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Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change

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Abstract:	The loss of agro-biodiversity, climate changes and food insecurity are major challenges in the Mediterranean countries with potentially multidimensional consequences. With respect to salinity, approximately 18 million ha, corresponding to 25% of total irrigated land in the Mediterranean area, are salt affected. Intensive cropping and the excessive use of expensive inputs such as water and fertilizers aggravate this situation. Understanding how we could improve crop productivity in salinized environments is therefore critical to face these challenges. Our comprehension of fundamental physiological mechanisms in plant salt stress adaptation has greatly advanced over the last decades. However, many of these mechanisms have been linked to salt tolerance in simplified experimental systems whereas they have been rarely functionally proven in real agricultural contexts. The sustainability of farming systems in salt affected Mediterranean soils can be effectively achieved by the use of salt-tolerant halophyte plants even more effective through the use of intercropping, crop rotation and aquaponics. Moreover, if these halophyte plants are removed from the soil to grow other species, pressure on generating salt-tolerant crop plants would be reduced and much healthier crop plants would be cultivated in less stressed saline soils. This paper will focus on the sustainable practices based on the cultivation of halophytes in saline soils by highlighting some experimental activities carried out at laboratory and field levels in the last few years.
Suggested Reviewers:	Hans-Werner Koyro Hans-Werner.Koyro@bot2.bio.uni-giessen.de He has a long experience with halophyte research.
	Tim Flowers t.j.flowers@sussex.ac.uk He has a long experience with halophyte research.
Response to Reviewers:	

Tunis, 22 July 2021

Dear Editor,

I herewith re-submit you a revised version of the manuscript entitled “Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change” to be considered for publication in Environmental and Experimental Botany.

The manuscript has been thoroughly revised according to the comments raised by the editor and two Reviewers of the previous submission, which have been very helpful to improve the review.

I hope this new revised version of the manuscript can now be acceptable for publication in Environmental and Experimental Botany.

Sincerely yours,

Karim Ben Hamed

Corresponding author

RESPONSES TO REVIEWER COMMENTS

The authors would like to thank to the reviewers for all comments and suggestions that greatly improved the quality and clarity of the manuscript. The responses to the comments of the reviewers are included below and required changes are made to the revised manuscript.

Editor comments:

In line with the comments from the referees, please also address my comments 1 to 5.

1) See if there is more recent literature on the extent of salinization in Europe (the references you quote are generally ten years old) and if there is not more recent data note this in your conclusions to the section.

Response: This information is now included in section 1 (Page (P): 3; Lines (L): 64-66)

2) Condense Sections 2 and 3 to a single short section highlighting those aspects of the physiology of halophytes relevant to title of your review. The adaptations seen in halophytes have been extensively reviewed.

Response: Sections 2 and 3 are now condensed to a short section (Section 2 in the revised Mn).

3) Section 4.1 and 4.2. Please combine these sections, tabulate the data available and evaluate the value of intercropping rather than describing published data. Tables are a valuable way of presenting data without the need for extensive text; the real value of a review is in drawing conclusions from ‘all’ the published data.

Response: Following the Editor’s request, these sections are now combined (Section 3) and details of results were tabulated (Table 1, Table 2).

4) Sections 4.3 is worthy of its own section as is Section 4.4. Section 5 should be integrated into the other sections

Response: Section 4.3 and 4.4 become section 4 and 5, respectively. Section 5 is now integrated into section 3, section 3.2 with a revised title “Potential uses of halophyte biomass, after desalination process”

5) Throughout please gather and analyse the data available to present conclusions rather than summarise already published data.

Response: Done

Reviewer comments:

Reviewer #1:

The authors submitted a manuscript with the title "Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change".

The title is very promising, the topic is relevant and the authors are authorities in their fields of research. In the highlight the original ideas are well reflected. Halophytes might be able to desalinize the soil and increase the productivity of corresponding (glycophyte) crop plants species. Therefore, some halophytic species might be suitable to be used as intercropping and rotating species to reduce soil salinity. Many Mediterranean halophytes are well accepted in the population because there is a tradition and therefore there is a demand on the Mediterranean market.

1) However, many parts of the review remain superficial without revealing new insights or directions.

Response: We revised the review accordingly.

2) Also the list of references is far from being complete and up-to-date.

Response: Done. We apologise for the missing references. All the references highlighted by the reviewer were checked. Some of them were correctly cited in the reference list while a couple of them were badly written and this prevented their matching in the list (as for Meyer, and Simpson). Others were indeed uncited and were added in the revised manuscript.

3) Actually, there is a disproportional number of articles from the labs of the authors included.

Response: We tried to cite the available references published by the different authors, that would be the most relevant to the focus topic of the review.

4) Chapter 3 and Figure 1 can be deleted because both contain known facts published many times already that are not relevant to the focus topic.

Response: According to reviewer's suggestion, Chapter 3 and Figure 1 of the original submission are now deleted.

5) The other figures are highly simplified as can be found like this in many textbooks. Here it would be important to design graphs or schemes that reflect, for example, the remediation effects of halophytes.

Response: Following the reviewer' suggestion, figure 2 and 3 were deleted, and replaced by a figure (Figure 1 in the revised Mn) that describes generally the remediation effects of halophytes on saline soils.

6) What is the fate of the plant material containing high salt concentrations after remediations processes? That is a major question not touched in detail here.

Response: Done. We agree with the reviewer about the importance of stressing this point and, accordingly, a paragraph on this aspect of phytoextraction was added in the revised manuscript. In this context, the cultivation of halophyte crops and their harvest for a productive use as fodder, feed, raw material for extraction of pharmaceuticals, food additives, etc., deserves a particular importance, contributing to effective removal (P5, L 116-140)

7) Tables containing species and data of intercropping and crop rotations systems, either successful or less successful results, from the Mediterranean area are essential for this review.

Response: Following the suggestion, one table (Table 1) is added, summarising the results reported in literature on intercropping and rotation systems. This way, description of results was a little bit rearranged, pointing mainly to discuss success or failure of these approaches.

8) Chapter 4.3. contains only 4 references although it is a very important topic and many more approaches are currently underway, in the middle east and elsewhere.

<u>Response:</u> According to this comment, this section (section 5 in the revised Mn) was improved.

9) For Chapter 4.4. many more successful examples can be described, maybe also summarized in a table.

<u>Response:</u> As required by the reviewer, in the revised manuscript we described more examples of halophyte aquaponics (Section 6) and integrated them into a table (Table 2).

10) Chapter 5 is titled "Economic applications…" but no economic data are included, only potential applications. Again, more facts would be of interest for the reader.

<u>Response:</u> This section is now inserted in section 3, as suggested also by the Editor, with a revised title "Potential uses of halophyte biomass, after desalination process"

11) Also the conclusion remains rather descriptive and vague and there are not clear recommendations or pleas.

<u>Response:</u> The conclusion was revised accordingly.

Minor

12) The paper is well written, there are only some spelling errors in species names and references.

<u>Response:</u> Done

Reviewer #2:

The review by Hamed et al. "Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change" is very interesting.

1) Nonetheless, I found things that need changing and/or need clarification or need to be rewritten for improved clarity. The requested changes are all highlighted in yellow, and the changes required shown in a sticky note, in the attached pdf.

<u>Response:</u> We thank the reviewer for all the valuable suggestions in the attached reviewer pdf file. We revised the Mn following the highlighted requests and addressed the questions and comments shown in this file.

2) Among them, please give a better discussion of the topic of soil desalination as mentioned in a few notes.

<u>Response:</u> Done. According to this comment and as you commented in the pdf file, soil desalination by halophytes was highlighted in section 2 and section 3 (P5, L116-140), also supported by a figure (Figure 1 in the revised Mn) that describes the possible remediation effects of halophytes on saline soils.

3) The figures need appropriate legends as those shown in the manuscript are inexistent or insufficient for a complete comprehension of them. Further, Figure 1 is not cited in the text.

<u>Response:</u> These figures are deleted.

4) There are several references missing in the bibliography and/or not well cited in the text.

Response: We apologise for the missing references. All the references highlighted by the reviewer were checked. Some of them were correctly cited in the reference list while a couple of them were badly written and this prevented their matching in the list (as for Meyer, and Simpson). Others were indeed uncited and were added in the revised manuscript.

5) Further, the text needs to be uniformised as the citations are properly formatted: they are cited in different ways.

Response: We have checked the format of the whole manuscript including the lack references and formating some references. All the literature cited has been checked in depth.

Highlights

- Halophytes can desalinize the soil and increase the productivity of crops
- Some halophytes are used as intercropping and rotating species to reduce soil salinity
- Many halophytes are efficient when they are integrated in aquaponic systems
- Many Mediterranean halophytes have potential multipurpose uses.
- Halophytes may find niches in the demanding Mediterranean market.

Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change

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Abstract

The loss of agro-biodiversity, climate changes and food insecurity are major challenges in the Mediterranean countries with potentially multidimensional consequences. With respect to salinity, approximately 18 million ha, corresponding to 25% of total irrigated land in the Mediterranean area, are salt affected. Intensive cropping and the excessive use of expensive inputs such as water and fertilizers aggravate this situation. Understanding how we could improve crop productivity in salinized environments is therefore critical to face these challenges. Our comprehension of fundamental physiological mechanisms in plant salt stress adaptation has greatly advanced over the last decades. However, many of these mechanisms have been linked to salt tolerance in simplified experimental systems whereas they have been rarely functionally proven in real agricultural contexts. The sustainability of farming systems in salt affected Mediterranean soils can be effectively achieved by the use of salt-tolerant halophyte plants even more effective through the use of intercropping, crop rotation and aquaponics. Moreover, if these halophyte plants are removed from the soil to grow other species, pressure on generating salt-tolerant crop plants would be reduced and much healthier crop plants would be cultivated in less stressed saline soils. This paper will focus on the sustainable practices based on the cultivation of halophytes in saline soils by highlighting some experimental activities carried out at laboratory and field levels in the last few years.

Keywords: Agriculture, aquaponics, biodiversity, crop rotation, domestication, halophytes, Mediterranean climate, intercropping, phyto-desalination, salinity, sustainability.

1. Challenges of agriculture in the Mediterranean area

The major challenge of agriculture in the world is to feed about 9.8 billion of individuals in 2050 and 11.8 billion in 2100. The situation becomes more challenging when today 690 million people are undernourished globally, with an additional 83 to 132 million people estimated in 2020 due to COVID -19 pandemic (FAO, 2020). Moreover, United Nations reports estimate that in 2050, 68 % of the population will live in the cities (United Nations, 2018). This means a decreasing number of farmers for a growing number of people to feed.

The Mediterranean region is one of the hotspots of the global biodiversity, with a remarkable richness in cultivated and wild species characterising this area. Its flora diversity has an outstanding from 15000 to 25000 species, 60% of which are unique to the region according to the International Union of Conservation of Nature IUCN (IUCN, 2008). Meanwhile, the Mediterranean basin is among the most threatened regions by climate change in the world (IUCN 2008). The Intergovernmental Panel on Climate Change (IPCC) predicts temperatures in the Mediterranean area will increase between 2 and 4°C, whereas rainfall will decrease between 4% and 30%, by 2050 (IPCC, 2013). This situation could be concomitant with the increasingly frequent events of drought, extreme climatic events and agro-biodiversity loss, with the northern side of the region experiencing similar conditions to those occurring today on the southern shores. The soils of the Mediterranean basin including European and African areas are characterized to be shallow, with low organic carbon contents, high $CaCO_3$ contents and therefore offer limiting availability for some nutrients such as iron leading to chlorosis in several crops (Lagacherie et al., 2018). The recent study published by Hassani et al. (2020) estimated that the area of salt-affected soils in Europe was 24 Mha being approximately 2.05% of the total salt affected area at worldwide level (1,171.8 Mha). Moreover, approximately 18 million ha, corresponding to 25 % of total irrigated land in the Mediterranean area, are salt affected (FAO, 2011). In Italy, salinization affects almost all regions, accounting approximately for 3.2 Mha of soil (Dazzi and Lo Papa, 2013). In Spain, about 3% of the 3.5 million hectares of irrigated land are severely affected by salts and another 15% is at serious risk (Acosta et al., 2011). In Tunisia, salinity affects 10 % of the total surface area and 20 % of irrigated lands. Water is a scarce resource in most of the Mediterranean countries. Nowadays, many southern Mediterranean countries exhibit water availability below the benchmark threshold of 1000 m^3/person/year. In addition, lower water availability than this threshold is also reported for some Northern countries such as Spain, Greece and Italy, although on average they exceed the 1000 m^3/person/year threshold (Mancosu et al., 2015). Agriculture is the main water-consuming sector, being responsible for about 70.7% of freshwater withdrawals, accounting for 45% in the North and 82% in South and East and weighs heavily on fertilizer consumption, estimated at 141.3 kg/ha (FAO and CIHEAM, 2015). Problems of sea water intrusion due to groundwater overexploitation are currently encountered in coastal areas of Italy, Spain, Greece and North Africa (Garcia-Caparrós et al., 2017; Payen et al., 2016). The decreasing availability of freshwater makes increasingly necessary the use of saline-sodic and/or of treated wastewaters for irrigation to sustain crop productivity, with the consequence of increasing the risk of soil and water salinization (Oron et al., 2002).

2. Improving crop productivity under salinity: Remediation effects of halophytes

The most effective solution to meet the growing demand for food is to increase the productivity of already cultivated lands (FAO, 2011). Nevertheless, this agricultural intensification is often associated with a high cost, a large consumption of water, energy and pesticides, in addition to soil depletion, loss of biodiversity and climate change. The current agricultural practices are increasing soil and water salinity, and unsustainable water use is leading to growing scarcity. As a result, many already dry and water-scarce regions have been hampered by more frequent droughts severely affecting agriculture. An average of 2,000 hectares of irrigated land in arid and semi-arid areas across 75 countries are degraded by salt every day and water scarcity already affects every continent (FAO, 2011). An alternative solution to palliate this environmental problematic may be the restoration of non-arable or marginal lands in the Mediterranean area and in areas such as North Africa and the Middle East.

Considered also as marginal lands, the salt affected agricultural soils in the Mediterranean region could be suitable for growing salt tolerant crops (Glenn et al., 1998). One of the key factors to improve salt tolerance of commercial crops cultivated in salt affected soils is to reduce the amount of salt transported from roots to shoots. This can be achieved by grafting a salt-sensitive cultivar onto a salt-tolerant one, and by conventional breeding. However, these approaches can have some limitations such as the reproductive barriers and the risk of undesirable traits transfer (Turan et al., 2012). Transcriptome sequencing may provide a functional view of the mechanisms to salinity tolerance. In addition, the use of transgenic plants to achieve information about the response of higher plants to salinity is a strategy widely addressed in numerous research groups (Hernández, 2019). Nevertheless, success has not been achieved at field level (Panta et al., 2014). Alternatively, soil phytodesalination, based on the capacity of some halophytes to accumulate enormous sodium quantities in their shoots, and latter removal is proposed as an innovative and cost-effective biological approach to desalinize the soil and to increase the productivity of salt sensitive crops (Debez et al., 2011; Koyro et al., 2014; Panta et al., 2014).

Halophytes are able to adapt to saline environments by different mechanisms. Halophytes have anatomical and physiological adaptations as well as an efficient metabolic responses to promote osmotic and homeostasis adjustment (Flowers and Colmer, 2008; 2015; Hasegawa, 2013; Bose et al., 2014; Acosta-Motos et al., 2017; Hernandez, 2019; Ben Hamed et al., 2020). From the point of view of phytoremediation, based on their salt tolerance, halophytes can use distinct mechanisms such as salt accumulation, excretion and salt exclusion (Figure 1). Salt accumulators are able to uptake and accumulate high total salts (more specifically sodium) in their tissues and to produce high aerial biomass. Salt excreting halophytes, absorb salts and excrete them by salt glands or bladders, conducting salts from the soil into the air. Salt excluding halophytes prevent salts from entering their tissues; resulting in low rates of salt translocation to shoots (Jesus et al., 2015). Since plant salt uptake in aerial biomass is key element for efficient remediation, accumulating and excreting halophytes would be more appropriate than excluding plants. Perennial accumulators would allow for a more prolonged period of salt accumulation throughout the year than annual ones. The root architecture and the growth rate of halophyte species represent key parameters for its suitability as phytoextractor. Moreover, many halophyte species are able to exude from roots several compounds stimulating soil microbial and enzyme activity favouring the decomposition of detritus to organic matter (Jing et al., 2019; Figure 1).

The fate of halophyte biomass, i.e. harvesting or leaving in the fields, is another important determinant of the success of desalting process. Plant, or at least shoot, harvesting would allow the more efficient salt removal. This aspect is important mainly in crop rotation programs, while in intercropping systems, because of the simultaneous growth with halophytes, crops are expected to benefit of the salt absorption regardless of the halophyte removal from the site. One major question in remediation programs is how to manage the salt-rich halophyte material. Depending on the plant species (herbaceous, shrub, or tree), the salt concentration, the harvested portion (i.e. stem-leaves or seeds), etc., the biomass may undergo different destinies, such as fodder, feed, edible oil, timber, fibre, biofuel, energy production, essential oils, source of bioactive compounds (Barreira et al., 2017; Agudelo et al., 2021; Turcios et al., 2021; Ozturk et al., 2019; Ortiqova, 2019; Castañeda-Loaiza et al., 2020; Stevanovic et al., 2019).

3. Alternative agricultural practices in salt-affected soils using halophytes

The reduced salt levels in the crop rhizosphere under halophyte cultivation would result in a better adaptation of the salt-sensitive plants to these extreme environments, allowing their cultivation in marginal underutilized lands or in salt-affected agricultural soils (Garcia-Caparros et al., 2020). Different strategies can be adopted to achieve this desirable outcome, such as halophytes integration in intercropping or rotation systems, which could require of domestication of some halophyte species or ecotypes particularly promising.

3.1. Halophyte use in intercropping and crop rotation systems

The use of intercropping systems in agriculture is a traditional practice diffused worldwide since long time, based on the evidence of reciprocal benefits and yield increase in comparison to the monoculture in a low input system (Glaze-Corcoran et al., 2020; Maitra et al. 2021). In intercropping systems, two (or more) crops are cultivated simultaneously in the same row, or in adjacent rows close enough for biological interaction, for an extensive proportion of their growth period. This cultivation method, that is still largely diffuse in developing countries, in the first world has been almost completely substituted by intensive monoculture systems, using high-yielding cultivars, mechanization, and massive application of chemicals (such as fertilizers and pesticides) (Machado, 2009, Ehrmann and Ritz, 2014, Maitra et al., 2021). Recently, however, the growing need of sustainable production systems, as well as the advances in the knowledge of the biochemical-physiological mechanisms at the basis of the success of intercropping cultivation, has attracted the interest of farmers towards the reintroduction of polycultures also in developed countries (Bracken, 2008; Gaudio et al., 2019; Glaze-Corcoran et al., 2020).

Particularly attracting is the use of halophytes as intercropping species to mitigate the salt stress for sensitive crops. By overcoming the limits for successful cultivation of cash crops in marginal areas, halophytes have the potential to enable more sustainable and resilient agriculture systems. Despite this increasing interest, few researches were conducted to validate the effectiveness of integrating halophytes in intercropping systems, and most of the published results were obtained in greenhouse experiments. Successful and unsuccessful responses obtained in intercropping experiments are summarised in table 1. A number of these researches used tomato (*Lycopersicon esculentum* Mill) as the cash crop species, being tomato one of the most cultivated species worldwide, particularly in the Mediterranean region. Tabulated studies mainly concentrated on the effects of *Suaeda salsa* L., *Salsola soda* L., *Portulaca olearacea* L. and *Atriplex hortensis* cultivation to improve tomato performance. Graifenberg et al. (2003)

highlighted one possible limit of the intercropping systems, *i.e*. the competition among intercropped plants for light, nutrients and water, ultimately leading to a crop yield lower than in monoculture.

Generally, the intercropping systems have been successful in ameliorating plant adaptation to salinity and in increasing crop yield under greenhouse conditions, while there is still the need to validate these results in field trials, because of the few studies conducted in open field and sometimes there is contradictory evidence(Table 1). Simpson~~s~~ et al. (2018) reported that, despite the good performance of *A. hortensis* L. and *P. oleracea* L. in greenhouse trials, these species were unable to reduce soil salinity in field conditions and to ameliorate plant water status and fruit quality of intercropped watermelon. Association of the two halophytes *Bacopa monnieri* L. and *Sesuvium verrucosum* improved the chemical and physical characteristics of a saline soil, allowing after 240-days desalting period, the co-cultivation of maize (*Zea mays*) with a yield of 8.5 t ha^{-1} (Lastiri-Hernández et al. 2020). In line with this, intercropping *S. salsa* with cotton under three-year field conditions significantly decreased soil salinity and bulk density, while increasing soil porosity, soil organic carbon, root growth, total aboveground biomass and cotton yield, when compared with conventional monoculture system (Liang and Shi, 2021). Similar results were obtained by intercropping cotton with *S. salsa*, *M. sativa* L., or *Cuminum cyminum* L. (Guo et al., 2020).

The mixed cultivation was adopted, and is still practiced, as subsistence farming, because of the reciprocal benefits between the two cultivated species in a low input system and the possibility to harvest at least one product in the case of one crop failure. In the case of halophytes intercropping, the latter benefit is less evident, though many halophytes are traditionally eaten or used as feed (Panta et al., 2014; Petropoulos et al., 2018 a, b). Additional uses and valorisation of halophyte biomass will be discussed in the next paragraph. In the case of forage, mixed cultivation has the advantage to complement the characteristics of the two species to obtain a product with better quality than a monoculture. An example of a successful intercropping of forage plants is reported by Hedayati-Firoozabadi et al. (2020), who tested the influence of irrigation with saline water on different planting ratios of sorghum (*Sorghum bicolor*), a high-quality forage crop, and kochia (*Bassia indica*), a halophyte species with low quality as forage. While under non saline irrigation the monoculture was the best choice, under saline conditions the intercropping system, particularly with the 2/1 sorghum/kochia ratio, resulted in a better quality in terms of reduced content of ash, neutral detergent fiber and acid detergent fiber. Similarly, an intercropping cultivation of the halophyte *Kochia scoparia* with two moderately salt tolerant fodder species (*Cyamopsis tetragonoliba* and *Sesbania aculeata*) was effective in reducing the negative effects of salinity and increasing the forage yield (Ghaffarian et al. 2020).

To maximize the productivity of an intercropping system, crops with different nutrient requirements, rooting ability, canopy shape and height, must be chosen, also taking care to avoid the onset of competition between species. In this context, it is important to highlight that halophytes could even increase soil salinity, because of retention of high transpiration rates under saline conditions, leading to drawing up of saline groundwater near coastal regions (Wendelberger and Richards 2017), with progressive increasing disturbance of crop growth.

Moreover, it is undoubted that intercropping systems, despite of their many advantages, require more manpower, considering most modern farm machinery (both for planting and harvesting) designed to work on monocultures (Maitra et al., 2021). While intercropping is based on the co-cultivation of different plant species, crop rotation, or sequential cropping, is set up on temporal succession of two or more crops (Dury et al., 2012). Therefore, crop rotation can encompass some benefits of both intercropping and monoculture. The basic principle of crop rotation is the cultivation of one crop able to restore the nutrients taken up by the previous one, in order to limit the use of fertilizers, thus reducing the environmental impact of agriculture. One well-known example is nitrogen restoration operated by leguminous plants grown in succession of cereals or other crops (Stagnari et al., 2017). Of course, rotation should also be economically sustainable, so the plant species used for the sequential cropping are usually chosen among the cash crops or the forage species, to ensure a constant income over time (Dogliotti et al., 2004).

In the case of halophytes, the economic profitability must go hand in hand with their desalting ability, which is the main benefit brought by their use as rotating crop. Halophyte-mediated desalting and fertilization of soils can be in fact exploited to allow a better growth performance of many cashcrops. Managing crop rotation in salt-affected soils needs to select suitable crops (species or cultivars) with varying degree of salt tolerance and high economic value to be grown after variable extent of soil reclamation achieved thanks to halophyte cultivation.

Ben Asher et al. (2012) demonstrated the effectiveness of SWAP (soil, water, atmosphere, plant) model to simulate crop rotation in saline environments, by comparing modelled and measured data derived from several experimental sites located in Israel, Turkey and Portugal, using lettuce as salt-sensitive species, and *Tetragonia tetragonioides* and *P. oleracea* as desalting species. These authors also highlighted the importance to know the maximum salinity level that can be tolerated by the desalting species without experiencing yield reduction and loss of economical income, in order to profitably include halophytes in crop rotation programs.

Examples of successful cultivation of crop species after desalting are reported in table 1. A small-scale experiment carried out in soil-filled pots proved the ability of *Sesuvium portulacastrum* L. to desalt~~ing~~ an experimentally salinized soil that, after plant removal, was used as substrate for barley (*Hordeum vulgare* L.) cultivation (Rabhi et al., 2010). This research demonstrated a better growth performance of barley and lower Na^+ and higher K^+ levels in its shoots, suggesting the possibility of a successful employment of this halophyte to restore salt-affected fields for a subsequent cultivation of glycophyte crops. The desalination potential of *S. portulacastrum* was also demonstrated in larger scale field plots (Muchate et al., 2016). Another small-scale field experiment showed that the plantation of *Spinacia oleracea* in saline soil considerably decreased the electrical conductivity of the soil over 90 days of plantation. Subsequent to this growth period, the phytodesalinized soil supported the significant growth of rice (Muchate et al., 2018).

Recently Barcia-Piedras et al. (2019) proved the effectiveness of *Arthrocnemum macrostachyum* as desalting species in artificially salinized soil under non-leaching conditions. Such a desalting activity resulted in earlier, faster and better emergence of barley, while wheat (*Triticum durum*), which is more salt sensitive than barley, was unable to germinate unless it was sown in remediated soils.

A successful remediation of saline areas was achieved thanks to a 4-year period of liquorice (*Glycyrrhiza glabra*) cultivation, after which the soils were returned to a cotton/wheat crop rotation (Kushiev et al., 2005). A noteworthy increase in the yield of both crops was achieved, demonstrating the capacity of liquorice in restoring abandoned saline soils into productive fields with a low-cost approach. Moreover, liquorice cultivation produced high quality forage and roots for pharmaceutical and beverage production, providing potential additional income to farmers.

Despite these encouraging reports, the massive literature on the desalting properties of the halophytes and their ability to improve soil structure and fertility, very few studies have validated such potential on the growth and yield of a glycophytic crop cultivated in succession with halophyte. Accordingly, there is a need to additional tests, particularly under field conditions, to confirm and optimize the sustainable use of halophytes in crop rotation systems in marginal degraded lands.

3.2. Potential uses of halophyte biomass, after remediation process

Halophytes are abundant in Mediterranean coastal areas and can cope with adverse stressful conditions, such as high salinity and intense UV radiation intense UV radiation (40-60 Wm^{-2}

UV-A and 2-3 Wm^{-2} UV-B), partially due to the synthesis of several bioactive secondary metabolites, as for example phenolic compounds and alkaloids (Hupel et al., 2011). Besides their protective role for the plant, these molecules display important biological activities, including anti-oxidant, anti-inflammatory, antidiabetic and neuroprotective, which may explain the several ethnomedicinal and-veterinary uses of different halophyte species (Ksouri et al., 2012; Arya et al., 2019, Oliveira et al., 2021). For example, *Salicornia* L. species (sea asparagus) are used in traditional medicine against obesity and diabetes while *Crithmum maritimum* L. (sea fennel) and *Portulca olearacea* (common purslane) are used as diuretic and antiscorbutic (Pereira et al., 2017; Hwess et al., 2018). Being rich in mineral salts and having high water content, *P. olearacea* also has soothing properties for irritations of the bladder and urinary tract (Hwess et al., 2018). Another study shows that purslane vegetable contains high levels of omega-3 fatty acids for a land vegetable, as well as significant amounts of vitamin A, vitamin C, magnesium, potassium, calcium and iron (Simopoulos et al., 2004).

Halophyte's ethnomedicinal uses and chemical richness opens a cornucopia of naturally available bioactive products with a high added value in different commercial segments like the food, veterinary and pharmaceutical industries. Several Mediterranean species are edible and highly procured in the food industry due to their nutritional properties (Petropoulos et al., 2018 a; b). This is the case of *Arthrocnemum macrostachyum* reported for its high commercial value and highly valued in gourmet cuisine (Barreira et al., 2017). *Helichrysum italicum* subsp. *picardii*, *Crithmum maritimum*, and *Artemisia campestris* subsp. *maritima* are potential sources of herbal health-promoting beverages (Pereira et al., 2017a; b; Pereira et al., 2018). Other Mediterranean species like *Lithrum salicaria* and *Polygonum maritimum* are source of raw material for pharmaceutical and other related industries (Lopes et al., 2016; Rodrigues et al., 2018). A recent review by Oliveira et al. (2020) showed that essential oils in halophytes can be used as animal feed additives to improve ruminant health and productivity. Some anti-nutritional compounds like saponins, tannins and flavonoids can have anthelminthic and anti-bloat properties, besides their possible effects on the ruminal biohydrogenation and fermentation patterns and on the management of oxidative-related disorders (Oliveira et al., 2021). This novel line of research would deliver sustainable and integrative alternatives for veterinary practices.

From all the above referred it is easy to deduce that halophyte plants may find niches in the demanding market for novelties, as for example as herbs, vegetables, fresh gourmet products, and animal feed. One challenge that limits halophyte cultivation is the lack of knowledge about consumers' acceptance of halophyte products, which are fundamental to the commercialization of halophytes because farmers will start investing in the crop only if there is marketing potential

(Centofanti and Banuelos, 2019). Halophyte's species will take a little to make people believe that they are good food for them, although some are used by certain communities for this purpose (Menzel and Leith, 1999). However, there are potentials to extract good quality oil from them (Weber et al., 2007), they could also serve as a source of feed, fiber and forage and this would not have any problem of acceptability.

To take halophytes from the laboratory to the farm and thus scale up its production, it is also important to create a value chain, which allows for the production of fresh and processed halophyte-based food products. To increase profitability of halophyte cultivation, there is a need for a whole system to add more value to halophyte-based food products in addition to practices that increase its yields. It is also necessary to build public awareness and increase consumer knowledge about the nutritional and health benefits of halophyte-based food products.

4. Halophyte domestication

Besides the use of halophytes in intercropping or rotation systems, two possible approaches to achieve a saline agriculture are: i) improving the salt-tolerance of cultivated crops, or ii) domestication of halophytes. An update on molecular strategies for the generation of salt-tolerant crops using halophytes for interspecific hybridization or as donors of candidate genes for glycophyte transformation is reported by Ferreira Barros et al. (2021). Moreover, evidence is accumulating on the potential of halophyte root microbioma to improve the salt-tolerance of non-host crops, as demonstrated, for example, in rice and cucumber seedlings colonised by rhizospheric bacteria or endophytic fungi isolated from *S. soda* (Yuan et al., 2016).

Domestication of halophyte is a needed step for profitable cultivation of these species. A major impediment to their massive use in agriculture is the standardization of their performance, being halophytes mainly wild plants. Another constraint is the need to ensure the farmers the availability of a constant supply of the most suitable species. However, the main limit is probably related to the low growth rate, uneven seed germination, and the accumulation of toxic or bitter compounds in their tissues, characters that in cash crops species have been ameliorated by the long-term process of domestication (Gepts, 2004). Brown et al. (2014) discussed a strategy for domestication of wild halophytes for their employment as seawater-irrigated crops, based on the approaches used for domestication of other wild species. One first aspect identified by these authors is the better performance of halophytes in environments similar to those where they usually grow in nature. Accordingly, a prerequisite for their successful domestication is the choice of the wild species based on the location where the cultivation might be set up. In other words, latitude, environmental parameters, proximity to the coast, and other characteristics of the native place of the wild species must be as similar as possible to those of the agronomic fields where the crop might be grown. Also, a good knowledge of the life cycle of the wild species in their native environment is pivotal in driving the choice of the best candidate species. After this first step, several crop cycles must be operated until the occurrence of the so-called domestication syndrome, i.e. the modification of those traits indicative of the divergence of the cultivated species from its wild ancestor towards domestication, such as synchronization of flowering, fruit ripening, seed germination, loss of bitterness, reduced content of toxic compounds, increased fruit and seed size (Meyer~~s~~ et al., 2012). Another important objective of plant domestication is the shift of the metabolic resources towards aboveground, economically interesting, organs (leaves, fruit and seeds). Domestication via mass selection takes many generations of crosses and requires several experiments, sometimes unsuccessful and often lasting decades. Besides, it would allow fixing only few desirable traits. However, it allows selection of parent lines for selective breeding programs. An example of this approach in halophyte domestication is reported by Zerai et al. (2010), who adopted two breeding programs involving also hybridization and pedigree breeding, producing cultivars of *Salicornia bigelovii* Torr with a noteworthy phenotypic variability and higher seed yields or higher biomass yield, in the lines selected by Eritrea or Arizona breeding programs, respectively. The research proved the feasibility of developing a halophyte crop by conventional breeding methods though none of these lines were tested in open field conditions and introduction of additional traits such as lowering of toxic compounds in the edible parts of the plant, resistance towards biotic stress, reduced plant size to cope with lodging, synchronization of flowering and seed production, improved retention of seeds, rapid germination, strong growth and vigor is desirable.

A successful example of halophyte domestication is represented by quinoa (*Chenopodium quinoa* Wild.), a pseudocereal that has about 2500 accessions and a great agronomic potential. Indeed, it is increasingly cultivated globally thank to its good nutritional value and high tolerance to salinity and other environmental stresses (Zhou et al. 2017).

A prerequisite for a successful use of halophytes as crops is the genetic characterization of the accessions collected from different sites, aimed to the development of well characterised lines for breeding, together with the definition of the optimal conditions for seed germination and plant cultivation. Singh et al. (2014) performed an extensive characterization of *Salicornia* and *Sarcocornia* spp, followed by germination trials and cultivation of selected accessions in hydroponics (with or without sand as a supporting medium) with different salinity levels up to harvestable size, to evaluate the optimal growth conditions. This study allowed to detect high physiological plasticity in *S. dolichostachya* and, accordingly, a potential cultivation under low-to-high salinity conditions, both under flooded and drained environment, while *S. ramosissima* was more suitable for dry areas. Moreover, seed dimorphism of *Salicornia* spp. did not affect timing of germination, thus preventing the need for growers to separate seeds into small- and large-size groups before sowing. To maximise biomass production, delaying flowering is mandatory. The critical day length required to inhibit flowering depend on ecotypes and it is generally higher for genotypes from northern latitudes. It is therefore important to select the right genotype-light regimen combination to maximise vegetable production.

Ventura and Sagi (2013) highlighted the difficult to generalise the salt tolerance mechanisms and the growing performance studied in small scale experiments to the real cultivation under agricultural field conditions. However, in the case of *Salicornia* and *Sarcocornia*, many greenhouse and field experiments were performed, and different cultivation systems have been already tested, varying irrigation system, daylength, harvest regimen, making these plants a sort of model for the development of other halophyte species whose commercial cultivation is still at its beginning. These authors also suggest that investigating the halophyte behaviour directly in filed studies and, even better, directly in the farmer's fields, would fasten the domestication process and the profit generation.

The improvement of crop characteristics by plant breeding is just at the beginning for halophytes, so many efforts are still to be done to achieve the desirable goal of making halophytes increasingly adaptable to sustainable farming systems. A possible difficulty in the domestication programs could derive from the limited availability of germplasm collections to sustain the breeding tests. Therefore, it is mandatory to collect and preserve valuable germplasm as a pre-requisite for research and breeding programs.

However, the recent advances in identification of the genetic traits associated with salinity tolerance pave the way for an efficient and accelerated selection of the most promising parent lines without the necessity of laborious and time-consuming screening procedures, and for the improvement of the wild plant genetic resources, once demonstrated the inheritability of these traits.

5. Halophyte aquaponics

The capacity of halophyte plants to uptake great amounts of salt ions and to adapt to extreme environments, hardly suitable for conventional crops, makes them optimal candidates for the design of marine aquaponics systems. Aquaponics is a multitrophic food production system integrating aquaculture, *i.e.*, fish (or other aquatic animal species) farming, with hydroponic plant production (König et al., 2018).

A recent review by Custodio et al. (2017) evaluated the information deriving from published researches on halophyte ability to remediate effluents from aquaculture systems. The most studied species were *Aster tripolium* (5 studies), *Salicornia europaea* (4 studies), *Phragmites australis* (3 studies) and *Salicornia dolichostachya* (2 studies). The experiments were set up in different geographic areas with diverse climates and generally reported significant removal of nutrient loadings supporting the potential of profitable incorporation of these plants into integrated multi-trophic aquaculture (IMTA) systems. Alternatively, constructed wetlands (CWs) planted with halophytes demonstrated a good removal efficiency of total N and P, sometimes approaching the total elimination (Buhmann and Papenbrock, 2013; Lymbery et al., 2006, Webb et al., 2012).

Many studies on the integration of halophytes in aquaculture systems have been already published; few of them were listed in Table 2. Several examples were successful in decreasing many indexes of water pollution, among which the biological oxygen demand (BOD) and both nitrate and nitrite N (Lin et al., 2003). However, they were very low efficient in phosphate removal, probably due to the high hydraulic loading and/or the low phosphate uptake by some halophyte species. Previous studies reported a more efficient phosphate removal, that was inversely related to the hydraulic loading, by a combination of *Phragmites australis* with two other halophyte species, *Ipomoea aquatica* and *Paspalum vaginatum* (Lin et al., 2002a, b).

Boxman et al. (2017) highlighted the need to optimize the conditions of the aquaponic system that integrates the most appropriate halophytes. They observed a positive contribution of *Sesuvium portulacastrum* and *Batis maritima*, grown hydroponically in diluted sea water, in lowering the nitrate levels of water effluents deriving from the platy fish (*Xiphophorus* sp.) tank. The same authors (Boxman et al., 2018) also proved the effectiveness of these halophyte species to support red drum (*Sciaenops ocellatus*) farming in a prototype, commercial-scale marine aquaponic system that included a moving bed bioreactor (MBBR) for nitrification and a sand filter for solids removal and denitrification (Table 2). An efficient growth performance of whiteleg shrimp (*Litopenaeus vannamei*) and some halophytes (*Atriplex hortensis*, *Salsola komarovii* and *Plantago coronopus*) was achieved by Chu and Brown (2021) in a marine aquaponic system by adjusting salinity to a compromise level compatible for both the animal and the plant species (Table 2). The results obtained reported a better growth performance of the shrimp (higher final weight and weight gain rate) under higher saline conditions, whereas in the case of halophytes, the trend was the opposite with a lower growth under higher saline conditions and also a reduction of nutrient uptake. Accordingly, the intermediate saline condition (i.e., 15 ppt) was suggested as the optimal condition for the development of shrimp-halophyte marine aquaponics (Table 2).

In the case of super intensive fish or shrimp farming, the nutrient load of the effluents may be efficiently reduced by the combination of halophyte cultivation with polychaete-assisted sand filters (Marques et al. 2017).

However, despite water effluents from aquaculture is a rich source for most macronutrients, plants cultivated in aquaponic system could suffer micronutrient deficiency, that may reduce the commercial production of halophyte biomass. The fast growth rate in a nutrient-rich environment needs integration of the limiting nutrient, like molybdenum for *S. europaea* (Ventura et al. 2010), iron for *Salicornia dolichostachya* (Singh et al., 2014), *Aster tripolium* (Ventura et al., 2013) and *Apium graveolens* (Sbai and Haouala, 2018). However, species-specific response to micronutrient supplementation in a saline aquaponic system was reported by Doncato and Costa (2021), who observed increased growth and biomass production of *Paspalum vaginatum* Sw. while *Salicornia neei* Lag. was unaffected by mineral supplementation in water and even underwent an important reduction of shoot biomass following foliar fertilization. Interestingly, Maciel et al. (2020) observed a modification of the lipidome of two halophytes (*Salicornia ramosissima* and *Halimione portulacoides*) cultivated in a marine aquaponic system in comparison to the wild populations. Specifically, both halophytes presented higher levels of glycolipids (and *H. portulacoides* also of phospholipids) bearing n-3 fatty acids, that undoubtedly increase the market value of these species, having the n-3 polyunsaturated fatty acids recognised healthy properties (Shahidi and Ambigaipalan, 2018).

In the light of the few examples reported above, it emerges that halophytes could be successfully integrated in marine aquaculture systems to meet the need to increase the production of fishes, crustaceans and molluscs in a sustainable and economically profitable way, promoting integration of green and blue revolution.

Conclusion

Nowadays, the use of the modern genetic engineering tools is allowing the development of high salt tolerant cultivars but due to the long term required to obtain them and the high degree of soil salinity in several parts of the world, the use of halophytes seems to be one of the most feasible option to feed the population. These halophytes can be used for the restoration of saline soils mainly due to the physiological and biochemical characteristics triggered by them over the evolution compared to the glycophytes allowing them the survival under these harsh conditions. Different alternative agronomic practices including halophytes such as intercropping or rotation implemented at worldwide level are giving promising results level in terms of yield and quality in cash crops species mainly related to the reduction of soil salinity levels exerted by halophytes. This fact led us to continue with this research line conducting different cropping systems for their establishment in the Mediterranean arid and semi-arid regions. Not only at agronomic level halophytes can be of special interest since they can be combined simultaneously with the production of animal aquatic species in marine aquaponics systems offering to the population a dual system of feeding (crops and marine species) with reduced environmental impact. Besides, halophytes are an invaluable source of nutraceutical and medicinal compounds which many of them are still unknown. The successful adoption of sustainable halophyte farming systems will offer to the worldwide population new sources of food with interesting healthy properties as well as an environmental solution to restore the biodiversity severely affected by the human action and climate changes.

Credit author statement

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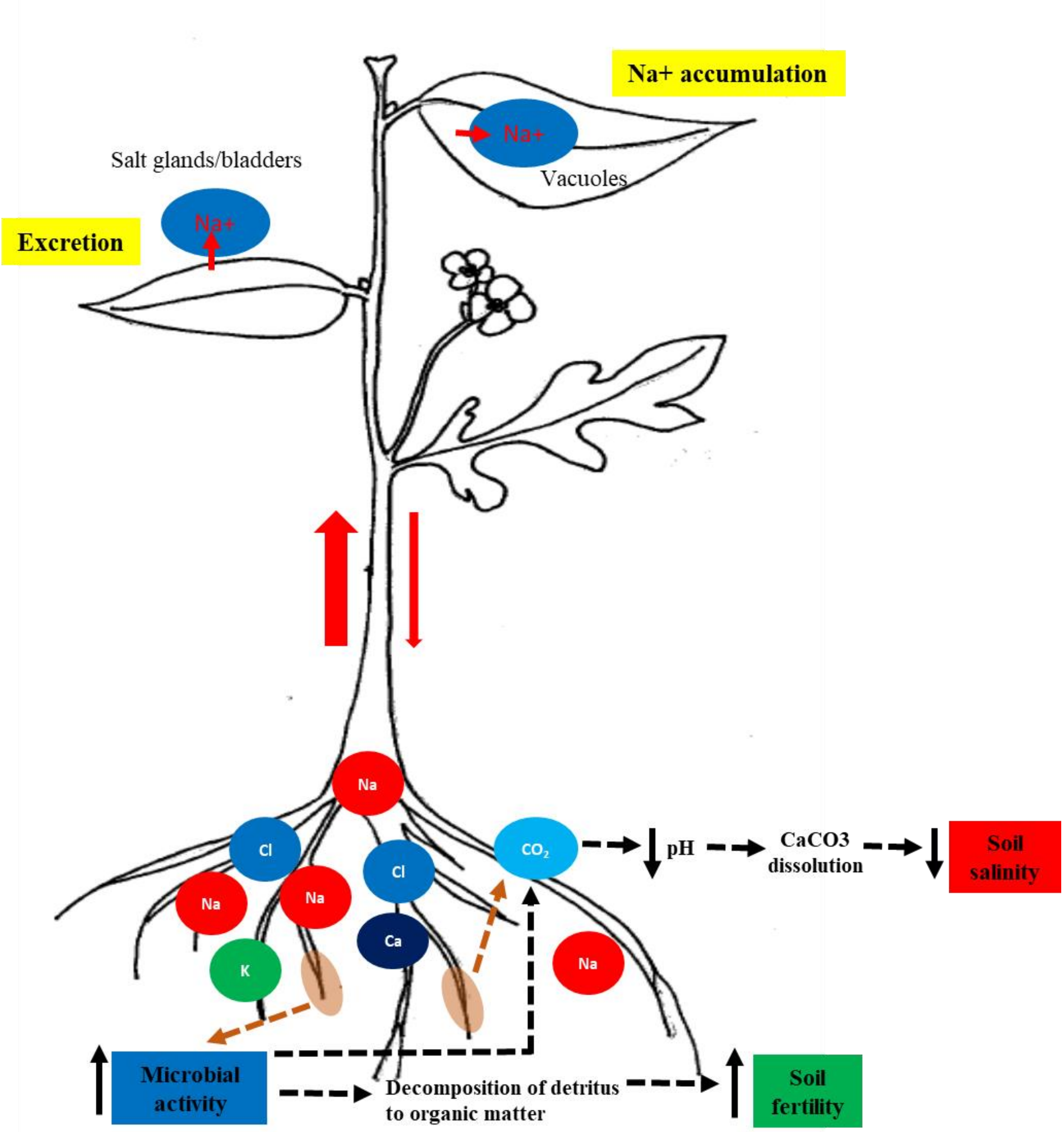

Figure 1. Remediation effects of halophytes on saline soils.

Table 1. Examples of successful and unsuccessful use of halophytes in intercropping (IC) and crop rotation (CR) systems, carried out under greenhouse conditions (G) or in field experiments (F)

Halophyte species	Crop species	Cultivation system	Experimental conditions	Successful responses	Unsuccessful responses	References
Suaeda salsa L.	*Lycopersicon esculentum* Mill	IC	G, closed insulated pallet	lower Na levels in the root medium and tomato leaves lower incidence of blossom end rot of tomato fruit	no effect on tomato growth reduction no effect on reduced tomato yield	Albaho and Green (2000)
Salsola soda L. *Portulaca oleracea* L.	*Lycopersicon esculentum* Mill	IC	G, soil-filled benches	higher PO_4^{3-} and Ca^{2+} uptake by tomato plants reduced Na level in tomato leaves higher tomato yield	lower tomato growth and yield by high sowing density of the halophytes	Graifenberg et al. (2003)
Portulaca oleracea L.	*Lycopersicon esculentum* Mill	IC	G, sandy soil-filled benches	higher tomato yield higher K absorption		Zuccarini (2008)
Salsola soda L.	*Lycopersicon esculentum* Mill	IC	G, sandy soil-filled benches		lower tomato plant biomass and lower fruit yield halophyte competition	Zuccarini (2008)
Atriplex hortensis L.	*Lycopersicon esculentum* Mill	IC	G, sandy soil-filled benches	higher tomato yield		Zuccarini (2008)
Portulaca oleracea L.	*Lycopersicon esculentum* Mill	IC	G, soil-filled pots	lower Na levels in tomato leaves and roots higher Ca and Mg levels in tomato leaves and roots higher K in tomato leaves	no effect on reduced fruit weight	Karakas et al. (2019)
Salsola soda L.	*Lycopersicon esculentum* Mill	IC	G, soil-filled pots	higher fruit weight under high salinity lower Na levels in tomato leaves and roots higher Ca and Mg levels in tomato leaves and roots higher K in tomato leaves		Karakas et al. (2019)
Salsola soda L.	*Capsicum annuum*	IC	G, hydroponics	higher fruit yield under moderate salinity	no effect on reduced fruit yield under severe salinity	Colla et al. (2006)
Mesembryanthemum crystallinum	*Vigna unguiculata*	IC	G, soil-filled plastic trays plus hydroponics	lower Na levels in soil and cowpea leaves lower chlorophyll loss lower decrease of photosynthesis rate		Nanhapo et al. (2017)
Atriplex hortensis L.	*Citrullus lanatus* (Thunb.)	IC	F, saline irrigation	higher watermelon yield	no reduction of soil salinity no effect on plant water status and fruit quality	Simpsons et al. (2018)
Portulaca oleracea L.	*Citrullus lanatus* (Thunb.)	IC	F, saline irrigation		no reduction of soil salinity no effect on plant water status and fruit quality lower watermelon yield (possible competition)	Simpsons et al. (2018)
Bacopa monnieri (L.) Wettst *Sesuvium verrucosum* Raf	*Zea mays*	IC	F	lower soil EC and pH higher soil porosity maize cultivation with high yield		Lastiri-Hernández et al. (2020)
Suaeda salsa Medicago sativa L	*Gossypium hirsutum* L.	IC	F	lower soil EC, salt accumulation and pH higher soil porosity and organic carbon content higher root mass density and cotton yield		Liang and Shi (2021)

Suaeda salsa Medicago sativa L. *Cuminum cyminum* L.	*Gossypium hirsutum* L.	IC	F	lower soil salt accumulation	no effect on cotton yield and biomass	Guo et al. (2020)
Bassia indica	*Sorghum bicolor*	IC	F, different planting ratios	better quality, particularly with the 2/1 sorghum/bassia ratio	lower sorghum yield with 1/2 sorghum/bassia ratio due to halophyte competition	Hedayati-Firoozabadi et al. (2020)
Kochia scoparia	*Cyamopsis tetragonoliba* *Sesbania aculeata*	IC	F	higher leaf K levels, water content and chlorophyll higher forage yield in simultaneous intercropping with *C. tetragonoliba* and . *aculeate*		Ghaffarian et al. (2020)
Sesuvium portulacastrum L.	*Hordeum vulgare* L.	CR	G, Soil-filled pots	lower shoot Na levels higher shoot K levels and higher biomass production		Rabhi et al. (2010)
Spinacia oleracea	*Oryza sativa*	CR		Lower soil EC significant growth of rice		Muchate et al. (2018)
Arthrocnemum macrostachyum	*Hordeum vulgare* L. *Triticum durum*	CR	G, artificially salinized soil	lower Na levels in soil earlier, faster and better emergence of barley wheat germination		Barcia-Piedras et al. (2019)
Glycyrrhiza glabra	*Gossypium hirsutum* L./*Triticum aestivum* L.	CR	F	lower Na levels in soil higher soil organic matter higher percentage of seed germination and yield		Kushiev et al. (2005)

Table 2. Examples of successful and unsuccessful use of halophytes in aquaponic systems. CW, constructed wetland; FWS, free water surface; SF, subsurface flow; RAS, recirculating aquaculture system; MBBR, moving bed bioreactor; BOD, biological oxygen demand; SS, suspended solids; TAN, total ammonium; DIN, dissolved inorganic nitrogen, DIP, dissolved inorganic phosphorus, TDN, total dissolved nitrogen.

Halophyte species	Aquatic animal species	Aquaponic system	Successful responses	Unsuccessful responses	References
Salicornia europaea L.	shrimp, sole and turbot	CW pilot filter beds integrated into a RAS	lower DIN under ambient nitrogen loading lower DIP	no significant removal of DIN under high TDN loading	Webb et al. (2012)
Juncus kraussii	rainbow trout (*Oncorhynchus mykiss*)	pilot-scale CW, SF	lower nitrogen and phosphorus active uptake by the soil-plant ecosystem increase with high nutrient levels. no effect of salinity on N removal	reduced P removal by salinity reduced growth of *J. kraussii* by salinity	Lymbery et al. (2006)
Phragmites australis	Pacific white shrimp (*Litopenaeus vannamei*)	pilot-scale CW unit: FWS and SF CWs arranged in series, integrated into an outdoor RAS	lower BOD$_5$, SS, TAN, nitrates and nitrites	scarce phosphate removal	Lin et al. (2003)
Sesuvium portulacastrum *Batis maritima*	platy fish (*Xiphophorus* sp.)	bench-scale marine aquaponic systems	lower nitrate and nitrite levels in water effluents		Boxman et al. (2017)
Sesuvium portulacastrum *Batis maritima*	red drum (*Sciaenops ocellatus*)	prototype, commercial-scale marine aquaponic system with MBBR and sand filter	efficient removal of N load prevention of nitrate accumulation production of organic fertilizer support of a high fish biomass density production of edible halophyte biomass		Boxman et al. (2018)
Atriplex hortensis *Salsola komarovii* *Plantago coronopus*	whiteleg shrimp (*Litopenaeus vannamei*)	marine aquaponic system	higher salinity: better growth performance of the shrimp hower salinity: better growth performance of the halophytes intermediate saline condition: optimal condition for the integrated shrimp-halophyte marine aquaponics	higher salinity: lower growth of halophytes and reduced nutrient uptake lower salinity: lower growth of the shrimps	Chu and Brown (2021)
Halimione portulacoides	flatfish (*Solea senegalensis* Kaup)	land-based aquaponic system with sand filter hosting the polychaete *Hediste diversicolor*	lower organic matter and DIN		Marques et al. (2017)
Salicornia neei Lag. *Paspalum vaginatum* Sw *Apium graveolens* L	Pacific white shrimp (*Litopenaeus vannamei*)	saline aquaponic system integrated or not with micronutrient supplementation in water or as foliar spaying	higher growth and biomass production of *P. vaginatum* with micronutrient supplementation in water	scarce development of *A. graveolens* plants in this aquaponic system no effect on *S. neei* growth by microutrient supply in water lower shoot biomass of *S. neei* by foliar fertilization lack of knowledge on the toxicity of water supplemented with micronutrients to animals	Doncato and Costa (2021)

Conflict of Interest

The authors declare that they have no conflict of interest.

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