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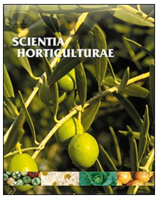

Seawater potential use in soilless culture: A review

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ABSTRACT

Available freshwater counts on less than 1% of the water on Earth and of such share an average of 70% is absorbed by the agricultural sector. Since the rhythm of freshwater withdrawal is faster than its regeneration, measures have to be taken in order to preserve such an important resource. The use of seawater in soilless culture is an interesting option to limit freshwater withdrawal for food production, with any additional negative imput into soils. The present review aims at describing the state of the art of seawater as an irrigation complementary source in soilless culture, providing a critical overview on the available information on the subject and on the potential and constraints of its implementation at a commercial level.

1. Introduction

Belonging to the renewable, though finite, resources, water counts on Earth about 1.4 billion cubic kilometers in total, as both surface or underground water (FAO, 1995). Of this amount, seawater represents about 97% while almost 2% is locked in ice. Accordingly, available freshwater counts on less than 1% (FAO, 1995), and among the many uses to which it is destined, the agricultural sector absorbs an average of its 70%, reaching up to 90% in the Middle-East and North Africa (MENA) regions (SDSN, 2013). In addition to that, the increasing population will further augment the pressure on the Earth's natural resources (FAO, 2017). Since the rhythm of freshwater withdrawal is faster than its regeneration, measures have to be taken in order to preserve such an important resource. Alternative water sources for irrigation can represent a valid help for the preservation of the already overexploited freshwater. In particular, seawater is considered a realistic option in agriculture, either desalinized or blended with freshwater (Yermiyahu et al., 2007).

Even if in recent years numerous large-scale seawater desalination plants have been built, such a technique is anyhow very energivourous and thus presents environmental concerns (Elimelech and Phillip, 2011). Besides, desalination cost has decreased because of technical improvements in a world of increasing fossil fuel prices (Karagiannis and Soldatos, 2008). Nevertheless, in developing countries, often characterized by water shortage, desalination has been generally excluded because of the economic conditions (Wade, 2001). A different option is to use seawater as a complementary irrigation source at concentrations not harmful for the cultivated crops.

Seawater is the most abundant source of water of the planet and its specific composition represents a well balanced ionic environment for plants (Boyko, 1966): in fact, despite its very high chloride content (about 75% NaCl and 10% of $MgCl_2$), seawater is rich in all nutritive elements needed by plants, as reported in Table 1 (Hoagland and Arnon, 1938). It also includes the necessary trace elements and micro-organisms, living or dead (Boyko and Boyko, 1966; Eyster, 1968). It is also found in scientific literature that plant salt tolerance when treated with seawater seems to be multiplied compared to NaCl solutions treatments at comparable electrical conductivity (EC) in the majority of species (Boyko and Boyko, 1966). Nevertheless, such statement has not been supported enough by further specific investigations up to day, even if the results of an experiment on red leaf lettuce suggest a similar assumption (Sakamoto et al., 2014). According to Breckle (2009), a large scale sustainable agriculture relying on pure seawater is not feasible for several reasons, among which the sodium concentration of full strength seawater resulting in toxic effects for the majority of species and in the deterioration of soil structure, especially without an efficient leaching system. On the other hand, we assist to a recent return to studies investigating such a possibility with the aim of recovering lost coastal soil while minimizing inputs (i.e. freshwater). Again according to Breckle (2009), small-scale seawater irrigation may be suitable and economically viable, as for example on anyhow saline coastal areas. Among these recent studies in this direction, a latter-day discovery regards a new strain of rice developed by the Chinese scientist Yuan Longping and his research group giving a higher yield compared to most commercial U.S. harvests when grown at a salinity of 10% seawater (Brueck, 2018). Furthermore, an accurate report on the seawater tolerance of potato, cabbage, onion, carrot, lettuce and barley crops tested in open field experiments in The Netherlands was recently published (de Vos et al., 2016). The results showed that irrigation water up to a salinity level of 5–7 $dS\,m^{-1}$ can be

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Table 1
Main mineral elements composition of Hoagland nutrient solution and of seawater.

Hoagland		Seawater	
	ppm		ppm
N	210	N	0.9
K	235	K	380
Ca	200	Ca	400
P	31	P	0.1
S	64	S	884
Mg	48	Mg	1272
B	0.5	B	4.6
Fe	1 to 5	Fe	0.02
Mn	0.5	Mn	0.01
Zn	0.05	Zn	0.014
Cu	0.02	Cu	0.09
Mo	0.01	Mo	0.002
		Na	10561
		Cl	18980

used for crop production of some varieties of the tested crops without any yield loss (de Vos et al., 2016). Seawater as a complementary source of irrigation, despite its several constraints, seems to answer to the need of sustainable and resources-saving practices in agriculture. Quoting the words of prominent experts: the heart of new agricultural paradigms for a hotter and more populous world must be powered and irrigated as much as possible by sunlight and seawater (Fedoroff et al., 2010).

On the other hand, irrigating with seawater on fertile and well-structured soils would lead to a salt contamination occurring through Ca^{2+}/Na^{2+} exchange and consequent clay dispersion (Ventura et al., 2015). Nevertheless, cropping systems avoiding such problems do exist and, in addition to that, are also characterized by consistent water saving compared to soil cultivation: soilless methods allow to prevent soil contamination and environmental concerns as the irrigation water is reused until its depletion. Soilless cultures can provide high-quality products with an efficient use of resources, i.e. water, fertilizers, pesticides and hand-labour. Protected cultivation is spreading worldwide, counting by 2000 nearly 1.7 million hectares of greenhouses, tunnels and direct covers (Jouet, 2001). Considering the recent China's expansion, estimated to reach 1.5 million tunnels and greenhouses, the worldwide total protected cultures surface are estimated to be of more than 2 million hectares. Of such surface, the majority of cropping is still based on soil, even if hydroponics and other soilless systems are increasing and rapidly expanding (Pardossi et al., 2004).

The potential of seawater irrigated soilless culture is mainly represented by the most accurate control over the supply of water. Seawater as a controlled complementary irrigation source may reach multiple goals: i) it allows the saving of a significant amount of freshwater; ii) it exploits the seawater nutrient content; iii) in certain cases, the enhancement of several plant metabolites, precious for human health, could be obtained. On the other hand, major constraints are linked to crop yield, generally reduced by salinity stress, and to the increase of sodium and chlorides into the edible products (Ullah et al., 1994). Despite not all the physiological and biochemical mechanisms behind plants salt tolerance or sensitivity have been unrevealed, the response of many greenhouse crops to salinity, both in terms of yield and of product quality, is nowadays established (Pardossi et al., 2004). In the present review we describe the state of the art of seawater as a complementary irrigation source in soilless culture, providing a critical overview on the available information on the subject and on the potential and constraints of its implementation at a commercial level.

2. Soilless culture and water saving

Soilless culture is defined as "any method of growing plants without the use of soil as a rooting medium, in which the inorganic nutrients absorbed by the roots are supplied via the irrigation water" (El-Kazzaz, 2017; Resh, 2012). It is considered as a modern practice, but growing plants with similar techniques has been often tried throughout the ages, probably first by Egyptians several hundred years B.C. (Hussain et al., 2014; Raviv and Lieth, 2008). Soilless systems offer an important alternative to soil cultivation in case of soil and/or water issues, as for example, among the most important, water shortage and salinization (Olympios, 1999). The three main soilless systems are liquid hydroponics, solid media culture and aeroponics. Hydroponics is further categorized in open or closed systems, depending on the collection and reuse (i.e. in closed systems) of the nutrient solution until its depletion. Solid media culture systems can in the same way be open or closed and several substrates are used for plants anchorage (i.e. perlite, vermiculite, coconut coir), as long as characterized by water and air holding capacity and by an easy drainage. Aeroponics, in the end, enables the maximum utilization of space by growing plants with roots suspended in air sprayed every 2–3 minutes, plants getting nutrients and water from the solution film that adheres on roots (Hussain et al., 2014). This diversity of techniques makes soilless culture adaptable to very dissimilar situations, with the common potential application in providing food in areas characterized by soil and water availability issues (Sheikh, 2006).

A number of crops can be grown on commercial level in soilless culture, principally fruits and vegetables. Examples are *Fragaria ananassa* (Strawberry), *Lactuca sativa* (Lettuce), *Lycopersicon esculentum* (Tomato), *Phaseolus vulgaris* (Green bean), *Beta vulgaris* (Beet), *Cucumis sativus* (Cucumbers), *Cucumis melo* (Melons), *Allium cepa* (Onion) and many others (Hussain et al., 2014). Accordingly, soilless culture can play an important role in providing essential vitamins, minerals, and dietary fibre (FAO, 2003). Even more, it could help in fulfilling the recommended minimum intake of fruits and vegetables per person, food categories which are nowadays not consumed enough in several world regions (WHO and FAO, 2003), with reasons to be found in lack of tradition in their cultivation and use (Orsini et al., 2013), or because appropriate environment requirements (i.e. soil and water) are missing. Thus, soilless systems can promote diversification of crops and species, hence of consumption behaviors.

In addition to that, considerable amounts of water are saved in soilless culture compared to soil cultivation, with a significantly increase of water use efficiency (Raviv and Lieth, 2008), in terms of both yield and gross income (Pardossi et al., 2004). In fact, no percolation losses occur when growing plants with roots directly in contact with the growing media. Moreover, water for soil leaching is in this case unneeded, such amount of water depending on several parameters: site-specific estimates of total precipitation, irrigation, evapotraspiration, soil bulk density and porosity, solute characteristics and distribution (Baes and Sharp, 1983). Leaching represents the best strategy to maintain favorable salt balance and prevent detrimental salt accumulation in the soil profile (Sanchez and Silvertooth, 1996), yet it requires large volumes of water. In areas characterized by water shortage such practice is generally avoided, with direct consequences on soil structure and fertility. Among other reasons behind soilless methods water saving, the potential evaporation is reduced as the indoor climate is characterized by higher humidity and less radiation and wind compared to the outside (Pardossi et al., 2004). Because of all that, the saving of about 10 to 30% of water compared to soil cultivation is achievable in soilless culture (Sheikh, 2006), especially with the closed-recirculating systems characterized by no drainage nor evaporation from the surface, with an overall more accurate control over the supply of water (Olympios, 1999). Soilless culture thus contribute to limit the freshwater withdrawal of the agricultural sector, assuring food production with a considerable reduction of freshwater use, guarantying high-quality products and possibly making productive alternative sources of water, i.e. seawater.

3. Seawater as a complementary irrigation source

Literature offers plenty of experiments testing crops responses to salinity stress. In the majority of trials, salt stress is administered through NaCl solutions; concurrently, the number of experiments using diluted or full strength seawater is increasing. Considering both kinds of experiments, the general and firstly observed effect of salinity is the reduction of plants growth rate (Roy et al., 2014), this decrease changing between species and varieties (Shannon and Grieve, 1998). Growth reduction easily translates to yield reduction. Reasons are to be found in many factors, and between the most important: water and osmotic stress, ion toxicity, nutritional disorders, oxidative stress, metabolic processes alterations, membrane disorganization and genotoxicity (Munns, 2002). In fact, plants major processes, such as photosynthesis, protein synthesis and energy and lipid metabolism, are negatively affected (Parida and Das, 2005) and the salt-induced osmotic potential diminution limits the water availability for the plant, inducing water stress consequences (West et al., 1986; Yeo et al., 1985). Moreover, ion toxicities and/or nutritional deficiencies can occur if a specific ion prevails or because of competition effects between different ions (Bernstein et al., 1973).

It's worth noting that yield reduction is not always confirmed in crops grown in soilless systems with seawater at full strength or at different concentrations/dilutions. Overall, researchers working on this topic concluded that seawater in the growing media, up to certain concentrations, does not negatively affect the productivity. Maximum thresholds are to be found according to the species or to the variety (Shannon and Grieve, 1998). In addition to the species- and cultivar-specific salinity tolerance, plants ability to cope with salt stress is strongly enhanced when plants are not suddenly shocked, but allowed to gradually acclimate to salt stress (Noaman et al., 2002; Parida and Das, 2005). In fact, acclimation allows plants to better cope with salinity with several physiological, biochemical and molecular strategies. Among the most important: the accumulation, exclusion or compartment of ions; the synthesis of osmotic solutes to keep the ionic balance in the vacuoles; the enhanced production of antioxidant compounds and plants hormones (i.e. ABA and cytokinins); the expression of early salt induced (ESI) genes in the roots (Noaman et al., 2002; Parida and Das, 2005). Increasing salt tolerance by acclimating plants could extend the seawater use both reaching higher thresholds of seawater tolerance and including less tolerant species to be potentially grown with seawater. Together with acclimation, also the seeds priming with salt proved to enhance plants salt resistance in a number of species (i.e. hot pepper, melon, maize and many others) (Ashraf and Rauf, 2001; Khan et al., 2009; Sivritepe et al., 1999). Interestingly, in the context of increasing crops salt tolerance, soilless methods have an advantage linked to the roots system oxygenation: in fact, salinity seems to be less dangerous on soilless grown plants compared to soil cultivation, because roots ability of excluding toxic ions (i.e. Na^+) and of withstanding high osmotic pressure is enhanced by the full oxygen supply to roots, which are more oxygenated then in soil conditions (Raviv and Lieth, 2008). In the end, as mentioned before, environmental concerns related to salt accumulation in soil would not occur because the nutritive solution is used until its depletion for plants growth and is not meant to get in contact with soil or water reservoirs.

As mentioned before, quality improvements in plants grown with seawater were generally assessed: certain plant secondary metabolites are in fact accumulated in response to stress condition, as an adaptation to the environment (Ramakrishna and Ravishankar, 2011). In the tested species grown with seawater, such enhancement is due to the plant adaptation to the salinity stress. To a certain extent, several compounds known for their healthy properties and organoleptic qualities (i.e. antioxidants, soluble solids, sugars, mineral elements) are linked to the plant defense system, hence the possibility of enhancing their concentration by growing crops with diluted seawater have been investigated and not all mechanisms have been revealed yet (Sgherri et al., 2008). As the increase of the endogenous concentration of such high nutritive compounds can be precious for the nutritive characteristics of food (Di Baccio et al., 2004; Sgherri et al., 2008), salinity, in some cases, may then result to be favorable for yield and, even more, for its quality (Shannon and Grieve, 1998).

3.1. Tomato crop

Tomato (Solanum lycopersicum L. or *Lycopersicon esculentum*) is an important food and industrial crop, cultivated all over the world including those areas facing water shortage or deterioration (Sgherri et al., 2007), i.e. water salinization. Being classified as a moderate salinity-tolerant species (Maas and Hoffman, 1977), tomato's relation to its salt tolerance has been studied from the 70's. Rush and Epstein (1976), for example, investigated salt-sensitive and salt-tolerant (i.e. ecotypes from the Galapagos Islands) genotypes of tomato assessing a far stronger salt resistance in the Galapagos ecotypes which were surviving in a full strength seawater nutrient solution (EC roughly corresponding to 50 dS m^{-1}), while the salt-sensitive cultivar could not in most cases withstand levels higher than 50% seawater (Rush and Epstein, 1976). Such genotypes were firstly used in breeding programs with the aim of transferring genetic information from the salt-resistant ecotypes to cultivated tomato; the process did not give the expected results, mainly because the new cultivars, although salt tolerant, showed characteristics not suitable for commercial purposes. Thus, subsequent research focused on the identification of peculiar physiological traits among accessions characterized by different salinity tolerance that might be useful in future breeding programs. Among the main results, succulence and good selectivity for potassium over sodium proved to be important characteristics associated to salt-tolerance in tomato (Cuartero et al., 1992), useful for speeding up the selection procedures. Nevertheless, to date, creating new salt tolerant tomato cultivars with breeding programs faces many obstacles, mainly because traits related with salt tolerance are not combined in a single donor genotype (Cuartero and Fernandez-Munos, 1999). Therefore, more information about the traits related to the desired features are still needed.

Priming strategy has been also tested in tomato to enhance its salt tolerance. For example, seeds that were primed for 36 h with 1 M NaCl proved to extend salt tolerance of the grown plants (Cuartero and Fernandez-Munos, 1999). Similar results were obtained by Pill and collaborators (1991), with 'Ace 55' tomato seeds primed with synthetic seawater resulting in a higher germination percentage compared to untreated seeds in saline medium at different temperatures (i.e. 10 °C and 30 °C).

Along with the not resolutive breeding effort, several trials were performed to determinate the seawater tolerance threshold of cultivated tomato, assessing, in the meanwhile, the characteristics of fruits. Overall, seawater irrigation generally reduced the crop yield. Nevertheless, irrigating tomato with different seawater concentrations, according to the tested variety, in particular between 10 to 20% seawater (roughly EC of 8 dS m^{-1} to 14 dS m^{-1}), increased the nutritional value of the product. It is a long time that tomato crop is studied to evaluate eventual high quality characteristics enhancements in response to salinity stress. In 1988, Hobson used diluted seawater to evaluate eventual quality improvements in cherry tomatoes, assessing a decrease in fruit size but also an improvement in composition. Similar results have been obtained even more recently in closed-loop rock wool experiments: despite the reduction of fruit yield (kg/plant), fruits dry matter and total soluble solids were reported by several authors to increase with the use of seawater concentrations of 10% and 12% compared to control. Importantly, besides the fact that fruits were all marketable, fruits dry matter and total soluble solids are particularly desirable for the canned tomato industry as they improve the quality of the processed product (Sgherri et al., 2008, 2007). In addition to that, the concentration of reducing sugars (RS) and titratable acidity (TA) also increased in the berries exposed to seawater irrigation, resulting testier then control ones (Sgherri et al., 2008). A similar significant increase was previously observed by Ullah and collaborators (1994) in a pot experiment in seawater irrigated tomato fruits. In particular, glucose, fructose, citric and ascorbic acid increased proportionally to salinity, with glucose concentrations up to 139% and fructose up to 101% above the control treatment. Likewise, seawater irrigation in a soil experiment lead to fruit size decrease, yet to the increase of both sugar content and acidity (Kawai et al., 2002). This is in accord with the results of Araki and collaborators (2009), who administered a short-term (i.e. 2 weeks) salt stress through deep seawater irrigation in a soilless tomato culture, with the growing medium EC reaching 13.5 dS m^{-1}: again, fruits fresh weight was restricted but dry matter ratio was instead increased. Furthermore, seawater enhanced the concentration of Na^+, K^+ and Mg^{2+} and the sugar concentration in the phloem sap, assessing high quality characteristics in the obtained tomatoes (Araki et al., 2009). Similarly, a two weeks seawater treatment in soilless culture enriched tomato fruits with sugar, minerals, functional amino acids and good flavor without occurrence of extremely small-sized fruits and blossom-end rot (Kitano et al., 2008). Again, Sgherri and collaborators reported the increase of many other improving quality compounds in 10%–12% seawater treated tomatoes: NADPH, NADPH/$NADP^+$, ascorbic acid (Vitamin C), α-tocopherol (the main representative of Vitamin E in tomato, according to Seybold et al., 2004), total ascorbate, dihydrolipoic all resulted to be increased compared to control tomatoes (Sgherri et al., 2008, 2007). Indeed such compounds linked to the nutritional value of the product are related to oxidative processes depending on natural physiological processes (i.e. ripening), but they can also be enhanced by environmental changes, as in this case by salinity conditions (Sgherri et al., 2008). In fact, the increased synthesis of antioxidants is considered as one of plants adaptive mechanisms to biotic and abiotic stresses (Sgherri et al., 2008). Accordingly, salt stress can enhance both the sweetness and the quality of fruits (Ullah et al., 1994). Such results obtained trough seawater irrigation present similarities with those obtained testing tomato crop salinity tolerance with NaCl: plants treated with NaCl solution at 15.7 dS m^{-1} showed reduced fruit size and fruit water content, yet increased the soluble solids, carbohydrates, sodium and chloride concentrations. Also, titratable acidity increased upon irrigation with saline water, whereas the fruit redness significantly decreased together with P, K^+, Mg^{2+} and NO_3- fruit concentrations. In the end, total carotenoids and lycopene concentrations gradually increased from the control to the 4.4 dS m^{-1} treatment, then decreasing at higher salinity levels (De Pascale et al., 2001). Overall, major differences in the response to salinity are observable among different varieties: interestingly, certain of those show promising responses to seawater irrigation by producing more yield compared to non saline conditions (Al-Busaidi et al., 2009). Furthermore, controlled stress application in soilless culture can then be reliable for production of high quality and value-added tomato (Kitano et al., 2008).

3.2. Vegetables crops

Leaf vegetables have been deeply tested under seawater irrigation in soilless systems. Such crops owe their particular importance to their spread cultivation and consumption, to their strong role in alleviating hunger and malnutrition and to the fact that are profitable crops, thus highly efficient soilless systems have been optimized on their particular needs. Because of all these reasons, the majority of trials investigating seawater in soilless systems, after the tomato crop primacy, focus on leaf vegetables. Literature reports studies on red pepper and cucumber as well.

3.2.1. Lettuce

Lettuce (*Lactuca sativa* L.) growth was tested under increasing seawater concentrations up to 20% (roughly EC 14 dS m^{-1}) in hydroponics and in pots experiments (Atzori et al., 2016; Lee et al., 2011; Sakamoto et al., 2014; Turhan et al., 2014). Different results obtained in trials testing diverse cultivars indicate certain traits to be probably cultivar-dependent. Focusing firstly on growth, *Lactuca sativa* cv. Mother-red growth was not negatively affected by seawater up to EC 10.6 dS m^{-1} (Sakamoto et al., 2014), whereas *Lactuca sativa* L. cv. Canasta resulted in a reduced growth starting from EC of 6.12 dS m^{-1} (Atzori et al., 2016) and cv. Funly from EC of 3.7 dS m^{-1} (Turhan et al., 2014). In a different experiment studying four vegetable crops response to seawater spray at concentrations reaching 100% seawater (E.C. 44.7 dS m^{-1}), lettuce assessed plant height values comparable to control when sprayed with seawater up to 100% concentration, whereas plants fresh weight decreased compared to control at 50% and 100% seawater concentration (Lee et al., 2011). On the contrary, the four cv. 'Zhongfeng', 'Nanshu', 'slender leaf endive', 'broken leaf endive' fresh and dry weights of shoots and roots and the leaf area decreased with increasing seawater concentrations (Yang et al., 2011). Similarly, two cultivars (i.e. 'Ballerina' and 'Severus') of lettuce were tested this time with NaCl solutions corresponding to EC of 1.6, 2.6, 3.6 and 4.6 dS m^{-1}, assessing acceptable performances in hydroponics at EC not higher than 3.6 dS m^{-1}, whereas the highest EC lead to average yield reduction of 51.5%, with a smaller sensitivity of cv. Ballerina (Miceli et al., 2003). Nevertheless, a study under soilless Hymec cultivation assessed a significant increase of leaf width, leaf number and shoot dry weight at 10% seawater concentration compared to control, while at 25% seawater concentration lettuce growth was significantly inhibited and at 75% seawater concentration plants died at a certain extent (Liang et al., 2007).

In the majority of the above described experiments, the concentration of nutritionally important mineral elements, such as K^+, Ca^{2+}, Cu^{2+} and Mg^{2+}, was investigated in relation to increasing seawater. Overall the results assessed the augmentation of those element concentration in leaves accordingly with increasing salinity. Despite the augmentation of nutritionally important mineral elements, Na^+ and Cl^- showed significant increases too. Sakamoto and collaborators (2014) also observed a significant seawater-related increase of the concentration of anthocyanins, carotenoids and sugar content in leaves. The results on cv. Canasta, on the other hand, did not report significant changes in polyphenols and carotenoids, whereas soluble sugars decreased with increasing salinity compared to control (Atzori et al., 2016). In Turhan and collaborators' pot experiment (2014), lettuce cv. Funly was irrigated with 0%, 2.5%, 5%, 10%, 15%, and 20% seawater: total soluble solids, total sugar, and protein content significantly increased at low salinity levels (2.5% and 5%) while decreased with higher seawater concentrations compared to control. Also, the two cv. tested by Miceli et al. (2003) obtained quality improvements due to the reduction of leaf nitrate content in salt treated plants. Similar results on nitrate content were also obtained on four lettuce cultivars, together with an initial increase of chlorophyll *a* and *b* content and with a significant increase if the protein, soluble sugar and vitamin C content at 14.5% seawater concentration (Yang et al., 2011). On the opposite, nitrates in 25% seawater treatment were proved to increase compared to control by Liang et al. (2007). In the same experiment, the authors assessed a significant increase of soluble sugars and free amino acids in 25% seawater treatment plants, whereas at 10% N, P and K content were not significantly different from control (Liang et al., 2007).

3.2.2. Minor vegetables

Two other leaf vegetables spread and consumed in a number of regions are chard (*Beta vulgaris* L.) and chicory (*Cichorium intybus* L.) crops. In hydroponic conditions such crops were successfully grown with 15% seawater, thus up to EC values of 9.2 dS m^{-1}, not assessing significant differences compared to control in terms of biomass production and fresh and dry weight (Atzori et al., 2016). Similar results on chard crop were also obtained using diluted seawater at EC levels of 4.8 and 7.4 dS m^{-1}. In particular, EC 4.8 dS m^{-1} treated plants reached a biomass comparable to control, while EC 7.4 dS m^{-1} assessed an even higher dry biomass (Zhang et al., 2008). Likewise, chicory crop was proved to tolerate 10% seawater concentration with a biomass production, chlorophyll content and photosynthesis rate in line with control values (Atzori et al., 2016). Accordingly, in an experiment testing chicory cv. Puna salinity tolerance in hydroponic conditions no significant differences in biomass production were observed between the 50 mmol L^{-1} NaCl treatment (corresponding to EC of 7.1 dS m^{-1}) and control plants (Boyd and Rogers, 2004). On the contrary, when treated with 20%, 30% and 40% seawater concentration chicory growth resulted to be significantly inhibited (Sun et al., 2009). Also, Na^+, Cl- and K^+ in seedlings shoot and root increased with increasing salinity (Atzori et al., 2016; Sun et al., 2009). Such elements augmentation was also found in chard, where Na^+, Ca^{++}, Cu^{++} and Mg^{++} accumulation rose with increasing seawater concentration, while no significant differences were assessed among treated and untreated plants for K^+, Fe^{++} and Zn^{++} accumulation in leaves (Atzori et al., 2016). Chicory crop was also tested in both hydroponics and soil (pots) conditions to evaluate an eventual enhancement of the crop water use efficiency when grown in salt conditions: it was proved that growing chicory with a share of 10% seawater (corresponding to EC of 6.1 dS m^{-1}) in hydroponics lead to the higher biomass production per unit of water compared to conventional hydroponics (freshwater and nutritive solution only) and to pot cultivation with and without the 10% seawater share in the irrigation water (Atzori et al., 2019). Such results confirm the increased water use efficiency in the tested soilless system compared to soil cultivation, also suggesting that hydroponics allows, at least for the chicory crop, a higher salinity tolerance compared to soil cultivation. Overall, chard and chicory crops proved to have a considerable higher tolerance to salinity compared to lettuce. Such tolerance is probably connected with their salt resistant ancestors, having possibly inherited salt resistance traits (Shannon and Grieve, 1998). For example, the wild sea beet (*Beta vulgaris* subsp. maritima) is believed to be the ancestor of both leaf and root beets. Similarly, *Cichorium intybus* is native of the Mediterranean region, where it is easily found as weed in saline areas (Boyd and Rogers, 2004; Shannon and Grieve, 1998). Along with the unreduced growth performances, seawater in the growing media lead to an increase of a number of mineral elements in such crops: Ca^{2+}, Cu^{2+}, Fe^{2+}, Mg^{2+}, Zn^{2+} in chard leaves and K^+ and Cu^{2+} in chicory leaves (Atzori et al., 2016), representing an interesting case of biofortification obtainable in saline conditions. Likewise, Na^+ increased accordingly with seawater: this last parameter needs attention as it can result in toxicity effects if consumed beyond certain amounts.

Leaf perilla (*Perilla frutescens* var. japonica Hara), red pepper (*Capsicum annuum* L.) and cucumber (*Cucumis sativus* L.) were also studied with diluted seawater at 1%, 5%, 10%, 20%, 50%, 100% sprayed on leaves. Leaf perilla plant height was negatively affected by seawater spray at 20%, with seedlings death at 50% and 100% seawater concentration. Besides, plants fresh weight increased with lower seawater concentrations (i.e. 1% and 5%) compared to control, reaching again values comparable to control at 10% and 20% seawater concentration. Similarly, the plants growth of red pepper decreased in all the diluted seawater concentration, whereas plant fresh weight was comparable to control except for the 100% seawater treatment. On the opposite, cucumber plants did not show any difference among treatments and control regarding plant height, with the average plants fresh weight increased according with increasing salinity starting from 1% up to 50% seawater treatment, whereas 100% seawater treated plants did not survive (Lee et al., 2011). Supporting studies on such crops response to seawater are not present in literature, whereas several experiments evaluating red pepper and cucumber salinity tolerance trough NaCl solution administration have been made. Among the more important, Navarro et al. (2006) investigated the red pepper salinity tolerance and antioxidant compounds production through NaCl solutions treatments (i.e. 0, 15 and 30 mM NaCl). Salinity overall decrease pepper yield, with plant growth parameters such as plant height, total leaf area and dry weight significantly reduced at salinities higher than 25 mM NaCl in two hybrids (Chartzoulakis and Klapaki, 2000). Nevertheless, experimental results proved that the use of moderate salinity was beneficial for the quality properties of red pepper due to the increase of the antioxidant activity in the hydrophilic (HAA) and lipophilic (LAA) fractions (Navarro et al., 2006). Focusing on cucumber response to salinity, a number of studies investigating its salt response have been published showing differences among cultivars and hybrids. The 'Pepinex' hybrid, for instance, was proved to well stand up to a salinity level of 8.5 mM NaCl, whereas higher salinity concentrations caused stomatal closure and a significant reduced photosynthetic rate (Chartzoulakis, 1994). Besides salt tolerance experiments, trials have been made with the aim of investigating the feasibility of increasing fruit yield and quality of cucumber under NaCl stress by using salt tolerant rootstocks. In a 2009 study, self-grafted cucumber plants (Cucumis sativus L. cv. Jinchun No. 2) and plants grafted onto the commercial salt tolerant rootstock Figleaf Gourd (Cucurbita ficifolia Bouche) and Chaofeng Kangshengwang (Lagenaria siceraria Standl) were tested to determine fruit yield, quality and mineral composition: plants grafted on the salt resistant rootstocks had an overall improved fruit quality under NaCl stress due to an increased soluble sugar content, titratable acidity and vitamin C (Huang et al., 2009). A summary about glycophytes grown with seawater is available in Table 2.

3.3. Edible halophytes

In a context of saline agriculture salt loving halophytes deserve a special attention, and in particular the edible species. Halophytes are defined as salt tolerant plants capable of growth and reproduction at soil salinities greater than 200 mM NaCl: such value roughly corresponds to a salinity greater than the one of half strength seawater (Flowers and Colmer, 2008). Such species can grow and reproduce on saline soils that kill 99% of the other species (Flowers and Colmer, 2008) and they are estimated to consist in 5000–6000 species, or 2% of total world angiosperm species (Glenn et al., 1999). The domestication and cultivation of the edible species in a saline agriculture context could be regarded as an interesting approach to consider (Glenn et al., 1998; Rozema and Flowers, 2008; Rozema and Schat, 2013; Ventura et al., 2015), allowing the exploitation of the great availability of brackish and seawater and of their important content of macro and micronutrients that are essential for plants growth (Rozema and Flowers, 2008). In fact, the interest on such species is timely because of their ability of food production while growing in salt-rich environments. Despite the majority of experiments test the growth performance of edible halophytes through NaCl solutions irrigation (Aghaleh et al., 2009; Ayala and O'Leary, 1995; de Vos et al., 2013; Eisa et al., 2012; Hameed et al., 2015; Harvey et al., 1981; Hussin et al., 2013; Khan et al., 2000a,b; KHAN et al., 2000; Ksouri et al., 2007; Moghaieb et al., 2004; Parida et al., 2002; Qiu et al., 2003; Redondo-Gomez et al., 2010; Reginato et al., 2014; Rodriguez et al., 2005; Tada et al., 2014; Ventura et al., 2014; Yang et al., 2007), literature offers a growing number of trials investigating halophytes salt response to seawater irrigation. Two annual Salicornia and two perennial Sarcocornia ecotypes were grown at different seawater concentrations (i.e. 50%, 75% and 100%) to investigate yield production and the nutritional value, being Salicornia recently introduced as a fresh vegetable crop in a number of countries. Increasing seawater percentages did not affect Ca^{2+} and Mg^{2+}, increased slightly K^+ and strongly Na^+ and Cl^-. Total polyphenol, β-carotene and ureides, famous for their antioxidant properties, increased together with the crop nutritional value accordingly with increasing seawater. In addition to the antioxidant properties, the seawater grown ecotypes were proved to be an important source of omega-3 polyunsaturated fatty acids, also precious for human consumption (Ventura et al., 2011). The seawater tolerance of Salicornia was also studied in a greenhouse and outside experiment investigating its crop potential. Irrigation was made by 20% and 40% seawater and the experiment results assessed an increased relative growth rate at all tested salinity levels compared to the control, thus identifying salt conditions as growth stimulants for such species (Katschnig et al., 2013).

Another potential saline crop, the herbal edible perennial *Plantago*

Table 2
Summary of experiments on seawater soilless grown glycophytes.

Species	Cultivar	Salinity	Growth	Ions	Antiox	Source
Hydroponics						
Lycopersicon esculentum	L. escukntum MIlI cv. VF 36	M	=	–	+	Rush and Epstein, 1976
	L. cheesmanii ssp. Minor (Hook.) C.H. Mull.	H	=	–	–	
Lactuca sativa L.	cv. Mother-red	M	=		+	Sakamoto et al., 2014
	cv. Canasta	L	= -	+	=	Atzori et al., 2016
Beta vulgaris L.		L	=	+	=	Atzori et al., 2016
Cichorium intybus L.		L	=	+	=	Atzori et al., 2016
Soilless other then hydroponics						
Lycopersicon esculentum	cv. Jama, Gimar wild type, Gimar gf, Gimar nor	L	=		+	Sgherri et al., 2007
	cv. Naomi	L	=		+	Sgherri et al., 2008
	cv. Hausu-momotarou	M	+	+	+	Araki et al., 2009
Lactuca sativa L.	cv. Zhongfeng, Nanshu, slender leaf endive, broken leaf endive	L	–		+	Yang et al., 2011
		L-M-H	+ - -		= + -	Liang et al., 2007
Cichorium intybus L.		L-M-H	= - -	+ + +		Sun et al., 2009
Pots						
Lycopersicon esculentum	cv. Lukullus	L-M	= -	+ -	+ +	Ullah et al., 1994
Lactuca sativa L.		L-M-H	= - -			Lee et al., 2011
	cv. Funly	L-M	= -		+ -	Turhan et al., 2014
Beta vulgaris L.	subspp. cycla	L-M	= +			Zhang et al., 2008
Perilla frutescens *	var. japonica Hara	L-M-H	+ = -			Lee et al., 2011
Capsicum annuum L. *		L-M-H	= = -			Lee et al., 2011
Cucumis sativus L. *		L-M-H	+ + -			Lee et al., 2011

Salinity levels are divided as follows: L = low salinity, 0–10% seawater, EC 0–8 dS m^{-1}; M = medium salinity, 10–30% seawater, EC 8–18 dS m^{-1}; H = high salinity, 30–100% seawater, EC 19–54 dS m^{-1}. Symbols +, -, = represent increases, diminutions or comparable results compared to control conditions. *Such species were tested under seawater spray at the leaf level only.

coronopus L., was tested at 0, 25, 50, 75 and 100% seawater salinity. Its salinity threshold was reached at 25% seawater, with growth, net photosynthesis, water use efficiency and stomatal conductance negatively affected at higher salinities. The accumulation of Na^+ and Cl^- in leaves tissues was observed with the consequent change in leaf osmotic potential. Besides, in response to the stress conditions the production of organic solutes resulted to be enhances, with sorbitol as the most abundant sugar produced (Koyro, 2006). Likewise, quinoa (*Chenopodium quinoa* cv. Titicaca) seedling emergence and antioxidative pathway were evaluated in response to 25, 50, 75 and 100% seawater irrigation and to other salts (i.e. NaCl, $CaCl_2$, KCl and $MgCl_2$): total antioxidant capacity was always higher under salt stress than in control plants. In fact, total phenols increased in seeds treated with NaCl and seawater, with the greatest increase observed in seawater irrigation conditions (Panuccio et al., 2014). In Table 3 those experiments are presented in summary.

3.4. Non-food crops

Along with trials focusing directly on edible fruits or leaves, other species have been tested to understand the biochemical and physiological mechanisms beyond seawater adaptation of the whole plant, with the aim of improving and/or selecting crops with salt tolerance traits (Di Baccio et al., 2004). For example, an experiment on sunflower (*Helianthus annuus* L.) grown with 10% and 20% of seawater investigated the oxidative responses of the plant. Different responses to the two concentrations were assessed: in particular, growth reduction, due to oxidative stress, was observed at 20% whereas 10% seawater grown plants did not differ from control. In both cases plants were able to regenerate antioxidant molecules, with considerable differences between roots and shoots (Di Baccio et al., 2004). In another experiment on sunflower plants irrigated with higher seawater concentrations (i.e. 20% and 30%), both cv. Katharina and Piacenza ecotype increased their Cl^- and Na^+ concentration with increasing seawater. Also, both seawater concentrations reduced the N content whereas the P content resulted unaffected (Izzo et al., 2008).

Jin and collaborators (2007) assessed the possibility of growing *Aloe vera* L. up to 60% seawater: its main osmotic adjustment mechanism was found to be the accumulation of inorgatic cations in roots. Also, five ecotypes of the Jerusalem artichoke (*Helianthus tuberosus* L.) were grown in hydroponics at 15% and 30% seawater and several molecules resulted to be stimulated in plants exposed to seawater: antioxidant enzimes, organic acids, proline, soluble sugars and inorganic solutes, even if with important ecotypic variabilities (Xiao-hua et al., 2009).

The use of brackish water is under study for the cultivation of floricultural plants too. Such plants have always been irrigated with good quality water due to their high economic value. Nevertheless, alternative water sources can be required because of the limited supplies of freshwater in several countries. A number of species, such as *Bougainvillea glabra*, *Ceanothus thyrsiflorus*, *Leptospermum scoparium*, *Leucophyllum frutescens* and *Ruttya fruticosa*, demonstrated a high ion concentration in their leaves that could be a trait for their relative salt tolerance, as little growth reduction and few symptoms of injury in the leaves were observed (Cassaniti et al., 2009). Furtermore, saline water

Table 3
Summary of experiments on seawater soilless grown edible halophytes.

Species	Salinity	Growth	Ions	Antiox	Source
Salicornia persica	M-H	+ +	+ +	+ +	Ventura et al., 2011
Sarcocornia fructicosa	M-H	+ +	+ +	+ +	Ventura et al., 2011
Salicornia dolichostachya Moss	M-H	+ +	+ +		Katschnig et al., 2013
Plantago coronopus (L.)	L-M-H	= - -	- - -		Koyro, 2006
Chenopodium quinoa cv. Titicaca	L-M-H		+ + +	+ + +	Panuccio et al., 2014

Salinity levels are divided as follows: L = low salinity, 0–25% seawater, EC 0–15 dS m^{-1}; M = medium salinity, 25–50% seawater, EC 15–25 dS m^{-1}; H = high salinity, 50–100% seawater, EC 25–54 dS m^{-1}. Symbols +, -, = represent increases, diminutions or comparable results compared to control conditions.

showed beneficial effects for the cultivation of some species: the dry weight of container-grown rose was observed to increase with increasing Cl^- accumulation in leaves (Cabrera and Perdomo, 2003), while a short exposure to a low concentration of salt (i.e. 12.5 mM Na_2SO_4) enhanced subsequent shelf life of the annual herb coriander (Bashtanova and Flowers, 2012). Cassaniti and Romano (2011) identified a wide group of halophytes that could be utilized for ornamental purpose that are naturally adapted to salinity because growing in the Mediterranean area, belonging to the families Aizoaceae (i.e. *Mesembryanthemum crystallinum* L., *Tetragonia tetragonoides* (Pall.) Kuntze), Apiaceae (i.e. *Crithmum maritimum* L.,), Asparagaceae (i.e. *Drimia maritima* (L.) Stearn), Chenopodiaceae (i.e. *Atriplex portulacoides* L.,) and several others. However, since salt tolerance can vary within different species belonging to the same family (Grieve et al., 2005; Shannon and Grieve, 1998), punctual investigations are required for every species showing a potential.

4. Potential and constraints

The potential of seawater irrigated soilless culture is mainly represented by the combination between the most accurate control over the supply of water of soilless systems together with the controlled use of an abundant and free alternative water source. In addition to that, the potential of such technique is made stronger by the crops response to salt stress through the production of secondary metabolites and the accumulation of mineral elements which have beneficial effects for human alimentation. Nevertheless, salt stress can also be the cause of Na^+ and Cl^- accumulation and can lead to severe damages in crops production if not carefully administered. Individuating the crop-specific seawater concentration that balances the just described potentials and constraints has thus crucial importance. Also, due to species and cultivars different response to seawater stress, before considering this technique for commercial purposes, research would be needed in respect to each potentially cultivable species and cv.

Even if salt tolerance of greenhouses crops is well established, and practices can be applied to alleviate the negative effects of salinity, the effectiveness of these cultural practices however depends on many factors (i.e. crop genotype, environmental and cultural conditions). These practices do not seem completely reliable and compatible with the need of standardized cultivation techniques and constant (predictable) crop yield and product quality (Pardossi et al., 2004). Because of that, seawater irrigated soilless culture still need to be deeply investigated before being considered by crops growers. Nevertheless, this research area offers an interesting perspective for countries with limited freshwater availability and nearby coastal areas. Discoveries in this field might potentially offer new productive methods focusing on the preservation of freshwater and, in the meantime, on the sustainable exploitation of an abundant resource as seawater.

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