Use and utilization of *Salicornia bigelovii* (Torr.) as an emerging resource in coastal systems

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ABSTRACT

Objective: To conduct a comprehensive analysis of the scientific literature published between 2000 and 2023 on *Salicornia bigelovii*, aiming to identify the state of the art, the most relevant research areas, and the current and potential application of this species.

Design/Methodology/Approach: An analysis of publications, document selection, and connections between studies were performed, focusing on scientific literature published between 2000 and 2023 on *S. bigelovii* in major scientific databases. Additionally, a trend analysis was conducted considering various disciplines applied to the utilization of this halophyte.

Results: Over the study period, an increasing research trend on *Salicornia* was observed, with multiple authors highlighting its economic, environmental, and social value.

Limitations of the study/Implications: This review focuses on literature published on source platforms between 2000 and 2023.

Findings/Conclusions: *Salicornia bigelovii* holds significant potential as an emerging natural resource within coastal systems.

Keywords: halophytes, salinity, sustainability, innovation.

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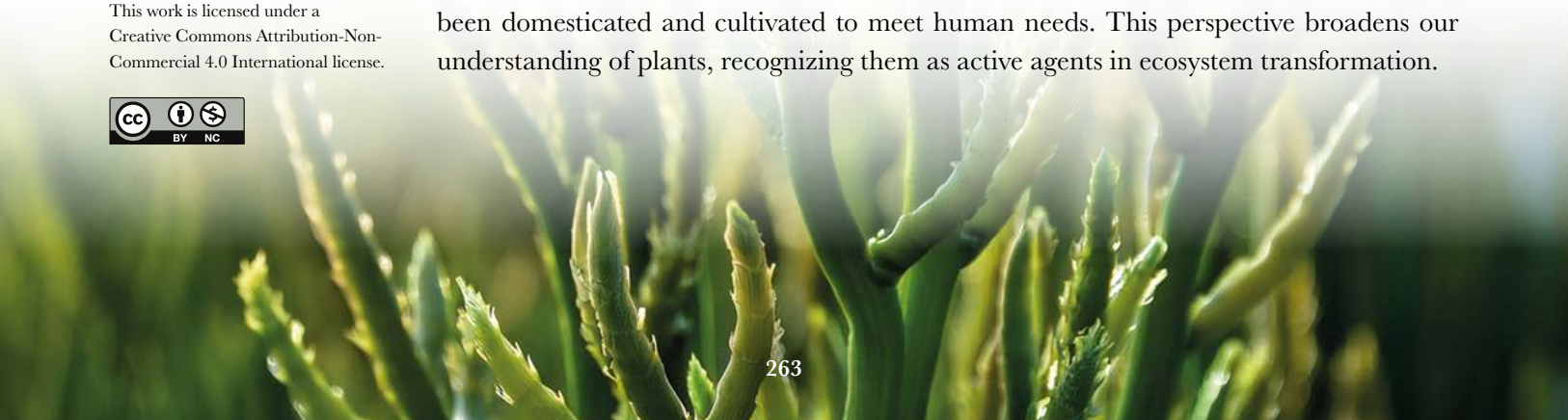
INTRODUCTION

Coastal ecosystems are highly relevant due to their high productivity, acting as major reservoirs of organic matter accumulated through sedimentation processes (Calva *et al.*, 2011). However, these areas are exposed to high salt concentrations due to their environmental characteristics, negatively impacting the growth of certain plants and soil health, thereby reducing their agricultural productivity potential. Soil salinity is one of the oldest challenges in agriculture, affecting crop production and sustainability (Soca *et al.*, 2016; Munns & Tester, 2008; Ramírez *et al.*, 2017).

Historically, science has studied plants due to their importance as essential resources. In his work The Botany of Desire, Michael Pollan (2001) discusses how plants have been domesticated and cultivated to meet human needs. This perspective broadens our understanding of plants, recognizing them as active agents in ecosystem transformation.



Halophytes are a group of plants that enable the utilization of saline soils; among them, *Salicornia bigelovii* has evolved to thrive in adverse environments (Flowers & Colmer, 2008; Khan *et al.*, 2019). Commonly known as "sea asparagus," this species flourishes in high-salinity conditions and contributes to the stability of coastal ecosystems (Panta *et al.*, 2014; Isca & Seca, 2014). Furthermore, due to their characteristics, halophyte-based crops could enhance the availability of water and arable land for the production of food crops or biofuels (Zerai *et al.*, 2010; Hossain & Talukder, 2018).

This research proposes that *Salicornia bigelovii* use in agricultural systems enhances the sustainability of saline soils by increasing productivity, rehabilitating degraded lands, and providing industrial and energy resources, thanks to its tolerance to high salinity levels and its contribution to food security under adverse conditions. Despite these advantages, knowledge about the use and industrial applications of *Salicornia bigelovii* remains limited (Santos *et al.*, 2022), highlighting the need for an in-depth review of its current status and potential utilization. This is particularly relevant in the global context of environmental degradation and soil salinization, where interest in plants like *S. bigelovii* has been increasing.

This study aims to conduct a systematic review of the current knowledge on *Salicornia bigelovii*, identifying the state of the art in research, the most relevant study areas, and the existing and potential applications of this plant. Through a comprehensive methodological approach, scientific publications from the past 23 years will be analyzed to highlight trends, knowledge gaps, and research opportunities. This effort seeks to contribute to a deeper understanding of *Salicornia* and its role in agricultural and environmental sustainability, proposing it as a key resource to address contemporary challenges such as climate change, food security, and the conservation of coastal ecosystems.

MATERIALS AND METHODS

Analysis of Publications, Document Selection, and Research Connections

Systematic Literature Review: A review of scientific literature published between 2000 and 2023 was conducted, with some exceptions beyond this period for explanatory purposes.

Document Search and Selection: Bibliographic reference search engines were used on source platforms such as Redalyc, World Wide Web, Scielo, Ecology, PubMed, Nature Journal, ACS Publications, Springer, Elsevier, and MDPI through the Google Scholar search engine, which was chosen for its suitability in organizing information. Relevant documents were identified using the keywords "*Salicornia bigelovii*" (3,800 related articles found), "halophytes" (472 related articles), "salinity" (496 related articles), and "alternative crop" (463 related articles), as well as Boolean operators (AND, OR, NOT) to refine the search. Documents were primarily selected in English and Spanish; however, research in Korean and Chinese was also identified, translated, and considered for review.

Preliminary Reading and Selection Criteria: A total of 4,054 research studies related to *Salicornia bigelovii* within the established period were identified, from which 240 were selected for preliminary reading. The exclusion criteria were primarily based on the year of publication, the academic fields in which the studies were conducted, and their

research objectives. After this initial filtering, a focused reading of the selected documents was conducted, emphasizing the abstract, introduction, and conclusion. If an article met specific criteria such as research focus, primary objective, and contribution to the field, it was downloaded for in-depth reading and analysis. At this stage, document selection criteria were related to topics such as saline soil remediation, sustainable agriculture, natural resource management, sustainability, and green engineering applied to *Salicornia bigelovii*.

Summary Compilation: A summary was created in an Excel table for each selected article, including the year of publication, author names, a summary highlighting the main contributions and objectives, academic field, and the journal of origin.

Manuscript Classification: The manuscripts were classified based on their focus, including the most relevant research areas, current and potential applications, and the various uses of *S. bigelovii*.

Analysis of Researcher Connections: The software ResearchRabbit was used as a tool for exploring scientific literature, classifying research studies, and connecting them with similar investigations to identify relationships among studies on the topic. This software was chosen for its specific functionality, which facilitates the analysis and visualization of scientific literature.

Node Diagram: A node diagram was created to determine the relationship and influence of the selected studies in relation to similar ones. This graph represents the studies included in the analysis, their relevance, influence, and interactions between publications, as well as their correlation with other research on the same topic. It consists of a total of 80 nodes, including 9 independent nodes and 71 interconnected nodes, with 8 research connections. The size of each node indicates the degree of influence a study has on other connected nodes through citations. The lines connecting the nodes represent citation relationships between publications. The absence of a line between two nodes indicates no direct citation relationship. Green nodes represent the studies considered for this work, while blue nodes represent studies that cover the same topic or research area but were not used for this article. For both colors, the more intense the color, the more recent the study, while a lighter color indicates an older study. The thickness or direction of the lines does not represent any particular characteristic.

Trend Analysis

Identification of Key Nodes:

a) Co-citation Analysis: This focuses on examining how studies cite each other over time (Leydesdorff & Cohendet, 2020). This method allows for the identification of frequently cited and well-recognized publications, indicating their relevance and authority in the field.

b) Article Selection Process: Using the ResearchRabbit software, a compilation of publications related to *Salicornia bigelovii* was created. A node graph visualizing the co-citations was generated.

c) Centrality Analysis: The article by Cárdenas-Pérez (2021) was identified as a central node in the co-citation network, indicating that its content is widely referenced.

d) Implications of Key Nodes: These graphs provide insights into emerging trends in research and can identify thought leaders in the field.

Trends in the Number of Publications:

a) Data Compilation of Publications: This was done by extracting annual information on the number of articles published about *Salicornia bigelovii* from 2000 to 2023.
b) Graphical Analysis: A graph was created to display the number of publications per year, based on the Google Scholar database, to visually represent the growth of academic interest in this plant.
c) Linear Regression Analysis: A linear regression analysis was performed using Minitab 18 to examine the relationship between the year of publication and the number of publications. Publication data from 2000 to 2023 were used. The year of publication was used as the predictor variable (independent variable, X), and the number of publications as the response variable (dependent variable, Y). A linear model of the form $Y=\beta_0+\beta_1X+\varepsilon$ was fitted to the data, where β_0 represents the intercept, β_1 the slope, and ε the error term. The model parameters (β_0 and β_1) were estimated using the ordinary least squares method. The model's goodness of fit was assessed using the coefficient of determination (R^2), which indicates the proportion of variance in the response variable explained by the model.
d) Interpretation and Discussion: Growth factors and motives were identified through analysis of the information.

Knowledge Gaps:

a) Critical Literature Review: Special attention was paid to the approaches and topics addressed. Areas where research was scarce or lacked depth were observed.
b) Specific Identification of Gaps: The areas of study with deficiencies in the analyzed articles were identified.
c) Implications for Future Research: Based on the knowledge gaps, opportunity areas for future research were determined.

Classification of Research Areas:

a) Classification and Grouping: Based on the literature review and data collection, the most relevant research areas related to *Salicornia bigelovii* were classified. Categories were created based on themes commonly addressed in the studies.

Creation of a Summary Table:

A table was created for each research area, including the name, key researchers, context of the study, and main findings.

Discussion of Interrelationships and Opportunities:

Interrelationships between research areas were discussed, and their potential was determined.

RESULTS AND DISCUSSION

Current State of Knowledge

The co-citation network analysis reveals a structure where the article by Cárdenas-Pérez (2021) occupies a central position. However, the works of Glenn (1991; 1999), Ventura (2015), Sharma (2016), Zerai (2010), Song (2015), Panta (2014), and Flowers (2015) also play significant roles, with larger sizes and numerous connections to other nodes (Figure 1). This suggests that these works have a major influence on the formation of knowledge regarding *Salicornia bigelovii*, acting as central nodes or hubs within the network. Additionally, other articles with a significant number of citations occupy relatively central positions, indicating their importance in the field. Several clusters of densely interconnected nodes suggest areas of common research. For instance, a cluster including nodes like Zerai (2010), Glenn (1991; 1999), Rathore (2016), Khan (2006), Chaudhary (2018), and others, indicates a shared interest in certain study areas. Meanwhile, another cluster includes articles related to the properties and applications of *Salicornia*. The presence of some peripheral nodes with few connections suggests that there are more specific or pioneering studies that differ from the main body of research.

The co-citation network provides a visualization of the landscape of research related to *Salicornia bigelovii*, identifying the most influential publications, interconnected research groups, and potential future research areas.

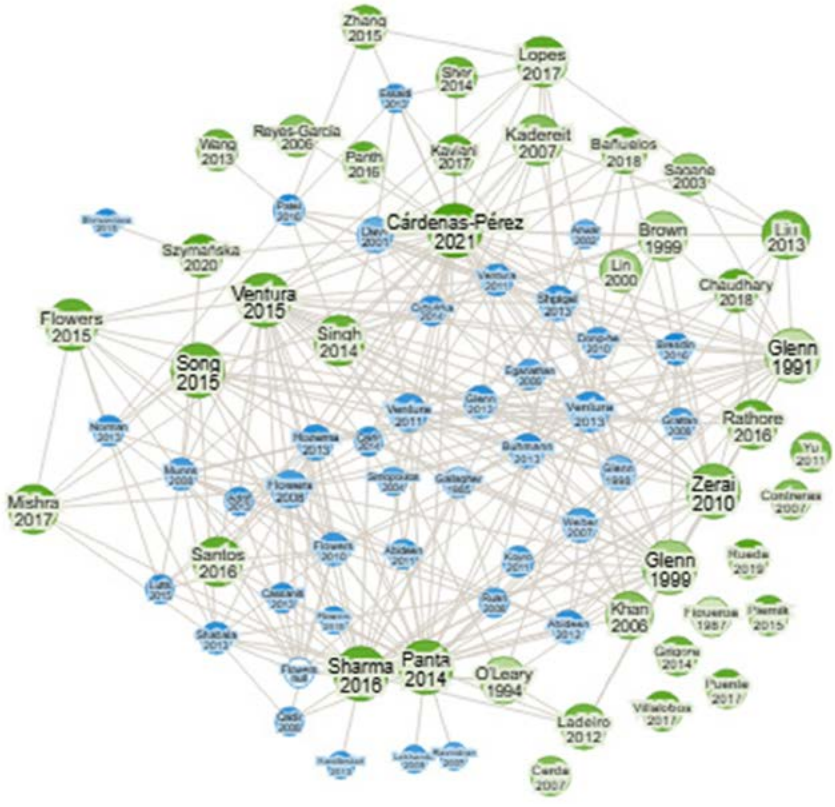


Figure 1. Co-citation network related to research on *Salicornia*.

The number of publications related to *Salicornia bigelovii* research has notably increased in the last two decades (Figure 2), showing a growing interest in its potential as an emerging resource. However, knowledge gaps remain, particularly concerning the management and optimization of large-scale cultivation for industrial and/or commercial use.

The analysis of publication data over time (2000-2023) shows a strong positive linear trend (R^2=0.896), modeled by the equation $y = 11.77x - 23514$, where y represents the number of publications and x the year. This result indicates a consistent increase in the number of publications during the studied period, with an average increase of approximately 11.77 publications per year. However, the presence of dispersion around the regression line suggests the influence of additional factors not considered in this simple linear model, requiring future research to identify and quantify their impact on the publication output related to *Salicornia bigelovii*.

On the other hand, a lack of research with a holistic or complex approach was identified, particularly studies that evaluate the long-term environmental, economic, and social impacts of Salicornia within coastal ecosystems and agroecosystems. Most studies focus on specific aspects of the plant, and occasionally its botanical benefits. This highlights areas of opportunity for research ventures that can provide a deeper understanding of the subject of study.

Relevant Research Areas

Studies on *Salicornia bigelovii* and other halophytes have increased in various aspects and applications since 1987, highlighting ten key scientific areas of interest, including: phytoremediation, diversity and evolution, salinity, nutritional and medicinal benefits, halophyte plant ecology, biotechnological applications, and antibacterial properties (Table 1).

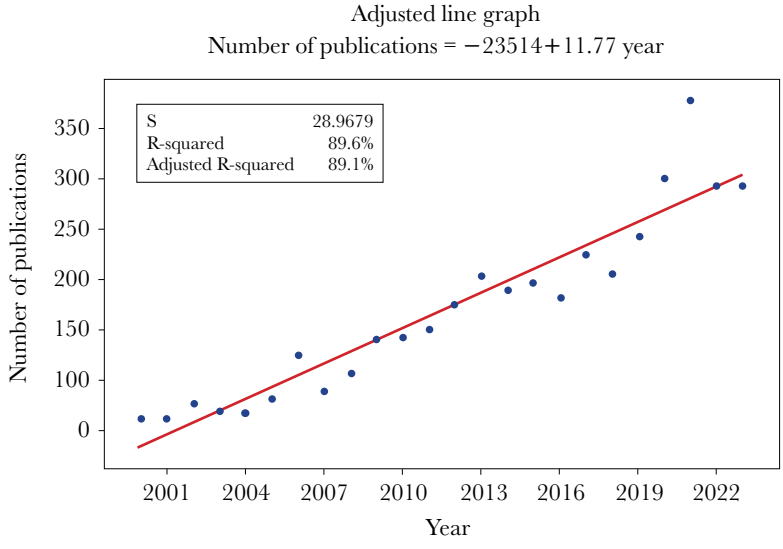


Figure 2. Temporal trend of scientific publications on *Salicornia bigelovii* (2000-2023).

Table 1. Relevant Research Areas on Halophyte Plants Worldwide.

Area of Study	Author and residence	Research and area of study	Proposals
Phytoremediation	Figueroa *et al.* (1987) (España)	Analysis of the plant–environment relationship. (Spain)	Deployment of phytoremediation strategies involving *Salicornia* for the restoration of contaminated soils.
	Sepúlveda *et al.* (2012) (Chile)	Analysis of the phytoremediation capacities of *Salicornia* through mineral absorption. (Peru and Chile)	Research on metabolic pathways to optimize its use in agriculture.
Diversity and evolution	Kadereit *et al.* (2007) (Alemania)	Genetic diversity and evolutionary analysis of *Salicornia*, with the identification of foundational species. (Global)	Promotion of conservation efforts for Salicornia species in their natural habitat.
Salinity and alkalinity	Rueda-Puente *et al.* (2011) (Mexico)	Identification of saline and alkaline soils in approximately half of the globally irrigated lands. (Global)	Promotion of halophyte cultivation to rehabilitate lands affected by salinity.
Nutrirional and medicinal benefits	Yu *et al.* (2011) (China)	Identification of antibacterial properties useful in the food industry. (China)	Conducting studies on the production of natural antioxidants as alternatives to synthetic ones.
	Wang *et al.* (2013) (China)	Identification of high polyunsaturated fat content in *Salicornia* with antioxidant and antitumor properties. (Unspecified)	Promotion of the development of supplements using *Salicornia* extracts.
	Zhang *et al.* (2015) (China)	Analysis of blood pressure behavior in SD rats with *S. bigelovii* vegetable salt. (China)	SPS has the potential to become a new type of salt substitute that could help prevent hypertension, kidney, and liver issues in humans.
Ecology of halophytic plants	Mishra y Tanna (2017) (India)	Identification of salt tolerance in crops from coastal areas and salt marshes of *Salicornia* (India).	Promotion of the use of *Salicornia* in sustainable agricultural systems in coastal regions.
	Coc-Coj *et al.* (2020) (Guatemala)	Identification of halophyte proliferation in various saline habitats, from coastlines to deserts and savannas. (Global)	Research on its performance under different environmental conditions.
Biotecnological applications	Coc-Coj *et al.* (2020) (Guatemala)	Identification of the great potential of halophytic plants in biotechnological applications. (Global)	Research on its use in biofuel production and the development of new biotechnological products.
Antibacterial properties	Al-Aradi *et al.* (2020) (Irak)	Analysis of the properties of *Bacopa monnieri* with potential for pharmacological applications. (Iraq)	Research on interactions between Salicornia and bioactive compounds to develop new antimicrobials.
Agricultural productivity	Cerda *et al.* (2007) (Mexico)	Evaluation of saline soil remediation through the cultivation of forage grasses. (Mexico)	Use of forage crops with chloride-tolerant species to make use of saline soils.
	Terrazas-Rueda (2019) (Mexico)	Testing of biosaline cultivation in arid desert soil for the utilization of saline land. (Mexico)	Salt leaching through biosaline cultivation for the recovery of agricultural soils.
	Ladeiro (2012)	Analysis of the potential of using halophytes for the utilization and remediation of saline soils. (Global)	Use of halophytes in commercial crops/exploitation of saline soils.

Based on the presented information, trends and patterns in the research and potential applications of *Salicornia* and other halophytes are identified, highlighting not only their properties and uses but also the importance of the geographical contexts in which these studies are conducted (Figure 3). The diversity of study areas provides a global scientific perspective on the cultivation and benefits of these plants. The research by Rueda-Puente *et al.* (2011), which emphasizes global soil salinity issues, proposes finding solutions adapted to different geographical contexts. In regions where agriculture faces soil salinization, *Salicornia* cultivation could represent an alternative for restoring soil health and maximizing production under adverse environmental conditions.

On the other hand, the research by Sepúlveda *et al.* (2012) in Peru and Chile highlights the importance of understanding the phytoremediation capabilities of *Salicornia* in specific ecosystems, taking into account variables such as soil composition and water availability. This geographical approach is crucial, as environmental conditions can vary significantly within the same coastal region, affecting the effectiveness of phytoremediation interventions.

In the health sector, the studies by Wang *et al.* (2013) and Yu *et al.* (2012) conducted in China highlight the nutritional benefits of *Salicornia* and its impact in a country with a large and growing population that demands healthy food alternatives. The findings could be significant in terms of food security and nutrition, particularly in rural or peri-urban areas where the traditional diet is insufficient.

Additionally, the delineation of the study area in research on antibacterial properties, such as in the study by Al-Aradi *et al.* (2020) in Iraq, suggests a need for region-specific research on the use of native or easily adaptable natural resources in the fight against local pathogens. This is essential, as the medicinal properties of plants vary between species and their ecological context.

Salicornia's ability to adapt to diverse habitats, ranging from coastal areas to deserts and savannas (Coc-Coj *et al.*, 2020), highlights its resilience and potential for use in different geographies. This calls for research on its applications in other areas with varied climatic conditions and cultural references. From a macro perspective, the analysis suggests that

Figure 3. Geographical location of research related to the use and exploitation of halophyte plants conducted worldwide.

geographical aspects play a crucial role in formulating effective strategies for utilizing *Salicornia*. Integrating geospatial data in future studies could help maximize its impact in areas of interest, generating solutions tailored to the specific challenges of each region while contributing to global goals.

Current and Potential Uses

Salicornia, also known as "sea asparagus," is a halophytic plant that thrives in adverse conditions, giving it great potential for utilization in agricultural, industrial, and environmental sectors (Table 2).

Salicornia is a plant with various forms of utilization due to its properties and significant impacts across multiple sectors. Its ability to grow in saline environments and use seawater or wastewater for irrigation positions its cultivation as sustainable agriculture for coastal and desert regions (Terrazas-Rueda *et al.*, 2019). This adaptation allows the use of unproductive

Table 2. Utilizations of *Salicornia bigelovii*.

Utilization	Property	Current	Potential
Sustainable Agriculture	Ability to grow in saline soils and use seawater or wastewater for irrigation.	Enhances the utilization of unproductive land. It represents an alternative for sustainable agricultural production in coastal and desert areas (Panta *et al.*, 2014).	A solution for water scarcity and soil salinization, promoting food production in coastal and desert areas..
Biofuel Production	The seeds contain between 12% and 30% oil.	A viable alternative for biodiesel production (Glenn *et al.*, 1991).	Renewable energy production in regions where other crops are not sustainable.
Phytoremediation of soils	Ability to absorb heavy metals and contaminants.	Rehabilitation of contaminated and degraded lands (Brown *et al.*, 2014).	Use in environmental restoration programs.
Nutrition and feeding	Rich in proteins (27.2-31.3%).	Source of nutrients in animal feed as forage and human consumption, through direct consumption and products such as salads and sauces (Ventura *et al.*, 2015).	Nutrient solution in regions with water scarcity, as well as a functional food.
Cosmetic and Pharmaceutical Products	Antioxidant and antimicrobial properties.	Used in beauty products and medical treatments (Ahn *et al.*, 2011).	Development of new medications and cosmetics.
Chemical and Energy Industry	Fatty acids as components.	Used as a biofuel and for bioethanol production (Sharma *et al.*, 2016; Bañuelos *et al.*, 2018).	Use in the production of sustainable materials and in the biofuel industry.
Environmental Interest	Salt tolerance, water absorption capacity, CO_2 capture, morphological structure, biofiltration, biomass production, and resistance to extreme conditions.	Assists in desalination, improves groundwater quality, captures CO_2, regulates coastal erosion, and acts as a biofilter for contaminants (Isca and Seca, 2014).	Promote environmental sustainability, contributing to climate change mitigation and strengthening coastal ecosystems.

land affected by soil salinization and water scarcity, making this plant a viable innovation for agricultural production in the context of climate change and limited water resources (Panta *et al.*, 2014).

In the biofuel industry and other chemical compounds, due to the oil content in *Salicornia* seeds and its versatility, its extensive cultivation presents an opportunity to develop biodiesel in regions where other crops do not thrive (Glenn *et al.*, 1991). This promotes energy sustainability, income diversification for farmers in areas with poor or degraded soils, and provides an alternative to conventional materials and fuels with a significant environmental impact (Sharma *et al.*, 2016; Bañuelos *et al.*, 2018).

Regarding the phytoremediation of contaminated soils, *Salicornia's* ability to absorb heavy metals and other pollutants highlights its usefulness in rehabilitating degraded soils and transforming contaminated areas into arable land and other usable spaces (Brown *et al.*, 2014). Additionally, *Salicornia's* nutritional properties make it an attractive ingredient for both animal and human food, especially in water-scarce regions, thereby improving food security in these areas (Ventura *et al.*, 2015). Due to its antioxidant and antimicrobial properties, *Salicornia* holds great potential as an active ingredient in new products for the cosmetics and pharmaceutical industries (Ahn *et al.*, 2011). Its application aligns with current trends towards using natural and sustainable ingredients in these industries.

Salicornia is an option for recovering and maintaining saline ecosystems due to the environmental services it provides, such as improving groundwater quality, regulating coastal erosion, and acting as a biofilter (Isca and Seca, 2014). As we have pointed out, the multiple properties and capabilities of *Salicornia*, harnessed for agronomic, industrial, and environmental purposes, make it a key resource for addressing contemporary challenges in terms of economic and ecological sustainability, enhancing the resilience of coastal areas against global environmental changes.

CONCLUSIONS

The literature review on *Salicornia bigelovii* allowed for the identification of the current state of knowledge regarding this halophyte and its potential as a key resource in sustainable agriculture, biotechnology, and environmental remediation. Through the analysis of co-citations and the organization of available information, the importance of this plant in contexts of salinity and water scarcity was highlighted, while significant gaps in the conducted research were also noted. The evidence indicates that, although interest in *Salicornia* has grown, an integrated research approach is required to assess its large-scale cultivation and the long-term impact of its use in ecosystems with potential for establishment. To contribute to achieving sustainability at local and global levels, future research on *S. bigelovii* could focus on developing strategies that maximize its utilization in various applications and evaluate its effects on communities and the environment. This combination of efforts could position *Salicornia bigelovii* as a viable solution to contemporary challenges in agricultural production and the conservation of natural resources.

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