RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
56 (4) 1621-1631, 2024
http://doi.org/10.54910/sabrao2024.56.4.27
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

PHYTOREMEDIATION AND NUTRITIONAL POTENTIAL OF THE ICE PLANTS (*MESEMBRYANTHEMUM CRYSTALLINUM* L.)

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SUMMARY

Ice plant (*Mesembryanthemum crystallinum* L.) is an edible plant with a high content of healthy minerals and ingredients beneficial to human health. The presented study aimed to summarize the key findings in terms of phytoremediation capabilities and nutritional values of the ice plant. A rigorous scientometric review technique and Tree of Science heuristic analyses helped compile all those findings. The scientometric review used various databases (Scopus and Science Direct) following the PIO (Population, Intervention, and Outputs) strategy, which helped to formulate the search equations and identify the most relevant articles published in the last two decades. According to scientometric mapping, the scholarly work on *M. crystallinum* enhanced by 12.65% between 2006 and 2023, focusing on its phytoremediation potential, salt adaptability, antioxidant capacity, and phenolic compounds. The present findings emphasized more investigation regarding its potential uses in the food sector, namely, its phytoremediation capacities for cleaning up contaminated water and soil.

Keywords: Ice plant (*M. crystallinum* L.), salt stress, flavonoids, phytoremediation potential, salt adaptability, antioxidant capacity, phenolic compounds

Key findings: Reports on *Mesembryanthemum crystallinum* L. revealed a 12.65% increase in studying its phytoremediation capability, salt adaptation, antioxidant capacity, and phenolic compounds from 2006 to 2023. The study also highlights the importance of further research on its possible applications in the food industry, particularly its phytoremediation capabilities for treating polluted water and soils.

Communicating Editor: Dr. Kamile Ulukapi

Manuscript received: December 31, 2023; Accepted: April 08, 2024.

Citation: Yapias RJM, Soto JP, Victorio JPE, Huamaní RG, Astete JAQ, Areche FO, Araujo VJS (2024). Phytoremediation and nutritional potential of the ice plants (*Mesembryanthemum crystallinum* L.). *SABRAO J. Breed. Genet.* 56(4): 1621-1631. http://doi.org/10.54910/sabrao2024.56.4.27.

INTRODUCTION

Ice plant (*M. crystallinum* L.) is an annual plant belonging to the genus *Aizoaceae*. Its bladder-type cells also look like ice crystals on the surface of stems and leaves, which contain ingredients beneficial for the human body, such as inositol, beta-carotene, and various healthy minerals. Reports also indicated ice plants carry out various physiological activities, such as antioxidant properties, blood sugar-lowering activities, and antibacterial effects (Lee *et al.,* 2015; Śliwa-Cebula *et al.,* 2020).

Additionally, the plant has a remarkable ability to adapt to harsh environments. It develops resistance mechanisms against various environmental stresses, such as drought, salinity, high temperatures, low-quality substrates, oxidative stress, heavy metals, and intense light, highlighting its great biotechnological potential. Model experiments showed that the ice plant could adapt and develop in high Cu, Ni, Zn, and Cd ion concentrations. Śliwa-Cebula *et al.* (2020) reported in their findings that *M. crystallinum* has prominent qualities that could benefit environmental purposes, such as effective NaCl accumulation, phytoremediation of Cr, Ni, and Cu, and phytostabilization of Cd (Figure 1a).

M. crystallinum L. has been an investigation subject with an 11.5% increase in research over the past 20 years regarding its phytoremediation capacity, antioxidant capacity, phytochemicals, and salts adaptability (Figure 1b). The investigation of the plant's ice-like epidermal bladder cells (EBC), its most unique traits, has also been progressive. Liquid vacuoles also help with acclimatization, control water and salt retention, and store phytochemicals, including myo-inositol, pinitol, and flavonoids (Sun *et al.,* 2022; Xia *et al.,* 2022).

Although academic research publications on *M. crystallinum* have grown by 12.65% from 2006 to 2023, and as per scientometric mapping, a considerable increase of 24.48% occurred since 2016. The predominant focus of ice plant research was visible in European and Asian nations, as shown by 48.78% of the publications. In contrast, the research on *M. crystallinum* L. can have three categories per the overlap analysis. They included phenolic components, phytochemical features, antioxidant activity, salinity adaptation, techniques and equipment for growing edible ice plants, and evaluation of phytoremediation capacities for purifying contaminated soils and water (Bailey *et al.,* 2021; Rodríguez-Hernández and Garmendia, 2021). Claims have it that the ice plant has many physiological activities, including antimicrobial effects, blood sugar-lowering activities, and antioxidant capabilities. This research's objective sought to comprehensively summarize the most valuable facts about the ice plant's phytoremediation capabilities and nutritional qualities.

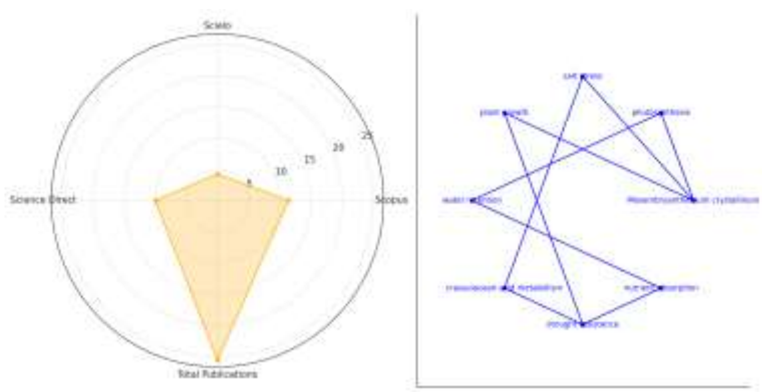


Figure 1. Evolution of publications* (up to August 2023) on a) nutritional value and phytoremediation capacity and b) *M. crystallinum*. *Searches carried out on August 9, 2023, in the Scopus database, Scielo, and Science Direct.

METHODOLOGY

Study scope and database selection

The scientometric study depended upon the research manuscripts published in the journals registered with the Scopus bibliometric network. The Scientific American and Science Direct certified collection relied upon the time frame of 2006 through 2023. We selected the time frame of 2006–2023 after obtaining 150 research articles in an initial search that was not time-limited. Among these research publications, the first was in 2001, the second in 2003, and the third in 2005. Since there was a gap between those two years, the counting began from 2006 onwards, with publishing observed in this field since then. The assessment was on Scopus, Scielo, and Science Direct because of their meticulous indexing methodology, which enables the retrieval of the most up-to-date papers and ensures comprehensive coverage in the research process. The PIO (Population, Intervention, Outputs) technique was most applicable to identify the foremost relevant search phrases, with these three sectors also discussed herein.

Population

The study population was the ice plant's (*M. crystallinum* L.) phytoremediation capacity and nutritional values. Searching Keywords for population were 'Phytonutrients from *M. crystallinum,*' 'phytoremediation using *M. crystallinum,*' and 'edible plant.'

Intervention

Emphasis centered on the content of phytonutrients, bioactive compounds, soil decontamination capacity, and wastewater purification using the ice plant (*M. crystallinum* L.). Searching Keywords for intervention were 'Bioactive compounds,' 'Nutrients,' 'Antioxidant capacity,' 'Heavy metal phytoextraction,' 'cadmium,' 'Contaminated floors,' and 'Contaminated water.'

Outputs

Nutritional contribution and the ability to tolerate, absorb, accumulate, and degrade contaminating compounds (heavy metals) by the ice plant (*M. Crystallinum* L.). The search keywords for outputs were 'health benefits,' 'nutritional contribution,' and 'phytoremediation capacity.'

Scientometric analysis and visualization in VOSviewer

The VOSviewer software also permitted acquiring scientific knowledge, connections, and maps. A thorough general description was helpful for a holistic understanding of the target topic studied throughout time (Cobo *et al.,* 2011) to visualize trends and patterns in the ice plant's phytoremediation capacity and nutritional values.

Additionally, employing the Science Direct, Scielo, and Scopus databases helped provide a thorough scientometric study. The said investigations have three main sectors. The initial portion was to follow the citation trajectory throughout time, which was the evolution of *M. crystallinum's* scientific productivity. Secondly, a section provided the country-by-country breakdown based on three criteria—output, effect, and quality. The third part evaluated how scholars work together, specifically, the most fruitful journals and what topic groups affiliated with them.

Tree of Science (ToS)

The ToS tool begins with developing a search equation with representative terms about the phytoremediation capacity and nutritional value of the *M. crystallinum* L. In the presented investigations, the search equation consisted of three (Phytonutrients from *M. crystallinum,* phytoremediation using *M. Crystallinum*, and edible plant), (bioactive compounds, nutrients, antioxidant capacity, heavy metal phytoextraction, cadmium, contaminated floors, contaminated water), and (health benefit, nutritional contribution, and phytoremediation capacity), which captured 125 scientific documents from the database of the Scopus, Scielo and Science direct.

The tree of science (ToS) underwent analysis and construction considering the volume of citations and the indicators of entry, exit, and intermediation, referring to those research publications that have a high degree of entry and zero exit as root documents, to those who have a high degree of intermediation, such as the trunk, and items with zero input degree and high output degree, such as leaves. Displaying chronological categories distribution depended on the research documents' publication.

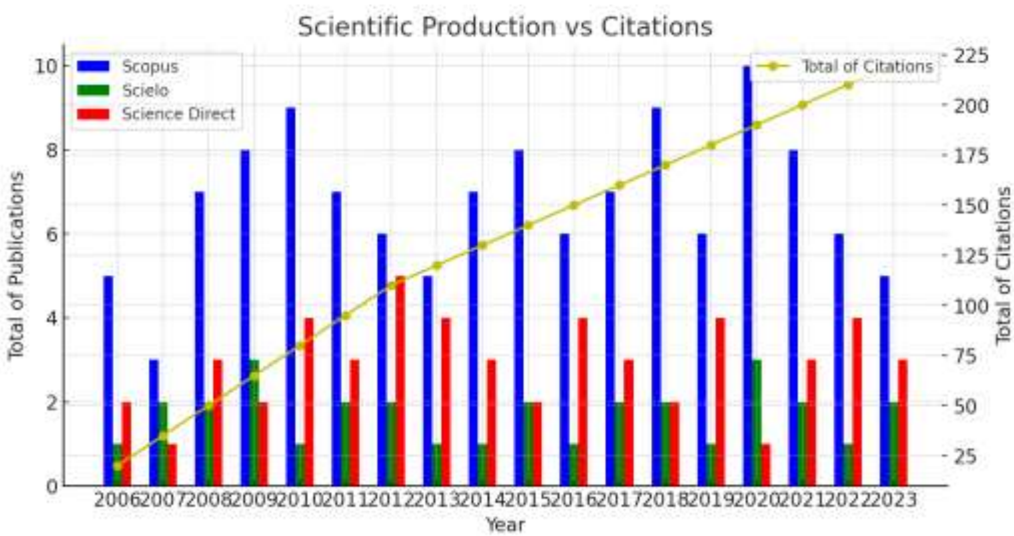
FINDINGS

Scientometric analysis

Scientific production

The performance of the annual scientific production on *M. crystallinum* comprised the search sources, i.e., Scopus, Scielo, and Science Direct (Figure 2). The research publications published year after year, from 2006 to August 2023, were inclusive. The red line showed the total scientific production without duplicates, while the yellow line indicated the number of citations received yearly.

The identified 125 records related to the phytoremediation capacity and nutritional values of *M. crystallinum*. Authentication also showed that between 2006 and 2009, 17 research publications (13.6%) existed, revealing the said research field is in a preliminary stage. Furthermore, the Scopus and Science Direct indicated more publications than Scielo (Figure 2). A report of a significant positive growth rate (23.4%) emerged between 2010 and 2016. It was also due to the higher scientific production (54 articles) and sustained citation rates influenced by various research published in those years. However, it was striking that only six research publications appeared in 2012among the three databases.



	Number of articles found in the different databases																	
Scopus	2	4	3	4	6	7	6	4	5	5	8	6	5	7	6	5	6	5
Sky	1	3	4	*3*	7	5	4	6	4	4	7	5	4	5	5	8	4	3
Science Direct	3	2	5	4	5	4	5	4	6	7	10	4	6	8	9	6	5	6

Figure 2. Annual scientific production of *M. crystallinum* in Scopus, Scielo, and Science Direct.

Country analysis

The search for nutritious plant sources and the global concern to recover contaminated soils and waters identified *M. crystallinum* as a promising alternative to treat these specific problems. Research in this field continues to develop in different countries. Therefore, it was very crucial to carry out an analysis of the research manuscripts published worldwide. This information will provide an overview of research interests within a country and its interactions with other nations and regions. This analysis used three indicators. The first indicator was an analysis of the scientific publications, which refers to the number of research articles published on *M. crystallinum*. The second indicator was the impact of the said research articles, as supported by the number of citations received. Finally, using the method according to the Scimago quartiles, the study evaluated the quality of the research articles.

The academic research productivity in descending order of articles highlighted the scholarly production of the United States with 23 articles, and the second highest impact with 253 citations was 14.70% (Table 1). Moreover, the United States has been strengthening its position with the quality of articles, with 15 research publications in Q1 journals. Japan and Poland also excelled by adding 39 research articles (31.20%). Japan ranks second for output, with 21 articles, including 11 in high-impact journals (Q1). The same manifested in the number of citations it has received (208). The research in Japan focused on evaluating the antioxidant capacity, phenolic compounds, and the possibility of producing *M. crystallinum*in hydroponic systems.

The scientific collaboration among the countries showed that the United States was the most active country in producing investigations related to the application of *M. crystallinum*in in phytoremediation of the contaminated soils and waters (Figure 3). In the United States, the researchers contributed 23 of 125 articles related to this field, representing 18.40%. For their part, Japanese researchers contributed 21 articles, which represents 16.80%. Researchers from Poland and Germany contributed 18 and 15 articles, respectively, representing 26.40%. Countries with no emphasis yet on studying the *M. crystallinum* were Mexico and Spain.

Magazine analysis

The analysis of the different magazines proceeded from two perspectives. The first perspective examines the productivity of the top 10 journals, while the second explores the visualization of research topics through a citation network. Table 2 revealed that eight journals rank highest in the Scimago quartiles (Q1), followed by one journal in Q2, one in Q3,

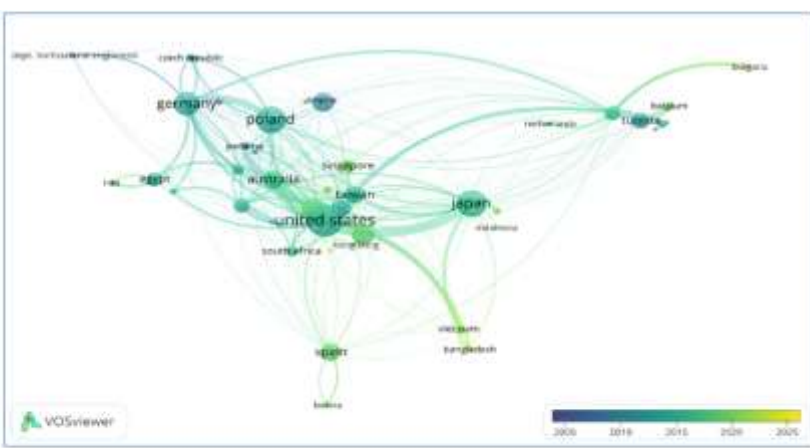


Figure 3. Collaboration network between countries.

Table 1. Top 10 most productive countries in *M. crystallinum*.

Country	Production		Citation		Q1	Q2	Q3	Q4
United States	23	18.40%	253	14.70%	15	3	2	3
Japan	21	16.80%	208	12.09%	11	5	4	1
Poland	18	14.40%	183	10.63%	8	3	3	4
Germany	15	12.00%	174	10.11%	9	2	3	1
China	13	10.40%	293	17.02%	7	3	1	2
South Korea	11	8.80%	209	12.14%	6	3	0	2
Russian Federation	8	6.40%	134	7.79%	4	3	0	1
Australia	7	5.60%	96	5.58%	4	1	0	2
Mexico	5	4.00%	76	4.42%	3	0	2	0
Spain	4	3.20%	95	5.52%	4	0	0	0

Table 2. Top 10 most productive magazines in *M. crystallinum*.

Journal	Scopus	Sky	Science Direct	Impact factor	H index	quartile
Journal of Plant Physiology	5	2	4	0.88	150	Q1
Frontiers in Plant Science	4	2	3	1.23	187	Q1
International Journal of Molecular Sciences	4	1	4	1.15	230	Q1
Russian Journal of Plant Physiology	3	1	4	0.31	57	Q3
Journal of Experimental Botany	4	1	3	1.82	276	Q1
Plant Production Science	3	1	3	0.74	57	Q1
Functional Plant Biology	2	2	3	0.71	129	Q1
Plant Physiology	2	1	4	2.17	344	Q1
Plantarum Biology	3	2	1	0.36	89	Q2
Biological Invasions	2	1	3	0.87	123	Q1

and none in the Q4 category. It indicates the quality of academic research publications on *M. crystallinum*. The magazine with the most published articles was the Journal of Plant Physiology, which also has one recent study, i.e., Interactive effects of salinity stress and irrigation intervals on plant growth, nutritional value, and phytochemical content in *M. crystallinum* L. (Mndi *et al.,* 2023).

Author collaboration network

This section discussed the analysis of the most productive authors and their scientific collaboration networks. Most researchers were from the United States and Poland, affiliated with the Władysław Szafer Institute of Botany of the Polish Academy of Sciences, Krakow, Poland, and the University of Nevada, Reno, United States. Meanwhile, two researchers came from Russia, associated with the Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, Moscow, Russian Federation (Table 3). The top two authors with the most publications include Professor Miszalski, who also investigated, i.e., Phytoremediation of metal-contaminated bottom sediments by the common ice plant (*M. crystallinum* L.) in Poland (Śliwa-Cebula *et al.,* 2023).

Tree of Science

The study presents the networks generated from the study topics within the framework of the ToS algorithm. The science tree revealed the antioxidant capacity, phytochemicals, adaptation to salt stress, flavonoids, phytoremediation, and photosynthetic activity of *M. crystallinum*, and these topics were the most outstanding.

Table 3. Scientific production of the 10 best researchers.

No.	Investigator	Total items*	Scopus h-index	Membership
1	Miszalski Z	18	23	Władysław Szafer Institute of Botany of the Polish Academy of Sciences, Krakow, Poland
2	Cushman JC	17	63	University of Nevada, Reno, United States
3	Kuznetsov VV	14	27	Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, Moscow, Russian Federation
4	Barkla BJ	13	33	Southern Cross University, Lismore, Australia
5	Agarie S	12	19	Kyushu University, Fukuoka, Japan
6	Yen HE	10	15	National Chung Hsing University, Taichung, Taiwan
7	Nosek M	9	12	Uniwersytet Pedagogiczny im. Komisji Edukacji Narodowej, Krakow, Poland
8	Shevyakova NI	7	22	Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, Moscow, Russian Federation
9	Abdelly C	5	65	Center de Biotechnologie de Borj Cédria, Hamam Lif, Tunisia
10	Kuźniak E	2	twenty	University of Lodz, Lodz, Poland

*Scopus + Scielo + Science direct

Root

Nutritional value and cultivation of M. crystallinum *L.*

As the world's population grows, global food production rises, adding pressure on already scarce resources, such as clean irrigation water and cropland. Furthermore, increased soil salinity and dry conditions caused by climate change have become critical and adverse environmental conditions for crop plants (Zaghloul *et al.,* 2019). Therefore, it is of primary importance to study plant responses to salinity and drought to understand better the optimal conditions for the production of ice plants (*M. crystallinum* L.).

Ice plant, also known as glacier lettuce, is an edible annual succulent that belongs to the family Aizoaceae. Ice plants are native to the coastal regions of Southern Africa, with a wide distribution along the coastal areas of Europe, the United States, Mexico, Chile, the Caribbean, and Western Australia (Kim *et al*., 2018). Consumption of the said species as a leafy vegetable already exists in several countries, such as New Zealand, India, Germany, and the Netherlands. Reports of the medicinal value of the species leaf extract have come from Tunisian folk medical treatments for eye infections and as a remedy for throat and mouth infections. The leaf juice also helps relieve lung irritation, water retention, painful urination, and inflamed respiratory system. Therefore, the said species classification indicates it as a highly functional food.

Furthermore, the ice plant is also a considerable salt- and drought-tolerant species, with numerous laboratory experiments published elucidating the physiological and molecular mechanisms behind the individual effects of salinity and drought. However, the combined effect of these stress factors on *M. crystallinum* remains unknown. No past research on the subject exists, especially on the relative yields of minerals, phytochemicals, antioxidants, and proximate substances under different salinity levels.

Stem

***Antioxidant and phytochemical properties of* M. crystallinum**

The *M. crystallinum* extract showed significant antioxidant activity with a significant inhibitory effect. These interesting bioactivities could refer to specific polyphenols in its extract, mainly flavonoids that showed inhibitory effects against some enzymes (Kang and Joo, 2023).

Another vital characteristic of *M. crystallinum* is its ability to resist and extinguish oxidative stress because it has a powerful antioxidant system that includes enzymatic and non-enzymatic components. Enhanced synthesis of particular secondary metabolites under stress conditions possibly protects cellular structures from oxidative effects. Natural antioxidants were prevalent in all parts of *M. crystallinum*, and typical compounds that exhibit antioxidant activities include phenols, carotenoids, and vitamins. Among the various types of natural antioxidants, polyphenols constitute the chief powerful compound due to their multiple applications in foods, cosmetics, pharmaceuticals, and medicinal industries.

In *M. crystallinum*, stimulation of the synthesis and accumulation of polyphenols generally becomes a response to biotic and abiotic stresses, such as salinity, probably causing secondary metabolites to play a fundamental role in adapting halophyte species to this restriction. Past studies have shown that the amount of polyphenols and antioxidant activities in crop plants depend on biological factors (genotype, organ, and ontogeny) and edaphic and environmental conditions (Kim *et al*., 2018).

In Tunisia, identifying massive flora of halophyte species with multiple interests (food, forage, fuel, oil, wood, therapeutic pulp, and fiber production) transpired (Hwang *et al.,* 2019). For example, the facultative halophyte *M. crystallinum*, a prostrate succulent plant covered by large bladder cells that are salt accumulators, gave the plant a distinctive shiny appearance and is known for its antiseptic properties.

M. crystallinum response to the salinity

The ice plant (*M. crystallinum* L.) has become indistinguishable from the salt stress response model because of its systematic development under controlled environmental conditions and salinity. It can also address salinity by improving water use efficiency (Tran *et al*., 2020). Moreover, salinity responses result in physiologically active compounds, such as phenolics and flavonoids, consumed by people to prevent health problems (Haider *et al*., 2012; He *et al*., 2022).

Salt stress induces the accumulation of high concentrations of phytochemicals (d-pinitol, myo-inositol, and d-ononitol) in the cytosol. Considering the above facts, assessing antiradical and radical scavenging properties is vital to determine the basis of the phenolic concentration of ice plant extracts. As a result, this plant is highly tolerant of salinity and drought (Nishijima *et al*., 2017) evaluating the life cycle in soil with a NaCl concentration equivalent to seawater (500 mM), found that 500 mM NaCl showed a leaf growth rate similar to that of the control group (0.5 × Hoagland solution) within the initial five days of salt treatments and then delaying growth after seven days. Considering carbon fixation, salt-stressed ice plants have performed less carbon fixation compared with C3 plants. However, the studies showed that environmental conditions affected the growth of ice plants and bioactive compounds (compatible solutes, myo-inositol, and pinitol). Cultivation methods require developing under controlled environments to overcome these difficulties.

Production of edible *M. crystallinum*

Effective and sustainable technologies, combined with high economic value salt-tolerant crops, could be a viable way to recover the degraded coastal soils by mitigating salt stress, improving soil health, and increasing production per unit area. Therefore, introducing and cultivating ice plants, with their high salt tolerance and economic profitability, in the coastal soils could be options for a feasible approach to develop saline agriculture (Libik-Konieczny *et al*., 2017). Biochar has been a widely used multifunctional material for soil improvement and other types of environmental management. The multiple benefits of using biochar supplementing neutral and acidic soils have gained wide reporting. These include increased nutrient use efficiency, increased crop yields, and mitigation of greenhouse gas emissions.

Hypothetically, biochar could improve the growth of ice plants by enhancing the soil’s nutrient condition, altering soil properties and existing microorganisms in the soil, and alleviating salt stress (Hwang *et al.,* 2019). An experiment succeeded, using a pot and evaluating the effect of biochar individually and in combination with mineral fertilizer on the growth and quality of ice plants, evidencing the best photosynthetic performance and physiological responses to oxidative damage of ice plants grown with biochar**.**

Phytoremediation capacity of *M. crystallinum*

Proposing *M. crystallinum* as a suitable model for phytoremediation of degraded soils, especially the remediation of bottom sediments contaminated with heavy metals, is dependent on its unusual biochemical and physiological properties. It was due to high levels of antioxidant systems (low molecular weight enzymes) in *M. crystallinum*, which contributes to its resistance against heavy metal toxicity, resulting from various cellular reactions, especially those involving free radicals and reactive oxygen species. Also, generating large quantities of dicarboxylic and tricarboxylic acids (malate and citrate) under stress, especially in the phase of Crassulacean acid metabolism (CAM), can flow through the roots as exudates that enrich the soil (Śliwa-Cebula *et al.,* 2023). These compounds could also interact with metal ions produced within the rhizosphere, especially by binding cations. However, it can have a resilient, positive biostimulant action on the soil microbiota, whose interaction with the soil involves various mechanisms and can lead to altering the bioavailability of the elements (Nosek *et al.,* 2020).

In this sense, research progresses that carries out phytoremediation tests with the ice plant under laboratory conditions (Nosek *et al.,* 2019). The *M. crystallinum* L. can contribute to developing suitable methods for the phytoremediation of soils and waters contaminated with trace metals. However, limitations still exist to knowing the efficiency of phytoremediation in real contamination conditions because most documented studies involved different materials, such as urban sludge, sewage sludge, mixtures of sediments with soil, and generally contaminated with low concentrations of metals.

Interestingly, the sodium accumulated by *M. crystallinum* provides more support for adaptation capabilities in metal-contaminated bottom sediments (Amari *et al*., 2014). However, by examining phytoremediation with *M. crystallinum*, it was of particular interest to verify the potential for metal accumulation in plant tissues along with the removal of these contaminants from substrates. The said idea had support from previous studies showing the ability of *M. crystallinum* to absorb Ni, Cd, Cu, and Zn efficiently, and more recently, the Cd and Cr (Amari *et al.,* 2014; Nosek *et al.,* 2019).

Current and future challenges

After the scientometric analysis of the phytoremediation capacity and nutritional values of *M. crystallinum*, the need to investigate its potential uses in the food industry, especially its phytoremediation capacity to treat contaminated soils and water, can be evident. Therefore, new research requires applying *M. crystallinum* in producing noodles, drinks, jams, ointments, and baking products (Kang and Joo, 2023). Making prototypes should also adapt to the climate of each region and evaluate the contaminant removal capacity in tropical and subtropical areas. However, studies related to applying this type of vegetation in cold climates are still to be achieved, including implementing this vegetation in riparian areas in rivers and lagoons (Kang and Joo, 2023).

Likewise, the treatment of wastewater with *M. crystallinum* in rural areas and the reuse of its effluents as irrigation water requires investigation within the framework of a circular economy, which contributes to the need of each country to find water alternatives, which is also a source to develop agriculture, particularly critical in rural areas (Śliwa-Cebula *et al.,* 2023). The analysis of the recovered documents also made it possible to show that *M. crystallinum,* combined with other species to improve its phytoremediation capacity, revealed the need to continue researching and evaluating the synergy of several species in the treatment of contaminated soil and water (Pajuelo *et al.,* 2023).

Phytoremediation using *M. crystallinum* could help mitigate the impacts of climate change through soil reclamation and water purification. Other potential studies include evaluating microplastic remediation using constructed wetlands with *M. crystallinum*, estimating the carbon footprint caused by wastewater treatment, explore the possibility of using biomass extracted from wetlands as fuel and fertilizer, thereby reducing the need for synthetic fertilizers (Islam *et al*., 2022).

CONCLUSIONS

Highlighting the academic production of the United States, Japan, and Poland with 62 articles (49.6%) showed the importance of the ice plant (*M. crystallinum* L.). The authors Miszalski, Z., and Cushman, JC also excelled with 19 and 18 research publications, respectively. Considering all the described approaches for the processing and treatment of toxic bottom sediments with *M. crystallinum*, it is evident that efficient phytoremediation requires the choice of the most suitable variant of substrate formulation, followed by plant growth. In any case, applying the common ice plant could be beneficial in properly handling the material, i.e., allowing phytoextraction and the removal of potentially toxic elements from sediments and revitalizing the soils containing sediments.

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