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Halophyte Plants Cultured in Aquaponics Hold the Same Potential for Valorization as Wild Conspecifics from Donor Sites

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Abstract: Halophytes have gradually been introduced in marine integrated multi-trophic aquaculture (IMTA) systems due to their capacity to bioremediate nutrient-rich marine effluents and their potential use for human consumption due to their content of omega-3 and omega-6 fatty acids (FA). To foster the valorization of halophytes produced using an IMTA framework for human consumption, it is important that culture conditions keep or enhance their FA profile, when compared to that displayed by conspecifics in the wild. The main objective of the present study was to compare the FA profiles of three halophyte species (*Halimione portulacoides*, *Salicornia ramosissima* and *Sarcocornia perennis*) cultured in aquaponics coupled to an IMTA system with that of wild conspecifics retrieved from donor sites. The FA profiles were compared considering different plant organs (edible parts and roots) and sampling dates (spring, summer and autumn). Results show that the FA profiles of specimens cultured in aquaponics were significantly different from that of wild conspecifics, displaying a high content of omega-3 FAs in edible parts, particularly during summer, and mostly in the form of α-linolenic acid (ALA, 18:3*n*-3). In more detail, for the specimens cultured in aquaponics, ALA concentration in the edible parts of each species ranged from 5.10 to 7.11 μg mg^{-1} DW in *H. portulacoides*, from 5.66 to 9.19 μg mg^{-1} DW in *S. ramosissima* and from 5.49 to 7.20 μg mg^{-1} DW in *S. perennis*. Concerning the omega-6 linoleic acid (LA, 18:2*n*-6) identified in edible parts, the concentrations ranged from 2.25 to 2.46 μg mg^{-1} DW in *H. portulacoides*, from 3.26 to 4.84 μg mg^{-1} DW in *S. ramosissima*, and from 2.17 to 3.06 μg mg^{-1} DW in *S. perennis*. The nutritional quality was assessed through the ratio of PUFA/SFA, for both wild and cultured plants, and revealed values well above the threshold (0.45), the threshold value indicative of good nutritional quality. Overall, the culture conditions tested in the present work reinforce the potential of aquaponics coupled to marine IMTA to produce high-quality halophytes suitable for human consumption.

Keywords: α-linolenic acid; fatty acids profile; cultured halophytes; aquaponics

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1. Introduction

Building upon the Goals for the Millennium, the United Nations (UN) elaborated further and proposed Sustainable Development Goals (SDG) and targets for the year 2030, with 17 areas of critical importance for humanity and the planet having been identified [1]. From these, SDG 14—"life below water" aiming to "conserve and sustainably use the oceans, seas and marine resources for sustainable development"; and SDG 2—"zero hunger" aiming to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" [2] are aligned with the UN/FAO's blue growth initiative, targeting responsible and sustainable fisheries and aquaculture [3]. These SDG are also in line with EU blue growth strategy targeting sectors that have a high potential for sustainable

jobs and growth [4]. Under this strategy, aquaculture is seen as an opportunity to ensure a better use of marine resources and improve nutrition, therefore holding the potential to support SDG14 and SDG2 aims and targets. In this context, an increase in science based-knowledge might enhance the link between the development of environmental and economic sustainable aquaculture, namely by reducing the dependency from wild specimens, ensure the nutritional value of cultured specimens and enhancing their overall added value.

Aquaponics, a variation of the integrated multitrophic aquaculture (IMTA) concept, combines two technologies: recirculation aquaculture systems (RAS) (e.g., fish-farm) and hydroponics plant production (soilless cultivation of crops) [5]. In a similar way as for agriculture (part of SDG 2), where aquaponics appears to be a solution to achieve a sustainable agricultural production system [6], aquaponics holds the potential to play a significant role in aquaculture production [7,8]. In an aquaculture environment, namely in marine aquaculture, these systems use nutrient-rich effluents from fish production to culture a range of extractive species, such as salt tolerant plants, i.e., halophytes. These extractive species can occupy different trophic levels enabling reuse of the entire pool of available organic matter that result from fish production. Relevant examples are deposit feeders like polychaetas that can feed on particulate organic matter (POM), filter-feeders like bivalves that can feed on dissolved organic matter (DOM), and primary producers that feed on dissolved inorganic nutrients. In aquaponics, the excess of organic matter and especially the excess of dissolved inorganic nutrients in the fish farm effluent becomes a source of energy for primary producers, stimulating the recycling of nitrogen and phosphorus, and net growth [7].

Halophytes have been gradually introduced in marine aquaculture systems to enhance the implementation of more sustainable practices, due to their extractive capacity and suitability for bioremediation of nutrient-rich marine effluents, as well as their attractive use for human consumption [9,10]. Relevant examples regarding the use of halophytes as a primary driver for the mitigation of nutrient-rich effluents from super-intensive marine fish farm are the works using *Suaeda esteroa* Ferren & S.A. Whitmore, *Salicornia bigelovii* Torr., and *Atriplex barclayana* D.Dietr. [11]; *Salicornia europaea* L. [12]; *Salicornia persica* Akhani [13], and *Halimione portulacoides* (L.) Aellen [14]. In addition, a growing number of studies have highlighted the advantages of the use of halophyte plants as food for human consumption, namely *Salicornia* spp. [12,15], *Sarcocornia perennis* (Mill.) A.J. Scott, *Salicornia ramosissima* J. Woods, and *Arthrocnemum macrostachyum* L. [16]. Wild specimens of the above-mentioned halophyte species are recognized to be rich in omega-3 and omega-6 fatty acids (FA) [17], specifically α-linolenic and linoleic acid (ALA, 18:3*n*-3 and LA, 18:2*n*-6, respectively) [18]. These essential FA are the precursors of some of the most important polyunsaturated fatty acids (PUFAs) for human nutrition, such as 20:4*n*-6 arachidonic acid (AA), 20:5*n*-3 eicosapentaenoic acid (EPA) and 22:6*n*-3 docosahexaenoic acid (DHA) [19–21]. Therefore, from a valorization perspective, focused on human consumption, it is of paramount importance that the production of halophytes in aquaponics associated to marine fish production keep or enhance their FA profile, to remain as or more appealing to consumers than conspecifics collected from the wild.

This study aims to compare the FA profiles of halophytes cultured under aquaponics conditions with that of wild specimens harvested from donor sites. The present study addresses three halophyte species from family Amaranthaceae (*Halimione portulacoides* (L.) Aellen, previously known as *Atriplex portulacoides* (L.); *Salicornia ramosissima* (J.) Woods; and *Sarcocornia perennis* (Miller) A. J. Scott), whose potential for aquaponics production as part of IMTA systems has already been documented (e.g., [12,14,22]), as well as their nutritional properties for human consumption [16,23–25]. In brief, *H. portulacoides* is an evergreen halophyte present in salt marshes along the Atlantic coast of Europe [26,27]; *S. ramosissima* is a pioneer annual halophyte, commonly distributed in the salt marshes of the Iberian Peninsula [28]; and *S. perennis* has a perennial life cycle being one of the most common halophytes in low-middle elevations of salt marshes in Europe [28]. The FA

profile of each selected halophyte was studied in spring, summer, and autumn, as these are the three most active seasons, compared to winter. To evaluate whether the nutrient-rich effluent from a super-intensive marine fish farm affected the FA profiles of halophytes cultured in aquaponics, their profile in these valuable biomolecules was analyzed and compared with that from wild specimens. The following null hypothesis was tested: H_o1: there are no significant differences in FA profiles in the edible parts and roots, at spring, summer, and autumn of *H. portulacoides*, *S. ramosissima*, and *S. perennis* from the wild and cultured in aquaponics.

2. Materials and Methods

2.1. Short Description of the Donor Site and Selected Halophyte Species

The halophyte species used in the present study were collected in Ria de Aveiro coastal lagoon salt marshes (40 °38′ N 08 °44′ W). This coastal system is approximately 45 km long and 10 km wide with one single connection with the Atlantic Ocean. The lagoon geomorphology is characterized by four main channels, each of them with small channels and islands, large areas of intertidal sand and mudflats, seagrasses meadows, and one of the largest continuous saltmarshes in Europe [29]. The region is characterized by a temperate maritime climate with an average temperature of 14 °C and precipitation of 1000 mm [30]. Figure 1 features the three selected species, which can be briefly described, according to Flora Iberica (Castroviejo, 1986), as follows:

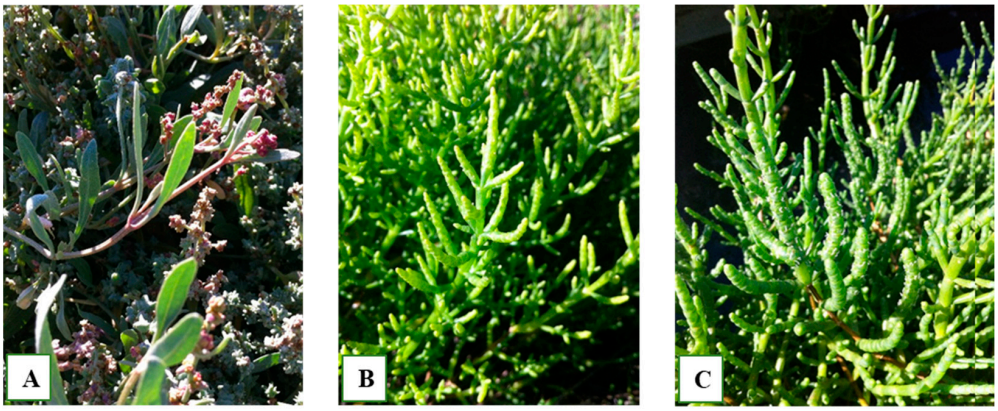

Figure 1. Halophytes *cultured in* aquaponics tanks supplied by the effluent from a super intensive fish farm: (**A**) *Halimione portulacoides*; (**B**) *Salicornia ramosissima* and (**C**) *Sarcocornia perennis*.

Halimione portulacoides—shrubby perennial up to 150 mm tall, with woody stems at the base and succulent leaves at the top. Stems can grow prostrate, ascending or erect. Leaves (spatulate or lanceolate to linear-lanceolate, exceptionally deltoid) are opposite in the lower part and alternate in the upper part of the plants, with a light petiole. The inflorescences consist of inconspicuous flowers.

Salicornia ramosissima—annually erect, rarely decumbent subshrub up to 400 mm tall. Stems are generally quite branched, terminating in spike-like apparently jointed inflorescences, with two opposite three-flowered cymes partly hidden in the internode tissue. Each cyme holds one large central flower and two smaller lateral flowers. The central flower has its base generally covered by the scarious margin of the lower segment.

Sarcocornia perennis—perennial subshrub up to 700 mm tall, with woody steams at the base, prostrate to procumbent, and above with fleshy-articulated, erect-ascending, simple or sparingly branched stems. Leaves are reduced to a sharp scale with a hyaline border. It has a spiciform inflorescence, lateral or terminal, formed by opposing triflora crests at the base of each fertile core-and decussate. The central flower is slightly larger than the lateral ones.

2.2. Aquaponics System

Figure 2 details schematically the experimental set-up employed, showing the water flow of the organic rich effluent originating from a super-intensive marine RAS system to produce Senegalese sole (*Solea senegalensis*) to aquaponics tanks.

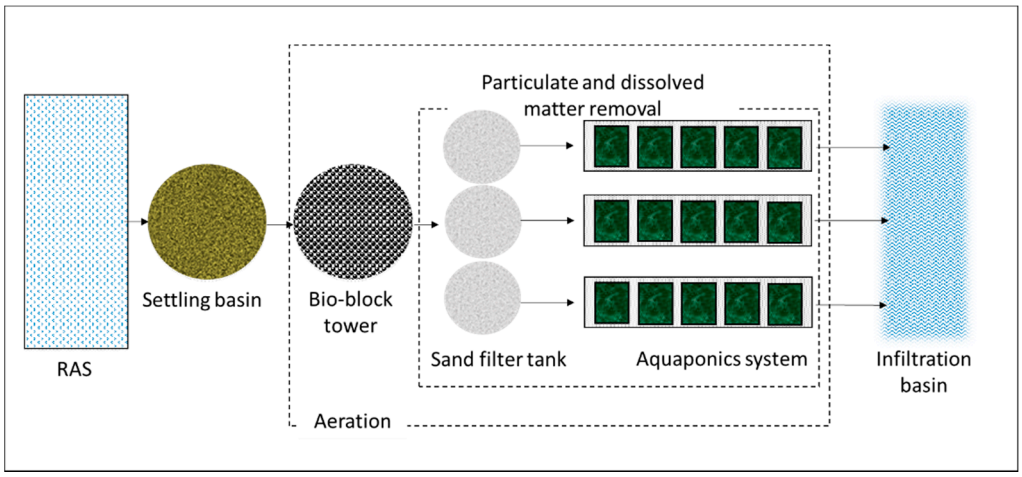

Figure 2. Configuration and design of aquaponics system coupled to sand filters tanks.

In brief, the organic rich effluent was pumped from a settling basin to a 4 m^3 header tank coupled to a bio-block tower (to aerate and increase oxygen levels, from ~2 mg L^{-1} to 8–9 mg L^{-1}). From there the aerated effluent was allowed to flow by gravity at 180 L h^{-1} to sand filter tanks (1–2 mm grain size), each with a volume of 1 m^3 and a surface area of 1 m^2. Sand filter tanks were set-up in parallel, with each one of them being connected to an aquaponics tank. Each aquaponics tank was 6 m long by 1 m wide and 0.3 m deep. To maximize effluent retention time within each tank, 11 alternating wooden barriers were placed transversally to the flow. A full water renewal was achieved ≈ every 12 h. For this study, due to the tanks inter-variability regarding nutrient dynamics [14] one tank stocked with each of the selected halophytes was selected to have composite samples of the halophyte plants covering the 6 m long × 1 m wide tank (see below for further details).

2.3. Stocking and Sampling of Halophytes

The aquaponics tanks were stocked with selected halophyte species as follows: *H. portulacoides* grafts were kept in Hoagland's nutrient solution and transplanted to the aquaponics tank after new roots were recorded [14]; *S. ramosissima* new shoots (circa 50 mm) were washed to remove the sediment from the rhizosphere and transplanted to the aquaponics tank; and *S. perennis* grafts were transplanted directly to the aquaponics tank. Each aquaponics tank was stocked with circa 800 plants equally distributed over nine styrofoam trays floating in the tank water. The aquaponics experiment started in March, with halophytes being randomly sampled at donor sites in Ria de Aveiro and at each aquaponics tank in the three following seasons: spring (May), summer (July) and autumn (October). Sampling from each aquaponics tank was performed by haphazardly selecting two plants from each of the nine floating Styrofoam trays (thus assembling a composite sample of 18 specimens), with an identical number of specimens per halophyte species also being sampled in each donor site. Each halophyte plant was separated into plant organs (edible parts and roots) and subsequently freeze-dried and stored at −80 °C for posterior FA analysis. During the experimental period temperature, salinity and pH of the effluent was monitored in situ, using a WTW—conductivity meter 3110/set 1 equipped with TetraCon® 325 and WTW—pH 330i/set equipped with SenTix® 41. Effluent aliquots were filtered (Whatman GF/C) and analyzed for phosphates (PO_4-P) and ammonium (NH_4-N) following the standard methods in Limnologisk Metodik, 1992, and dissolved inorganic nitrogen (NO_x-N) using a flow injection system (FIAstar 5000 Analyzer, Höganäs, Sweden).

2.4. Fatty Acid Methyl Ester Analysis

The derivatization of FA for gas chromatography (GC)-FID analysis was performed following the methodology described by Aued-Pimentel et al. [31] with some adaptations. Briefly, all freeze-dried samples were powdered and homogenized, being weighted accurately in a sovirel/pyrex glass tube (~50 mg of plant organs, and after 1 mL of a solution of *n*-hexane containing the FAME internal standard FA 21:0 (heneicosanoic acid) (0.021 g L^{-1}) was added. In the same tube, it was added 0.2 mL of a methanolic KOH solution (2 mol L^{-1}). The tube was sealed and mixed vigorously in a vortex shaker for 2 min. Following this procedure, 2 mL of a saturated NaCl solution was added to the tube, and the mixture was centrifuged during 5 min at 3000 rpm and the organic phase separated. Afterwards, 0.8 mL of organic phase was transferred into a vial and the excess of solvent was evaporated with gas nitrogen. The oil obtained was dissolved in *n*-hexane (1 mL) and analyzed using a GC-FID. Separation of FA was performed using a 7890B gas chromatograph (GC) system with a flame ionization detector (FID). The detector and injector were kept at 250 °C, with the carrier gas used being hydrogen. FA were separated in a fused-silica capillary column, DB-FFAP column (30 m × 320 µm × 0.25 µm) (Agilent 123-3232) with the following temperature programme: 75 °C (initial), 20 °C min^{-1} to 155 °C (4 min), 2 °C min^{-1} to 180 °C (16.5 min), 4 °C min^{-1} to 250 °C (44 min). The identification of the FA was done by matching the retention times with previously inject internal standards. The FA content (µg mg^{-1} DW) in the samples analyzed was calculated considering the relation between mass, the area of fatty acids, and the internal standard (21:0).

2.5. Statistical Analysis

Statistical analysis regarding each halophyte species was performed using PRIMER v6 with the PERMANOVA+ add-on. A resemblance matrix using the content (µg mg^{-1} DW) of each FA in each halophyte was performed using the Bray-Curtis similarity coefficient, following a log (x + 1) transformation to empathize the compositional differences rather than on quantitative differences [32]. Permutational multivariate analysis of variance (PERMANOVA) was used to assess the differences between FA profiles of wild versus cultured halophytes, considering edible parts and roots and the three sampling dates (spring, summer and autumn). Three factors were included in test design: (1) condition was introduced as a fixed factor, with cultured and wild being used as levels; (2) sampling dates were introduced as a fixed factor, with spring, summer, and autumn being used as levels; (3) plant organs were introduced as a random factor nested in conditions, with edible parts and roots being used as levels. The statistical significance of multivariate variance components was tested using 9999 permutations of residuals under a reduced model, with significance level of 0.05. Therefore, a permutation analysis of multivariate dispersions (PERMDISP) was used if the PERMANOVA result showed a significant difference [33]. A Principal Coordinates Analysis (PCO) was performed to calculate the variability in FA content considering the factors. This analysis enables to plot the inter-individual differences in FA content along the first two axes into the multidimensional space. For a detailed description of the statistical analysis described above please refer to Clarke & Gorley [34].

3. Results

3.1. Aquaponic System Characterization

During the experimental period, water temperature displayed the same trend among the three aquaponics tanks, following expected seasonal variations. Temperature ranged between 18.2 °C (autumn) and 21.4 °C (summer) in the tank with *H. portulacoides*, between 19.1 °C (autumn) and 23.1 °C (summer) in the tank with *S. ramosissima*, and between 18.1 °C (autumn) and 22.3 °C (summer) in the tank with *S. perennis*. Concerning pH, this parameter showed a higher variability, ranging from 7.47 (autumn) to 7.76 (summer) in the tank with *H. portulacoides*, 7.45 (autumn) to 8.73 (summer) in the tank with *S. ramosissima* and 7.24 (autumn) to 7.57 (summer) in the tank with *S. perennis*. The average concentration

of dissolved inorganic phosphorous (DIP) and dissolved inorganic nitrogen (DIN) during the experimental period is available in Table S1 (Supplementary Material).

In the head tank the average concentration of DIP was 0.32 ± 0.11 mg L^{-1} (in spring DIP = 0.29 mg L^{-1}, in summer DIP = 0.21 mg L^{-1} and autumn DIP = 0.50 mg L^{-1}), while the average concentration of DIN (DIN = NO_x-N + NH_4-N) was 8.9 ± 1.3 mg L^{-1} (in spring DIN = 9.5 mg L^{-1}, in summer DIN = 10 mg L^{-1} and autumn DIN = 6.8 mg L^{-1}). The average concentration of dissolved inorganic nutrients (DIP +DIN) in both the inlets and outlets of each halophytes aquaponics tank increased over time, indicating that the concentration of dissolved inorganic nutrients from the RAS system increased during the experimental period. The removal capacity of DIP displayed by each halophyte species was negligible, as in average DIP concentrations were higher in the outlet of the aquaponics tank than in the inlet. Concerning DIN, the removal capacity of each halophyte species was higher in the summer (circa 90%). In detail, DIN removal capacity in spring, summer, and autumn, was 13%, 91%, and 51% in the tank with *H. portulacoides*, 12%, 89%, and 21% in the tank with *S. ramosissima*, and 52%, 98%, and 60% in the tank with *S. perennis*, respectively.

3.2. Halimione portulacoides Fatty Acids Profile

In the extracted oil of *H. portulacoides* were identified fourteen different fatty acids. The results obtained (see Tables 1 and 2) showed that the most representative polyunsaturated fatty acids (PUFA) in the edible parts, considering cultured and wild halophytes was the ALA fatty acid. In detail, ALA content in edible part was 5.29, 7.11 and 5.11 μg mg^{-1} DW for cultured halophytes and 7.32, 2.05 and 4.03 μg mg^{-1} DW for wild halophytes for spring, summer and autumn, respectively. The roots of cultured and wild halophytes showed linoleic acid (LA, 18:2*n*-6) as the most abundant PUFA, with 3.18, 1.91 and 3.42 μg mg^{-1} DW cultured halophytes and 1.43, 1.27 and 0.96 μg mg^{-1} DW for wild halophytes during the spring, summer, and autumn, respectively. Oleic acid (18:1*n*-9) was the most representative monounsaturated fatty acid (MUFA) with similar concentrations in both in edible parts and in the roots. The content of 18:1*n*-9 in edible parts was 0.78, 1.10 and 0.81 μg mg^{-1} DW and 0.34, 0.45, and 0.79 μg mg^{-1} DW in the roots in aquaponics systems. Wild specimens showed a different trend with 1.57, 0.64, and 0.67 μg mg^{-1} DW in the edible part and 0.43, 0.46, and 0.27 μg mg^{-1} DW in the roots, during the spring, summer, and autumn, respectively. The most representative saturated fatty acid (SFA), considering the edible parts and roots, was palmitic acid (16:0) in both cultured and wild halophytes.

Table 1. Fatty acid profile (μg mg^{-1} DW) of aquaponics *Halimione portulacoides* in edible plant parts and roots biomass in spring, summer and autumn. Values are averages 3 replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 16:3*n*-3; 18:2*n*-6; 18:3*n*-3; 20:2*n*-6.

Fatty Acids	Aquaponics					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	1.82 ± 0.11	2.35 ± 0.10	1.81 ± 0.04	1.64 ± 0.12	1.49 ± 0.10	2.01 ± 0.07
18:0	0.10 ± 0.01	0.15 ± 0.01	0.12 ± 0.00	0.08 ± 0.00	0.08 ± 0.01	0.12 ± 0.01
20:0	0.06 ± 0.00	0.08 ± 0.00	0.08 ± 0.00	0.04 ± 0.00	0.05 ± 0.00	0.12 ± 0.01
22:0	0.12 ± 0.00	0.20 ± 0.01	0.26 ± 0.01	0.17 ± 0.02	0.21 ± 0.02	0.38 ± 0.02
24:0	0.39 ± 0.02	0.51 ± 0.09	0.57 ± 0.02	0.17 ± 0.01	0.14 ± 0.01	0.28 ± 0.01
∑SFA	2.49 ± 0.14	3.29 ± 0.21	2.84 ± 0.07	2.10 ± 0.15	1.97 ± 0.14	2.91 ± 0.12
16:1*n*-7	ND	ND	ND	0.09 ± 0.01	1.29 ± 0.11	0.77 ± 0.02
16:1*n*-9	0.17 ± 0.01	0.20 ± 0.01	0.12 ± 0.00	ND	ND	ND

Table 1. *Cont.*

Fatty Acids	Aquaponics					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
18:1*n*-9	0.78 ± 0.03	1.10 ± 0.04	0.81 ± 0.01	0.34 ± 0.02	0.45 ± 0.02	0.79 ± 0.03
18:1*n*-7	0.03 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.08 ± 0.01	0.50 ± 0.03	0.34 ± 0.02
20:1*n*-7	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00	ND	ND	ND
∑MUFA	1.03 ± 0.04	1.41 ± 0.05	1.04 ± 0.01	0.51 ± 0.04	2.24 ± 0.16	1.90 ± 0.07
16:3*n*-3	0.40 ± 0.02	0.25 ± 0.01	0.14 ± 0.00	ND	ND	ND
18:2*n*-6	2.41 ± 0.13	2.46 ± 0.12	2.25 ± 0.04	3.18 ± 0.20	1.91 ± 0.09	3.42 ± 0.10
18:3*n*-3	5.29 ± 0.29	7.11 ± 0.33	5.10 ± 0.08	0.45 ± 0.04	0.25 ± 0.01	0.71 ± 0.02
20:2*n*-6	0.13 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	ND	ND	ND
∑PUFA	8.23 ± 0.44	9.92 ± 0.46	7.59 ± 0.12	3.63 ± 0.24	2.16 ± 0.10	4.13 ± 0.12
PUFA/SFA	3.30	3.01	2.67	1.73	1.10	1.42

Table 2. Fatty acid profile (μg mg^{-1} DW) of wild *Halimione portulacoides* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 16:3*n*-3; 18:2*n*-6; 18:3*n*-3; 20:2*n*-6.

Fatty Acids	Wild					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	2.94 ± 0.01	0.97 ± 0.02	1.52 ± 0.08	0.71 ± 0.00	0.69 ± 0.10	0.46 ± 0.01
18:0	0.21 ± 0.01	0.07 ± 0.00	0.10 ± 0.00	0.05 ± 0.01	0.04 ± 0.01	0.04 ± 0.00
20:0	0.11 ± 0.00	0.06 ± 0.00	0.09 ± 0.01	0.10 ± 0.00	0.10 ± 0.00	0.06 ± 0.00
22:0	0.21 ± 0.01	0.16 ± 0.00	0.28 ± 0.03	0.22 ± 0.01	0.39 ± 0.02	0.25 ± 0.01
24:0	0.57 ± 0.03	0.50 ± 0.04	1.16 ± 0.10	0.13 ± 0.02	0.19 ± 0.01	0.11 ± 0.01
∑SFA	4.04 ± 0.06	1.76 ± 0.06	3.15 ± 0.22	1.21 ± 0.04	1.42 ± 0.14	0.92 ± 0.03
16:1*n*-7	ND	ND	ND	0.03 ± 0.00	0.08 ± 0.02	0.01 ± 0.00
16:1*n*-9	0.23 ± 0.00	0.05 ± 0.00	0.12 ± 0.01	ND	ND	ND
18:1*n*-9	1.57 ± 0.01	0.64 ± 0.13	0.67 ± 0.03	0.43 ± 0.01	0.46 ± 0.06	0.27 ± 0.01
18:1*n*-7	0.10 ± 0.00	0.04 ± 0.00	0.05 ± 0.00	0.04 ± 0.00	0.14 ± 0.03	0.03 ± 0.00
20:1*n*-7	0.07 ± 0.00	0.03 ± 0.00	0.04 ± 0.00	ND	ND	ND
∑MUFA	1.97 ± 0.01	0.76 ± 0.13	0.88 ± 0.04	0.50 ± 0.01	0.66 ± 0.11	0.31 ± 0.01
16:3*n*-3	0.34 ± 0.00	0.05 ± 0.00	0.12 ± 0.01	ND	ND	ND
18:2*n*-6	2.91 ± 0.02	0.80 ± 0.01	1.52 ± 0.07	1.43 ± 0.03	1.27 ± 0.14	0.96 ± 0.01
18:3*n*-3	7.32 ± 0.02	2.05 ± 0.05	4.03 ± 0.19	0.34 ± 0.01	0.21 ± 0.03	0.16 ± 0.00
20:2*n*-6	0.15 ± 0.00	0.15 ± 0.01	0.16 ± 0.02	ND	ND	ND
∑PUFA	10.72 ± 0.04	3.05 ± 0.07	5.83 ± 0.29	1.77 ± 0.04	1.48 ± 0.17	1.12 ± 0.01
PUFA/SFA	2.65	1.73	1.85	1.46	1.04	1.22

PERMANOVA test performed for edible part of *H. portulacoides* revealed that there were significant differences among the FA profiles for cultured and wild *H. portulacoides* (Pseudo-F1,17 = 697.03; $p = 0.0001$). A major part of this variability can be explained by

the first two axes of the PCO performed, with 91.0% of total variance being explained for *H. portulacoides*, with PCO1 axis explaining 60.2% of total variance and clearly separating cultured from wild specimens. Significant differences were also recorded in the FA profiles during spring, summer, and autumn (Pseudo-F2,17 = 210.3; $p = 0.0001$). Regarding root part, the PERMANOVA test revealed that there were significant differences among the FA profiles for cultured and wild *H. portulacoides* (Pseudo-$F_{1,17}$ = 530.31; $p = 0.001$). The first two axis of the PCO analysis (Figure 3) explained 90.6% of total variance, with PCO1 axis explaining 79.3% of total variance and clearly separating cultured in aquaponics from wild specimens. Significant differences were also recorded in the FA profiles during spring, summer, and autumn (Pseudo-F2,17 = 44.354; $p = 0.001$). All species, regardless of being wild or cultured in aquaponics, displayed a PUFA/SFA ratio > 0.45, the threshold value indicative of good nutritional quality see Tables 1 and 2.

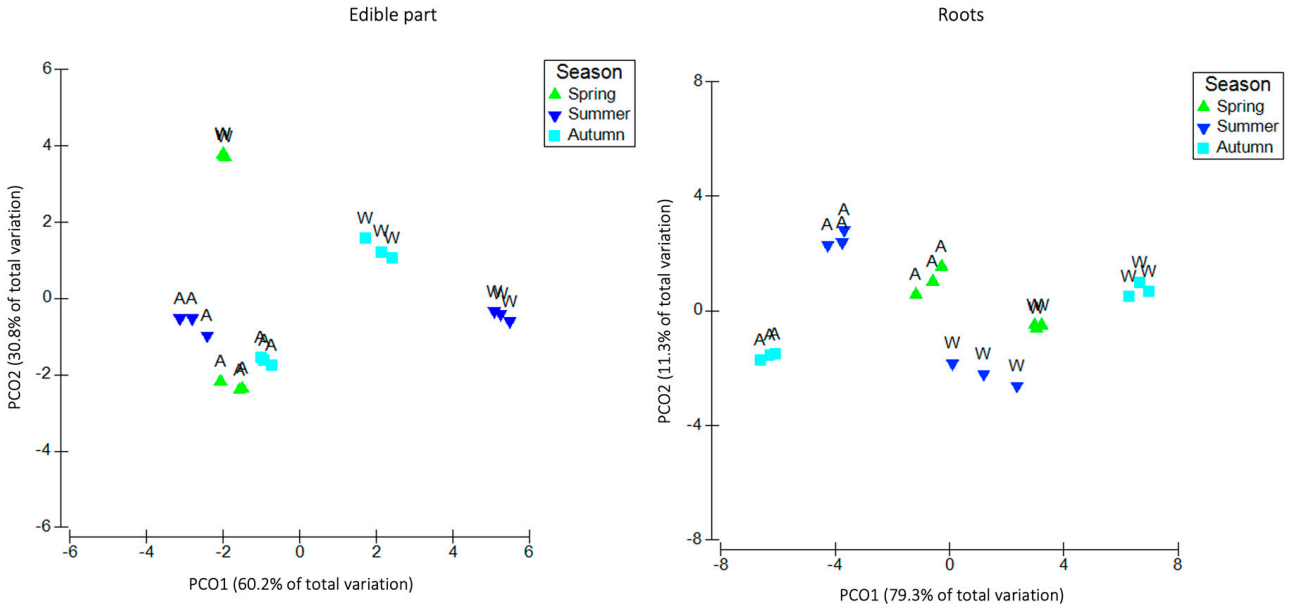

Figure 3. Principal coordinates analysis of the fatty acid profile for cultured in aquaponics (A) and wild (W) *H. portulacoides* in spring, summer and autumn in edible parts and roots.

3.3. Salicornia ramosissima Fatty Acids Profile

In *S. ramosissima* fourteen different fatty acids were identified. The most representative PUFA in the edible parts, considering cultured and wild halophytes was the ALA fatty acid (Tables 3 and 4). In detail, cultured halophytes showed in edible part an ALA content of 7.02, 9.19, and 5.66 μg mg^{-1} DW and 9.18, 7.96, and 5.41 μg mg^{-1} DW for wild halophytes for spring, summer, and autumn, respectively. The roots of cultured and wild halophytes presented LA as the most abundant PUFA, with 5.24, 2.21, and 2.85 μg mg^{-1} DW cultured halophytes and 5.28, 2.09, and 1.28 μg mg^{-1} DW for wild halophytes during the spring, summer, and autumn, respectively. Oleic acid was the most representative MUFA with similar concentrations both in edible parts and roots in both cultured and wild halophytes. In both cultured and wild halophytes, palmitic acid was the most representative SFA, considering the edible parts and roots.

Table 3. Fatty acid profile (μg g^{-1} DW) of aquaponics *Salicornia ramosissima* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3; 20:2*n*-6.

Fatty Acids	Aquaponics					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	2.84 ± 0.09	2.77 ± 0.06	2.93 ± 0.07	2.98 ± 0.36	2.71 ± 0.00	1.94 ± 0.08
18:0	0.31 ± 0.01	0.36 ± 0.01	0.26 ± 0.01	0.13 ± 0.02	0.16 ± 0.00	0.14 ± 0.01
20:0	0.11 ± 0.00	0.11 ± 0.00	0.11 ± 0.00	0.16 ± 0.02	0.13 ± 0.00	0.16 ± 0.01
22:0	0.17 ± 0.00	0.14 ± 0.00	0.22 ± 0.01	0.30 ± 0.04	0.26 ± 0.01	0.34 ± 0.01
24:0	0.29 ± 0.01	0.25 ± 0.00	0.33 ± 0.01	0.56 ± 0.10	0.37 ± 0.01	0.35 ± 0.01
∑SFA	3.73 ± 0.11	3.63 ± 0.07	3.85 ± 0.10	4.13 ± 0.55	3.63 ± 0.02	2.93 ± 0.12
16:1*n*-7	ND	ND	ND	0.22 ± 0.03	1.11 ± 0.03	0.34 ± 0.02
16:1*n*-9	0.29 ± 0.01	0.12 ± 0.00	0.16 ± 0.01	ND	ND	ND
18:1*n*-9	0.24 ± 0.00	0.25 ± 0.00	0.33 ± 0.01	0.19 ± 0.03	0.27 ± 0.00	0.43 ± 0.02
18:1*n*-7	0.06 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.26 ± 0.04	0.63 ± 0.01	0.29 ± 0.01
20:1*n*-7	0.02 ± 0.00	0.02 ± 0.00	0.05 ± 0.00	ND	ND	ND
∑MUFA	0.61 ± 0.01	0.42 ± 0.00	0.57 ± 0.02	0.67 ± 0.10	2.01 ± 0.04	1.06 ± 0.05
18:2*n*-6	4.28 ± 0.10	3.26 ± 0.05	4.84 ± 0.10	5.24 ± 0.58	2.21 ± 0.03	2.85 ± 0.10
18:3*n*-3	7.02 ± 0.16	9.19 ± 0.15	5.66 ± 0.18	1.03 ± 0.12	0.39 ± 0.01	0.66 ± 0.02
20:2*n*-6	0.04 ± 0.00	0.03 ± 0.00	0.07 ± 0.00	ND	ND	ND
∑PUFA	11.34 ± 0.26	12.48 ± 0.20	10.57 ± 0.28	6.27 ± 0.70	2.60 ± 0.04	3.51 ± 0.12
PUFA/SFA	3.04	3.43	2.75	1.52	0.72	1.19

Table 4. Fatty acid profile (μg g^{-1} DW) of wild *Salicornia ramosissima* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3; 20:2*n*-6.

Fatty Acids	Wild					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	3.49 ± 0.16	2.86 ± 0.05	2.74 ± 0.07	2.68 ± 0.33	1.03 ± 0.03	0.57 ± 0.04
18:0	0.32 ± 0.01	0.26 ± 0.00	0.16 ± 0.01	0.10 ± 0.01	0.05 ± 0.00	0.03 ± 0.00
20:0	0.11 ± 0.01	0.06 ± 0.00	0.08 ± 0.00	ND	ND	ND
22:0	0.12 ± 0.01	0.16 ± 0.00	0.26 ± 0.00	0.32 ± 0.05	0.16 ± 0.00	0.13 ± 0.02
24:0	0.25 ± 0.01	0.26 ± 0.01	0.32 ± 0.01	0.48 ± 0.08	0.29 ± 0.01	0.23 ± 0.04
∑SFA	4.19 ± 0.20	3.60 ± 0.06	3.56 ± 0.09	3.58 ± 0.47	1.53 ± 0.04	0.96 ± 0.10
16:1*n*-7	ND	ND	ND	0.06 ± 0.01	0.02 ± 0.00	0.01 ± 0.00
16:1*n*-9	0.29 ± 0.01	0.36 ± 0.01	0.21 ± 0.00	ND	ND	ND
18:1*n*-9	0.38 ± 0.02	0.26 ± 0.00	0.39 ± 0.01	0.32 ± 0.04	0.12 ± 0.00	0.08 ± 0.01
18:1*n*-7	0.05 ± 0.00	0.06 ± 0.00	0.11 ± 0.00	0.08 ± 0.01	0.03 ± 0.00	0.03 ± 0.01
20:1*n*-7	0.03 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	ND	ND	ND

Table 4. *Cont.*

Fatty Acids	Wild					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
∑MUFA	0.75 ± 0.03	0.74 ± 0.01	0.77± 0.01	0.46 ± 0.06	0.17 ± 0.00	0.12 ± 0.02
18:2*n*-6	4.31 ± 0.21	3.66 ± 0.06	4.82 ± 0.11	5.28 ± 0.65	2.09 ± 0.04	1.28 ± 0.09
18:3*n*-3	9.18 ± 0.38	7.96 ± 0.13	5.41 ± 0.12	0.75 ± 0.09	0.30 ± 0.01	0.25 ± 0.02
20:2*n*-6	0.03 ± 0.00	0.06 ± 0.00	0.07 ± 0.00	ND	ND	ND
∑PUFA	13.52 ± 0.59	11.68 ± 0.19	10.30 ± 0.22	6.03 ± 0.74	2.39 ± 0.05	1.53 ± 0.11
PUFA/SFA	3.23	3.24	2.89	1.68	1.56	1.59

Concerning to edible part, PERMANOVA test revealed significant differences among the FA profiles for cultured and wild specimens (Pseudo-$F_{1,16}$ = 222.46; p = 0.0001). This variability can be explained by the first two axes of the PCO performed, PCO1 axis explaining 75.2% of total variance plus PCO2 axis explaining 19.1% of total variation. During spring, summer, and autumn were also recorded significant differences in the FA profiles (Pseudo-$F_{2,16}$ = 606.97; p = 0.0001). For the root part of *S. ramosissima*, PERMANOVA test showed significant differences among the FA profiles for cultured and wild specimens (Pseudo-$F_{1,17}$ = 924.81; p = 0.0001), with the first two axis of the PCO analysis (Figure 4) explained 99.5% of total variance, with PCO1 axis explaining 90.4% of total variance and clearly separating cultured in aquaponics from wild specimens. Displayed the same trend with significant differences among the spring, summer, and autumn (Pseudo-$F_{2,17}$ = 90.671; p = 0.0001). Wild and cultured *S. ramosissima* presented a PUFA/SFA ratio > 0.45, indicative value of good nutritional quality see Tables 3 and 4.

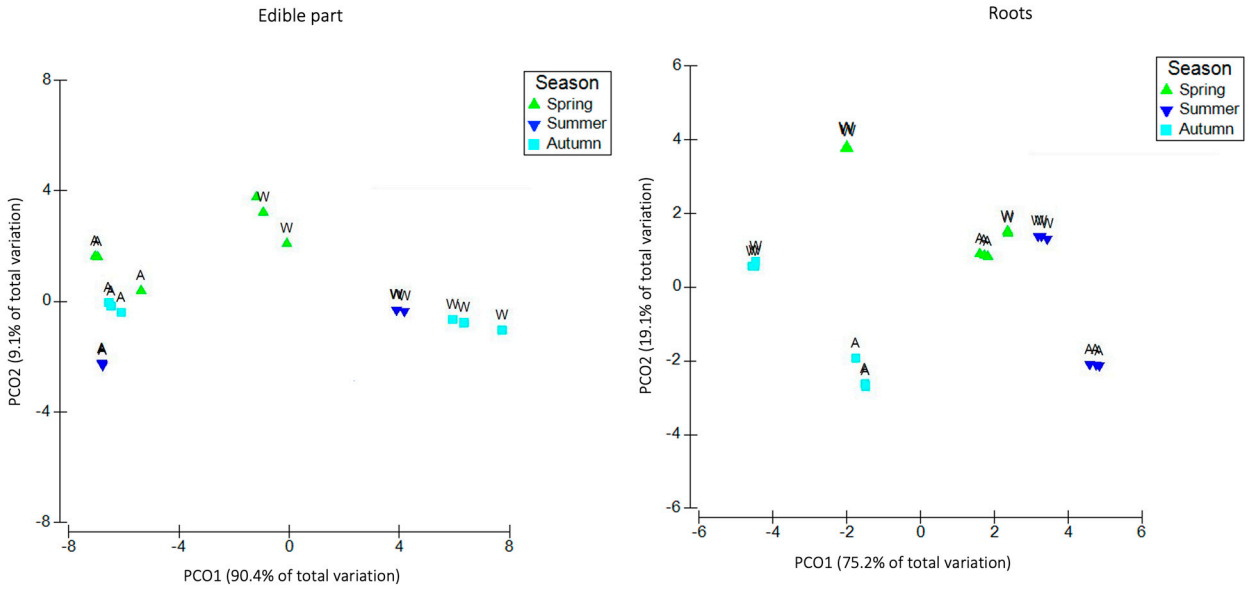

Figure 4. Principal coordinates analysis of the fatty acid profile for cultured in aquaponics (A) and wild (W) *S. ramosissima* in spring, summer, and autumn in edible parts and roots.

3.4. Sarcocornia perennis Fatty Acids Profile

In the extracted oil of *S. perennis* were identified eleven different fatty acids. Tables 5 and 6, display the fatty acids profile of cultured and wild *S. perennis* in edible part and roots biomass in spring, summer, and autumn. The most representative polyunsaturated fatty acids (PUFA) are in the edible parts, considering cultured halophytes was the ALA fatty

acid, with 5.49, 7.20, and 6.64 μg mg^{-1} DW. Regarding wild halophytes during the spring and summer, the most representative polyunsaturated fatty acids (PUFA) was ALA fatty acid displaying 6.17 and 6.19 μg mg^{-1} DW, respectively. During the autumn, the most representative polyunsaturated fatty acid was linoleic acid (LA) fatty acid with 1.96 μg mg^{-1} DW. Otherwise, the most abundant PUFA in roots was LA fatty acid, displaying 4.75, 2.81, and 3.03 μg mg^{-1} DW for cultured halophytes and 1.97, 1.49, and 1.62 μg mg^{-1} DW for wild halophytes during the spring, summer, and autumn, respectively. Oleic acid (18:1n-9) was the most representative monounsaturated fatty acid (MUFA) with similar concentrations both in edible parts and in the roots in cultured and wild halophytes during spring, summer, and autumn. Regarding saturated fatty acid (SFA), palmitic acid (16:0) was the most representative FA in both cultured and wild halophytes, considering the edible parts and roots during the spring, summer and autumn.

The PERMANOVA test performed for edible part of *S. perennis*, showed significant differences among the FA profiles for cultured and wild specimens (Pseudo-$F_{1,17}$ = 47.39; p = 0.0001). This variability can be explained by the first two axes of the PCO performed (Figure 5), with 97.2% of total variance being explained for *S. perennis*, with PCO1 axis explaining 57.4% of total variance. Significant differences were also recorded in the FA profiles for cultured *S. perennis* during spring, summer, and autumn (Pseudo-$F_{2,17}$ = 7.5066; p = 0.0008). Regarding roots of *S. perennis*, the PERMANOVA test revealed significant differences among the FA profiles for cultured and wild specimens (Pseudo-$F_{1,17}$ = 5020; p = 0.0001. This variability can be explained by the first two axes of the PCO performed, with 98.6% of total variance being explained for *S. perennis*, and with PCO1 axis explaining 88% of total variance. PERMANOVA test displayed the same trend with significant differences among the spring, summer, and autumn (Pseudo-$F_{2,17}$ = 357.33; p = 0.0001). Cultured and wild *S. perennis* displayed a PUFA/SFA ratio > 0.45, signifying good nutritional quality, shown in Tables 5 and 6.

Table 5. Fatty acid profile (μg g^{-1} DW) of aquaponics *Sarcocornia perennis* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3.

Fatty Acids	Aquaponics					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	1.97 ± 0.05	2.60 ± 0.07	2.53 ± 0.26	2.15 ± 0.07	2.02 ± 0.05	2.40 ± 0.06
18:0	0.14 ± 0.00	0.15 ± 0.01	0.14 ± 0.02	0.10 ± 0.00	0.11 ± 0.00	0.19 ± 0.01
20:0	0.05 ± 0.00	0.06 ± 0.00	0.06 ± 0.02	0.13 ± 0.01	0.13 ± 0.00	0.15 ± 0.00
22:0	0.08 ± 0.00	0.13 ± 0.00	0.12 ± 0.04	0.19 ± 0.01	0.23 ± 0.01	0.23 ± 0.01
24:0	0.13 ± 0.00	0.16 ± 0.00	0.15 ± 0.05	0.31 ± 0.02	0.29 ± 0.01	0.22 ± 0.01
∑ SFA	2.37 ± 0.05	3.10 ± 0.08	3.00 ± 0.39	2.88 ± 0.11	2.78 ± 0.08	3.19 ± 0.09
16:1*n*-7	ND	ND	ND	0.04 ± 0.00	0.34 ± 0.01	1.28 ± 0.03
16:1*n*-9	0.09 ± 0.00	0.15 ± 0.00	0.22 ± 0.02	ND	ND	ND
18:1*n*-9	0.43 ± 0.01	0.46 ± 0.01	0.37 ± 0.05	0.35 ± 0.01	0.34 ± 0.01	0.49 ± 0.01
18:1*n*-7	ND	ND	ND	0.05 ± 0.00	0.26 ± 0.01	0.52 ± 0.01
∑MUFA	0.52 ± 0.01	0.61 ± 0.01	0.59 ± 0.07	0.44 ± 0.01	0.94 ± 0.03	2.29 ± 0.05
18:2*n*-6	2.17 ± 0.05	2.69 ± 0.08	3.06 ± 0.31	4.75 ± 0.17	2.81 ± 0.09	3.03 ± 0.07
18:3*n*-3	5.49 ± 0.09	7.20 ± 0.18	6.64 ± 0.50	0.75 ± 0.03	0.40 ± 0.01	0.42 ± 0.01
∑ PUFA	7.66 ± 0.14	9.89 ± 0.26	9.70 ± 0.81	5.50 ± 0.20	3.21 ± 0.10	3.45 ± 0.08
PUFA/SFA	3.23	3.19	3.23	1.91	1.15	1.08

Table 6. Fatty acid profile (μg g^{-1} DW) of wild *Sarcocornia perennis* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3.

Fatty Acids	Wild					
	Edible Plant Part			Root		
	Spring	Summer	Autumn	Spring	Summer	Autumn
16:0	2.83 ± 0.13	2.75 ± 0.17	1.54 ± 0.02	0.90 ± 0.01	0.72 ± 0.01	0.76 ± 0.03
18:0	0.18 ± 0.02	0.19 ± 0.02	0.18 ± 0.00	0.07 ± 0.00	0.05 ± 0.00	0.06 ± 0.00
20:0	0.08 ± 0.01	0.09 ± 0.01	0.07 ± 0.00	0.19 ± 0.00	0.14 ± 0.01	0.20 ± 0.01
22:0	0.15 ± 0.01	0.15 ± 0.02	0.20 ± 0.00	0.36 ± 0.01	0.26 ± 0.01	0.47 ± 0.02
24:0	0.24 ± 0.02	0.23 ± 0.03	0.23 ± 0.01	0.49 ± 0.05	0.32 ± 0.02	0.74 ± 0.04
∑SFA	3.48 ± 0.19	3.41 ± 0.25	2.22 ± 0.03	2.01 ± 0.07	1.49 ± 0.05	2.23 ± 0.10
16:1*n*-7	ND	ND	ND	ND	ND	ND
16:1*n*-9	0.24 ± 0.01	0.26 ± 0.01	0.10 ± 0.00	ND	ND	ND
18:1*n*-9	0.48 ± 0.02	0.34 ± 0.02	0.66 ± 0.03	0.34 ± 0.01	0.36 ± 0.00	0.51 ± 0.02
18:1*n*-7	ND	ND	ND	0.06 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
∑MUFA	0.72 ± 0.03	0.60 ± 0.03	0.76 ± 0.03	0.40 ± 0.01	0.40 ± 0.01	0.59 ± 0.02
18:2*n*-6	3.32 ± 0.13	3.21 ± 0.21	3.61 ± 0.11	1.97 ± 0.04	1.49 ± 0.02	1.62 ± 0.06
18:3*n*-3	6.17 ± 0.27	6.19 ± 0.33	1.96 ± 0.02	0.37 ± 0.01	0.34 ± 0.00	0.34 ± 0.01
∑PUFA	9.49 ± 0.40	9.40 ± 0.54	5.57 ± 0.13	2.34 ± 0.05	1.83 ± 0.02	1.96 ± 0.07
PUFA/SFA	2.73	2.76	2.51	1.16	1.23	0.88

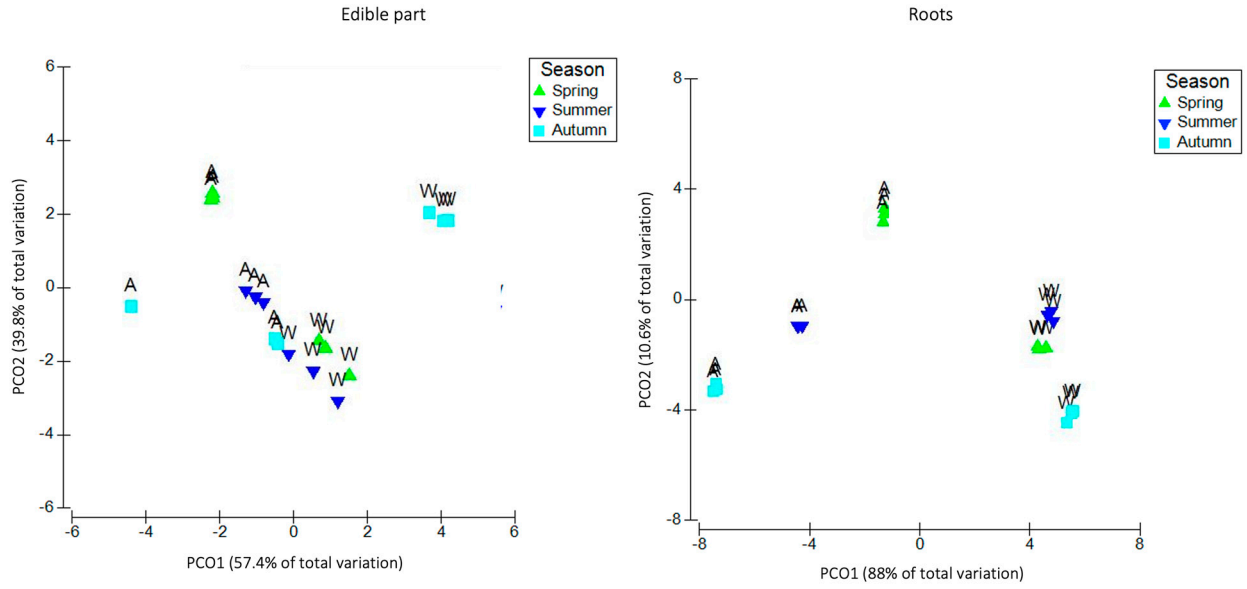

Figure 5. Principal coordinates analysis of the fatty acid profile for cultured in aquaponics (A) and wild (W) *S. perennis* in spring, summer and autumn in edible parts and roots.

4. Discussion

Halophytes are widely recognized to be well-adapted and thrive under saline environments, developing different morphological, anatomical, and physiological strategies [35]. The added value of culturing halophytes using aquaculture effluents has already been demonstrated through irrigation [21], constructed wetlands [36], and IMTA sys-

tems [12,14,22]. Other studies on the use of halophytes in IMTA systems, for nutrient uptake and remediation of aquaculture effluents have also provided promising results [14,22,37]. In the present study we build upon the potential of the three halophytes, *H. portulacoides, S. ramosissima*, and *S. perennis,* cultured in an aquaponics system, to bioremediate the pool of dissolved inorganic nutrients and further evaluate their potential for valorization, though the fatty acid profile as an indicator of their nutritional value.

As extractive species for dissolved inorganic nutrients it would be expected for them to have a net decrease in the nutrient's concentration in the outlets of each halophyte's aquaponics tank, namely during the growing season due to its incorporation into halophytes biomass. However, this was not the case for DIP as other sources, such as mineralization of organic dissolved mater, a temperature-dependent process, might have contributed to mask the uptake od phosphorus by the halophyte plants being cultured. Nevertheless, there is still room to enhance the valorization potential of this practice if the nutritional properties of cultured specimens is shown to be at least comparable to that of conspecifics in the wild. The FA profile of the halophytes cultured under aquaponics conditions differ significantly from that of wild specimens from donor sites. The presence of high levels of omega-3 and omega-6 FA in edible part and roots, respectively, highlight the nutritional value of these halophytes when cultured under aquaponics conditions. The FA profile of the three species, *H. portulacoides, S. ramosissima*, and *S. perennis*, considering both wild plants and specimens cultured in aquaponics, were dominated by three main FAs: palmitic (16:0), LA (18:2*n*-6), and ALA (18:3*n*-3). Both the omega-3 ALA and the omega-6 LA are known to be essential FA for humans [20,38], as they cannot be synthetized de novo and play a key role for human health [15,39]. Being the main precursor of several longer chain and more unsaturated omega-3 FAs, such as EPA and DHA [19,20], ALA is considered an adequate food source to supply and maintain the adequate levels of DHA in mammals [40]. EPA and DHA are paramount for a number of vital organ functions and intracellular activities [39]. According to previous studies, C18 FAs are the most representative FAs in halophytes, with *S. ramosissima* with 39.60% (of total FA) of ALA and 20.02% (of total FA) of LA and *H. portulacoides* with 43.53% (of total FA) of ALA and 14.21% (of total FA) of LA [17]; *Salicornia persica* with 48.28% (of total FA) of ALA and 1.72% (of total FA) of LA and *Sarcocornia fructicosa* with 44.17% (of total FA) of ALA and 1.46% (of total FA) of LA [25] (see Supplementary Material Tables S1–S6 FA profile presented as percentages of relative abundance). In the present study, the three halophytes cultured in aquaponics revealed a high content of ALA in the edible part of the plant during summer and autumn, compared to that displayed by conspecifics in the wild, highlighting the nutritional value as an edible vegetable. The significant increase in ALA content in cultured halophytes may be due to the high salinity. In a recent study [41], Li and Song observed under high salinity an increase of ALA content in euhalophyte *Suaeda salsa* playing an important role in regulating intracellular fatty acid unsaturation. In addition, the high content of ALA in chloroplast membranes acts as protection for plants against damage during cold spells, as a process for acclimation [42]. In general, the C18 FA in plants play an important role in the modulation of membrane properties to adapt to variation of growth conditions associated to biotic and abiotic stresses. Moreover, these biomolecules are a reserve of carbon and energy in triacylglycerols and are precursors of bioactive compounds with multiple bioactivities [43]. LA content in three halophytes cultured in aquaponics is similar to conspecifics in the wild, being predominate in the roots. Linoleic acid FA and ARA are the most useful form of omega-6 FA for human nutrition, in human tissues, and LA is an essential FA that is converted mostly in ARA [18,44,45].

Results suggest that under the aquaponic conditions, halophytes were not nutrient limited. When calculating the PUFA/SFA ratio, an indicator of good nutritional quality and good health status [46,47], our data show that both wild and cultured *H. portulacoides*, *S. ramosissima*, and *S. perennis* displayed a ratio above the threshold value indicative of good nutritional quality (0.45). Moreover, the PUFA/SFA ratio was often higher in halophytes cultured in aquaponics than in wild conspecifics, evidencing a higher level

of FA unsaturation. These findings support the suitability for human consumption of *H. portulacoides*, *S. ramosissima*, and *S. perennis,* cultured in aquaponics, namely in IMTA systems coupled to marine RAS system. A comparable finding was also previously reported by Bertin et al. [45], with the halophyte *Sarcocornia ambigua* (Amaranthaceae) also exhibiting a PUFA/SFA ratio averaging 3.4 (higher than the indicator value of good nutritional quality), hence being considered suitable for human consumption.

One major advantage of aquaponic systems is their resistance and resilience against threats from soil-borne pests and diseases [7]. Beyond this advantage, the following additional benefits from cultured halophytes coupled to marine IMTA systems for human consumption, can be highlighted: (i) in opposition to freshwater, saltwater is not a limited resource [48]; (ii) it enables the reduced dependency on wild specimens of halophytes, which is particularly relevant as most are classified under environmental regulations (e.g., EU Habitat Directive; Bern Convention on the Conservation of European Wildlife and Natural Habitats; RAMSAR convention on wetlands); (iii) it is a sustainable way to improve food production [5,8] in line with SDG2; (iv) RAS provides a continuous source of high quality nutrient-rich effluents for aquaponics [14] so no additional input is required [21]; (v) it promotes the recycling of nutrients, minimizing losses, and environmental impacts on water bodies receiving the effluent; (vi) it promotes water filtration, thus reducing the costs of wastewater treatment [8,14,49], being in line with SDG14; and (vii) it is in line with the framework for circular economy [50]. The production of halophytes in aquaponics coupled to a marine IMTA system can be regarded as an important way to create added value, through the retention of nutrients within the productive system and avoidance of their loss to the environment, thus achieving the objectives of the 2030 Agenda for Sustainable Development [50].

5. Conclusions

The present study shows that the halophytes *H. portulacoides*, *S. ramosissima*, and *S. perennis* cultured under IMTA conditions display a FA profile rich in omega-3 and omega-6 FA, thus holding the same potential for valorization as wild conspecifics from donor sites. The cultivation of these species for human consumption through aquaponics is therefore technically viable and can be applied to enhance food production in line with SDG2 aims and targets, while fostering the implementation of more sustainable practices in aquaculture as advocated in SDG14 aims and targets.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app112411586/s1, Table S1. Concentration of dissolved inorganic phosphorous (DIP) and dissolved inorganic nitrogen (DIN) along the experimental period in *H. portulacoides* aquaponics tank system, *S. ramosissima* aquaponics tank system, and *S. perennis* aquaponics tank system. Table S2. Fatty acid profile (percentage of relative abundance) of wild *H. portulacoides* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 16:3*n*-3; 18:2*n*-6; 18:3*n*-3; 20:2*n*-6. Table S3. Fatty acid profile (percentage of relative abundance) of aquaponics *H. portulacoides* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 16:3*n*-3; 18:2*n*-6; 18:3*n*-3; 20:2*n*-6. Table S4. Fatty acid profile (percentage of relative abundance) of wild *S. ramosissima* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3; 20:2*n*-6. Table S5. Fatty acid profile (percentage of relative abundance) of aquaponics *S. ramosissima* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated

fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7; 20:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3; 20:2*n*-6. Table S6. Fatty acid profile (percentage of relative abundance) of wild *S. perennis* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3. Table S7. Fatty acid profile (percentage of relative abundance) of aquaponics *S. perennis* in edible plant parts and roots biomass in spring, summer, and autumn. Values are averages of three replicates ± standard deviation. ND: fatty acid not detected. Saturated fatty acids (SFA): 16:0; 18:0; 20:0; 22:0; 24:0. Monounsaturated fatty acids (MUFA): 16:1*n*-7; 16:1*n*-9; 18:1*n*-9; 18:1*n*-7. Polyunsaturated fatty acids (PUFA): 18:2*n*-6; 18:3*n*-3.

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