Comparative Study of Chemical Composition of the Halophyte Species Native to the Persian (Arabian) Gulf

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Extensive comparative characterization was performed to explore halophytes native to the Persian (Arabian) Gulf. Ten species collected from the Western region of Abu Dhabi, United Arab Emirates (UAE) were analyzed for their lignocellulosic components as well as for ash and extractives content. It was found that the species significantly differ in the content of carbohydrates, lignin, total ash-free extractives and total ash. The total ash content was found to negatively influence the content of carbohydrates. Based on the characteristics, it is concluded that *Cornulaca aucheri* is the most attractive as a source of carbohydrates, and *Tetraena (Zygophyllum) qatarensis* has the potential to produce the highest yield of the extractives fraction.

Keywords: Halophytes; Biomass characterization; Extractives; Biorefinery; Second generation feedstock

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INTRODUCTION

Halophytes are salt-tolerant plants and represent a potential green biomass resource in coastal and desert areas. They can tolerate harsh climatic conditions, including high water and soil salinity, high temperatures, and humidity. These plants thrive in conditions that would be lethal to most glycophytes (plants that grow in non-saline conditions), which makes them attractive to researchers (Khan and Qaiser 2006; Flowers and Colmer 2008; Rozema and Flowers 2008). For example, the Persian (Arabian) Gulf region is characterized by higher than average temperatures and seawater salinities, compared to other continental climate regions and bodies of water, respectively. During the summer, the seawater salinity can reach up to 50 PSU, which is higher than the normal Indo-Pacific oceanic salinity (about 35 PSU), while the air temperature can approach 50 °C (Coles 2003; Pain and Abdelfattah 2014). Over 20 species of halophytes grow naturally in the Gulf region (Böer and Saenger 2006). These native species include *Arthrocnemum macrostachyum* (Moric.) C. Koch, *Halocnenum strobilaceum* (Pall.) M. Bieb., *Halopeplis perfoliata* (Forssk.) Schweinf. & Aschers., *Anabasis setifera* DC., *Salsola rosmarinus* (Ehrenb. ex Boiss.), *Salsola drummondii* Ulbr.; *Caroxylon imbricatum (Forssk.)* Akhani and E. H. Roalson (Basionym: *Salsola imbricata* Forssk.), *Binertia sinuspersici* Akhani, *Salicornia sinus-persica* Akhani, *Suaeda iranshahrii* Akhani & Freitag, *Suaeda vermiculata* Forssk., *Avicennia marina* (Forssk.) Vierh., *Tetraena (Zygophyllum) qatarensis* (Schweinf.) Beier & Thulin var. *qatarensis* (Hadidi) Alzahrani & Albokhari (Brown 2006; Ghazanfar *et al.* 2014).

Currently, these previously listed native halophyte species have no particular large-scale commercial/economic uses, except for some attempts to use them as fodder for small ruminants (Kraidees *et al.* 1998). However, halophytes have been historically used in many cultures as medicinal plants (Popp 1984; Rashid 1994; Daoud *et al.* 2001; Towhidi and Zhandi 2007; Custódio *et al.* 2012; Ksouri *et al.* 2012; Rodrigues *et al.* 2014; Yang *et al.* 2014). The medicinal properties are attributed to the therapeutic properties of their secondary metabolites, which are mostly present in the extractives fraction of the plant. Secondary metabolites are bioactive compounds, produced by plants, which are generally not directly involved in normal growth and reproduction. These bioactive compounds include protective compounds, which halophytes and other extremophiles produce as a special adaptation against the harsh environmental conditions, *e.g.*, high salinity, which could otherwise cause damage in cell DNA, RNA, and proteins due to the production of reactive oxygen species (ROS) (Singh and Gabani 2011; Flowers and Colmer 2015).

In general, plants have evolved two antioxidative pathways to combat possible cellular damage caused by ROS: an enzymatic pathway, which involves enzymes such as superoxide dismutase and catalase, and a non-enzymatic pathway, which includes antioxidants, such as tocopherol, carotenoids, ascorbate, phenolic compounds, alkaloids, glutathione, and non-protein amino acids that scavenge free radicals (Gill and Tuteja 2010). As an adaptation to stressful environmental conditions, halophytes are more likely to produce higher levels of these enzymes and antioxidants. For example, the review by Bose *et al.* (2014) presents many studies in which halophytes have exhibited higher antioxidant levels and enzyme activity compared to glycophytes. Similarly, Ellouzi *et al.* (2011) found that α-tocopherol levels were two to five times higher in a halophyte *Cakile maritima* versus a related glycophyte *Arabidopsis thaliana*, particularly when exposed to salt concentrations above 10 ppm. Additionally, osmolytes, such as glycine betaine and proline, which are produced by halophytes to adjust osmotically to saline conditions, may also provide protection against free radicals (Jithesh *et al.* 2006).

Due to the extreme stress that the halophytes native to the Gulf region experience, they are likely to be superproducers of protective compounds. Particularly, the antioxidants may have potential commercial applications in the production of high-value nutraceuticals and pharmaceuticals. Cybulska *et al.* (2014a) reviewed the phytochemical profile of halophytes native to United Arab Emirates (UAE) and found many examples of species with potentially useful extractives. For example, *S. vermiculata* extract contains phenolic compounds and triterpenoids, which have been shown to prevent cardiovascular diseases (Oueslati *et al.* 2012). Also, the extract of *T. qatarensis* has antimicrobial effects (Mahasneh 2002), whereas *A. macrostachyum* and *Salsola* spp. contain flavonoids and phenols with antioxidant and anti-inflammatory properties (Custódio *et al.* 2012; Abdou *et al.* 2013; Akbar and Yahya 2011). Several species of the family Zygophyllaceae are Middle-Eastern halophytes that have been previously studied for their phytochemical potential (Amin *et al.* 2010, 2011; Hussein *et al.* 2011). From the extractive fractions of *Tetraena alba* and *Zygophyllum gaetulum* species, essential oils and bioactive compounds were isolated (Jaouhari *et al.* 2000; Tigrine-Kordjani *et al.* 2006; Tigrine-Kordjani *et al.* 2011).

Biofuels have a key role in green transition and decreasing greenhouse gas emissions to the atmosphere. However, the use of first generation feedstocks, such as starch and edible oils, is considered unsustainable due to high competition with food resources. A biorefinery from second generation feedstocks targeting only the production of biofuels is rarely economically profitable, but introducing value-added products to the process would improve the feasibility (Severo *et al.* 2019). Besides extractive fractions, halophytes

have lignocellulose structure (with some compositional differences), which can be used as a feedstock for production of second-generation biofuels. Therefore, the extractives could potentially be used for the productions of some high-value compounds, and the leftover fraction used for the production of biofuels. As halophyte extracts have shown antimicrobial, anti-inflammatory, and even cytotoxic properties (Ksouri *et al.* 2021; Omaruyi *et al.* 2021; Rashid 1994; Rodrigues *et al.* 2014), they would potentially provide a bio-based alternative to some petroleum-based antibiotics and cancer drugs, which are also sourced from over-exploited oil reservoirs.

Considering these aspects, halophyte biomass may present an avenue for local biofuel production in the Middle East (Flowers and Colmer 2008; Brown *et al.* 2014; Cybulska *et al.* 2014c), as traditional second-generation lignocellulosic feedstocks, including cereal straws and agricultural residues, are scarce in the arid regions or cannot be produced sustainably. Furthermore, as halophytes can thrive on lower quality (saline or nutrient-lacking) soils using saline water for irrigation, cultivation of these plants would reduce the need for fertile soil and freshwater irrigation. This would also further reduce the competition with food production. Besides advantages in the cultivation phase, preliminary studies (Cybulska *et al.* 2014c) show that milder process conditions are required to pretreat halophyte straw (severity factor < 4.0) compared to the processing of commonly used feedstocks. This means pretreatment in lower temperatures or with shorter retention time (Brudecki *et al.* 2012; Cybulska *et al.* 2013). Thus, halophytes could be considered as an alternative for the traditional second-generation feedstocks.

In this work, an assessment was carried out of the compositional differences among a variety of halophyte species native to the Gulf region, collected in the summer along the coastal areas of Abu Dhabi, UAE. The samples of *Arthrocnenum macrostachyum, Bienertia sinuspersici, Caroxylon imbricatum, Salsola drummondii, Halopeplis perfoliata, Suaeda vermiculata, Cornulaca aucheri, Tetraena (Zygophyllum) qatarensis, Tetraena aff coccinea* (*Zygophyllum aff. coccineum*), and *Salicornia sinus-persica* were characterized in order to evaluate their suitability for biorefinery applications. All characterized plant species are members of *Chenopodioideae* and most of them belong to the Amaranthaceae family, excluding two *Tetraena* (*Zygophyllum*) species belonging to the *Zygophyllaceae* family. Amounts of lignocellulose compounds were analyzed, in an aim to find alternative raw materials for possible biofuel production, and the amount of extractive material was determined, as it could be valorized as value-added products.

EXPERIMENTAL

Sample Collection and Pretreatment

Plant samples of *A. macrostachyum* (AM), *B. sinuspersici* (BS), *C. imbricatum* (CI), *S. drummondii* (SD), *H. perfoliata* (HP), *S. vermiculata* (SV), *C. aucheri* (CA), *T. qatarensis* (TQ), *T. aff coccinea* (TC) and *S. sinus-persica* (SS) were collected on 8 July 2014 from a coastal site in the Western region of Abu Dhabi (52.554 N 24.129 E). This region (also known as the Al Dhafra Region or *Al Gharbia* in Arabic) is located between the areas of Al Hamra and Al Ruwais. After collection, samples were air-dried and milled to achieve ≤ 1mm particle size using laboratory-scale knife mill (IKA, 10 MF Basic).

Chemical Analysis

Standard procedures of lignocellulosic biomass characterization were employed (based on NREL protocols listed in the following sections). First, the amount of extractive

material in plant biomass was determined. Subsequently, the content of lignocellulose compounds (carbohydrates and lignin) was analyzed. Extractable and structural ash content were measured in order to determine the feasibility of extractive-ash removal by a freshwater wash.

Determination of water- and ethanol-soluble extractives

Three quantities were measured during this analysis: water-soluble extractives, ethanol-soluble extractives, and total extractives, which is the summation of two previously mentioned fractions. Amounts of extractives were determined by measuring the content of dissolved solids from the obtained extracts. Total extractives were also determined as a weight loss of extracted solid sample (Sluiter *et al.* 2008c).

Dried and milled sample (3 g) was placed in an alundum thimble and extracted in sequence with water and ethanol (100 g) using a Soxhlet apparatus. Both extractions were run for 12 h (3 to 4 and 5 to 6 cycles per hour for water and ethanol, respectively). The extractive-free material was removed from the thimble and oven-dried overnight at 105 °C to determine total (including volatile and non-volatile) extractives (Eq. 1).

Non-volatile water- and ethanol-soluble extractives were measured as solids content in the extracts (by evaporating the solvent in a vacuum oven and weighing the solid residue), and their amounts were calculated using Eq. 2,

$$TE = \frac{TS - W_{dried\ extracted\ biomass}}{TS} * 100 \quad (1)$$

where *TE* is total extractives (g/100gTS), *TS* is total solids of the original biomass (g), and $W_{dried\ extracted\ biomass}$ is the weight of the extractive-free biomass removed from the thimble and dried (g),

$$NE = \frac{W_{dried\ water\ or\ ethanol\ extract}}{TS} * 100 \quad (2)$$

where *NE* is non-volatile extractives (g/100gTS), and $W_{dried\ water\ or\ ethanol\ extract}$ is weight of the dried ethanol extract (g).

Determination of Lignocellulosic Components (carbohydrates and lignin)

Extractive-free biomass was analyzed for carbohydrates and lignin content via strong acid hydrolysis, following NREL standard protocol (Sluiter *et al.* 2008b). The dried extractives-free sample (0.3 g) was digested in sealed pressure tubes with 3.00 mL of 72% sulfuric acid for 1 h, after which the reaction was quenched by adding 84 mL deionized water to achieve 4 % solution of the sulfuric acid. The tubes were placed in an autoclave at 121°C for 1 h to complete the digestion. After cooling, the hydrolysate was filtered through a fritted ceramic funnel, and the filtrate was analyzed for free sugars (glucose, xylose and arabinose) and organic acids (acetic, lactic and formic acids) using High Performance Liquid Chromatography (Agilent 1260 Infinity Bio-inert Binary LC). The Hi Plex-H column (Agilent) and refractive index detector (RID) were used to determine the concentrations of glucose, xylose, and arabinose at 65 °C using 0.005 M H_2SO_4 as the mobile phase (eluent) with a flow rate of 0.6 mL/min. Carbohydrate content in the extractive-free biomass was calculated as presented by Eq. 3,

$$Sugar_{extractives-free} = \frac{C_{anhydro} * V_{hydrolysate} * \frac{1g}{1000mg}}{TS_{extractives-free}} * 100 \quad (3)$$

where $Sugar_{extractives\text{-}free}$ is sugar (carbohydrate) content in the extractive-free biomass (g/100gTS), $C_{anhydro}$ is concentration of a measured sugar converted to its polymeric form,

additionally corrected for degradation during the dilute-acid step of the hydrolysis (using a recovery factor measured by spiking sample replicates with a standard) (g/L), $V_{hydrolysate}$ is the volume of the hydrolyzate (mL), and $TS_{extractives\text{-}free}$ is the extractive-free total solids content (g).

The carbohydrate content in the extractive-free biomass does not reflect its content in the original plant; thus the carbohydrate content on the "as received" basis was additionally calculated to reflect the original plant composition (Eq. 4).

$$Sugar_{as\ received} = Sugar_{extractives-free} * \frac{(100-extracts)}{100} \quad (4)$$

Klason lignin (acid insoluble lignin) was calculated based on the weight measurement of the dry residue remaining after the acid digestion corrected for ash (Eq. 5). Lignin content in the original plant was then calculated following the principle of Eq. 4,

$$AIL_{extractives-free} = \frac{(W_{AIL}-W_{ash})}{TS_{extractives-free}} * 100\% \quad (5)$$

where $AIL_{extractives\text{-}free}$ is acid insoluble lignin (g/100gTS), W_{AIL} is the weight of acid insoluble lignin after drying at 105 °C (g) and W_{ash} is the weight of the residue after baking at 575 °C (g).

Determination of ash (structural, extractable and total)

Total ash (TA) was measured in the original plant following the NREL protocol (Sluiter *et al.* 2008a) (Eq. 6). Extractable ash (EA) was analyzed by measuring the total solids and then ash content in the water extracts, and then relating it to the dry matter raw sample (Eq. 7). Ash content measured in the extractive-free material (after extractable ash removal) was characterized as structural ash (SA) (Eq. 8).

$$TA = \frac{AWR}{TS} * 100\% \quad (6)$$

where *TA* is total ash content (g/100gTS) and *AWR* is ash weight in the raw biomass (g).

$$EA = \frac{AWE}{TS} * 100\% \quad (7)$$

where *EA* is extractable ash (g/100gTS) and *AWE* is ash weight in the extract (g).

$$SA = \frac{AWEF}{TS} * 100\% \quad (8)$$

In Eq. 8, *SA* is structural ash (g/100gTS) and *AWEF* is ash weight in the extractive-free biomass (g).

Statistical Analysis

Statistical mean comparison and testing for significance of differences were performed using Tukey's Honestly Significant Difference (HSD) (Eq. 9), as it allows comparisons among multiple means and it is relatively conservative. All the characterization analyses were performed in duplicates (n=2).

$$\text{HSD} = q\sqrt{\frac{MSE}{n}} \quad (9)$$

where HSD is Tukey's Honestly Significant Difference, q is the critical value from studentized range table for $p < .05$, *MSE* is mean square of error, and *n* is the number of replicates per treatment.

Two hypotheses were tested: H_o: $\mu_i = \mu_j$ and H_a: $\mu_i \neq \mu_j$ (i and j represent different populations, *i.e.* different halophyte species). The null hypothesis (H_o) was rejected when $\left|\bar{X}_i - \bar{X}_j\right| >$ HSD.

RESULTS AND DISCUSSION

Determination of Water- and Ethanol-soluble Extractives

In general, little or no differences were observed among the species in terms of ash-free extractives content. There was no significant difference in the amounts of ethanol-soluble material between any of the studied plant species. For the water-soluble material, the differences were found to be significantly different only between *T. qatarensis* (17.08 g/100gDM), *C. aucheri* (12.79 g/100gDM), and *S. sinus-persica* (10.17 g/100gDM). For other plant species, there was no significant difference in the content of water-soluble extractives.

Even after removal of the extractable ash, the extracted fraction can still be considered high, constituting between 17 to 30% of the dry matter content, depending on the species (Fig. 1). Water extractives were found to represent the majority of the total extractives value for all the plants, except for *S. sinus-persica*, which showed similar contents for both water- and ethanol-soluble extractives. In *S. sinus-persica*, the amount of ethanol-soluble material (8.82 g/100gDM) is nearly double compared to the species with the second highest content of ethanol extractives (4.48 g/100gDM in *H. perfoliata*).

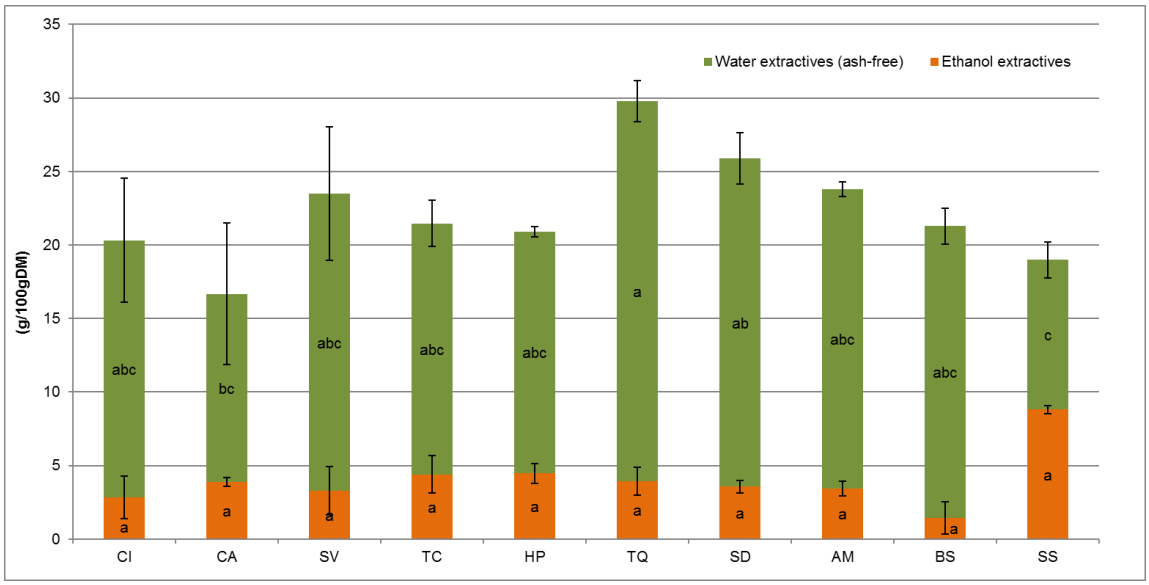

Fig. 1. Total cumulative amount of extractive material in the dry matter of analyzed halophyte species. Different letters denote statistically significant differences ($p < .05$) among the mean values, determined individually for each analyzed component. CI: *C. imbricatum,* CA: *C. aucheri,* SV: *S. vermiculata,* TC: *T. aff coccinea,* HP: *H. perfoliata,* TQ: *T. qatarensis,* SD: *S. drummondii,* AM: *A. macrostachyum,* BS: *B. sinuspersici,* and SS: *S. sinus-persica*.

Previous studies revealed that using water or hydroalcoholic extraction solvents considerably influenced the extraction capacity of bioactive compounds from halophytic and non-halophytic plants in a positive way (Chavan *et al.* 2001; Trabelsi *et al.* 2010; Omoruyi *et al.* 2012). Thus, alternative solvents could be considered when targeting the production of bioactive botanical extracts. The large fraction of extractive material in the biomass could indicate high concentrations of high-value bioactive compounds in the plant. Such plants would be desirable for biorefinery, as value-added products could increase the feasibility of the process. However, a further examination of the detailed composition of botanical extracts would be needed in order to know the amount of different secondary metabolites in them and plan targeted compound and possible processing routes.

Determination of Lignocellulosic Components (carbohydrates and lignin)

All the species analyzed were found to contain the typical lignocellulosic components: extractives, carbohydrates, lignin, and ash (Fig. 2). The highest carbohydrate (total sugar) contents were found for *C. aucheri* (34.25 g/100gDM) and *S. sinus-persica*, (33.43 g/100gDM), suggesting these species to be the most attractive for possible alternative biofuel feedstock after extraction, as the hydrolyzed sugars will be consumed by micro-organisms in processing of biofuels, such as biogas or bioethanol. The lignin content was also found to be relatively low for most of the species (< 20 g/100gDM), making the plant biomass possibly more amenable for processing, as the recalcitrance of the biomass decreases with decreasing content of this protective polymer. Thus, less severe pretreatment conditions would also prevent the production of degradation products, such as furfural and hydroxymethylfurfural, which could be inhibitory for enzymatic hydrolysis or fermentation (Arora *et al.* 2012; Ran *et al.* 2014).

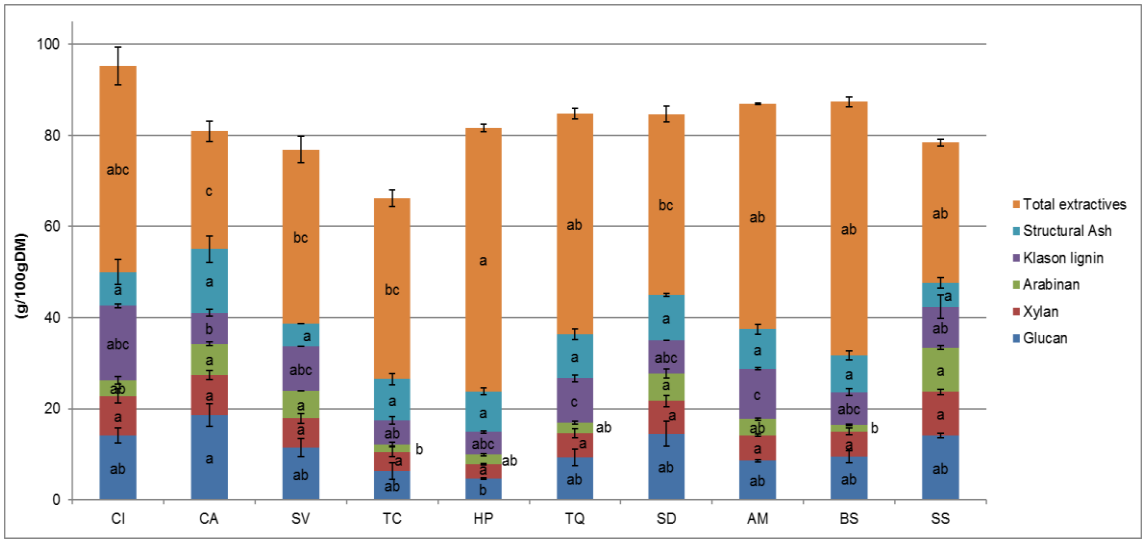

Fig. 2. Content of lignocellulosic components in the dry matter of analyzed halophyte species. Different letters denote statistically significant differences ($p < .05$) among the mean values, determined individually for each analyzed component. CI: *C. imbricatum,* CA: *C. aucheri,* SV: *S. vermiculata,* TC: *T. aff coccinea,* HP: *H. perfoliata,* TQ: *T. qatarensis,* SD: *S. drummondii,* AM: *A. macrostachyum,* BS: *B. sinuspersici,* and SS: *S. sinus-persica*.

Some significant ($p < .05$) species-specific differences were observed for concentrations of glucan, lignin, and total extractives. *C. aucheri* contains significantly lower amount of extractives (25.88 g/100gDM) compared to *H. perfoliata*, *T. qatarensis*, *A. macrostachyum*, *B. sinuspersici* and *S. sinus-persica*. On the other hand, the fraction of total extractive material in *H. perfoliata* (57.81 g/100gDM) was found to be significantly

larger than in *C. aucheri*, *T. aff coccieneum*, *S. vermiculata*, and *S. drummondii*. Considering the Klason lignin content, *T. qatarensis* (21.42 g/100gDM) and *A. macrostachyum* (23.85 g/100 gDM) were observed to contain significantly higher lignin content than other species, and these were the only species with a lignin content above 20 g/100gDM. *C. aucheri* contain significantly lower amount of lignin (6.80 g/100 gDM) compared to *T. qatarensis* and *A. macrostachyum*. *C. aucheri* also exhibited higher glucan content than any of the other studied species (18.60 g/100gDM). No significant differences were found in the xylan content of plants.

C. aucheri, as well as previously studied species native to the Gulf, have reported to contain high level of carbohydrates content (nitrogen-free extract), and the content was found to increase during dry periods (Morsy *et al.* 2008; Shaltout *et al.* 2008; Gad *et al.* 2012). However, when compared to other lignocellulosic biomasses, such as prairie grasses or corn stover (Cybulska *et al.* 2012), the glucan fraction of halophytes was found to be relatively low (< 20 g/100gDM) and the total extractives fraction relatively high (> 30 g/100gDM), as it contained the extractable ash washed out from the salty plants.

Determination of Ash (structural, extractable, and total)

For the studied halophyte species, Fig. 3 illustrates the ash distribution in the samples, showing the efficiency of the salt removal by water wash in form of the extractable ash value.

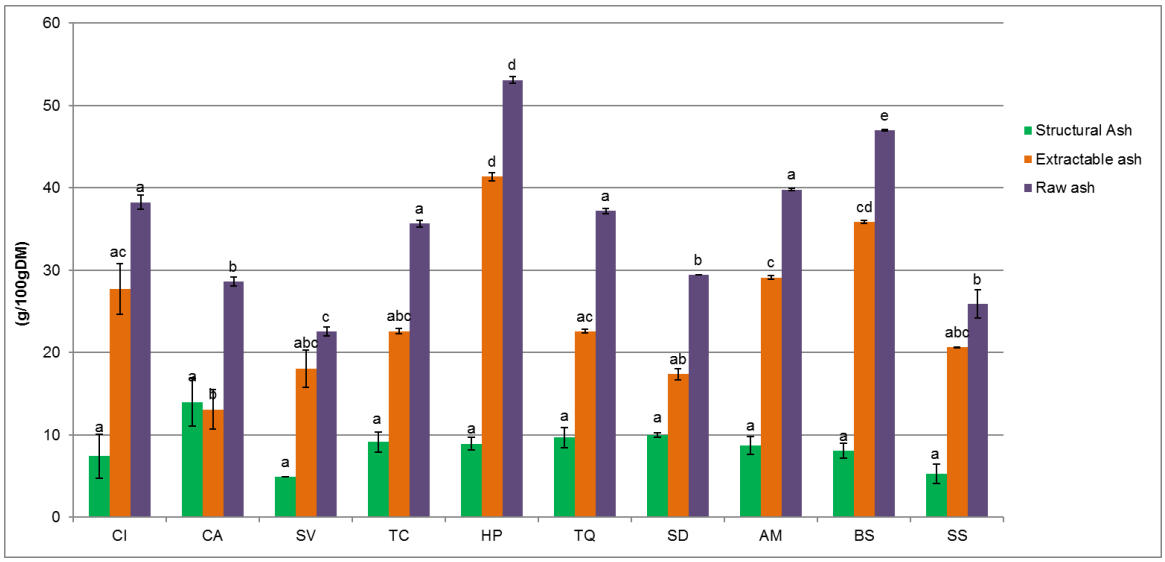

Fig. 3. Ash distribution in the dry matter of analyzed halophyte species. Different letters denote statistically significant differences ($p < .05$) among the mean values, determined individually for each analyzed component. CI: *C. imbricatum,* CA: *C. aucheri,* SV: *S. vermiculata,* TC: *T. aff coccinea,* HP: *H. perfoliata,* TQ: *T. qatarensis,* SD: *S. drummondii,* AM: *A. macrostachyum,* BS: *B. sinuspersici,* and SS: *S. sinus-persica*.

Extractable ash represents 45 to 80% of the total ash measured in the raw plant depending on the species. Significant differences in total (raw) and extractable ash content have been observed among the species. The amount of extractive ash was lowest in *C. aucheri* (13.10 g/100gDM) and highest in *B. sinuspersici* (35.88 g/100gDM). *H. perfoliata* and *B. sinuspersici* were found to contain the highest amount of total ash (54 g/100gDM and 47 g/100gDM, respectively), and *S. vermiculata* contained the lowest amount of total ash (23 g/100gDM). *C. imbricatum, T. aff coccinea, T. qatarensis,* and *A. macrostachyum*

were in the group containing medium amounts (30 to 40 g/100gDM) of total ash. No significant differences were found in the content of structural ash in the plant biomass.

Influence of Ash

Raw ash content in the plant was found to influence plant composition to an extent, as there was a correlation between ash and the amounts of some structural components in the species analyzed. Carbohydrate content in the plants was negatively correlated with ash content, the correlation being similar for both glucan and xylan (two most abundant carbohydrates in the lignocellulosic plants) with R^2 of -0.67 for each (Fig. 4A and 4B). No clear correlation was observed between the raw ash concentration and the content of ash-free extractive material and lignin, R^2 values being -0.35 and 0.34, respectively (data not shown).

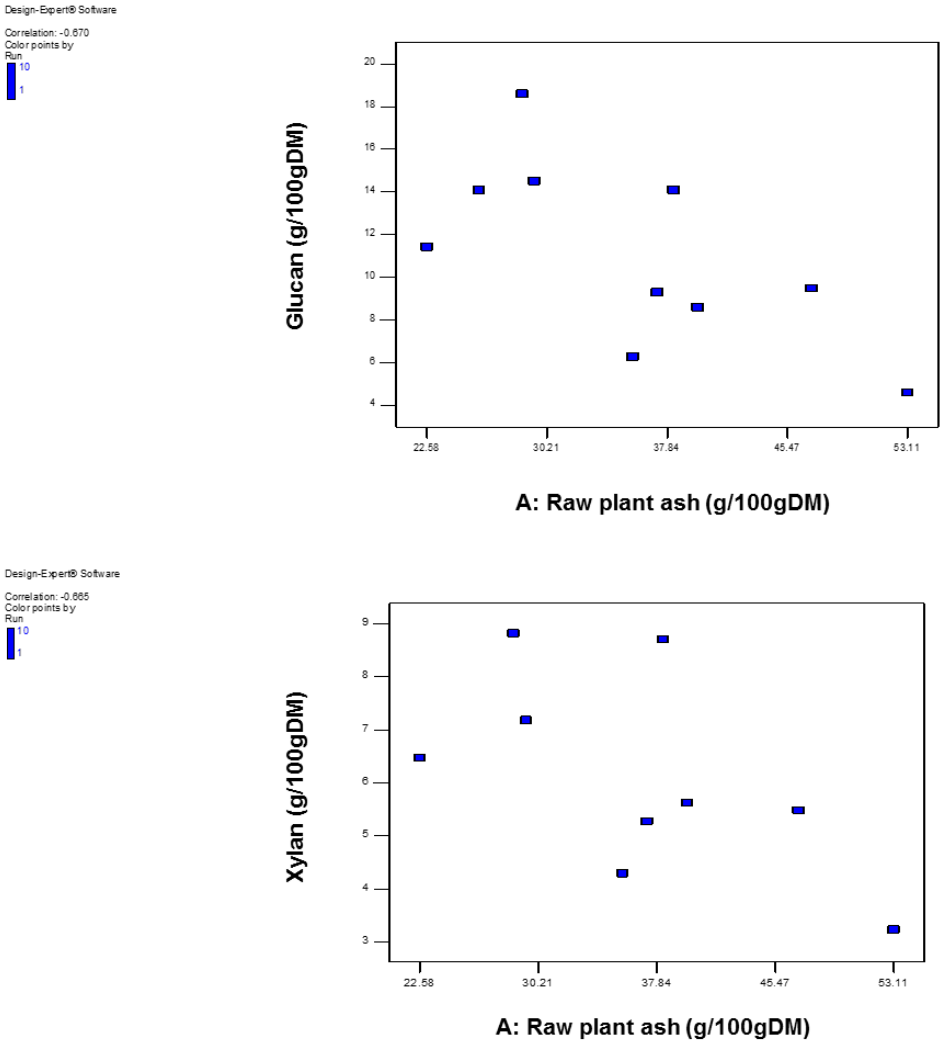

Fig. 4. Correlation between glucan (A) and xylan (B) content of halophyte biomass and the content of raw ash in examined halophyte samples

As the analyzed plant samples were collected from the same area, differences in the growing conditions may not influence the raw ash content. However, the observed differences among the species may be due to different salt uptake mechanisms of the plant species. Previous studies showed no correlation between structural ash content of saltbushes and soil salinity (Beadle *et al.* 1957; Welch 1978), whereas increasing the

salinity of nutrient solution increased the total ash content of the plant (Beadle *et al.* 1957). The differences in the raw ash content of plants were found to be significant in the present study (Fig. 3). Thus, the differences in the carbohydrate content among the analyzed halophyte species, being related to the raw ash content, are most probably caused by the different rates of salt uptake and retention mechanisms varying from species to species. The negative influence of ash on the carbohydrate content was also observed in a cultivation study of *Salicornia bigelovii*, where the relationship between plant ash content was and the irrigation water salinity and amount of nitrogen in the fertilizer during cultivation was examined (Cybulska *et al.* 2014b). Also, a decrease in soil salinity was reported to increase the carbohydrate content in the plant structure of in other halophytes, including three different *Salsola* species (Heidari-Sharifabad and Mirzaie-Nodoushan 2006).

CONCLUSIONS

1. It was found that the analyzed species contain significantly different amounts of carbohydrates, lignin, extractable ash, and ash-free water-soluble extractives.
2. Total ash content was found to negatively influence the content of glucan and xylan in the biomass (R^2 = -0.67). No correlation was seen between the total ash content and the content of the ash-free extractive material and lignin.
3. *Cornulaca aucheri* was found to have relative low lignin content and the highest glucan content of all characterized halophytes, whereas *Tetraena qatarensis* was found to contain the highest amount of the ash-free extractives.
4. *Cornulaca aucheri* would be the most promising feedstock for lignocellulose-based biorefinery processing, targeting the production of second-generation biofuels, and *Tetraena qatarensis* would be the best substrate for generating extractives-based products, as the extract from this species has reported to contains various bioactive compounds (Cybulska *et al.* 2014a).

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