Salicornia Species

Current Status and Future Potential

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31 Salicornia Species

Current Status and Future Potential

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31.1 INTRODUCTION

The salinization of agricultural soils is an ever-increasing challenge that poses major constraints to agricultural productivity worldwide. An estimated 7% of the world's total land area is salt-affected to some degree; this occurs in all climatic zones, but especially in the arid and semi-arid regions of the world (Wicke et al. 2011). The majority of these salt-affected soils have arisen naturally, through the release of soluble salts from weathering processes of parental material, with sodium chloride being the most abundant salt (Szabolsc 1989). Other natural processes include the deposition of oceanic salt by wind and rain and the intrusion of seawater in low lying coastal areas (Munns and Tester 2008). Besides the natural processes resulting in salinization over time, anthropogenic factors, such as land clearing of natural deep-rooted vegetation and irrigation, has resulted in the salinization of agricultural land. Irrigation and land clearing can lead to a rise in the water table and thereby an increased concentration of soluble salts in the root zone, through the processes of evaporation and capillary rise (Barrett-Lennard 2002). The extent and the severity of salinity will likely increase with climate change, resulting in an increased risk of flooding, rising seawater levels, and changes in the global precipitation pattern

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(Hossain 2010; IPCC 2018). In addition, the growing global population, expected to reach 9.7 billion in 2050, will require an unprecedented growth in food production and will thereby put further stress on already scarce land and water resources (United Nations 2019). Hence, there is an urgent need to find ways of utilizing saline land and saline water resources to maintain agricultural productivity and meet the growing global demand for food, water, and energy.

Most of the agricultural crops grown around the world are salt-sensitive glycophytes that suffer significant yield reductions when exposed to even mildly saline conditions, due to osmotic, and eventually, also ionic stress linked to the accumulation of salts in the leaf tissue (Munns and Tester 2008). Despite the high genetic diversity within crop species and advances in molecular genetics, little success has been made in developing new salt-tolerant varieties, as salinity tolerance is a multigenetic trait (Flowers et al. 2010; Ismail and Horie 2017). However, great potential lies in cultivating naturally salt-tolerant plants that can achieve comparatively larger biomass yields than conventional crops under saline conditions (Flowers and Colmer 2008; Flowers and Muscolo 2015). Halophytes can be defined as plants that can survive and reproduce in environments with a salinity level of 200 mM or above and constitute about 2% of the world's flora (Flowers and Colmer 2008; Bennett et al. 2013). Until now, the main interest in halophytes has been to gain insight into the physiological and molecular salt-tolerance mechanisms employed by these species, neglecting the crop potential of halophytes (Katschnig et al. 2013; Yvonne et al. 2013). It has been advocated that the most direct way of achieving salt-tolerant crops is through the domestication of these plants i.e. by enrolling potential halophytic crop plants in conventional plant breeding programs (Hodges et al. 1993; Zerai et al. 2010; Rozema and Flowers 2015). The species that have gained the most interest as crop species are *Atriplex* spp. (for forage), *Distichlis* spp. (for grain), and *Salicornia* spp. (as oilseed) (Glenn et al. 2013; Ventura et al. 2015). However, *Salicornia* has gained special commercial attention because of its other uses; it is currently being grown in Europe and North America as a vegetable, with attempts being made at large-scale commercial cultivation with seawater irrigation for production of oilseed and as an animal feed (Abdal 2009; Bailis and Yu 2012; Gunning 2016). However, throughout domestication process, there have been a range of agronomic challenges that have had to be tackled regarding its use as a seed crop, such as unsynchronized flowering, small seed size, seed shattering, and seed recoveries of <75% when harvesting (Glenn et al 1998; Zerai et al. 2010; Glenn et al. 2013). Breeding efforts have been deployed to improve these undesirable traits and new *Salicornia* varieties (such as SOS 10) have been developed (Glenn et al 1998; 2013; Zerai et al. 2010). Beside the production of seeds, alternative ways of utilizing other parts of *Salicornia* such as biomass and valuable components have been explored, and these will be elaborated in the following sections.

31.2 SPECIES AND GEOGRAPHICAL LOCATIONS

The genus *Salicornia* belongs to the family Amaranthaceae (previously Chenopodiaceae); it is an annual, succulent plant characterized by leafless stems and branches, with sessile flowers often arranged in 3-flower cymes per bract, and aggregated in dense terminal spike-like thyrses (Kadereit et al. 2007). The reproductive biology seems to be dominated by inbreeding in the diploid species, although out-crossing does occur particularly in the tetraploid species such as *S. bigelovii* (Noble et al. 1992). Most species have an erect or prostate growth habit, vary in height (10–60 cm), degree of branching (dependent on the environmental and climatic conditions) and have a preference for non-shaded sites (Davy et al. 2001). *Salicornia* spp. are widely distributed in the temperate, boreal, and subtropical parts of the northern hemisphere and can be found growing in and around coastal and inland salt marshes, salt pans, salt lakes, and mudflats. The environments that *Salicornia* inhabits are often affected by diurnal and seasonal fluctuations in the duration of submergence, waterlogging, and salinity levels. A high level of physiological plasticity has, therefore, been found in *Salicornia* spp. resulting in a broad phenotypic variation between populations under differing environmental conditions (Rozema et al. 1987). To cope with the stressful edaphic factors found in salt marsh environments, with salinities reaching twice the concentration of seawater (1 M NaCl), *Salicornia* spp. have developed extreme salt tolerance (Flowers et al. 1986; Glenn et al. 1991; Ventura and Sagi 2013). This high salt-tolerance relies on the compartmentalization of salts in the vacuoles accompanied by the synthesis of compatible solutes, enabling osmotic adjustment, while at the same time avoiding the toxic effects of Na^+ and Cl^- in the cytosol (Munns and Tester 2008). Compatible solutes such as sucrose, proline, and glycine-betaine not only serve to maintain osmotic pressure but also act as osmoprotective compounds that maintain protein integrity and protect the cytosol from ion toxicity and free radicals (Slama et al. 2015).

The *Salicornia* genus includes 25–30 species, although no present agreement exists on the exact number of accepted species (Kadereit et al. 2007). The high degree of physiological plasticity together with an extremely reduced leaf and flower morphology, providing few diagnostic characters, has led to a complex taxonomy (Kadereit et al. 2007; 2012). The complexity of the taxonomic characterization has also led to the use of the names *Salicornia europaea L.* and *Salicornia herbacea L.* in a broad sense to include many different genotypes, with same species being given different names in different regions (Davy et al. 2001; Kadereit et al. 2012). Depending on the region, *Salicornia* is known by the common names: samphire, sea asparagus, pickled sea–weed, crow's foot green, hamcho, glasswort, or sea-beans (Feng et al. 2013). Analysis of ribosomal DNA polymorphism and ETS sequence data have confirmed genetically distinct forms; however, these techniques have been insufficient to resolve morphologically distinct species (Noble et al. 1992; Singh et al. 2014). To discriminate between species, seed and fruit characters have been recognized as potentially useful diagnostic traits (Rhee et al. 2009).

Despite the taxonomic difficulties arising from phenotypic plasticity and morphological parallelism, some recognized species have attracted more interest than others. *S. europaea* (common glasswort) is one of the most common species found in Europe, characterized by an erect growth habit, height of 10–30 cm, and a fairly rich degree of branching (Davy et al. 2001). This species is mostly recognized for its culinary uses and medicinal properties and can be found at local markets around Europe and North America (Gunning 2016). *Salicornia bigelovii Torr.* (dwarf glasswort) belongs to the North American tetraploid branch of *Salicornia* and can be distinguished from other species by its acute and sharply mucronate leaf and bract tips (Kadereit et al. 2007). It can be found growing in subtropical regions, with an erect growth habit (up to 50 cm tall) and has been one of the most sought-after species in the effort to cultivate halophytes with seawater in coastal desert regions (Glenn et al. 1991; 1998; 2013; Hodges et al. 1993; Ventura et al. 2015).

31.3 CHEMICAL CHARACTERIZATION

Each species of *Salicornia* differs in its composition. This difference might simply be due to the difficulty in characterizing species and is more likely to be the result of environmental conditions, due to the large phenotypic plasticity. The variations within species can be attributed to variation in harvesting time, method of cultivation, and the fraction of the plant, which has undergone the analysis. Table 31.1 compares the compositional analysis of *S. arabica, S. bigelovii*, and *S. herbacea*. While the extremely low moisture and high carbohydrate contents stand out for *S. arabica*, the remainder of the components seems to be in agreement with studies of other species.

The compositional analyses of leaves and stems (also known as seed spikes or pods as referred to in the study) of *S. bigelovii* were compared against each other (Cybulska et al. 2014b). Since the cultivation was carried out at four salinity levels (10, 20, 30, and 50 ppt of NaCl concentration) and three fertilization levels (1.0, 1.5, and 2.0 g N/m^2), the influence of these parameters was also investigated in the same study. Table 31.2 shows that salinity had an effect on the total extractives, glucan, and lignin contents. The fertilizer concentration did not have a significant influence on any of the components. Salinity has a significant impact on the total extractives, lignin content, and glucan content.

S. brachiata was studied in greater detail; the crude polysaccharide fraction of the biomass was treated with four different solvents, namely cold water (CW), hot water (HW), ammonium oxalate (OX), and aqueous sodium hydroxide (ALK). In addition, the biomass was separated into roots, stems, and tips, a distinction,

TABLE 31.1
Compositional Analysis of Salicornia spp. (g/100 gm)

	S.arabica	***S.bigelovii***	***S.bigelovii***	***S.herbacea***		
Component	**Plant Powder**	**Fresh Tips**	**Seed**	**Tips**	**Shoots**	**Root**
Moisture	7.39–8.45	87.06–89.78		90.9	73.9	66.2
Crude Protein	1.11–1.37	1.44–1.64	30–33	1.7	2.0	2.0
Crude Lipid	N/A	0.36–0.38	26–33	0.2	0.3	0.3
Crude Ash	17.3–20.02	3.99–4.73	5–7	4.7	6.1	6.2
Salt	N/A	N/A	N/A	3.3	3.9	2.8
Total Sugar	86.32–86.33	4.02–4.94	N/A	2.2	13.4	22.8
Uronic Acid	2.96–3.7	N/A	N/A	0.3	1.4	1.9
Sulfate	9.64	N/A	N/A	N/A		
Crude Fiber	N/A	0.7–0.96	5–7	N/A		
References	(Hammami et al. 2018)	(Lu et al. 2010)	(Glenn et al. 1991)	(Min et al. 2002)		

TABLE 31.2
The Influence of Different Plant Fractions, Salinity of Water Used for Irrigation, and Fertilizer Concentration on the Composition of Raw *S. bigelovii*

				Significance†		
Component [g/100 g TS]	**Shoots**	**Tips**	**Shoots + Tips**	**Fraction (Shoots/tips)**	**Salinity [ppt]**	**Fertilizer [g N/m^2]**
Glucan	16.02–27.12	4.73–8.03	7.52–10.6	***	**	ns
Xylan	13.51–22.63	4.00–7.27	7.32–8.06	***	ns	ns
Arabinan	2.29–5.93	3.82–5.24	3.38–7.54	***	ns	ns
Klason Lignin	11.61–23.63	7.44–21.31	5.4–8.26	**	***	ns
Structural Ash	2.18–8.11	4.60–11.76	6.8	***	*	**
Total Extractives	25.82–44.04	54.04–66.97	50.13–57.23	***	***	ns
Water extractives ash-free			48.93–49.33	***	ns	ns
Ethanol extractives ash-free			2.0–2.22	***	***	ns

† *** = $P < 0.001$; ** = $P < 0.01$; * = $P < 0.05$; ns = not significant.

Source: Cybulska et al. 2014b

which has not been shown in Table 31.3, but can be found in the original study. The uronic acid and protein concentrations for *S. brachiata* are comparable to those in Table 31.1. The CW and HW fractions contained predominantly glucose, arabinose, and galactose, whereas the OX fractions of all the three parts were principally composed of arabinose, galactose, and rhamnose monosaccharides. Extraction of proteins was higher in the CW, HW, and OX extracts, and comparatively very low in the ALK extracts.

Hammani et al. (2018) measured the presence of various monosaccharides after the acid hydrolysis of *S. arabica*. Arabinose, galactose, ribose, xylose and glucose had the highest concentrations amongst all the monosaccharides detected in *S. arabica,* which is similar to the monosaccharides listed in Table 31.3 (Hammami et al. 2018).

The concentrations of minerals in *S. bigelovii* and *S. herbacea* are shown in Table 31.4. *Salicornia* has a high sequestration of salts and minerals, especially Na, K, Ca, and Mg. The deposition in shoot cells is caused by the fact that these minerals are transported in the transpiration stream; however, they are compartmentalized in vacuoles to avoid cytosolic toxicity, since the plant actively utilizes Na and Cl as osmolytes. These high levels are one of the reasons why *Salicornia* cannot be used as a staple food in the human diet in big proportions. However, the consumption of *Salicornia* in small amounts can provide a mineral supplementation, as well as due to phytochemicals – a supply of antioxidants (Cybulska et al. 2014a).

The total amino acids in *S. bigelovii* account for 10.8 g/kg of fresh weight (Lu et al. 2010). The various amino acids present in *S. bigelovii* and *S. herbacea* have been compared in Table 31.5. The amino acid concentrations vary depending upon the

TABLE 31.3
The Polysaccharide Fractions of *S. brachiata* Were Calculated Based on a w/w %

	Total Sugar	**Rhamnose**	**Ribose**	**Glucose**	**Xylose**	**Arabinose**	**Mannose**	**Galactose**	**Uronic Acid**	**Protein**
CW	45–56	2.9–6.14	1.19–2.26	6.98–39.66	1.94–3.93	24.58–34.29	5.11–10.05	17.69–51.99	0.49–1.34	5.50–10.0
HW	44–53	7.34–9.59	1.88–2.32	10.82–22.21	4.70–6.39	35.57–42.42	8.9–11.67	16.19–27.26	0.86–2.11	8.81–13.8
OX	39–54	10.0–28.0	1.37–2.05	9.07–10.13	1.96–5.11	35.94–39.82	5.67–8.91	17.02–27.34	1.31–1.85	6.13–7.94
ALK	52–58	0.7–12.87	2.93–3.85	0.20–5.23	4.62–86.16	9.77–53.58	0.5–3.44	2.65–17.48	0.57–1.24	1.75–4.56

Source: Sanandiya and Siddhanta 2014.

Abbreviations: CW = Coldwater extract; HW = hot water; OX = aqueous ammonium oxalate; ALK = aqueous sodium hydroxide.

TABLE 31.4
Analysis of Mineral Elements in *Salicornia* spp.

	S. bigelovii **(mg/100g of Fresh Weight)**	***S. herbacea*** **(mg/100g)**		
Mineral Elements	**Whole Plant**	**Tip**	**Shoot**	**Root**
Ca	60–64	237.5	158.8	22.1
Cd	0.1			N/A
Cr	<0.1			N/A
Cu	7.7–10.5	3.1	1.1	2.1
Fe	1	31.5	66.2	84.8
K	168–184	650.1	740.1	741.1
Mg	112–124	46.5	54.0	52.5
Mn	N/A	7.2	3.9	3.0
Na	927–1069	1003.4	1218.1	1333.8
Ni	N/A	1.1	0.7	0.4
P	17–19	N/A		
Pb	0.1–0.3	N/A		
Zn	39.1–41.9	13.4	29.6	2.4
References	(Lu et al. 2010)	(Min et al. 2002)		

TABLE 31.5
Amino Acid Profile of *Salicornia* spp.

	S. bigelovii **(mg/100g of Fresh Weight)**	***S. herbacea*** **(mg/100g)**		
Amino Acid	**Total Plant**	**Tip**	**Shoot**	**Roots**
Alanine	67–71	79.9	88.7	98.2
Arginine	66–70	77.0	36.1	57.0
Asparagine	114–118	137.1	140.2	165.5
Cysteine	3	-	-	11.1
Glutamic acid	160–166	144.8	160.5	182.3
Glycine	52–54	76.9	80.4	122.9
Histidine	25–27	34.0	79.3	54.4
Isoleucine	45–49	110.7	107.5	94.7
Leucine	93–95	115.5	98.1	128.4
Lysine	72–74	79.8	310.2	178.9
Methionine	9	23.2	52.2	23.3
Phenylalanine	54–56	73.2	63.3	67.7
Proline	73–93	88.8	18.4	86.8
Serine	66–70	67.5	72.7	94.2
Threonine	54–56	70.9	69.8	81.2
Taurine	-	7.6	21.4	37.7
Tyrosine	43–45	10.8	-	-
Valine	54–64	72.9	126.1	94.7
References	(Lu et al. 2010)	(Min et al. 2002)		

fraction of the plant being studied. Glycine is abundant in the roots but not in the stems and leaves. By contrast, proline is abundant in the leaves and roots, compared to the stems. Arginine, glycine, histidine, lysine, proline, and valine are other amino acids which have concentrations that vary with the part of the plant (leaf, stem, root) being sampled.

The fatty acid and oil contents of *Salicornia* seeds are shown in Table 31.6. Myristic, palmitic, stearic, and arachidonic acids are the main saturated fatty acids present in *Salicornia* biomass, but are a minor fraction of the total lipids present. Oleic acid is the only reported monounsaturated fatty acid. Linoleic (found in the highest concentration) and linolenic acid are the main polyunsaturated fatty acids. The presence of higher concentration of polyunsaturated fatty acids makes *Salicornia* a prospective biomass for advanced fuel production and an alternative source for essential fatty acids in the human diet.

The green succulent part of *Salicornia* is easy to process through simple juicing or cold pressing. Since this fraction of the biomass is high in moisture content, it is suitable for juicing. Twenty-five percent of the dry matter of the green fraction of *Salicornia* can be extracted as juice components, and 75% of the dry matter ends up in the fiber rich pulp (Alassali et al. 2017). The protein content of *S. europaea* is 2.3 mg/g of fresh weight (FW), which in other green herbaceous plants such as spinach and celery leaf are 2.6 mg/g of FW (Wang et al. 2007; Lu et al. 2010). The shoots of *S. herbacea* have been reported to contain less protein (1.9 mg/g FW) in comparison to the roots (2.2 mg/g FW). Based on the nitrogen content, the protein in the green fraction of *S. sinus-persica* was estimated to be 13% of the pulped biomass after juicing, on a dry matter basis (Islam and Adams 2000; Alassali et al. 2017). Of the dry matter content of the juice, 7.6% was comprised of proteins and 4.6% of lipids, while the remaining constituents were ash and sugars.

S. bigelovii has been reported to contain 569, 159, 58 mg/kg of fresh weight of total chlorophyll, β-carotene, and ascorbic acid, respectively (Lu et al. 2010). The rich presence of β-carotene and ascorbic acid, which are sources of vitamin A and C, respectively, emphasize the nutritional value of *Salicornia* and make a case for its regulated consumption in the human diet.

31.4 COMMERCIAL APPLICATIONS

Salicornia has value as a nutrient source for humans, feed for animals and fish, feedstock for biofuel production, in the pharmaceutical industry, in phytoremediation, and as biofilters for aquaculture. Amongst its various applications, we limit ourselves to discussing the most well-documented areas.

31.4.1 Food Products

The tender green tips of *Salicornia* have been used as food ingredients for salads, as garnishes, or cooked in the absence of salt in a similar manner to spinach. An Apulian traditional dish consists of boiled *Salicornia* cooked with extra virgin olive oil and garlic and often accompanied with fish or seafood (Loconsole et al. 2019). *Salicornia* contains various nutrients such as proteins, vitamins (e.g. C, B1) minerals,

TABLE 31.6
Fatty Acid Composition in Seeds of *Salicornia* spp.

Fatty Acid*	**Common Name**	***S. bigelovii* Oil (% of Lipids)**	***S. bigelovii* Oil (% of Lipids)**	***S. bigelovii* Seeds (% of Lipids)**	***S. europaea* Seeds (% of Lipids)**	***S. brachiata* Shoots (% of Lipids)**	***S. ramosissima* Shoots (% of Lipids)**
14:0	Myristic acid	-	0.18	-	-	-	0.29
16:0	Palmitic acid	7.7–8.7	8.50	7.0–8.50	6.0–7.8	23.7–27.9	21.59–22.69
18:0	Stearic acid	1.6–2.4	-	1.24–1.69	0.7–1.1	6.58–7.82	4.16–6.83
18:1 n-9	Oleic acid	12.0–13.3	19.99	12.33–16.83	21.0–22.6	3.04–9.2	2.21–5.73
18:2 n-6	Linoleic acid	73.0–75.2	63.40	74.66–79.49	69.8–72.4	25.36–26.04	19.04–21
18:3 n-3	Linolenic acid	2.4–2.7	1.34	1.5–2.3	-	28.18–29.94	38.97–40.23
20:00	Arachidonic acid	-	6.59	-	-	0.78–1.03	0.66–0.72
Total lipids (g/100g)		26–33	-	27.7–32.0	27–29	17.82	-
References		(Glenn et al. 1991)	(Attia et al. 1997)	(Anwar et al. 2002)	(Austenfeld 1986)	(Mishra et al. 2015; Patel et al. 2019)	(Maciel et al. 2018)

* Fatty acids are denoted by the number of carbons in the molecule, then the number of double bonds, followed by the position of the first double bond in relation to the methyl end.

polysaccharides, and bioactive compounds (Lu et al. 2010). This wide range of nutrients has propelled the increased use of *Salicornia* in human diets and puts this plant into a group of super foods alongside the likes of kale and quinoa (Rowney 2013). A quick search online can show hundreds of webpages recommending Salicornia-based recipes.

In one study, *S. herbacea* extract was mixed with milk and tested as yoghurt for human consumption in three varying concentrations, namely 0.25, 0.5, and 1% (w/v). 0.25% was considered the best suited for color, flavor, viscosity, sweetness, sourness, and overall palatability (Cho et al. 2008). The use of *S. herbacea* is reported to nutritionally improve the quality of traditional Korean soy sauce *meju* and *kanjang* (Kim et al. 2011). The Fe, K, and Mg contents of *makgeolli* (Korean wine) have also been reported to be higher in *Salicornia*-based wine than traditional wheat- and rice-based wine, thus suggesting the presence of *Salicornia* in the *nuruk* culture had enhanced yeast growth (Jeon et al. 2010). The bioactive profile coupled with a high protein content and the presence of chlorophyll, β-carotene, and ascorbic acid also allows for *Salicornia* to serve as a supplement for current types of fish feed (Lu et al. 2010). *Salicornia* is already being used by companies such as Phyto Corporation, Atecmar Coop, Koppert Cress, Radiant Inc, Chanel, and MAC in products like nutritional supplements, tea, chips, salt substitutes, toothpastes, skin care products, dairy products, animal feed, weight loss supplements, and superfood ingredients (Sung et al. 2009; Feng et al. 2013; Shin and Lee 2013; Karan et al. 2018). The high content of polyunsaturated fatty acids such as linoleic and linolenic acid (which cannot be produced in the human body) in *Salicornia* seeds make them a suitable source for essential fatty acids in human diet.

31.4.2 FEED PRODUCTS

There are some indications that *Salicornia* spp. can be used in livestock production. When *Salicornia bigelovii* was used as a substitute for Rhodes grass (*Chloris gayana)* as a forage for Damascus kid goats, there was a two-fold increase in consumption, thus offering a low cost and readily available substitute for goat feed (Glenn et al. 1992). Both washed (to reduce salt concentrations) and unwashed *S. bigelovii* was fed to goats. High salt concentrations in the forage did not inhibit the forage consumption patterns of the animals, however the water intake of the goats did slightly increase (Glenn et al. 1992). The increase in consumption of water by animals is an important factor when considering *Salicornia* as a feed supplement for livestock in arid regions, where fresh water is a scarce resource. *S. bigelovii* seed cake has also been mixed in broiler diets as an alternative protein feed (Attia et al. 1997).

31.4.3 PHYTOCHEMICALS

Phytochemicals are naturally occurring chemical compounds found in plants. These chemicals are classified on the basis of protective function, physical characteristics, and chemical characteristics (Meagher and Thomson 1999). Phytochemicals are not essential nutrients for human health; however, their role in boosting the human immune system to fight common diseases has been well documented (Taofiq et al. 2017). Halophytes have been considered useful in medicinal application due to the presence of a wide variety of secondary metabolites such as alkaloids, flavonoids, tannins, terpenoids, saponins, and coumarins (Bandaranayake 2002). Prior to describing the presence of phytochemicals in *Salicornia* spp. and their respective medicinal effects, it is worth mentioning how these various phytochemicals are categorized. Phytochemicals can be broadly categorized as primary and secondary metabolites. Primary metabolites include sugars, amino acids, and proteins. Secondary metabolites include alkaloids, phenols, terpenes, steroids, and saponins. Phenolics, which are a large portion of the secondary metabolites, can be further categorized into smaller groups such as flavonoids, tannins, and phenolic acids, based on the structure of the chemical compounds. Flavonoids are the largest and most studied group of plant phenols (Saxena et al. 2013). Phenolic acids are a diverse group that can be further subdivided into hydroxycinnamic acids and hydroxybenzoic acids (Taofiq et al. 2017). Caffeic, ferulic, p-coumaric, rosmarinic, chlorogenic, cinnamic, and sinapic acids are some of the most common hydroxycinnamic acids, which are of importance to *Salicornia* spp. Phenolic polymers, also known as tannins, can be further categorized into hydrolysable and condensed tannins.

S. europaea was reported to contain phenolic compounds, alkaloids, flavonoids, and saponins (Lellau and Liebezeit 2001). Flavonoids have been reported to be used in treating hypertension, scurvy, and cephalalgia, and possess anti-inflammatory abilities (Min et al. 2002; Lellau and Liebezeit 2003). Until now, nine flavonoids, four chromone compounds, four triterpenoid saponins, and one new triterpenoid saponin have been identified in *S. europaea* (Arakawa et al. 1982; Yin et al. 2012). The four triterpenoid saponins are oleanolic acid glucoside, chikusetsusaponin methyl ester, calenduloside E, and calenduloside E 6'-methyl ester, and the latest discovered, dihydroxyoleanenoic acid glucopyranosyl ester (Cybulska et al. 2014a). *S. europaea* ethanol extracts have been reported to contain high concentrations of quinic acid, rosmarinic, and p-coumaric acids and lower concentrations of hesperidin, rutin, malic, and rhamnetin acid (Zengin et al. 2018). While the presence of alkaloids in *Salicornia spp.* has been contradictory at times, it has been mentioned that the chemical diversity of each species is controlled by the environment and harvesting time, both of which influenced the results of the specific secondary metabolites analyses (Lellau and Liebezeit 2001). In addition, the location, date and even time of the day can influence the presence of secondary metabolites, thus making it difficult to accurately predict the exact concentrations of secondary metabolites in a particular species.

S. herbacea is commonly known as tungtungmadi in Korea and has been used in traditional medicine and as seasonal vegetables. *S. herbacea* has been used as folk medicine for treating diarrhea, nephropathy, and constipation (Rhee et al. 2009). Contemporary pharmacological studies have verified the antioxidative, anti-inflammatory, and immunomodularity capabilities of this halophyte. The manner in which *S. herbacea* extracts suppress inflammation suggests that they can be used in treating cancer, autoimmune diseases (e.g. rheumatoid arthritis), vascular diseases (e.g. atherosclerosis), and metabolic diseases (e.g. diabetes) (Rhee et al. 2009).

The antioxidative capacity of *S. herbacea* was tested in an ethyl acetate soluble fraction based on the scavenging activity of the 1,1-diphenyl-2-picrylhydrazyl free radical (Young et al. 2005; Wang et al. 2017). A chlorogenic acid is an ester of caffeic acid and quinic acid, both of which have individually been reported to possess antioxidative properties (Medina et al. 2007; Zengin et al. 2018). Tungtungmadic acid is a derivative of chlorogenic acid, which is chemically classified as 3-caffeoyl-4-dihydrocaffeoyl quinic acid (Young et al. 2005). Other bioactive compounds that have been reported to be extracted from *S. herbacea* include β-sitosterol, isorhamnetin-3-O-β-D-glucopyranoside, stigmasterol, uracil, quercetin 3-O-β-D-glucopyranoside, isoquercitrin 6”-O-methyloxalate, methyl 4-caffeoyl-3-dihydrocaffeoyl (salicornate), 3,5-dicaffeoylquinic acid, methyl 3,5-dicaffeoyl quinate, and 3,4-dicaffeoylquinic acid (Lee et al. 2004; Kim et al. 2011; Cho et al. 2016). Isorhamnetin-3-O-β-D-glucopyranoside has been identified to be a leading compound in treating diabetes and/or prevention of diabetes and its related complications (Lee et al. 2005). Betaine obtained in methanol extracts of *S. herbacea* has been claimed to lower the level of homocysteine in blood, and thereby providing protection against cardiovascular ailments (Rhee et al. 2009). *S. herbacea* extracts have been examined for their immunomodulatory abilities on monocyte/macrophage lineage cells (Im et al. 2006). Macrophages are unique cells in immune systems capable of a dual role, initiating immune responses and serving as effector cells.

S. brachiata is considered a traditional medicine for treating hepatitis and has been tested for its antiviral activity (Bandaranayake 2002). The presence of bioactive compounds, minerals, amino acids, polyphenols, proteins, reducing sugars, and pigments known for antioxidative properties such as betacyanin and betaxanthin has been reported (Escribano et al. 1998; Parida et al. 2018).

31.4.4 BIOFILTERS FOR AQUACULTURE

Unfiltered effluents from aquaculture contain large amounts of non-utilized nutrients and organic substances that can cause hypertrophication (also known as eutrophication) and toxification of adjacent ecosystems. The uncertainty of control parameters, such as pH, temperature, and dissolved oxygen level in open ponds, adds further to the complexity of estimating a reliable recovery of fish from open pond systems. The cost of procuring clean and fresh water while maintaining habitat suitable for discharge of effluents has led to an increased interest in Recirculatory Aquaculture Systems (RAS) (Martins et al. 2010; Dalsgaard et al. 2013). As RAS seems to provide viable alternative to current fish culture practices, however, this too like any new technology has its shortcomings. The high upfront capital cost of RAS and operating cost for maintaining the availability of clean water, round the clock electricity, and availability of nutrients are some of the cost factors that require optimization. Additionally, the cost associated with adding denitrification filtration systems that convert ammonia excreted by fish in the effluents to nitrogen, have high operating costs. A wide range of plants have been studied to conceptually design combined aquaculture and hydroponic systems (Watten and Busch 1984; Turcios and Papenbrock 2014). In this chapter, we restrict ourselves to focus on saline aquaculture systems and how salt-tolerant plants can be combined to design a hybrid aquaponic system. Halophytes can serve as biofilters in cleaning the effluents from aquaculture systems (Glenn, et al. 1999; Buhmann and Papenbrock 2013a; Buhmann et al. 2015). The use of plants as filters will have two impacts on an aquaculture system. First, it will reduce the stress on the filtration systems resulting in cost saving. Second, if the halophytes can be utilized commercially as food, feed, or biomass to derive biochemical products, they can provide an alternative revenue stream for aquaculture systems. This secondary revenue stream can offset the dependence of aquaculture industries on fish markets and provide a new avenue to diversify income portfolios (Buhmann and Papenbrock 2013b). Fish grown for commercial purposes in controlled environments such as RAS, take a large fraction of the nitrogen and phosphorus supplied in the feed. Using halophytes as biofilters can serve as the link between aquaculture systems and hydroponic cultivation.

Salicornia spp. have been studied to grow in constructed wetlands with the aim of reducing the treatment of waste-streams emanating from aquacultures. *Salicornia* has been confirmed to take up 85% of the nitrogen and 73% of dissolved inorganic phosphorous from wastewater into plant tissues (Webb et al. 2012). While the majority of nitrogen removal in wetlands happens due to microbial processes, the increased uptake by *Salicornia* can be accredited to its resilient adaptability to changing environmental conditions. The total uptake of nitrogen and phosphorous by *Salicornia* is significantly impacted by the surface versus subsurface flow and level of nutrients present in the flow streams (Brown et al. 1999; Shpigel et al. 2013). The growth and visual quality of *Salicornia* grown in a RAS-hydroponic systems has been reported to be excellent with the halophytes retaining 9% of the N and 10% of the P introduced from fish feed (Waller et al. 2015). While using *Salicornia* as a biofilter for aquaculture has economic value, the hydroponic systems coupled with aquaculture can help close the nutrient cycle, bringing us a step closer to circular production systems.

31.4.5 Fuels and Energy

Salicornia in early stages of growth is succulent and ideal for food consumption. As the plant matures, it loses moisture content, but remains high in protein and minerals. Once the plant dries out, the seeds can be separated from the straw fraction and utilized as a source for fuel, while the straw can serve as a source for extracting phytochemicals and carbohydrates. Thus, the same plant can be utilized for various purposes such as feed, fuels, type of fuel, and bioenergy.

The Sustainable Biofuels Research Consortium established in 2011, in Abu Dhabi, funded The Seawater Energy and Agriculture System (SEAS) project to investigate the possibility of integrating aquaculture, halophyte agriculture, and mangrove silviculture to produce sustainable biofuels. The SEAS project site was envisioned to consist of 10% aquaculture ponds, 70% *Salicornia* fields, and 20% mangrove wetlands (Warshay et al. 2017). *S. bigelovii* had been chosen for this project due to its high oil content in seeds (26–31%), of which 73–75% is linoleic acid (Glenn et al. 1991). *S. bigelovii* was studied to be hydro-processed into jet fuel or diesel or transesterified to produce fatty acid methyl esters (Warshay et al. 2011). The leftover fraction post oil seed processing (seed cake) is rich in proteins and could be used as animal fodder. The left over straw fraction of the biomass (which is not oilseeds) could be used as a feedstock via the Fischer Tropsch process for the production of jet fuel or diesel fuel through the cellulose to ethanol pathway or through gasification to produce syngas (Warshay et al. 2011). It was estimated that using a combination of one of these approaches, coupled with the utilization of the straw fraction would lead to 63–80 g of CO_2–equivalent reduction/passenger–km of greenhouse gas emission (68% reduction in GHG emissions) by substituting conventional fuels with biofuels from *S. bigelovii* (Warshay et al. 2011). However, the high concentration of salt in *Salicornia* posed a risk of corrosion of equipment and this also inhibited enzymatic hydrolysis and fermentation. The removal of salt needed to occur by washing the biomass with fresh water, which is a valuable resource in arid parts of the world. Thus, the removal of salt before processing the biomass for sugar recovery became a crucial step in determining the feasibility of biofuel production from *Salicornia*.

S. bigelovii biomass contains 5–16 g/100g of lignin and 16–55 g/100gm of carbohydrate in the total solids. Enzymatic hydrolysis at the optimized pretreatment temperature of 210°C resulted in 91% glucose recovery (Cybulska et al. 2014c). This corresponds to 100–111 kg ethanol/dry ton of *S. bigelovii*, while in comparison corn stover has an ethanol potential of 230 kg/dry ton (Kadam and McMillan 2003; Brown et al. 2014). However, it must be pointed out that *Salicornia* has a higher biomass yield per hectare (20 tons/ha) than corn stover (9.4 ton/ha) (Brown et al. 2018). In addition, *Salicornia* can be used for its oilseeds and the straw as protein rich feed, thus providing more product choices while utilizing less resources (arable land and fresh water for irrigation). Post pretreatment, *Saccharomyces cerevisiae* used in the simultaneous saccharification and fermentation of *S. bigelovii* has resulted in up to 98% ethanol yield (Bañuelos et al. 2018). While the cellulose sugars in the straw fraction can be utilized for ethanol production, the hemicellulose sugars can be used for biogas production (150 L methane/kg VS biomass) and the oilseed can be used for biodiesel or Bio-Synthetic Paraffin Kerosene production (Ashraf et al. 2016). The importance of moving from first generation (food-based biomass) to second generation (non-food based) biofuels has been well documented and discussed by Carriquiry et al. (2011). Species like *Salicornia* provide a new dimension in this regard, using non-arable land to grow crops that can be utilized for food and fuel (Marriott and Pourazadi 2017).

31.5 CONCLUSIONS AND FUTURE PERSPECTIVES

Salicornia spp. are widely distributed across the globe and are tolerant to saline water. With the discovery that these halophytes can be used as food, fuel, and in bio-products, more researchers undertook the task of classifying this genus and analyzing its constituents. The *Salicornia* genus includes up to 30 species, however, inbreeding, a high degree of physiological plasticity and few diagnostic characters, has led to an extremely challenging taxonomy, which has only begun to be better understood in the past two decades. *S. sinus-persica* was earlier misunderstood to be *S. europaea* until a taxonomic revision was published (Akhani 2008); no further studies of this species are available under this name. While *S. arabica, S. europaea,* *S. bigelovii, S. brachiata*, *S. ramosissima*, and *S. herbacea* have all been studied to varying extents (for their proximate compositional analysis, polysaccharide fractions, carbohydrate fractions, mineral elements, amino acid profile, and fatty acid composition) the most comprehensive information is available for *S. bigelovii, S. europaea*, and *S. herbacea*.

Salicornia spp. are halophytes that show promise for the production of biomass for a range of applications, including:

1. Selective nutrients and proteins for food to be consumed by humans
2. Value added chemicals that can be incorporated into animal feeds to lower the cost of fodder and enhance its quality
3. Phytochemicals which have been used traditionally to treat diseases and can now be selectively extracted from plants to treat patients suffering from chronic illness
4. Nutrient uptake from soil, especially when used in combination with aquaculture systems, which tend to release large quantities of underutilized nutrients in their effluent streams
5. Biofuels derived from the oil-rich seeds

Early research with *Salicornia* spp. was riddled with difficulties in identifying the species and in taxonomical challenges due to phenotypic plasticity and morphological parallelism; some of these still persist to this day, continuing to cause difficulties in identifying species. However, with persistent global interest in the species and curiosity in exploiting its oil-rich seeds and phytochemical potential, considerable progress has been achieved. To harness the benefits of this crop, we need to build upon the existing knowledge base by formulating research studies that help bridge information gaps.

On the cultivation and physiology front, the optimization of growth conditions (such as effects of salinity, soil nutrients, and weather conditions) for *Salicornia* using waste effluents streams from aquacultural effluents need to be demonstrated on a pilot scale. In addition, a growth manual needs to be developed which includes details on sowing time and depth, fertilizer timing and requirement, and harvest time, dependent on which fraction of the biomass is being sought. Taxonomic studies of species need to be undertaken on a global scale to verify the presence of distinct species and get an overview of the genetic variation of the species.

Insights on the complex senescence processes of different *Salicornia* species will spur innovation in designing robust processing steps for extracting plant derivatives. These processes should be able to utilize the varying proteins, secondary metabolites and oil, at different stages of growth to yield the most valuable product for that growth stage. In the past, plants have been utilized commercially for food, fuels, and primary metabolites. Rarely has one plant been able to provide all three products, while also without the need for fresh water for irrigation and arable land for cultivation. In these aspects, *Salicornia* is a truly novel biomass. In an era, that recognizes the importance of reducing and recycling waste, optimizing resource utilization, and developing alternative uses of energy, the production of *Salicornia* could be a strong contender in building a sustainable model for a circular economy.

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