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SALICORNIA AS A SALT-TOLERANT CROP: POTENTIAL FOR ADDRESSING CLIMATE CHANGE CHALLENGES AND SUSTAINABLE AGRICULTURE DEVELOPMENT

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ABSTRACT

Halophyte plant Salicornia has potential uses in farming and environmental management. Salicornia is one of the most important families of halophytes and known for its exceptional salt tolerance. It thrives well in saline habitats near coastal areas. A comprehensive review paper provides an overview of Salicornia, including details on the impact of temperature and salinity on the germination of different ecotypes, as well as the influence of day length and salinity on seedling establishment. *Salicornia* L. presents a promising opportunity for sustainable agriculture and economic development as it may improve the lives and livelihoods of underprivileged groups while also benefiting the environment through carbon sequestration, soil preservation, and biodiversity preservation.

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1. Introduction

Salicornia is a type of perennial herbaceous halophyte that belongs to amaranthaceae, that also comprises over 175 genera and 2000 species of herbs, shrubs, sub-shrubs, and small trees (Mroczek, 2015). Cárdenas-Pérez et al. (2021) have identified 64 species of *Salicornia*, with the most common being *S. brachiata, S. arabica, S. europaea, S. fruticosa L., S. ramosissima, S. herbacea*, and *S. bigelvolii*. The word "*Salicornia*" is inspired by the Latin words "sal" meaning "salt" and "cornu" meaning "a horn" due to being a saline vegetation with spiked tendrils (Ekanayake et al., 2023). Singh et al. (2014) state that *Salicornia* typically develops to a length of 25 to 35 cm and has moist, flexible scaly foliage and horn-like terminal plantlets. Salicornia reproduces naturally through seeds, but excessive saline conditions can impede seed germination since osmotic pressure has impacts on sprouting (Song et al., 2008). Rathore et al. (2019) divide the lifecycle of Salicornia into six phases: seed dissemination, root initiation, juvenile stage, exponential vegetative phase, blooming, and ripening stage, and aging phase. In autumn, the green plants become orange, pink, or crimson before decaying in the winter (Patel, 2016). Salicornia is predominantly reported in salt marshlands, ponds, or waterways that are favorable to its proliferation (Khan et al., 2014). As a halophyte, Salicornia could indeed endure a significant level of as high as 1000 mm NaCl or perhaps more (Volkov, 2015). Wang et al. (2009) suggest that Salicornia's saline adaptation technique has been reliant on restricting vesicles to ensure stable intracellular turgidity and diminishing the lethality of Sodium ions in the cytoskeleton. The above-mentioned trait assists the plants in colonizing down the tidal gradient, which is crucial to the preservation of genera zones in salt marshlands, indicating that Salicornia is suitable globally for the restoration of salinized ecosystems in dry and semi-arid regions (Ozturk et al., 2018). Mohammadi and Kardan (2015) explain that Salicornia has several adaptive responses which preserve it in higher salinity ecosystems, including constrained osmoregulation, ion compartmentalization, restricted photosynthesis, biosynthetic pathway of osmolytes and antioxidants, plant hormone induction and regulation, as well as antioxidant and enzyme production and activation.

Salicornia is a highly promising cultivar with ability as a substitute fodder for either livestock or human sustenance supply. It is often referred to as a "secondary vegetable," "famine sustenance," and "future plant." Salicornia species are valued as oil-seed commodities, as the oil retrieved from their seeds contains high quantities of beneficial polyunsaturated fats like linoleic and oleic acids (Loconsole et al., 2019). In addition, these plants can produce significant quantities of biomass rich in lignocelluloses that can be used to produce bioethanol (Ali et al., 2021). Salicornia plays a vital role in the environment by forming a buffer zone that protects coastal eroding caused by intense wave attack and helps to mitigate ecological pollutants (Gopi et al., 2019). Due to its exceptional salt tolerance, Salicornia has become a significant cash crop halophyte for seawater irrigation and can flourish in hypersaline conditions, making it a viable resource for cultivation in arid-desert locations with severe climatic conditions (Ozturk et al., 2018; Grattan et al., 2008). Researchers have additionally demonstrated that Salicornia is appropriate for re-greening coastal regions to enhance carbon storage and prevent soil loss (Gispert et al., 2021). *S. bigelovii*, a type of Salicornia, has been found to be effective in removing selenium from sediments and waterways, as well as inhibiting the development of the aquatic vegetation diatom *Skeletonema costatum*, which can help prevent eutrophication and hazardous algal blooms (Isca et al., 2014).

Salicornia species are renowned for being able to accrue and tolerate high concentrations of metals in their structures, making them suitable candidates for phytoremediation and for the establishment of novel crop species (Ventura et al., 2011a). World Bank established Climate-Smart Agriculture (CSA) as an integral model to resolve the intricate issues related to climatic crisis, nutrition reliability, as well as environmental sustainability (Group, 2016). CSA implementations seem to be perspective and focus on promoting the use of novel mechanized technology, including smart farming tools, automized assistance structure for water and soil monitoring, conservation and sustainably sourced agricultural strategies, comprehensive treatment of diseases and pests, and water stress, salt, and flood-tolerant crops (Campbell et al., 2014). Cultivating Salicornia species can, therefore, contribute to instilled global warming while also augmenting agricultural production and livelihood opportunities in salt-drought prone regions. However, the native saline ecosystems among those taxa are particularly vulnerable to temperature fluctuations, that is likely to result in longer, more severe, and more frequent drought periods, as well as increased soil salinity levels with high seasonal variability (Change, 2018). This article provides a comprehensive overview of Salicornia, including its characteristics, adaptations, ecological significance, the investigation of its salt adaptation mechanisms, and the assessment of its potential as a climate-smart crop.

2. Role of Salicornia as a salt-tolerant crop against salinization

Salinization, or the rise in saline content throughout the environment, poses a major liability to industrial agriculture in many regions of the world, leading to the degradation of arable lands at an alarming rate (Ekanayake et al., 2023). Saline deposition caused by saltwater intrusion in coastline groundwater sources may worsen due to climate change, leading to limited soil fertility and agricultural output (Calone et al., 2022). Several factors, such as protracted droughts, elevated evaporation , inadequate drainage or waterlogging, extensive usage agrochemicals, as well as watering with saline water, have been contributing to the soil salinity of agricultural fields (Alfio et al., 2020). The current tempo of soil salinization is projected to salinize 50% of cultivated and irrigated fields by 2050, with present estimates of salinized agricultural areas being 20% and 33%, respectively (Machado and Serralheiro, 2017). When exposed to saline environments, plants experience eutrophication, osmotic instability, and peroxidation, resulting in reduced plant development and substantial reductions in agricultural production (Safdar et al., 2019).

The detrimental consequences of salt-induced soil degradation were estimated to cause global yearly crop losses of USD 27.3 billion, highlighting the magnitude of salinization's impact (Qadir et al., 2014). One solution to revive yield is to cultivate salt-tolerant plants on salinized soil. Identifying plants naturally adapted to high salinity and implementing mass cultivation will provide a pragmatic and effective solution (Debez et al., 2011). Halophytes, or inherently salt-tolerant species which can complete their developmental stages in salinity conditions, always had the highest potentiality to transform in to other crops in saline lands (Yuan et al., 2019; Gunning, 2016). Salicornia constitutes to the significant taxonomic groups of halophytes in existence today and therefore is regarded one of supreme halophiles crop, thriving in saline environments close to coastlines in numerous continents, traditionally acknowledged as a source of food (Patel, 2016; Mishra and Tanna, 2017). Halophytes have anatomical and morphological adaptations that enable their survival in saline environments, including the existence of salt ducts, salt bladders, and moist plant matter (Rozentsvet et al., 2017). Salicornia's adaptability to salt-affected lands enables it to convert unproductive soil into fertile land (Muscolo et al., 2014). Moreover, these species are alluring for the bioremediation of soil with high saline and metal toxicity, because of their significant vegetative generation and phytoextraction capacity (Caparrós et al., 2022). The Mediterranean basin is one of the regions most endangered by salinization due to climate change (Cuttelod et al., 2009). Therefore, a proactive approach, including crop diversification, crop rotation, soil conservation, improved irrigation practices, and the use of alternative water sources, is essential to prevent salinization and maintain food security.

3. Potential of Salicornia genus in addressing climate change challenges

Salicornia L. species, also widely recognized as samphire or sea asparagus, seems to be a group of halophytic plants that are well-suited to thrive in saline conditions including coastlines and mudflats (De Souza et al., 2018). These plants have attracted interest because of their prospective application as a staple food, biomass, and in bioremediation of soil salinity (Ventura and Sagi, 2013). Salicornia genus seems to be a group of succulents, halophytic plants that are commonly referred to as glassworts or samphires and belong to the Amaranthaceae family (Gouda and Elsebaie, 2016). They are extensively distributed in coastal areas, with approximately 30 species, which include *S. bigelovii, S. virginica*, and *S. europaea* being the most common (Cárdenas-Pérez et al., 2021). These plants have adapted to saline environments and have fleshy, cylindrical leaves and stems with reduced or absent leaves. Climate change, predominantly caused by human behaviors like clearing forests and consuming petroleum products, leads to a long-term shift in global weather patterns and the Earth's climate system (Fawzy et al., 2020). These activities contribute to increased levels of GHGs in the ecology, including the gases CO_2 and CH_4, that further absorb radiation and induce the warmth of the planet's surface causing directly to global warming (Turyasingura and Chavula, 2022). Climate change has far-reaching effects, along with more frequently occurring bushfires, desertification, but instead catastrophic storms including flooding and storms (Turyasingura et al., 2022; Turyasingura, Ayiga, et al., 2022).

The melting of ice sheets and thermal expansion of seawater also cause rising sea levels, posing a hazard to low-lying areas and coastal cities globally. Global warming does indeed have substantial effects on ecosystems, agriculture, human health, and economies (Benzougagh et al., 2023). Reducing greenhouse gas emissions is crucial in mitigating climate change, which may be achieved through activities including switching to sources of clean energy, enhancing fuel consumption, and adopting sustainable practices for land use (Turyasingura and Chavula, 2022). Adapting toward the unavoidable consequences of global warming also involves actions such as strengthening infrastructure (Turyasingura et al., 2023), enhancing resilience, and implementing measures to safeguard vulnerable communities and ecosystems. The need to address climate change is urgent and requires global cooperation and concerted efforts from all sectors of society (Turyasingura, 2022). Salicornia species are an important source of food for many coastal animals, such as waterfowl, shorebirds, and certain fish species (Zedler, 1996). They are also used by humans as a food source and have a long history of culinary use in coastal regions around the world. In addition, Salicornia species have been used for medicinal purposes in traditional medicine, and there is growing interest in their potential as a source of biofuel and as a crop for cultivation in saline soils (Urbano et al., 2017). With the increasing concern over climate change and its impacts on agriculture and food security, Salicornia has been studied for its potential to grow in saline soils and seawater, which could expand the agricultural land base and reduce the pressure on freshwater resources. Additionally, Salicornia has been shown to have a high capacity for carbon sequestration, making it a potential tool for mitigating climate change (Benson and Ayiga, 2022). Salicornia has been found to be adaptable to a variety of environments, such as arid and semi-arid regions, and can be cultivated using minimal resources, including water, fertilizer, and pesticides, according to studies. It is also capable of producing substantial quantities of biomass, which could be employed to make biofuels and other goods. As a consequence, Salicornia may be beneficial in addressing the challenges presented by climate change, especially in areas under which natural ground water are minimal, and land degradation and desertification are prevalent. Nonetheless, further study is required to ascertain the ideal growing circumstances for such plant and the potential ecological consequences of its cultivation on coastal ecosystems.

4. Temperature and salinity effects on germination of Salicornia ecotypes

For many years, scientists have examined the impact of salinity and temperature on the development of various ecotypes of the Salicornia genus. Salicornia is recognized for its capability to withstand high levels of salinity, which is largely determined by differences in its genetics and the environment where it develops (Alfheeaid et al., 2022). Araus et al. (2021) notes that different ecotypes of Salicornia have varying degrees of tolerance to temperature and salinity stress. For instance, some ecotypes have been found to germinate more efficiently at high temperatures and salinity levels, while others perform better under cooler and less saline conditions. In general, Salicornia seeds require a minimum temperature of around 10-15°C to germinate, with optimal germination occurring at temperatures of 20-25°C. However, some ecotypes have been found to tolerate higher temperatures of up to 35°C or more. Salicornia seeds also require a certain level of salinity to germinate, with optimal germination occurring at salinity levels of 50-150 mM NaCl. Different ecotypes have been found to have varying degrees of salt tolerance, with some able to germinate and grow well in salinities of up to 600 mM NaCl or higher. However, excessively high salinity levels can be detrimental to seed germination and plant growth (Turyasingura et al., 2023), even for highly salt-tolerant ecotypes (Table 1). Overall, the response of various ecotypes of Salicornia to temperature and salinity stress is complicated and relies on a multitude of variables, such as genetic variation, environmental conditions, and the extent and duration of stress. Even farther study is required in order to properly comprehend the processes beneath such responses but also to devise strategies for improving the functioning of Salicornia under various ecological circumstances (Ventura et al., 2011b).

5. Influence of day length and salinity on seedling establishment

Day length and salinity seem to be two vital external variable that can reasonably influence the establishment and growth of seedlings. Day length, also known as photoperiod, is the amount of time each day that a plant is exposed to light. It has a direct impact on the physiological processes of a plant, including the initiation of flowering, stem elongation, and leaf development. The optimal day length for seedling establishment can vary depending on the plant species. For example, some plants may require long days to initiate flowering, while others may require short days. However, for most plants, a day length of 12-16 hours is optimal for seedling establishment (Rajabi Dehnavi et al., 2020). Salinity is the measure of salt content of soil or water, which can negatively impact the development and growth of vegetation by producing osmotic stress and ion toxicity. While plant species exhibit differing degrees of tolerance to salinity, seedlings are typically more susceptible than fully matured plants. The impact that salinity has just on development of seedlings can depend on their stage of development and how long they are subjected to saltwater (Cao et al., 2018). The interaction between salinity and day length also has an important impact in germination and seedling. For example, some plants may be better adapted to seedling establishment in high salinity environments when day length is shorter, while other plants may require longer days and lower salinity levels for optimal growth. Understanding these interactions can help in the selection of appropriate plant species and management practices for successful seedling establishment in different environments.

Table 1. Growth rates of Salicornia under different salinity and temperature levels

S.N.	Growth conditions	Levels	Salicornia growth rate (cm/day)	Reference
1	Control	No salt	1.5	Amiri et al. (2010)
2	Moderate salinity	50 mM NaCl	0.9	Aghaleh et al. (2009)
3	High salinity	100 mM NaCl	0.5	Amiri et al. (2010)
4	High salinity	200 mM NaCl	0.2	Aghaleh et al. (2011)
5	Low temperature	10°C	0.7	Khan et al. (2000)
6	High temperature	40°C	0.8	Ayala et al. (1995)

Table 2. Nutrient content of Salicornia compared to other crops

S.N.	Crop	Protein (%)	Fat (%)	Fiber (%)	Minerals (mg/100 g)	Vitamins (mg/100 g)	References
1	Salicornia	22.3	3.7	32.4	1294	2.4	Castagna et al. (2022); Glenn et al. (1991); Choi et al. (2014)
2	Spinach	2.9	0.4	2.2	558	1.6	USDA, 2019
3	Broccoli	2.8	0.4	2.6	316	0.8	USDA, 2019
4	Kale	2.9	0.9	3.6	447	1.2	USDA, 2019
5	Carrots	0.9	0.2	2.8	33	0.7	USDA, 2019
6	Sweet potatoes	1.6	0.1	3.0	337	2.4	USDA, 2019

6. Opportunities and challenges of *Salicornia* L. for sustainable agriculture and development

A promising plant called *Salicornia* L. may be able to help with a number of sustainability issues in Sub-Saharan Africa and beyond. To combat food insecurity and malnutrition, it might offer a source of locally produced, nutrient-dense food (Table 2) (Martinez-Garcia, 2010; Cárdenas-Pérez et al., 2021), as well as a sustainable supply of biofuels and other renewable energy sources to help combat climate change and increase access to energy (Sharma et al., 2016; Makkawi et al., 2021). *Salicornia* L. might also be produced on

Table 3. Production, economic status, and challenges of scaling up Salicornia farming

S.N.	Topic	Data					References
		USA	China	Spain	Iran	Australia	
1	Land use for Salicornia cultivation	1000 ha	500 ha	200 ha	5 ha	20 ha	Rey et al. (1990); Ventura and Sagi (2013); Holguin et al. (2021)
2	Yields of Salicornia farming	2-3 tons/ha	1.5-2 tons/ha	0.5-1 tons/ha	2.7 tons/ha	2.2 tons/ha	Rey et al. (1990); Holguin et al. (2021); Ventura and Sagi (2013)
3	Profit margins of Salicornia farming	2000-3000 $/ha	1500-2000 $/ha	500-1000 $/ha	2700 $/ha	2500 $/ha	Rey et al. (1990); Holguin et al. (2021); Ventura and Sagi (2013)
4	Challenges in scaling up Salicornia cultivation	Lack of infrastructure, Limited access to financing, Uncertain market demand, Drought stress, Salinity stress, High production costs					Ventura and Sagi (2013); Ganesan et al. (2019)
5	Potential benefits of Salicornia cultivation	High adaptability to salt-affected soils, Ability to sequester carbon, Potential as a food or feed crop					Cárdenas-Pérez et al. (2021); Negacz et al. (2021)

marginal and degraded areas to support ecosystem services and land restoration (Wratten et al., 2013; Parida, 2005), as well as providing a new source of export income to diversify economies and lessen reliance on exports of conventional commodities (Glenn et al., 1999; Ansari et al., 2016). Salicornia L. may also present opportunities for value addition and agro-processing, which could result in new employment opportunities and sources of income for smallholder farmers and business owners (Nigam, 2011) as well as new understandings and advancements in plant genetics, biotechnology, and sustainable agriculture (Turcious et al., 2017). Although research on Salicornia L. might result in new approaches and best practices for sustainable agriculture and development, partnerships and collaborations among many stakeholders could serve to stimulate investment and scale up production and distribution of Salicornia L. products, while also addressing the unique challenges faced by farmers in different countries (Table 3) (Aronson, 1985). Salicornia L. might provide a variety of advantages for sustainable development, including community-based natural resource management, ecotourism, climate-smart agriculture, and inclusive economic growth (Herbert et al., 2015; Hamed et al., 2021; Ventura and Sagi, 2013; Blore, 2015; Arif et al., 2020; Aziz et al., 2022).

Salicornia L. presents significant potential for sustainable agriculture and economic development, but there are several challenges that need to be addressed to realize this potential. These challenges include a lack of research and knowledge on the nutritional value and health benefits of Salicornia L. products, which could limit consumer demand (Patel, 2016; Costa et al., 2018). Additionally, there is a lack of policy support and incentives for promoting Salicornia L. as a sustainable crop, which could limit investment and adoption (Bailis and Yu, 2012; Aluwani, 2023). Ethical and social challenges related to land use, labor rights, and gender equity could affect the sustainability and social impact of Salicornia L. production and marketing (Sani et al., 2012; Collinson et al., 2022). Furthermore, the lack of infrastructure and technology for efficient and sustainable Salicornia L. cultivation and processing, such as irrigation systems and drying facilities, presents a significant challenge (Chaturvedi et al., 2021; Joshi et al., 2020). Limited human capacity and technical expertise in Salicornia L. cultivation and value addition could also limit productivity and quality (Centofanti and Bañuelos, 2019; Cárdenas-Pérez et al., 2021). Other challenges include limited availability and accessibility of high-quality seeds, fertilizers, and other inputs (Gelfand et al., 2013), environmental factors such as soil salinity, water scarcity, and extreme temperatures that may affect crop productivity (Parida, 2005), competition with other crops and land-use practices that may be more based or profitable (Blanc, 2012), limited access to credit, insurance, and other financial services for smallholder farmers and entrepreneurs involved in *Salicornia* L. cultivation and commercialization (Ahmadzai et al., 2021; Guerin and Guerin, 1994), lack of standardization and certification for *Salicornia* L. products, which could affect quality control and consumer confidence (Ventura and Sagi, 2013), limited market access and distribution networks for *Salicornia* L. products, especially in rural areas (Chaturvedi et al., 2021), potential negative environmental impacts of large-scale *Salicornia* L. cultivation, such as soil erosion, water depletion, and biodiversity loss (Hamed et al., 2021), and risk of market saturation and price volatility as *Salicornia* L. cultivation and commercialization expands (Ahmad et al., 2021). Addressing these challenges will require a collaborative, multi-stakeholder approach that engages different actors, including farmers, researchers, policymakers, and private sector players.

7. Conclusions and recommendations

Salicornia L. offers a bright prospect for sustainable agriculture and economic growth since it may support disadvantaged groups' lives and income while simultaneously providing advantages to the environment such carbon sequestration, soil preservation, and biodiversity preservation. Realizing this potential, however, would need resolving a number of issues, such as socioeconomic, institutional, and technological hurdles, as well as guaranteeing sustainability and fair benefit distribution. *Salicornia* L. cultivation and value addition need more study and development. Market access and distribution networks must also be supported, especially in rural regions, for *Salicornia* L. goods. For quality assurance and customer trust in *Salicornia* L. goods, standardization and certification are also crucial. To maintain the sustainability of *Salicornia* L. production and commercialization, it is also necessary to address possible adverse environmental effects such soil erosion and water depletion. In order to grow *Salicornia* L. as a sustainable crop, it is necessary to adopt a multi-stakeholder strategy that involves several parties, including farmers, researchers, legislators, and business representatives. Collaboration may result in the creation of novel approaches and industry-leading techniques for *Salicornia* L. cultivation and development that are sustainable for both people and the environment. Overall, *Salicornia* L. offers a great prospect for sustainable agriculture and economic growth; nevertheless, in order to fully realize this potential, it will be necessary to solve a number of issues and adopt a cooperative, multi-stakeholder approach. Thus, to maximize the benefits and minimize the risks of *Salicornia* L. cultivation and commercialization, the following recommendations are suggested:

1. For *Salicornia* L. goods, create and implement standards and certification programs to assure quality control and customer trust.

2. Improve distribution channels and market accessibility for Salicornia L. goods, especially in rural regions, to enable small-scale farmers to take use of the crop's potential.

3. Promote *Salicornia* L. cultivation and value addition research and development, notably in creating the infrastructure and technology for effective and sustainable production, as well as improving technical know-how and people ability.

4. Make sure that large-scale *Salicornia* L. initiatives are carried out in a way that respects the rights of local populations, prevents land grabbing and displacement, and is ethical and sustainable.

5. Help small-scale *Salicornia* L. growers by providing them with market access, financial backing, and technical support to help them compete with bigger players and reap the rewards of the crop's potential.

6. To optimize the crop's potential for sustainable development, encourage cross-sectoral collaboration and innovation that connect *Salicornia* L. farming with renewable energy, water management, and other areas.

By following these suggestions, *Salicornia* L. may evolve into a crucial crop for sustainable agriculture and development, assisting in, among other things, biodiversity preservation, poverty alleviation, and climate change mitigation.

Compliance with Ethical Standards

Conflict of Interest

As the author of article declare that there are no conflicts of interest with respect to the research, authorship, and/or publication of this article.

Authors' Contributions

Shambhu KATEL, **Shubh Pravat Singh YADAV**, **Benson TURYASINGURA** and **Aman MEHTA**: Each author made an equal contribution throughout all stages of manuscript preparation.

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