantly sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphorus (P), and iron (Fe)—while maintaining strict cellular homeostasis [17]. From a human nutritional perspective, the accumulation of K^+ , Ca^{2+} , and Mg^{2+} is particularly relevant, given their critical systemic roles in cardiovascular health, bone tissue development, and enzymatic regulation [36].

Among edible coastal halophytes, *C. maritima* has garnered significant interest owing to its highly favourable and complex nutritional profile. The young, etiolated leaves and emerging spring shoots deliver dense concentrations of dietary fibre, essential trace minerals, and the bioactive organic sulfur compounds characteristic of the Brassicaceae family [15]. Furthermore, cultivating *C. maritima* on marginal coastal soils or degraded lands offers the dual benefit of generating high-value food production without competing for increasingly scarce conventional arable land.

However, a critical agronomic consideration is that while mineral accumulation enhances the baseline nutritional value, excessive Na^+ levels may negatively impact crop palatability and dietary suitability. Consequently, cultivation conditions, irrigation electrical conductivity (EC), and harvesting practices must be precisely optimised to strike a balance between beneficial mineral enrichment and widespread consumer acceptance [36]. Ultimately, halophytes combine high nutritional quality with extreme environmental resilience, strongly supporting their emerging role in dietary diversification under increasing global soil salinisation.

5.2. Glucosinolates, Polyphenols, Flavonoids, and Antioxidant Compounds

Beyond their basal macronutrient composition, halophytes and specialised Brassicaceae vegetables act as vital biological reservoirs for bioactive secondary metabolites. The most prominent among these are structural glucosinolates, polyphenols, flavonoids, and a network of related antioxidant compounds, all of which contribute equally to the plant's abiotic stress survival and to human health promotion [37,38]. Among the Brassicaceae, *C. maritima* possesses a distinctive phytochemical profile characterised by sulfur-containing glucosinolates together with abundant phenolic compounds and flavonoids. The predominant glucosinolates identified in sea kale include sinigrin (allyl glucosinolate), gluconapin, epiprogoitrin, and glucosinalbate, which are hydrolysed by endogenous myrosinase following tissue disruption to produce biologically active isothiocyanates.

These compounds have attracted considerable attention because of their antimicrobial, antioxidant, chemoprotective, and potential anticancer properties. In addition, sea kale accumulates diverse phenolic acids and flavonoids that contribute to reactive oxygen species (ROS) scavenging, membrane protection, and enhanced tolerance to oxidative

stress. Collectively, these secondary metabolites not only improve plant adaptation to saline environments but also increase the nutritional and pharmaceutical value of *C. maritima*, supporting its development as a functional food and nutraceutical crop.

Glucosinolates are the hallmark sulfur- and nitrogen-containing secondary metabolites of the Brassicaceae family. *C. maritima* is particularly notable for its distinct array of structural glucosinolates. Biochemical profiling of the species reveals robust concentrations of aliphatic and aromatic glucosinolates, predominantly sinigrin (allyl glucosinolate), gluconapin (3-butenyl glucosinolate), epiprogoitrin (2(S)-2-hydroxy-3-butenyl glucosinolate), and glucosinalbate (4-hydroxybenzyl glucosinolate). Upon mechanical tissue disruption—such as chewing or chopping—these inert precursors are rapidly hydrolyzed by the endogenous enzyme myrosinase into volatile and biologically active products, primarily isothiocyanates. These resulting degradation products are widely documented for their potent antimicrobial activity and their promising chemoprotective and anti-carcinogenic properties in human metabolic pathways [31,39].

Concurrently, polyphenols constitute a broad group of secondary metabolites explicitly involved in defending the plant against severe environmental and oxidative stress. Their pronounced antioxidant properties stem from their biochemical ability to donate electrons, thereby neutralising destructive reactive oxygen species (ROS) and preventing oxidative lipid peroxidation within cellular membranes [32]. Flavonoids, representing the largest and most diverse subgroup of polyphenols, participate actively in cellular signaling processes, tissue pigmentation, and systemic stress responses, while simultaneously exhibiting robust antioxidant and anti-inflammatory activities in human diets [33].

Consequently, the co-accumulation of unique glucosinolate profiles alongside a rich matrix of phenolic compounds significantly elevates the commercial value of *C. maritima*, positioning it as a premium source of functional culinary ingredients and pharmaceutical biomolecules [15]. Although the phytochemical composition of *C. maritima* has been investigated in several studies, considerable variability exists among reports due to differences in plant organs, developmental stages, environmental conditions, and analytical methodologies. Furthermore, most studies have focused on targeted compounds, whereas comprehensive metabolomic analyses remain limited. These limitations hinder direct comparisons among studies and highlight the need for standardised analytical approaches.

5.3. Influence of Salinity on Secondary Metabolites

Rhizosphere salinity acts as a primary environmental catalyst for upregulating secondary metabolic pathways in plants. Prolonged exposure to saline conditions rapidly induces parallel osmotic and oxidative stresses, leading to the localised accumulation of ROS (Figure 6). To survive, the plant is forced to activate complex protective metabolic pathways [29]. As part of this coordinated defence response, plants frequently accelerate the biosynthesis of antioxidant metabolites, notably specialised phenolic acids and flavonoids. The metabolic activation of the phenylpropanoid pathway under moderate salinity regimes significantly broadens the plant's antioxidant capacity, thereby improving its overall stress tolerance parameters [34,38]. Similarly, in Brassicaceae species, glucosinolate biosynthesis is frequently stimulated through stress-induced alterations in primary sulfur metabolism and parallel downstream stress-signalling cascades [35].

Halophytes provide an unparalleled scientific model for investigating these mechanisms, as they naturally maintain elevated baseline concentrations of these protective metabolites. In many controlled cultivation scenarios, the introduction of moderate salinity—known as saline eustress—deliberately enhances phytochemical accumulation without inflicting severe physiological penalties on the plant's overall performance [29]. Moderate saline conditions stimulate the biosynthesis of several phytochemicals in *C. mar-*

itima, including glucosinolates, phenolic acids, flavonoids, and ascorbic acid, through activation of the phenylpropanoid pathway and sulfur metabolism. Controlled-environment studies indicate that moderate saline eustress enhances the accumulation of these compounds without substantially reducing biomass, whereas excessive salinity suppresses growth despite further activation of stress-related metabolism. Therefore, optimisation of salinity represents a critical agronomic strategy for maximising both crop productivity and phytochemical quality.

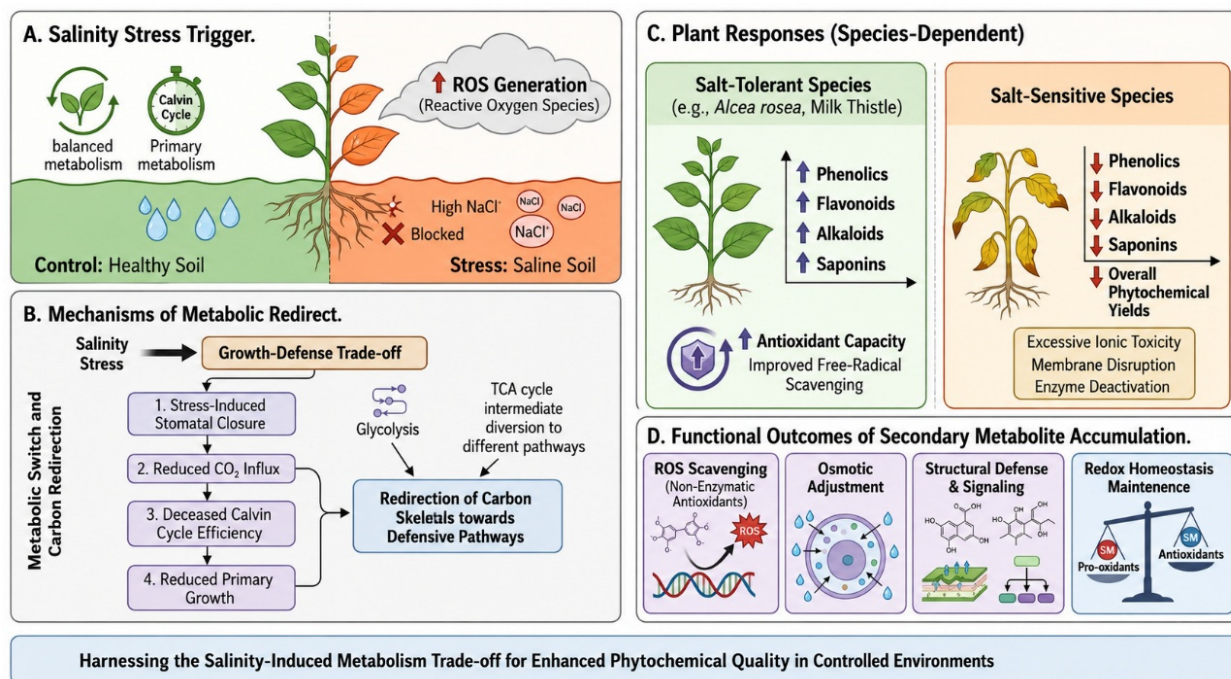


Figure 6. Influence of salinity stress on plant secondary metabolism: growth–defence trade-off and adaptive responses. Salinity stress induces osmotic and ionic stress, leading to excessive reactive oxygen species (ROS) production and reduced primary metabolism and plant growth (A). In response, plants redirect carbon and energy from growth-related processes toward the synthesis of defensive secondary metabolites through a growth–defence trade-off (B). This response varies among species, with salt-tolerant plants generally showing enhanced accumulation of phenolics, flavonoids, alkaloids, and saponins, together with improved antioxidant capacity, whereas salt-sensitive species exhibit reduced phytochemical production due to severe cellular damage (C). The resulting increase in secondary metabolites contributes to ROS scavenging, osmotic adjustment, structural defence, and maintenance of cellular redox homeostasis, highlighting the potential of controlled salinity to improve phytochemical quality while enhancing stress resilience (D).

However, the biological relationship between salinity concentration and metabolite yield is inherently non-linear. While a moderate stressor optimises phytochemical density, chronic or excessive salinity rapidly disrupts cellular homeostasis, severely reducing crop growth and total biomass accumulation. This creates a critical biological trade-off between maximising crop volume and optimising metabolite enrichment [34]. Precision management of specific salinity thresholds is therefore paramount for growers to simultaneously maximise harvestable yield and superior nutritional quality.

An important limitation of the available literature is the lack of standardised experimental protocols. Salinity treatments differ considerably among studies in terms of NaCl concentration, exposure duration, cultivation system, and developmental stage, making quantitative comparisons difficult. Consequently, although moderate salinity consistently appears to stimulate phytochemical accumulation, it remains challenging to

define universal optimum salinity levels for maximising both biomass production and nutritional quality.

5.4. Comparison with Other Brassicaceae Vegetables

While *C. maritima* shares the fundamental capability to produce high-value glucosinolates and phenolic compounds with conventional Brassicaceae crops, significant divergences exist regarding specific metabolite composition, inherent stress tolerance, and adaptive capacity in marginal environments [40].

Broccoli and Brussels Sprouts: These represent the most extensively researched Brassicaceae vegetables regarding their glucosinolate profiles (Figure 7). Broccoli is globally recognised for synthesising high concentrations of glucoraphanin (the direct precursor to the potent chemopreventive agent sulforaphane). Conversely, Brussels sprouts generally yield higher absolute total glucosinolate concentrations but with varying structural profiles [41].

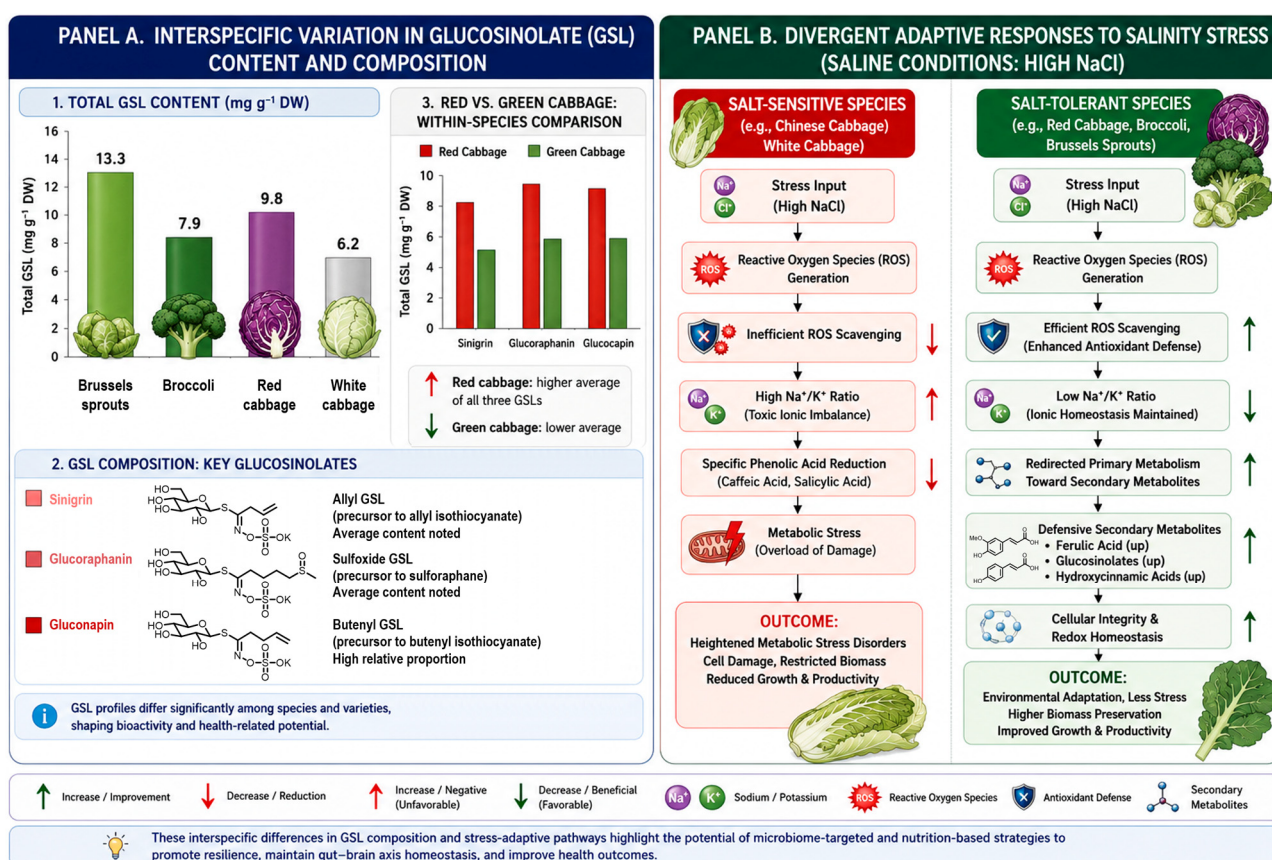


Figure 7. Interspecific variation in glucosinolates and divergent adaptive responses to salinity stress within the *Brassica* genus. **(A)** Comparative overview of total glucosinolate (GSL) content and composition among different *Brassica* crops (e.g., Brussels sprouts, broccoli, red cabbage, and white cabbage). Relative proportions of specific GSLs (glucocapin, glucoraphanin, sinigrin) highlight significant intra- and interspecific phytochemical variations. **(B)** Divergent physiological and biochemical pathways in response to high NaCl stress. Salt-Sensitive Species (**Left**): Salinity induces reactive oxygen species (ROS) generation that overwhelms the plant’s inefficient ROS scavenging systems, leading to a toxic, high cytosolic Na⁺/K⁺ ratio, specific phenolic acid reduction, metabolic stress, and ultimately restricted biomass and cellular damage. Salt-Tolerant Species (**Right**): Successful adaptation is mediated by efficient ROS scavenging and the maintenance of a low Na⁺/K⁺ ratio. These species actively redirect primary metabolism toward the synthesis of defensive secondary metabolites (e.g., ferulic acid, hydroxycinnamic acids, and specific glucosinolates), which stabilise cellular integrity, maintain redox homeostasis, and result in successful environmental adaptation and higher biomass preservation.

Kale and Chinese Cabbage: Responses to elevated salinity fluctuate markedly among these common species. Kale naturally exhibits relatively robust salt tolerance, managing to preserve its elevated levels of antioxidant phenolic compounds even under stress. In sharp contrast, Chinese cabbage is notoriously glycophytic and sensitive, suffering rapid reductions in cellular growth, membrane integrity, and metabolic stability upon exposure to minimal salinity [42].

These highly contrasting physiological responses underline the absolute necessity of selecting species equipped with evolutionary adaptation mechanisms for saline farming. Despite these promising characteristics, direct comparative studies between *C. maritima* and established Brassicaceae crops remain limited. Most comparisons are based on independent experiments conducted under different environmental conditions, preventing rigorous assessment of relative nutritional quality, salinity tolerance, or productivity. Well-designed comparative trials using standardised cultivation protocols would substantially strengthen the evidence supporting sea kale as a competitive alternative crop.

6. Biological Activities and Industrial Potential

6.1. Antioxidant, Antimicrobial, and Anti-Inflammatory Properties

The biological activities of halophytes and *Brassicaceae* vegetables are largely associated with their content of glucosinolates, phenolic acids, flavonoids, carotenoids, and related secondary metabolites. These compounds contribute to plant adaptation under stressful environmental conditions while also providing potential health-promoting properties [29,38]. The reported biological activities of *C. maritima* are directly associated with its phytochemical composition (Figure 8).

Phenolic compounds and flavonoids provide strong antioxidant activity by scavenging ROS generated during environmental stress, while glucosinolate hydrolysis products, particularly isothiocyanates, exhibit broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria. Comparative studies of the genus *Crambe* have demonstrated that *C. maritima* possesses one of the highest antioxidant capacities, reaching approximately 65 mg GAE g⁻¹ DW for total polyphenols and 10.63 mg CAE g⁻¹ DW for total phenolic acids during fruiting, together with strong free radical scavenging activity. Moreover, extracts from *C. maritima* inhibit important foodborne pathogens including *Staphylococcus aureus*, *Klebsiella pneumoniae*, and *Clostridium perfringens*, confirming their potential application as natural antimicrobial agents. Polyphenols and isothiocyanates also modulate inflammatory signalling pathways by regulating cytokine production and oxidative stress, suggesting possible roles in reducing the risk of chronic inflammatory disorders.

One of the most studied activities is antioxidant capacity. Environmental stresses such as salinity often stimulate the accumulation of phenolic compounds capable of scavenging reactive oxygen species (ROS), thereby reducing oxidative damage to cellular structures [32]. A comparative study by Vergun et al. [43] highlights the significant antioxidant and antimicrobial properties of the *Crambe* genus, suggesting their immense potential for use in pharmaceuticals and the food industry. However, their results demonstrate variability in bioactive compound content and activity across species and growth stages, emphasising the importance of selecting optimal harvest times [43]. Among the evaluated species, *C. maritima* demonstrates exceptional antioxidant capacity; its Total Polyphenol Content (TPC) increases significantly during maturation, peaking at 65 mg GAE g⁻¹ DW during the fruiting stage, while Total Phenolic Acid Content (TPAC) reaches its maximum of 10.63 mg CAE g⁻¹ DW concurrently. The antioxidant properties of ethanol extracts from five *Crambe* species—measured via Free Radical Scavenging Activity (FRSA)—ranged from 4.38 to 8.20 mg TE g⁻¹ DW, with *C. maritima* and *C. koktebelica* exhibiting the highest values at budding and flowering stages, respectively [43].

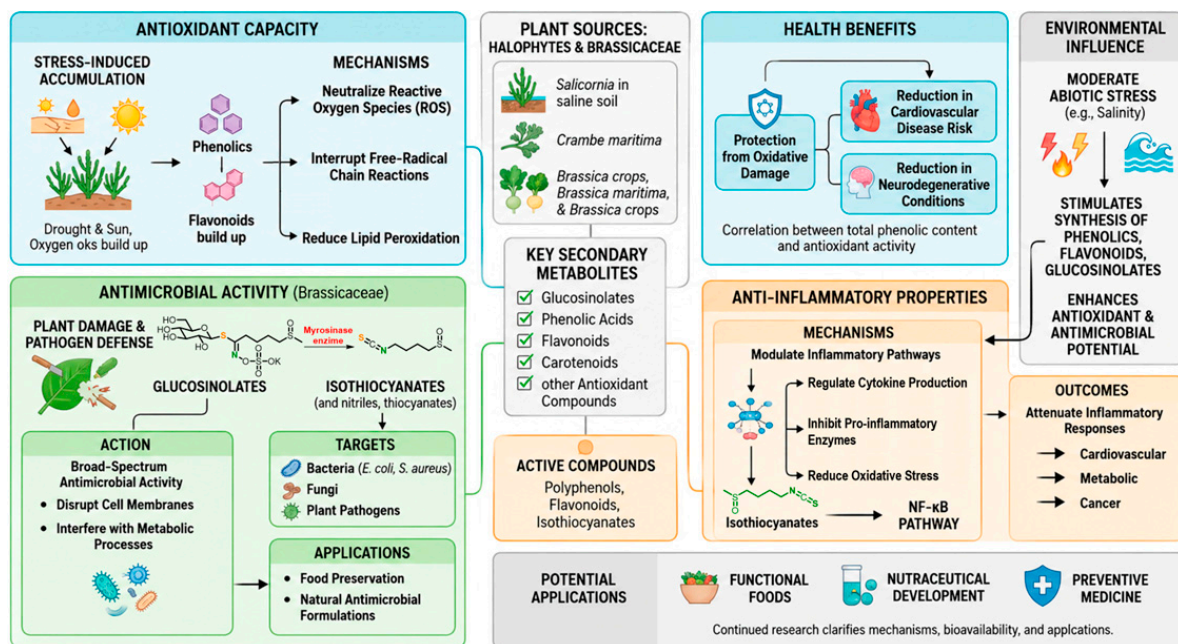


Figure 8. Biosynthetic pathways, mechanisms of action, and potential applications of secondary metabolites in halophytes and Brassicaceae. Moderate abiotic stress (e.g., salinity, drought) acts as an inducer for the synthesis of key phytochemicals (glucosinolates, phenolics, flavonoids, and carotenoids). These metabolites exert their biological effects through three main functional axes: (1) Antioxidant capacity: Neutralization of ROS, interruption of free-radical chain reactions, and reduction in lipid peroxidation, thereby mitigating chronic oxidative damage. (2) Antimicrobial activity: Hydrolysis of glucosinolates into isothiocyanates by the myrosinase enzyme, leading to membrane disruption and metabolic interference in bacteria, fungi, and plant pathogens. (3) Anti-inflammatory properties: Modulation of cytokine production and regulation of the NF-κB pathway, attenuating inflammatory responses associated with cardiovascular, metabolic, and cancerous pathologies. Together, these mechanisms underscore the potential of these extracts in the development of functional foods, nutraceuticals, and preventive medicine strategies.

These plants also exhibit antimicrobial activity, primarily due to glucosinolates and their hydrolysis products. Following tissue disruption, myrosinase converts glucosinolates into biologically active compounds such as isothiocyanates, which display inhibitory effects against a broad range of bacteria and fungi [39]. This is corroborated by direct testing of *Crambe* extracts against nine microbial strains, where extracts from underground parts showed greater antimicrobial activity compared to above-ground parts [43]. At the flowering stage, above-ground extracts of *C. maritima* exhibited measurable inhibition against critical pathogens, including *Staphylococcus aureus* (5.10 mm), *Klebsiella pneumoniae* (3.80 mm), and *Clostridium perfringens* (3.00 mm). Furthermore, significant inhibition against *S. aureus* and *Salmonella enterica* was observed for *C. hispanica* subsp. *abyssinica* and *C. steveniana* [43].

In addition, polyphenols and isothiocyanates can modulate inflammatory pathways by regulating cytokine production and reducing oxidative stress. Experimental studies suggest that these metabolites may contribute to the attenuation of chronic inflammatory processes associated with cardiovascular and metabolic diseases [33].

Although numerous in vitro studies demonstrate antioxidant and antimicrobial activities of *Crambe* extracts, these findings should not be directly extrapolated to human health benefits. The biological activity of isolated extracts frequently differs from that obtained through dietary consumption, owing to factors such as digestion, bioavailability,

metabolism, and effective dosage. Consequently, additional *in vivo* studies and controlled clinical trials are required before health-promoting claims can be fully substantiated.

6.2. Functional Food and Nutraceutical Applications

The high concentration of bioactive compounds found in halophytes and Brassicaceae vegetables has increased interest in their use as functional foods and nutraceutical ingredients (Figure 9). Functional foods are consumed as part of the normal diet and provide benefits beyond basic nutrition, whereas nutraceuticals are concentrated preparations of bioactive compounds intended to promote health or reduce disease risk [44]. The antioxidant and anti-inflammatory properties described above have positioned these plants as promising ingredients for the prevention of chronic diseases. Their phytochemical composition, particularly glucosinolates, polyphenols, carotenoids, and dietary fibre, has been associated with improved cardiovascular health, modulation of oxidative stress, and support of metabolic functions [45].

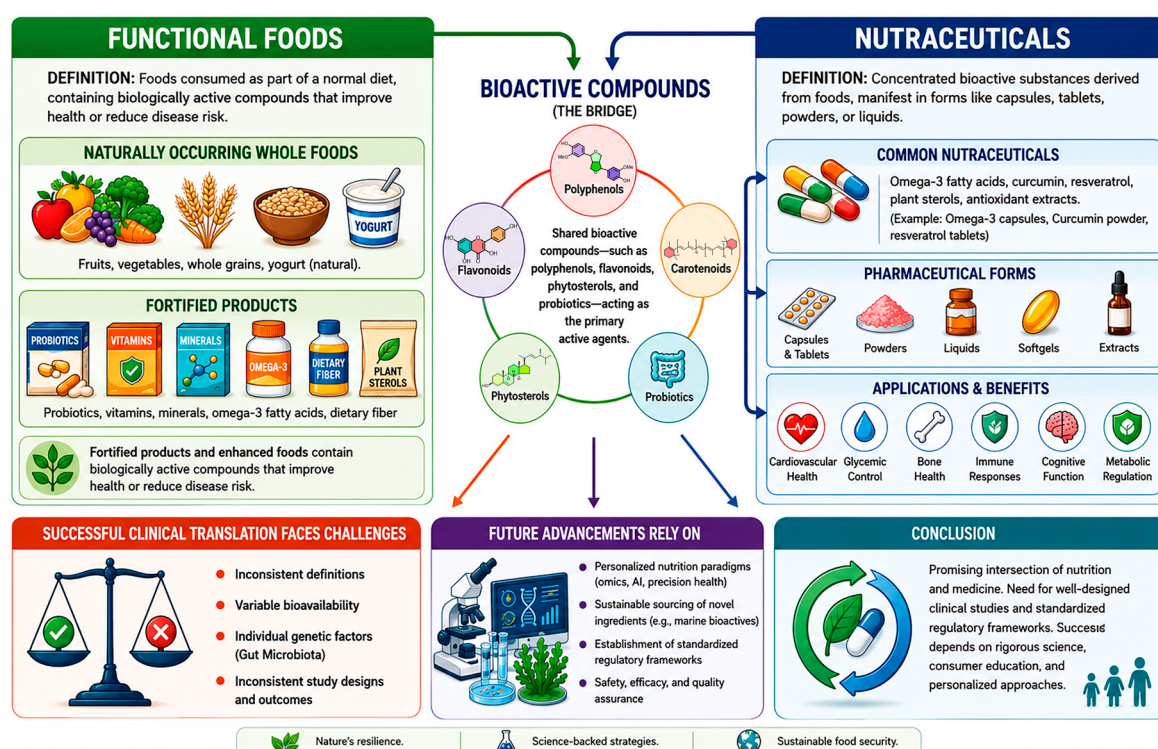


Figure 9. Conceptual framework differentiating functional foods and nutraceuticals, bridged by their shared reliance on bioactive compounds. Functional foods are conventionally consumed as part of a normal diet and contain biologically active compounds that improve health or reduce disease risk, encompassing both naturally occurring whole foods and fortified products. In contrast, nutraceuticals are concentrated bioactive substances extracted from foods and administered in pharmaceutical forms (e.g., capsules, powders) to modulate specific physiological pathways (Centre). The efficacy of both categories relies on shared bioactive compounds—such as polyphenols, flavonoids, and phytosterols—that act as primary active agents. (Bottom Panels) The successful clinical translation of these compounds faces challenges related to inconsistent definitions, variable bioavailability, and individual genetic factors. Future advancements rely on personalised nutrition paradigms, sustainable sourcing of novel ingredients (e.g., marine bioactives), and the establishment of standardised regulatory frameworks.

Brassicaceae vegetables such as broccoli, kale, and cabbage are already recognised as important dietary sources of health-promoting phytochemicals, while several edible halophytes are emerging as novel functional ingredients due to their nutritional value and

adaptation to sustainable agricultural systems. Extracts rich in phenolic compounds and glucosinolate derivatives are currently being investigated as nutraceutical formulations for healthy aging [46]. To maximise the efficacy of these formulations, extraction techniques must be carefully optimised; for instance, phytochemical studies have found that using a 70% ethanol solution is effective for extracting the maximum amount of hydroxycinnamic acids and flavonoids from the leaves of *Crambe koktebelica*.

The exceptional phytochemical composition of *C. maritima* makes it particularly suitable for functional food development. Glucosinolates and their isothiocyanate derivatives have been associated with chemoprotective effects, while phenolic acids, flavonoids, carotenoids, and dietary fibre contribute to antioxidant defence and cardiovascular health. Furthermore, extraction studies indicate that hydroalcoholic solvents, particularly 70% ethanol, efficiently recover hydroxycinnamic acids and flavonoids from *Crambe* leaves, providing a practical basis for developing standardised nutraceutical formulations. Nevertheless, the biological efficacy of these phytochemicals ultimately depends on their bioavailability, metabolism, and effective dosage, highlighting the need for additional human intervention studies. Despite promising evidence, the efficacy of functional foods and nutraceuticals depends on factors such as dosage, bioavailability, and individual physiological responses. Therefore, further clinical studies are needed to substantiate health claims and establish standardised recommendations [47].

In addition, commercialisation of sea kale as a functional food will require greater standardisation of raw material composition. Phytochemical profiles are strongly influenced by genotype, cultivation environment, harvest stage, and post-harvest handling, creating challenges for producing consistent functional ingredients. Developing quality standards will therefore be an essential step toward industrial applications.

6.3. Potential Uses in Pharmaceutical, Cosmetic, and Gourmet Markets

Beyond their nutritional value, bioactive compounds from halophytes and Brassicaceae species have attracted considerable commercial interest in the pharmaceutical, cosmetic, and gourmet sectors. The pharmaceutical and cosmetic potential of *Crambe* species is strongly linked to their diverse phytochemical composition. Besides glucosinolate-derived isothiocyanates, several species accumulate high concentrations of rutin, quercetin, kaempferol glycosides, hydroxycinnamic acids, and other flavonoids, compounds widely recognized for their antioxidant, anti-inflammatory, photoprotective, and anti-ageing activities. In addition, the high molybdenum reducing power recorded in *C. maritima* extracts demonstrates excellent electron-donating capacity, supporting their application as natural antioxidants in cosmetic and pharmaceutical formulations. These phytochemicals also enhance the commercial value of sea kale as a premium gourmet vegetable with added functional and health-promoting properties.

In the pharmaceutical industry, glucosinolate-derived isothiocyanates, polyphenols, and other phytochemicals are being explored as potential therapeutic agents. Species within the *Crambe* genus serve as valuable genetic reservoirs for these compounds; for example, the leaves of *Crambe tataria* contain significant amounts of phenolic compounds, with rutin identified as the most abundant component (reaching up to 654.38 mg kg⁻¹ using conventional extraction methods). Additionally, phytochemical profiling of *Crambe cordifolia* leaves confirms the presence of biologically active substances, including quercetin and glycosides of kaempferol. These compounds may contribute to the development of novel formulations targeting chronic diseases and age-related disorders, although challenges related to bioavailability remain [48].

In cosmetics, plant-derived extracts are increasingly incorporated into skincare products due to their protective effects against oxidative stress and skin aging. Polyphenol-rich

extracts are particularly valued for their photoprotective and anti-ageing properties [49]. The robust Molybdenum Reducing Power (MRP) observed in *Crambe* species—which reaches up to 129.12 mg TE g⁻¹ DW in *C. steveniana* and 120 mg TE g⁻¹ DW in *C. maritima* during fruiting [43]—underscores the potent electron-donating capacity of these extracts, making them ideal candidates for anti-ageing cosmetic formulations.

The gourmet food sector also represents a growing market. Several halophytes are appreciated for their distinctive salty flavour, texture, and culinary versatility, while Brassicaceae vegetables contribute characteristic sensory attributes and nutritional quality. Their use in premium foods aligns with consumer demand for innovative, sustainable, and health-oriented products [50], cementing the commercial potential of *Crambe* species as multifunctional sources of natural bioactive compounds.

7. Sustainability, Challenges, and Future Perspectives

7.1. Contribution to Saline and Climate-Resilient Agriculture

Climate change, escalating soil salinization, freshwater scarcity, and widespread land degradation are paramount threats to global agricultural productivity (Figure 10). In this critical context, halophytes have emerged as exceptionally promising crops for the development of climate-resilient agricultural systems, driven by their natural biological capacity to thrive under severe saline conditions where conventional glycophytic crops typically fail [51,52].

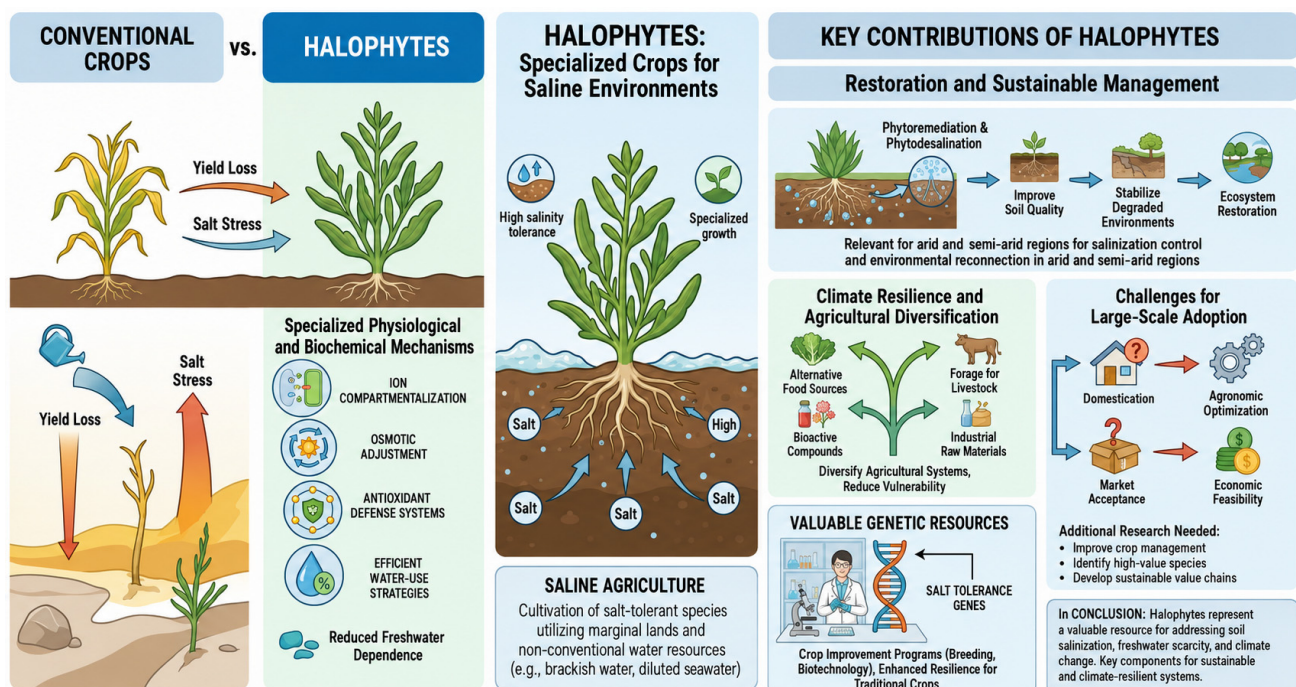


Figure 10. Role of halophytes in biosaline agriculture and climate resilience. The diagram contrasts conventional crops with halophytes, highlighting the physiological mechanisms that enable salt tolerance, including osmotic adjustment and ion compartmentalization, thereby reducing dependence on freshwater resources. It also illustrates their contributions to phytoremediation, agro-industrial diversification (food, feed, and bioactive compounds), and their value as genetic resources, while emphasizing the agronomic and economic challenges associated with their large-scale adoption.

Their diverse physiological adaptations—encompassing strict ion regulation, osmotic adjustment, and highly efficient water use—enable viable cultivation on marginal lands utilizing brackish water or diluted seawater. This directly mitigates the unsustainable pressure on rapidly depleting freshwater resources [52]. Beyond primary food production,

halophytes actively contribute to soil rehabilitation through vital phytoremediation and phytodesalinization processes, accelerating the restoration of degraded ecosystems and fundamentally improving the long-term sustainability of salt-affected landscapes [53].

Furthermore, halophytes diversify fragile agricultural systems by providing sustainable alternative sources of food, livestock feed, high-value bioactive compounds, and industrial raw materials. Crucially, they represent invaluable natural reservoirs of genetic traits associated with extreme salinity tolerance, which are anticipated to heavily support future crop improvement and introgression efforts [54]. Although large-scale commercial adoption remains limited, biosaline agriculture is increasingly recognized as an indispensable, complementary strategy for securing global food production under projected future climate scenarios [36].

7.2. Conservation, Domestication, and Breeding Challenges

Despite their undeniable agronomic potential, the vast majority of halophytes remain at an incipient stage of agricultural development. The rigorous conservation of their genetic resources is particularly urgent, as many of these species natively inhabit fragile coastal and inland saline ecosystems that are increasingly jeopardized by anthropogenic activities and climate change [55]. Protecting this specialized genetic diversity through highly coordinated in situ and ex situ conservation strategies is foundational for the success of future breeding programs [56].

A primary bottleneck remains domestication. Many prospective halophytes continue to exhibit restrictive wild characteristics—such as intense mechanical and chemical seed dormancy, irregular germination rates, asynchronous flowering, and variable biomass productivity—which severely limit scalable commercial cultivation and field mechanisation [57]. Targeted selective breeding is therefore strictly required to enhance baseline agronomic performance, ensure crop uniformity, and achieve market-ready suitability.

These necessary breeding efforts are substantially complicated by the inherently polygenic nature of salinity tolerance. Because multiple, distinct physiological pathways simultaneously contribute to stress adaptation, it is profoundly difficult to genetically improve stress tolerance while concurrently maintaining high agricultural productivity and product quality [5]. While recent advances in genomics, transcriptomics, marker-assisted selection, and gene editing provide powerful new mechanisms to accelerate crop improvement, comprehensive genomic resources remain severely limited for many wild species [23]. Ultimately, actively maintaining broad genetic diversity during the domestication bottleneck will be crucial to preserving the plants' adaptive capacity under continuously shifting environmental conditions.

Domestication of *C. maritima* should therefore be viewed as a multidisciplinary challenge rather than solely a breeding objective. Genetic improvement will need to proceed simultaneously with advances in seed technology, agronomic management, mechanised cultivation, and market development. Without coordinated progress across these areas, the transition from wild halophyte to commercially competitive crop is likely to remain slow.

7.3. Research Gaps and Future Opportunities for Commercialisation

Although scientific and commercial interest in halophytes has expanded substantially over the past decade, significant research and commercialisation gaps persist (Figure 11). A primary operational limitation is the acute lack of long-term, field-scale agronomic data. While extensive literature documents physiological responses under highly controlled greenhouse conditions, empirical information regarding long-term open-field productivity, scalable cultivation management, and realistic economic performance remains critically scarce [17].

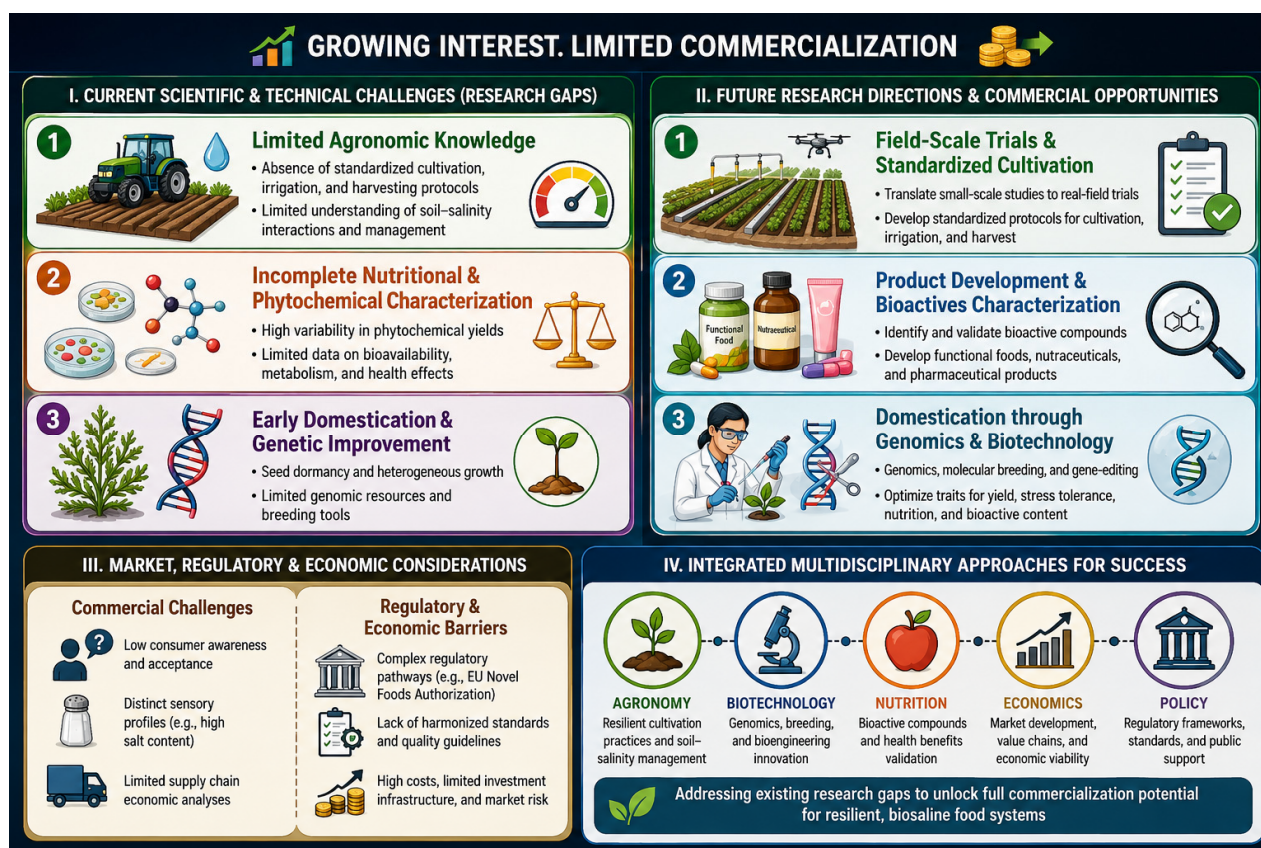


Figure 11. Research gaps and future commercialization pathways for halophyte-based agricultural systems. I. Current Scientific & Technical Challenges: Major research gaps include limited agronomic knowledge (e.g., an absence of standardized cultivation, irrigation, and harvesting protocols), incomplete nutritional characterization marked by high variability in phytochemical yields, and challenges associated with early domestication, such as seed dormancy, heterogeneous growth, and limited genomic resources. II. Future Research Directions: Overcoming these barriers requires translating small-scale experiments into standardised, field-scale trials. Furthermore, integrating advanced genomics, molecular breeding, and gene-editing will accelerate domestication, optimising traits for product development in the functional food, nutraceutical, and pharmaceutical sectors. III. Market and Regulatory Considerations: Economic viability is currently hindered by low consumer awareness, distinct sensory profiles (e.g., high salt content), a lack of detailed supply chain economic analyses, and complex regulatory hurdles (e.g., EU Novel Foods Authorisation). IV. Integrated Approach: Successful commercialisation demands a multidisciplinary framework that seamlessly integrates agronomy, biotechnology, nutrition, economics, and public policy to unlock the potential of resilient, biosaline food systems.

Despite the clear physiological and phytochemical advantages of *C. maritima* highlighted in this comparative analysis, its transition from a resilient coastal pioneer to a mainstream biosaline crop faces significant translational hurdles. As synthesised in Figure 11, the current reliance on small-scale and controlled-environment studies leaves critical gaps in our understanding of field-scale agronomic management and long-term yield stability under fluctuating environmental stress. Furthermore, while the baseline nutritional profile is promising, the high phenotypic variability in secondary metabolite accumulation—combined with the inherent challenges of early domestication such as profound seed dormancy and heterogeneous growth—necessitates targeted breeding and genomic interventions. Ultimately, unlocking the full commercial and pharmaceutical potential of *Crambe* spp. will require an integrated, multidisciplinary approach that not only resolves

these biological bottlenecks but also actively navigates the complex economic, sensory, and regulatory landscapes governing the introduction of novel functional foods.

Targeted research is also urgently required to more precisely characterise their nutritional composition, specific bioactive compound matrices, and subsequent bioavailability in human metabolic pathways. While halophytes are increasingly recognised as dense sources of essential minerals and phytochemicals, the explicit health benefits of many emergent species require rigorous validation through controlled clinical and nutritional trials [29,44].

Finally, broad commercialisation is constrained by currently limited consumer awareness, complex regulatory frameworks regarding novel foods, and underdeveloped agricultural supply chains. Sustained market acceptance will inevitably depend on optimising sensory characteristics, innovating product formulations, and executing the effective communication of both their nutritional density and environmental benefits to the consumer [58]. Furthermore, comprehensive techno-economic assessments evaluating exact production costs, profit margins, and specific market opportunities remain relatively scarce.

Although *C. maritima* has considerable potential as a high-value crop for biosaline agriculture, its commercial development remains at an early stage. Information on production costs, economic profitability, supply chain development, and market demand is still limited. In addition, challenges related to large-scale cultivation, seed availability, postharvest management, regulatory approval, and consumer acceptance must be addressed before widespread commercialisation can be achieved. Future studies should therefore integrate agronomic, economic, and market analyses to evaluate the commercial feasibility of this species under different production systems. Nevertheless, the future prospects for halophytic crops are highly promising. The unique biological ability of halophytes to exploit otherwise barren saline soils and non-conventional water resources aligns perfectly with urgent global initiatives to establish more resilient and sustainable agricultural systems. Their commercial applications extend far beyond fresh vegetables, successfully penetrating the functional food, nutraceutical, pharmaceutical, cosmetic, and animal feed markets, alongside their utility in ecosystem restoration [36]. Continued, deeply interdisciplinary research integrating advanced agronomy, biotechnology, human nutrition, economics, and agricultural policy will be absolutely essential to support their successful commercialisation and widespread global adoption.

Collectively, the available literature suggests that *C. maritima* possesses considerable potential as an emerging crop for saline agriculture; however, the evidence base remains uneven. Most published studies focus on physiological responses under controlled conditions, whereas long-term field trials, economic analyses, consumer acceptance studies, and life-cycle assessments remain scarce. Addressing these knowledge gaps should be considered a research priority to determine whether the species can move beyond niche cultivation toward broader commercial adoption.

Future research should also take advantage of emerging technologies to accelerate the domestication and sustainable cultivation of *C. maritima*. Integrating genomics, transcriptomics, metabolomics, and other omics approaches will improve our understanding of the molecular basis of salinity tolerance and other adaptive traits. In addition, genome-editing technologies such as CRISPR/Cas, molecular breeding, and microbiome-assisted cultivation offer promising opportunities to enhance stress resilience and productivity. The incorporation of precision agriculture tools for monitoring crop performance and optimizing resource use under saline conditions may further support the large-scale adoption of *C. maritima* in climate-resilient agricultural systems.

8. Conclusions

The escalating pressures of global climate change, freshwater depletion, and widespread soil salinisation necessitate a fundamental paradigm shift in modern agriculture. Edible halophytes, particularly *C. maritima* and related *Crambe* species, represent a highly promising frontier for developing sustainable, climate-resilient food systems. As demonstrated throughout this review, the physiological adaptation of sea kale to marginal coastal environments does not merely confer survival under extreme abiotic stress; it actively drives the biosynthesis of a highly valuable matrix of secondary metabolites. The rich accumulation of specific glucosinolates, flavonoids, phenolic acids, and essential minerals underpins the plant's robust antioxidant, antimicrobial, and anti-inflammatory properties, highlighting its considerable within the functional food, nutraceutical, and cosmetic industries.

However, the successful transition of *C. maritima* from a wild, underutilised botanical resource to a commercially viable horticultural crop faces significant translational hurdles. Primary among these are the domestication bottlenecks associated with robust seed dormancy, irregular crop uniformity, and the complex, polygenic nature of extreme salinity tolerance. Furthermore, there is a critical need to bridge the gap between physiological studies conducted in controlled environments and long-term, open-field agronomic and techno-economic assessments.

Ultimately, realising the full commercial and ecological potential of *Crambe* species will require a concerted, interdisciplinary approach. Integrating advanced selective breeding, optimised biosaline cultivation practices (such as the strategic use of saline eustress), and rigorous clinical validation of their health-promoting properties will be essential. By systematically addressing these challenges, *C. maritima* can be successfully integrated into future agricultural frameworks, offering a viable, high-value strategy for both global dietary diversification and the ecological restoration of salt-degraded landscapes.

Despite the growing body of research on *C. maritima*, important scientific challenges remain. Most available studies have been conducted under controlled conditions, whereas long-term field validation across diverse saline environments remains limited. In addition, the molecular mechanisms underlying salinity tolerance, genotype–environment interactions, and the role of the plant microbiome require further investigation. Future research should integrate physiological, omics-based, breeding, and agronomic approaches, together with economic assessments, to support the sustainable domestication and commercial adoption of *C. maritima* in biosaline agricultural systems.

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