

## Exploring the potential of *Salicornia*: A halophyte's impact on Agriculture, the Environment, and the Economy

Explorando el potencial de *Salicornia*: el impacto de una halófito en la agricultura, el medio ambiente y la economía

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### Abstract

*Salicornia*, a halophytic plant, garners attention for its environmental, energy, medicinal, and economic potential. It excels in environmental management through phytoremediation and carbon sequestration, thriving in saline environments to filter toxins and recycle nutrients. As a biofuel source, its oil-rich seeds and high biomass yield offer eco-friendly alternatives for biodiesel and bioethanol production, mitigating greenhouse gas emissions. *Salicornia*'s bioactive compounds exhibit significant potential in modulating the immune system and managing various diseases. Despite challenges such as production costs and regulatory barriers, *Salicornia* holds promise as a sustainable crop with diverse commercial applications. Scaling up *Salicornia* production and utilization requires addressing challenges related to cultivar development, production costs, and regulatory frameworks. However, with continued research and investment, *Salicornia* could emerge as a valuable resource for addressing food security, energy sustainability, and environmental restoration. Future research directions include exploring *Salicornia*'s nutritional composition, environmental sustainability, and epigenetic mechanisms, as well as optimizing extraction methods and intercropping systems. Understanding these aspects will contribute to unlocking *Salicornia*'s full potential as a versatile crop with wide-ranging benefits for human health, environmental conservation, and economic development.

**Keywords:** *Salicornia* applications; Halophytic plant; Environmental management; Biomass; Salinity; Food Plant; Salt tolerance

### Resumen

La *Salicornia*, una planta halófila, llama la atención por su potencial ambiental, energético, medicinal y económico. Sobresale en la gestión ambiental a través de la fitorremediación y el secuestro de carbono, prosperando en ambientes salinos para filtrar toxinas y reciclar nutrientes. Como fuente de biocombustible, sus semillas ricas en aceite y su alto rendimiento de biomasa ofrecen alternativas ecológicas para la producción de biodiesel y bioetanol, mitigando las emisiones de gases de efecto invernadero. Los compuestos bioactivos de *Salicornia* son prometedores en la inmunomodulación y el manejo de enfermedades. A pesar de desafíos como los costos de producción y las barreras regulatorias, la *Salicornia* es prometedora como cultivo

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sostenible con diversas aplicaciones comerciales. Para ampliar la producción y utilización de *Salicornia* es necesario abordar los desafíos relacionados con el desarrollo de cultivares, los costos de producción y los marcos regulatorios. Sin embargo, con investigación e inversión continuas, la *Salicornia* podría surgir como un recurso valioso para abordar la seguridad alimentaria, la sostenibilidad energética y la restauración ambiental. Las direcciones de investigación futuras incluyen la exploración de la composición nutricional, la sostenibilidad ambiental y los mecanismos epigenéticos de *Salicornia*, así como la optimización de los métodos de extracción y los sistemas de cultivos intercalados. Comprender estos aspectos contribuirá a desbloquear todo el potencial de la *Salicornia* como cultivo versátil con amplios beneficios para la salud humana, la conservación del medio ambiente y el desarrollo económico.

*Palabras clave:* Aplicaciones de *Salicornia*; Planta halófila; Gestión ambiental; Biomasa; Salinidad; Planta Alimenticia; Tolerancia a la sal.

## 1 Introduction

The name *Salicornia*, which means “salt” in Latin, is one of the most salt-tolerant plant species in the world since it is a halophyte and can survive 1000 mM or more of NaCl (Volkov, 2015; Lv et al., 2012). *Salicornia L.* is a genus of annual, halophytic plants in the family Chenopodiaceae with articulated, succulent stems that do not seem to have any leaves. The *Salicornia* genus, usually found in salty conditions, is the species of terrestrial plants most resistant to salt (Ventura & Sagi, 2013; Tóth et al., 2014). *Salicornia* plants have a simple morphology since they only generate spongy, apparently leafless branches (Kadereit et al., 2007). *Salicornia*'s main stem comprises small, clavate, or cylindrical internodes, each with a succulent, photosynthetic coating that gives the plant its articulated look. The terminal inflorescence has a spike-like appearance. *Salicornia* plants may live for over a year in subtropical conditions, although their life cycles are generally summer-annual (Davy et al., 2001).

Halophytes need salt exposure for optimal development and have evolved to endure extremely salinized conditions (Cárdenas-Pérez, et al., 2021; Grigore, et al., 2014; Singh et al.,

2014). Given the scarcity of freshwater resources for agriculture and the increasing soil salinity globally, there is a pressing need to develop novel crops capable of withstanding higher salt concentrations than current crop varieties (Yensen, 2006; Glenn et al., 1999; Ventura et al., 2011). Flowers & Colmer (2008) describe halophytes as plants that can reproduce and complete their life cycle at 200 mM or higher salinities, constituting around 1 % of all known plant species. Revaluing these marginal salt-affected areas, unsuited for traditional farming, requires utilizing these naturally salt-tolerant plants in agricultural applications (Holguin Pena et al., 2021). In their native environment, halophytes are found in salt deserts, marshes, and seashores (Hulkko et al., 2022). Halophyte plants, found close to beaches, have been used by humans for food, medicine, and their high salt content since the dawn of time (Ventura & Sagi, 2013; Lieth, 2000; Davy et al., 2001).

Halophytes serve as a source of secondary metabolites for medicines, as an antipathogenic agent, as a food additive, and as nutraceuticals, such as the flavonoid 3-O-D-glucopyranoside is employed in anti-obesity therapies (Kong & Seo, 2012; Loconsole et al., 2019; Patel, 2016; Cárdenas-Pérez et al., 2021). While underused in industrial and agricultural applications, halophytes offer much promise; one of the most critical halophyte genera in existence today is *Salicornia* (Cárdenas-Pérez et al., 2021). Although straw may be used as fodder, a soil conditioner, a solid fuel, or a cellulosic feedstock for liquid fuels, *Salicornia* seed oil can be utilized as a feedstock for biodiesel or hydro-processed fuels (Warshay et al., 2011). Seedcakes may be used as animal feed or as briquettes for solid fuel. Moreover, mangroves create byproducts like solid biomass for energy generation or leaves for nourishment (Bailis & Yu, 2012).

Before diversifying in the late Pliocene and early Pleistocene, *Salicornia* is thought to have derived from the perennial *Sarcocornia* in the Miocene (Kadereit et al., 2007). The species of this genus may survive in subarctic, subtropical, oceanic, and continental climates (Bashan et al., 2000). Even though *Salicornia* may flourish

in salty conditions, it has been hypothesized that extreme salinity may prohibit it from germination. Most coastal halophytes sprout in the spring when the salt level in the ground is reduced, as fresh water is more easily accessible and the temperature is favorable (Singh et al., 2014). The objective of this review paper is to provide an overview of the characteristics, potential applications, challenges, and future research directions of *Salicornia* as a halophyte plant with promising applications in agriculture and environmental management.

## 2 *Salicornia* in traditional and indigenous knowledge system

*Salicornia*, a resilient halophyte commonly found in coastal regions, has played a significant role in traditional and indigenous knowledge systems around the world. Its versatile properties have been harnessed by various cultures for centuries, showcasing its cultural, medicinal, and ecological importance. For instance, in the traditional knowledge system of the Guna people in Panama, *Salicornia* has been used as a natural dye for textiles and basket weaving (Friess et al., 2020). The vibrant green color of the plants enhances the aesthetic appeal of their crafts while also reflecting their profound understanding of local plant resources. Furthermore, *Salicornia* has been employed in traditional medicine systems for its potential health benefits. Research by Chrigui et al. (2023) highlights its use in traditional Indian medicine, where the plant is considered a valuable source of antioxidants and is utilized to treat conditions such as diabetes, inflammation, and liver disorders. The traditional knowledge of these medicinal properties has been passed down through generations and is still practiced today in many indigenous communities.

The sustainable harvesting and management practices associated with *Salicornia* in traditional knowledge systems contribute to the conservation of biodiversity and ecosystem resilience. Indigenous communities have developed intricate knowledge about the growth patterns, reproductive habits, and ecological relationships of *Salicornia*, ensuring the sustainable use of this valuable resource (Reyes-García et al., 2014).

This traditional knowledge system promotes a holistic approach to resource management, emphasizing the interconnectedness of humans and nature. Furthermore, *Salicornia* was also an important food source in the traditional diet of the Inuit communities in the Arctic region (Berkes, 2000). *Salicornia*'s nutritional value, rich in vitamins and minerals, made it a valuable food source for these indigenous communities (Ozturk et al., 2018).

The documentation and recognition of *Salicornia*'s role in indigenous knowledge systems are crucial for safeguarding cultural heritage and promoting sustainable development. Integrating traditional knowledge with modern scientific research can enhance our understanding of *Salicornia*'s potential applications and contribute to its conservation and sustainable utilization. Moreover, the cultural and ecological significance of *Salicornia* in traditional and indigenous knowledge systems is emphasized by Ozturk et al. (2018), who highlights the deep connection between local communities and the natural resources they depend on. This connection is not only essential for sustenance but also encompasses a broader understanding of the ecosystem and its dynamics. The traditional knowledge surrounding *Salicornia* not only reflects the accumulated wisdom of generations but also underscores the sustainable use and conservation of natural resources.

## 3 Agricultural application: Food crops, fodder, and soil improvement agents

The benefits of *Salicornia* as an edible crop have been shown by several research. However, Srivarathan et al. (2023) and Patel (2016) reported that few species of *Salicornia* plants contain high levels of salt, oxalate, and saponin, which are considered anti-nutrients, these substances can be eliminated to support the use of *Salicornia* as a 'sea vegetable'. The soft green tips of *Salicornia* have been cooked similarly to spinach without salt or as garnishes or elements in salads (Chaturvedi et al., 2021). *Salicornia* is a source of proteins, vitamins, minerals, polysaccharides, and bioactive substances (Lu et al., 2010). According to Guil

et al. (1997), there were significant quantities of ascorbic and dehydroascorbic acids (1 mg/g), as well as carotenoids (0.05 mg/g), whereas Kang et al. (2015) claimed that *Salicornia* growing in saltwater might have a high phenolic and flavonoid content. *Salicornia* is used more often in human diets due to its diversity of nutrients, placing it in the same superfood category as kale (*Brassica oleracea* var. sabellica) and quinoa (*Chenopodium quinoa*). The 30% edible oil in *Salicornia* seeds, with the remaining 70% being utilized as fodder, also makes them lucrative (Cárdenas-Pérez et al., 2021).

Only the delicate, green sections should be consumed since the salt and silica content of the reddish regions is too high. The shoots are used to make drinks like vinegar, makgeolli (a Korean rice wine), and nuruk in certain areas (Kim et al., 2013). According to research, *Salicornia* encourages the development of fermenting bacteria and improves the vinegar's quality (Seo et al., 2010). Several plants have also been recognized as good dietary salt sources for direct eating. *S. herbacea* powder may be processed into spherical granules that function similarly to NaCl (Shin & Lee, 2013). *Salicornia* salt (1.5 %) may be used to enhance the texture of frankfurters without having any discernible detrimental effects. The fortification positively benefits emulsion stability and cooking yield, respectively (Kim et al., 2014). Another unique investigation showed that the salt from *Salicornia bigelovii* prevented the hypertensive impact generally associated with NaCl. Zhang et al. (2015) found evidence of a liver and renal ameliorative impact connected to a drop in blood creatinine levels.

Further, certain *Salicornia* species might be utilized as feed for animals. In a research conducted in Arizona, USA, by Glenn et al. (1998), it was shown that consuming a diet rich in *S. bigelovii* had no influence on the quality of the meat and that sheep and goats given diets containing *S. bigelovii* acquired the same amount of weight as those fed diets including hay. As a superior alternative to conventional seed meals as a protein supplement in cow diets, they also found that *S. bigelovii* seed meal was used (Glenn et al., 1998). According to research on

*Salicornia* farming in Kuwait, the lamb 12.5 D44 exhibits the maximum growth rate of *Salicornia* on conventional alfalfa diets (Abdal, 2009).

The world's salinity regions are expanding due to fast climate change; thus, producing crops with high salt tolerance today is crucial to deal with the challenging scenario (Hasanuzzaman et al., 2014). The microbial populations in the soil and their enzymatic activity are negatively impacted by the buildup of salt in the soil (Luo et al., 2018). According to specific research, cultivating salt-loving plants may enhance the soil's physical qualities, reducing the number of salt ions that build up in the soil. Deep-rooted, salt-tolerant plants may function as tillage tools. This practice, known as "biological drilling," has stabilized soil structure by lowering soil mass density and increasing soil porosity and hydraulic characteristics. It also increases Na<sup>+</sup> leaching and replaces soil, which results in greater nutrient use efficiency (Silva et al., 2016). According to studies, growing halophytes in salty soils enhances the soil's physical and chemical characteristics, reduces crop stress, and has a significant potential to repair damaged land (Lei et al., 2018). Also, it enhances the soil's ecological and aesthetic qualities to make tourist destinations more appealing (Stanley, 2008).

#### **4 Environmental management application: Phytoremediation, coastal protection, and carbon sequestration**

An alternative approach to reducing atmospheric CO<sub>2</sub> involves increasing the productivity of desert region. Scientists have been examining the viability of cultivating native, salt-tolerant plants in arid regions to trap carbon. Intense halophyte production may worldwide absorb between 0.6 Gt and 1.2 Gt of carbon per year, according to research by Glenn et al. (2013). They only make up 7 % of the earth's surface, yet they effectively absorb atmospheric carbon via plants that thrive in salty environments. Recent decades have seen a significant increase in the importance of groundwater overexploitation concerns, particularly in comparable dry and semi-arid countries where coastal aquifers are particularly endangered by saltwater intrusion



(Alfarrah & Walraevens, 2018). Certain wild halophyte plants are utilized periodically for human and animal grazing as an alternative to coastal development when freshwater is limited (Glenn et al., 2013); the optimum use of soil and water results from developing and adopting novel seawater-irrigated crops. *Salicornia* may be seen as a new crop if handled responsibly on land and paired adequately with a workable saltwater supply (Garza-Torres et al., 2020).

*Salicornia* is significant because it can grow and reproduce in habitats with high salt levels and because of the oil in its seeds and the potential biomass it provides for the manufacture of bioethanol. It may be used as a biofilter to recycle the water and nutrients contained in marine aquaculture effluents and as a phytoremediator of salty soils polluted with heavy metals because of these characteristics. Ecologists claim that the plant is an essential part of the tidal zone because it acts as a buffer, reduces coastal erosion, and filters toxins out of the soil. For example, *S. bigelovii* has been effectively used to extract selenium from polluted water and soil.

Further, aquaculture effluents that have not been filtered are rich in nutrients and organic debris that may be eutrophic (also known as hypertrophic action) and harm neighboring ecosystems. The unpredictability of control variables like pH, temperature, and dissolved oxygen level in open ponds makes estimating a reliable recovery of fish from these systems more complex. Due to the expense of maintaining habitats that are appropriate for the discharge of effluents while still receiving clean, fresh water, recirculatory aquaculture systems (RAS) are growing in popularity (Martins et al., 2010). RAS seems to provide a feasible alternative to present fish culture techniques.

The ability of plants to thrive and procreate in salt-based environments makes them suitable candidates for biofilters to recycle water and other nutrients found in effluents from marine aquaculture and phytoremediators of saline soils contaminated with excessive metals (Cárdenas-Pérez et al., 2021). According to ecologists, this plant is a significant intertidal intercrop that serves as a buffer zone, prevents erosion along

the shore, and filters dangerous contaminants from the soil. *S. bigelovii*, for instance, has been successfully utilized to extract selenium from polluted water and soil (Lin et al., 2000). Reducing eutrophication and causing toxic algal blooms also aids in limiting the development of marine diatoms. Due to its salt tolerance and heavy metal toxicity, *Salicornia* has received interest as a plant treatment agent due to its capacity to thrive and reproduce, especially in settings rich in salt (Cárdenas-Pérez et al., 2021).

## 5 Fuel and energy application

Producing biofuels using halophytes could be a viable solution for generating eco-friendly and economically feasible bioenergy. Being the first halophyte species to be developed for agriculture, *Salicornia* species have been grown and harvested on test plots and farms in several nations, including the USA, Mexico, Egypt, the United Arab Emirates, Kuwait, and Saudi Arabia (Holguin Peña et al., 2021). *Salicornia* is edible when it is in its early stages. However, as it matures, it loses its moisture content. Its seed oil and dried biomass have been acknowledged as valuable sources of producing for biofuel production (Chaturvedi et al., 2021).

*Salicornia* considered a 'famine food,' shows great potential for energy plant products that can be used in bioethanol manufacturing for alternative transportation fuel (Cárdenas-Pérez et al., 2021). *Salicornia* seed oil is similar to currently used oils for transesterification, making it a viable option for conversion into biodiesel (Holguin Peña et al., 2021). The phase behavior of *Salicornia* oil at low temperatures is favorable, making it well-suited for use in biofuel formulations (ShenavaeiZare et al., 2021). The substantial content of essential polyunsaturated fatty acids, specifically linoleic and linolenic acid, make *Salicornia* a valuable source of biomass for advanced fuel production. The ability to produce ethanol from plant biomass is determined by the number of carbohydrate polymers (cellulose, hemicellulose) and aromatic polymer lignin present in fast-growing plant species like *Salicornia* (Munir et al., 2020). Bañuelos et al. (2018) successfully used

*Salicornia bigelovii* for bioethanol production. The biomass composition was comparable to traditional lignocellulosic biomasses, with a cellulose content of approximately 46.22 %  $\pm$  1.20 %, hemicellulose content of 14.93 %  $\pm$  0.37 %, and a low lignin content of 1.96 %  $\pm$  0.21 %.

The choice of halophytic species, cultivation methods, ripening stage of the plant, and environmental conditions affect the chemical composition of the biomass, such as its protein, lipid, and carbohydrate content required for good quality biofuel production. Culturing *S. europaea* at a concentration of 20 g/L NaCl in hydroponic systems resulted in the highest methane yield of 248 mL/gVS. Similarly, cultivating *S. ramosissima* using seawater irrigation in a greenhouse setting yielded methane up to 300 mL/gVS (Cayenne et al., 2022). *Salicornia sinus-persica* has a biomethane production potential of 22.12 ml/g Volatile Solid using seawater as media and anaerobic sludge as inoculum (Javid et al., 2016). *S. bigelovii* seeds have a protein content of 31 % and an oil content of about 28 %, making it a promising raw material for biofuel manufacturing with a production potential of up to 230 gallons of biodiesel per hectare cultivated. Highly productive species of *Salicornia* can produce between 13 to 25 tons of dry matter per hectare when irrigated with seawater.

Moreover, during the 200-day growing period, it can produce an average of 2 tons of seeds per hectare, comparable to conventional Soybean crop beans. This lignocellulosic biomass is converted into biofuel through enzymatic hydrolysis and microbial fermentation (Holguin Peña et al., 2021). According to Munir et al. (2020), genetic manipulation techniques are employed in these halophytes by either increasing their lipids content or improving the quality of their oil (Munir et al., 2020). For biodiesel synthesis, fatty acid methyl esters (FAMES) with a higher CN (cetane number) value are preferred. For example, *S. brachiata* has a seed oil content of approximately 22 %, with a saponification number of 129.89, iodine number of 29.7, and cetane number of 81.67. Similarly, *S. bigelovii* has a seed oil content of around 30 %, with a saponification number of 200.86, iodine number of 154.32, and cetane number of 38.78 (Sharma

et al., 2017). *Salicornia fruticosa* contains 26 % seed oil with suitable engine performance (SN 204.38, IV 93.6, and CN 51.96) (Abideen et al., 2015).

*S. brachiata* and *S. bigelovii* were used in the study by Folayan et al. (2019) to produce biodiesel, with the biodiesel derived from *S. brachiata* having superior fuel properties as a result of its higher cetane number, lower iodine values, and higher calorific value in comparison to that obtained from *S. bigelovii*. Due to its characteristics, using *Salicornia* seed oil directly as a substitute fuel in diesel engines can result in engine failures. Alkaline hydrolysis, hydrogenation, pyrolysis or cracking, micro-emulsification, mixing, fractionation, and transesterification are a few of the physical or chemical processes required to transform plant oils into biodiesel. In addition to being non-toxic, biodegradable, renewable, and not contributing to the net buildup of greenhouse gases, biodiesel fuel has many other advantages (Folayan et al., 2019).

An economic comparison between the energy return on investment (EROI) of bioethanol production utilizing Agave and *Salicornia* plants in the Emirate of Abu Dhabi was made in research by Belasari et al. (2015), as compared to agave, which had an EROI value of just 0.14, the *Salicornia* -based bioethanol process had a substantially better EROI value of 2.4. While *Salicornia* yielded 935 L.ha<sup>-1</sup> compared to Agave's 6750 L.ha<sup>-1</sup>, the findings indicate that *Salicornia* is the most advantageous alternative for producing bioethanol in the area. *Salicornia* -based biofuels are currently being developed and are not utilized extensively in commerce. *Salicornia* biofuel has a wide range of possible uses, although the most current study is concentrated on its usage as aviation fuel (Laveille et al., 2022). On January 16, 2019, Etihad Airlines launched the first commercial flight using aviation biofuels derived from *Salicornia* seed oil. Using petroleum-based fuels, *Salicornia* biofuel may be mixed to reduce greenhouse gas emissions and boost fuel economy (Joshi et al., 2020). Also, it is believed that using *Salicornia* species biomass to generate biogas is essential for maintaining the environment and using it as a

cheap source of energy (Turcios & Papenbrock, 2014).

## 6 Medicinal and nutraceutical application

*Salicornia* plants are rich sources of carbohydrates, proteins, lipids, phenolic compounds, flavonoids, sterols, saponins, alkaloids, and tannins. Component profiling, indexing, and water and alcohol extraction techniques have led to the identification of several bioactive substances in this plant. *S. herbacea* has been shown to contain dietary fibers, bioactive polysaccharides, proteins, lipids, sterols, flavonoids, and minerals like magnesium, calcium, iron, and potassium (Essaidi et al., 2013). Immunomodulatory polysaccharides have been identified in *S. herbacea* plants (Im et al., 2006). Further, Gas chromatography-mass spectrometry profiling of *S. ramosissima* has revealed the presence of esterified and free fatty acids, fatty alcohol, sterols, alkanes, and derivatives of aromatic acids. Aqueous and methanol extracts of *S. herbacea* enzyme-treated plants have been found to possess antioxidant properties that inhibit microsomal lipid peroxidation in the liver of rats.

The active component of the extract, isorhamnetin 3-O-D-glucopyranoside, affects the cytokine profile, interfering with inflammatory pathways (Kim et al., 2009). Several studies have investigated the potential anticancer properties of polysaccharides obtained from botanical sources, including *Salicornia*. Both natural and purified polysaccharides from *S. herbacea* have demonstrated anti-proliferative effects on human colon cancer HT-29 cells. The mechanism of action involves cell cycle arrest in the G2/M phase, followed by apoptosis (Ryu et al., 2009).

The methanol extract of *S. herbacea* has been found to interfere with cytochrome P450 CYP1A2, CYP3A4, and CYP2D6 enzymes to produce antibacterial effects. Antibacterial gold nanoparticles have also been generated from *Salicornia* plants (Essaidi et al., 2013). The rising levels of pollution and consumption of processed calorie-dense foods have contributed to the pandemic of diabetes. *Salicornia herbacea* powder has been found to improve the expression

of liver and muscle glucose transporters GLUT-4 and GLUT-2, as well as increase glycogen levels in the liver and muscle, making it a potential therapy for diabetes. *S. herbacea* polysaccharides have been found to activate nuclear factor-kappaB/Rel to induce nitric oxide generation from mice peritoneal macrophages and mouse leukemic monocyte macrophage RAW 264.7.

Another study found that *S. herbacea* polysaccharides affect the activation of monocytes and their conversion to macrophages. *Salicornia* is a halophytic plant that has been found to possess antibacterial properties. The potentially fatal condition of sepsis is caused by the breach of the membrane barrier (Li et al., 2009). When inflammatory tissue damage makes the membrane porous, the nuclear protein High Mobility Group Box One (HMGB1) is produced in excess by active. Inhibition of HMGB1 has been suggested as a potential therapeutic strategy for sepsis. Caffeoylated quinic acids from *S. herbacea* have been found to be effective HMGB1 inhibitors, thus helping to preserve the vasculature. Overall, the diverse range of bioactive compounds found in *Salicornia* plants highlight their potential as a source of natural remedies and functional foods.

## 7 Economic viability and market potential of *Salicornia*

*Salicornia* has gained attention for its diverse applications in agriculture, environmental management, fuel production, and medicinal uses. In recent years, there has been growing interest in exploring the economic viability and market potential of *Salicornia*-based products (Parida et al., 2019). The economic aspects of *Salicornia* include its cultivation, processing, and commercialization, and also include economic factors such as production costs, market demand, consumer acceptance, and regulatory considerations.

### 7.1 Economic considerations:

*Salicornia's* ability to thrive in saline environments offers a distinct advantage by reducing freshwater consumption and cutting

irrigation costs compared to conventional crops. However, initial investments in infrastructure and cultivation techniques, including the development of saltwater irrigation systems and optimized farming practices, may be necessary (Bailis & Yu, 2012). Al-Yamani et al. (2013) highlight the importance of site selection in agricultural productivity, influencing harvest yield, sustainability, and production costs. The yield potential of *Salicornia* varies based on factors such as cultivar, growing conditions, and cultivation practices. It's essential to conduct research and optimize cultivation techniques, such as nutrient management and crop spacing, to maximize yields. Additionally, the development of efficient harvesting methods is crucial for ensuring cost-effective and mechanized processes (Brown, 2019).

In Kuwait, Abdal et al. (2009) found that *Salicornia* produced biomass yields comparable to those achieved in Mexico. Furthermore, Ventura & Sagi (2013) reported that the harvest period of *Sarcocornia* could be extended to 17 rounds spread over more than two years, resulting in significant fresh biomass yields. Additionally, Chaturvedi et al. (2021) noted that using *Saccharomyces cerevisiae* in the simultaneous saccharification and fermentation of *S. bigelovii* led to a remarkable improvement in ethanol yield, reaching up to 98%. *Salicornia* can be processed into various value-added products, including oils, extracts, fibers, and bioactive compounds. To ensure economic viability, it's crucial to develop efficient and scalable processing methods. This involves implementing cost-effective extraction techniques, preservation methods, and quality control measures to maintain product integrity and maximize market value (Chaturvedi et al., 2021).

Moreover, analyzing the market and keeping track of price trends is crucial for evaluating the profitability of *Salicornia* ventures. Various factors such as competition, product quality, and availability can impact market prices, so stakeholders must assess potential risks and returns (Bailis & Yu, 2012; Parida et al., 2019). Cardenas-Perez et al. (2021) presented an intriguing application of using *S. brachiata* to produce cost-effective antibacterial nanoparticles

for the food and pharmacy sectors. Developing a robust value chain is vital for maximizing *Salicornia*'s economic potential. This involves integrating different stakeholders, including farmers, processors, distributors, and retailers, to ensure a seamless and efficient flow of *Salicornia*-based products. Collaboration and coordination among participants in the value chain can result in cost reductions, expanded market access, and improved product quality (Lyra et al., 2021).

Challenges addressed during value chain development, as highlighted by Lyra et al. (2021) and Ten Dam et al. (2023), include issues such as harvesting *Salicornia* fresh tips, implementing quality control and sanitization processes, managing weeds in *Salicornia* plantations, and addressing the lack of public awareness. Establishing *Salicornia*-based enterprises can contribute significantly to local economic development by providing income opportunities and curbing rural-urban migration. Training and capacity-building programs are essential for enhancing the skills of local communities and enabling their participation in the *Salicornia* value chain (Bailis & Yu, 2012).

## 7.2 Market potential:

The growing emphasis on sustainability, health awareness, and the preference for natural products presents opportunities for *Salicornia* across various industries, including food, pharmaceuticals, cosmetics, and functional foods. To capitalize on these opportunities, it's crucial to engage in consumer education and implement effective marketing strategies to stimulate demand and foster product acceptance (Lyra et al., 2021). Further, *Salicornia*-derived products can either complement existing consumer goods or be developed as standalone offerings. For instance, *Salicornia* oils can be used in culinary applications, *Salicornia* extracts find utility in nutraceuticals, while *Salicornia* fibers cater to the textile and material industries (Joshi et al., 2020).

The establishment of efficient supply chains and distribution networks is imperative for achieving commercial success. Collaborative



partnerships with farmers, processors, distributors, and retailers are necessary to ensure a seamless flow of *Salicornia*-based products from farm to market. Addressing logistical hurdles, maintaining product quality consistency, and adhering to regulatory standards are pivotal for accessing markets (Laveille et al., 2022). Supportive policies, incentives, and research grants can play a significant role in facilitating market expansion. Moreover, considerations regarding labeling, safety regulations, and quality standards are essential for building consumer confidence and ensuring alignment with market requirements (Fedoroff et al., 2010).

*Salicornia*-derived products hold promise as potential export commodities, opening avenues for international markets. Conducting thorough export market analysis, adhering to trade agreements, and ensuring compliance with international standards and regulations are pivotal steps for accessing and capitalizing on export opportunities (Joshi et al., 2020). For instance, Ein Mor Crops Ltd, an Israeli company, exports over 150 tons of *Salicornia* annually to Europe through various export channels (Gunning, 2016). Furthermore, continued investment in research and development is imperative for unlocking the full market potential of *Salicornia*. Innovations in cultivation techniques, processing methods, and product development can lead to the creation of novel *Salicornia*-based products that align with evolving consumer preferences. Collaborative efforts among researchers, industry stakeholders, and government agencies can drive innovation and foster market expansion (Robertson et al., 2019).

The environmentally friendly attributes of *Salicornia*-based products can contribute to a positive brand image, appealing to environmentally conscious consumers. Emphasizing the sustainability aspects of *Salicornia* can bolster market acceptance and attract environmentally responsible consumers and businesses (Custódio et al., 2021). In light of climate change impacts on traditional agricultural systems, *Salicornia* cultivation offers an alternative and resilient solution. This adaptability can be highlighted as a market advantage, particularly in regions grappling

with water scarcity and land degradation issues (Grigore & Vicente, 2023).

## 8 Opportunities and Challenges for scaling up *Salicornia* production and utilization

*Salicornia* has gained attention as a potential crop for biofuel, food, and feed production due to its high salt tolerance and oil content (Ahmadzai et al., 2021; Waller et al., 2015). However, scaling up *Salicornia* production and utilization poses both opportunities and challenges. One opportunity for scaling up *Salicornia* production is its potential as a sustainable biofuel feedstock. *Salicornia* has a high oil content, and the oil can be converted into biodiesel (Patel, 2016; Sharma et al., 2016). Additionally, *Salicornia* can be grown on marginal land that is unsuitable for other crops, which can reduce pressure on arable land and contribute to food security (Parida et al., 2019; Yadav et al., 2019). Another opportunity is *Salicornia*'s potential as a food and feed source. *Salicornia* is rich in protein, vitamins, and minerals and can be consumed as a vegetable or used as an ingredient in animal feed (Parida et al., 2019). *Salicornia* has been traditionally consumed in some parts of the world, such as Spain and Mexico, and is gaining popularity in other regions (Turcios et al., 2021; Sharma et al., 2016). However, scaling up *Salicornia* production also presents challenges.

One challenge is the need for improved *Salicornia* cultivars. Currently, there is a limited range of *Salicornia* cultivars available, and they may not be optimized for different regions or uses (Patel, 2016). Developing new cultivars with higher yields, better oil quality, and improved salt tolerance could increase the economic viability of *Salicornia* production (Holguin Pena et al., 2021). Another challenge is the high cost of *Salicornia* production. *Salicornia* requires irrigation with seawater or brackish water, which can be expensive due to the high energy and infrastructure costs associated with desalination (Al-Rashed et al., 2016). Additionally, *Salicornia* cultivation requires significant inputs of fertilizer and water, which can further increase production costs (Yozzo et al., 2000). Finally, there are regulatory and policy challenges that could

limit the scale-up of *Salicornia* production. Regulations on biofuel production and land use could impact the economic viability of *Salicornia* as a biofuel feedstock (Song & Wang, 2015).

The policies that support research and development of *Salicornia* cultivars and production methods could help overcome some of these challenges and facilitate the scaling up of *Salicornia* production (Abideen et al., 2015; Holguin Pena et al., 2021). Conclusively, *Salicornia* presents opportunities for sustainable biofuel production and food and feed sources, but scaling up its production and utilization requires addressing challenges such as cultivar improvement, high production costs, and regulatory and policy barriers.

While *Salicornia* has several benefits that are already widely recognized, it has yet to be utilized (Cárdenas-Pérez et al., 2021). This halophyte can utilize saltwater or aquaculture effluents in its development, significantly lowering the quantity of freshwater needed by agriculture (Hamed et al., 2021). Garza-Torres et al. (2020) claim that there are problems with how the soil and agroecosystem interact, which are holding up the implementation of this method. For instance, *Salicornia*'s lengthy life cycle (8–9 months) may result in higher handling and watering expenses, as well as management issues at different sizes and a decrease in the plant's acceptance as a popular food source (Lyra et al., 2021). Investors in this halophyte should consider its future applications and growing advantages, which exceed any potential disadvantages (Cárdenas-Pérez et al., 2021).

To fulfill the requirement for water required to grow this plant, saltwater or the same amount of energy used to run aquaculture ponds, which offer a considerable low-cost advantage, may be employed (Lyra et al., 2019). *Salicornia*, therefore, shows promise as a worthwhile substitute crop that may be utilized to create a meal with a high level of economic and gastronomic value while being produced responsibly (Ventura & Sagi, 2013). Various other benefits raise the likelihood that this crop will be used. Examples include its use in the environmental restoration of contaminated areas and endangered mangroves

and its function in enhancing aquaculture water effluents (Duarte & Cacador et al., 2021; Turcios & Papenbrock, 2014).

Moreover, *Salicornia* should be developed as a crop in the future that can be cultivated on unorthodox agricultural grounds (Ventura & Sagi, 2013). In this plant, several areas have reported various levels of cultivation success (Sardo, 2005). Covered *Salicornia* species like *S. bigelovii* are raised on farms for commercial use, particularly for producing salt, oil, biodiesel, and animal feed (Ismail et al., 2019). *Salicornia* also offers an essential supply of vegetable oil and agricultural support items like fodder and meal, making it a potential crop in Saudi Arabia's desert areas (Kumar et al., 2018). Saudi Arabia now imports vegetable oil worth over \$1 billion (Alfheaid et al., 2022). Singh et al. (2014) found that yields differed with cultivar, as shown by *S. dolichostachya*'s lower harvestable biomass yield than *S. ramosissima*.

Numerous *Salicornia* growing companies in Mexico have succeeded in their undertakings, as is the case with "Saline Seed Company," which earns a significant amount of its income from selling premium goods created from *Salicornia* employing saltwater. One of their key objectives is to advertise the plant as a gourmet food in gastronomy and to use it as a garnish or salad ingredient in its fresh and dried form. They also seek to develop sustainable enterprises by preserving natural harmony with nature. The main products of this company are fresh *Salicornia* stems, premium gourmet-grade *Salicornia* stems, *Salicornia* powder used as a mineral supplement, and salt shaker powder used as a substitute for regular salt for people with high blood pressure and fatty liver disease because it reduces sodium intake (Singh et al. 2014; Kudo & Fujiyama, 2010).

## 9 Future research directions

There has been an increased interest in *Salicornia* as a potential food source due to a recent scarcity of food (Cárdenas-Pérez et al., 2021). Several pieces of evidence attest to its beneficial effects on health (Gouda & Elsebaie et al., 2016). A potential

avenue for future research is to comprehensively assess the environmental sustainability and economic feasibility of large-scale *Salicornia* cultivation and harvesting for food production (Laveille et al., 2022). Additionally, determining its viability as a commercial crop by exploring the nutritional composition of different *Salicornia* species and ecotypes grown under varying environmental conditions could aid in identifying the most suitable strains for human consumption (Loconsole et al., 2019). Furthermore, investigating the potential of *Salicornia* to thrive in other saline environments, including salt-affected agricultural lands, and its potential role in mitigating soil salinity and improving soil health could provide valuable insights into the broader environmental benefits of *Salicornia* cultivation (Liang et al., 2017).

The cost of extracting oil from *Salicornia* is a significant factor that affects the commercial viability of *Salicornia*-based biofuels (Joshi et al., 2020). Ultrasound-assisted and supercritical fluid extraction are promising methods for extracting oil from *Salicornia* more efficiently (Cristina et al., 2018). Investigating more efficient extraction methods for increasing oil yield per biomass unit is essential to developing a sustainable and renewable energy source. *Salicornia* genus presents a challenge for taxonomic classification due to its adaptability and tolerance to a range of environmental conditions, limited distinguishing traits, and a tendency towards inbreeding (Jefferies & Gottlieb, 1982). Chaturvedi et al. (2021) suggested that *Salicornia europaea* and *Salicornia ramosissima* are reproductively isolated and show limited genetic variability, potentially due to factors such as inbreeding or genetic drift of the two species.

Future research on the investigation of the epigenetic mechanisms underlying phenotypic plasticity in *Salicornia*, such as DNA methylation and histone modifications, and how they interact with environmental cues to modulate gene expression and morphological traits are needed (Wafa'a, 2010). Studies have shown that intercropping *Salicornia* with salt-sensitive crops has multiple benefits for agriculture, including increased crop yield, improved soil quality, and economic advantages (Castagna et al., 2022). Additional research is necessary

to understand the underlying mechanisms governing the interactions between crops in intercropping systems and to optimize the design of such systems for diverse agricultural contexts (Barreto et al., 2020).

The evaluation of scaling up and implementing *Salicornia*-based biofiltration and phytoremediation systems in various regions and contexts has the potential to be a remarkable achievement for wastewater treatment plants, aquaculture systems, and industrial processes, not only contributing to the development of sustainable and resilient ecosystems but also creating opportunities for the establishment of new industries and job creation (Chaturvedi et al., 2021). Studying the potentiality of *Salicornia* to improve overall health and quality of life in managing metabolic conditions like diabetes, obesity, and cardiovascular disease, which involves identifying and characterizing specific bioactive compounds present in the plant, as well as evaluating their bioavailability and pharmacokinetics through in vivo studies, is an essential step in research that can provide insight into the mechanisms of action, optimal dosages, and administration methods for developing effective treatments (Mishra et al., 2015).

## 10 Conclusion

In conclusion, *Salicornia* stands out as a multifaceted plant with immense potential across various fields, including environmental management, energy production, medicine, and agriculture. Its remarkable ability to thrive in saline environments makes it a valuable asset for mitigating climate change, reducing dependence on fossil fuels, and promoting human health. Despite the challenges associated with scaling up its production and utilization, *Salicornia* presents promising opportunities for sustainable development and economic growth. Through collaborative efforts in research, technology development, and policy support, the barriers hindering its widespread adoption can be overcome. As we look towards the future, continued exploration of *Salicornia*'s properties, cultivation techniques, and market applications will be essential. By harnessing its full potential, we can pave the way for a greener, healthier, and

more resilient future for both humanity and the planet.

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### Conflict of Interest

The authors declare no conflict of interest regarding the publication of this manuscript.

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