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Multi-Criteria DEXi Analysis for the Selection of Crop Species for Saltwater Aquaponics

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Abstract: Saltwater aquaponics is a sustainable alternative system for food production. The success of this system largely depends on the selection of both fish and plant species, for which several features and criteria must be considered. This paper aims to identify the most suitable plant species for saltwater aquaponics by using a multi-criteria decision-making method also based on current literature. One simple model that contained one root criterion, four aggregated criteria, and four sub-criteria was created using DEXi software. The same model was evaluated considering two different salinity levels in the recirculating water: 10 (brackish water) and 35 (sea water) g L^{-1}. The relevance of the model structure was evaluated by the sensitivity analysis, through the 'plus/minus-1' analysis. Our results suggest that *Salicornia europaea* L. and *Portulaca oleracea* L. were suitable species for saltwater aquaponics at 35 g L^{-1}. Moreover, at 10 g L^{-1}, the suitable candidates were: *Salicornia bigelovii* Torr, *S. europaea* L., *Beta vulgaris* ssp. *maritima* (L.) Arcang, *Atriplex hortensis* L., and *P. oleracea* L. The DEXi analysis resulted in being an easy and effective tool to select proper species in similar contexts. DEXi can help to identify the hotspots of production processes, according to our results. Since the selected species are wild edible species or minor crops, the availability of their seeds is one of the main constraints of their cultivation in saltwater aquaponics.

Keywords: halophytes; hydroponics; glasswort; purslane; red orache; soilless culture

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1. Introduction

Marine–coastal and inland aquaculture contributes approximately 83% and 17% of the seafood production worldwide and in Europe, respectively [1]. The intensification of marine aquaculture is associated with a large production of wastes that negatively impact the sea environment [2]. Therefore, it is necessary to develop and apply new integrated sustainable production methods [3].

Aquaponics is the combination of tank-based animal aquaculture (e.g., Recirculating Aquaculture Systems, RAS) and soilless cultivation of plants involving microbiological processes [4]. Aquaponic production can be obtained with both freshwater and saltwater. Aquaponic systems that use saline water can be classified according to the salinity level as: haloponics (1–3 g·L^{-1}), moderately saline (3–10 g·L^{-1}), high salinity (10–35 g·L^{-1}), and maraponics (>35 g·L^{-1}) [5]. Saltwater aquaponics does not differ much from the freshwater aquaponics in terms of system design, but the selection of the species is highly affected by water salinity [6]. Euryhaline fish could adapt to large salinity ranges [7], while few plants tolerate high salinity levels.

Plants can be divided into two groups based on their salt tolerance: glycophytes and halophytes. The growth of glycophytes is markedly reduced by relatively low salt concentration and they are not able to complete their life cycle at high salinity. The most sensitive crops of glycophytes are harmed by 1.2 to 2.9 g·L^{-1} NaCl [8]. However, some salt-tolerant glycophytes can grow at quite high salinity levels (e.g., 4–8 g·L^{-1}). On the other hand, halophytes have developed various mechanisms (e.g., osmoregulation, synthesis of osmoprotectants, vacuolar compartmentation of Na^+ and Cl^-) to grow in saline conditions [9]. Halophyte plants are cultivated for the nutraceutical properties of their leaves [10]; some of them (e.g., *Salicornia* spp.) are gourmet vegetables with a high retail price.

The use of salt-tolerant plants has great potential for integration within saltwater aquaponics, where plants are grown using different soilless techniques (e.g., bag culture, nutrient film technique, floating system), which can increase plant tolerance to salinity stress [11]. Saltwater aquaponics is a relatively new application and needs further research and technological development to achieve satisfactory results on a larger scale [3].

Several features, as evaluated following different biological, economic, and social criteria, must be taken into account to select suitable plant species for saltwater aquaponics [12]. Multi-criteria decision-making (MCDM) methods can allow the integration of heterogeneous and uncertain information in an understandable framework to rank the project [13].

Decision EXpert (DEX) is a methodology for qualitative multi-attribute modeling, applied for over 40 years to complex real-world decision problems [14]. DEXi is a decision support system software based on the DEX methodology and decision rules ('IF-THEN'), which allows the breakdown of a decisional problem into less complex sub-problems represented by criteria. It combines a hierarchical decision model with an expert system approach based on qualitative scoring using words instead of numbers to assign the values [15]. In the agri-food sector, DEXi has been employed to assess hop hybrids [16], innovative cropping systems [17], genetically modified crops [18], the biological, physical and chemical properties associated with changes in soil quality [19], the environmental sustainability of different agronomic practices in horticultural rotations [20], and the environmental sustainability of aquaculture systems [12]. Rossi et al. [6] used DEXi for the selection of marine fish species for integrated multi-trophic aquaponic production in the Mediterranean area. The use of MCDM based on qualitative input information, such as DEXi, is suggested in case of multi-dimensional constraints [20]. Furthermore, the use of DEXi is suitable when judgments prevail, and it is difficult to provide a numerical answer [21]. Moreover, DEXi is an open access software that can be used to apply the same model, or its variants, in different geographical contexts. Finally, the results from the comparison of different MCDM with DEXi are scarce and often contrasting [21–23].

In saltwater aquaponics, growing conditions may be critical for plants and there are few species able to tolerate moderate to high salinity. In these conditions, a decision model that takes into account several parameters may be helpful to select the proper plant species considering production, economic, and technical aspects together. However, to the best of our knowledge DEXi has not been used for the selection of suitable plant species for saltwater aquaponic systems.

The goal of the present study was therefore to identify the most suitable plant species for saltwater aquaponics, in particular in the Mediterranean area, using a MCDM. To address this issue, we used DEXi, taking into account seven criteria and 14 indicators regarding crop production, seed availability, know-how, and economic relevance of 15 salt-tolerant glycophyte or halophyte species crops. An extensive literature analysis was conducted to assign the score to each indicator.

2. Materials and Methods

The analysis was performed following the guidelines proposed by Craheix et al. [15] using a 'top-down' approach. A group of academic experts in agriculture production, plant nutrition, hydroponics, aquaponics, aquaculture, and agricultural engineering, from five different countries (Italy 39.2%, Mexico 26.1%, India 21.7%, Turkey 8.7%, and Guatemala 4.3%), planned the design process of the model. Aquafarmers have been avoided because saltwater aquaponic is not yet commercially. Fifteen salt-tolerant plant species were selected for the present analysis. Their general features are summarized in Table 1.

Table 1. Species assessed for the selection of suitable species for saltwater aquaponics using DEXi method.

Scientific Name	Family	Comun Name	Response to Salinity
Aster tripolium L. [24]	Asteraceae	Sea aster	Salt-tolerant glycophyte
Atriplex hortensis L. [25]	Amaranthaceae	Red orach	Facultative halophyte
Beta vulgaris var. *cicla* L. [26]	Amaranthaceae	Swiss chard	Facultative halophyte
Beta vulgaris ssp. *maritima* (L.) Arcang [27]	Amaranthaceae	Sea beet	Salt-tolerant glycophyte
Cichlearia officinalis L. [28]	Brassicaceae	Scurvy grass	Salt-tolerant glycophyte
Crithmum maritimum L. [29]	Apiaceae	Sea fennel, rock samphire	Facultative halophyte
Diplotaxis tenuifolia (L.) DC. [30]	Brassicaceae	Perennial wallrocket	Salt-tolerant glycophyte
Inula crithmoides L. [31]	Asteraceae	Sea grass	Facultative halophyte
Portulaca oleracea L. [32]	Portulacaceae	Common purslane	Salt-tolerant glycophyte
Salicornia bigelovii Torr. [33]	Amaranthaceae	Pickleweed, sea-beans	Obligate halophyte
Salicornia europaea L. [34]	Amaranthaceae	Marsh samphire	Obligate halophyte
Salicornia fructicosa (L.) L. [35]	Amaranthaceae	Common glasswort	Obligate halophyte
Salicornia ramosissima J. Woods [36]	Amaranthaceae	Purple glasswort	Facultative halophyte
Salsola soda L. [37]	Amaranthaceae	Agretti	Salt-tolerant glycophyte
Tetragonia tetragonioides (Pall.) Kuntze [25]	Amaranthaceae	New Zealand spinach	Facultative halophyte

The model consisted of a simple tree structure that contained one root criterion ('Plant species selection'), four aggregated criteria, three aggregated sub-criteria, and 14 indicators (Table 2). The aggregated criteria and sub-criteria were evaluated by a three-value scale ('High', 'Medium' and 'Low'), meanwhile, indicators were evaluated only by two- ('High' and 'Low') or three-value scale ('High', 'Medium', and 'Low') to avoid a 'combinatory explosion' of decision rules [15]. A set of 81 decision rules was defined by the 'weight' function ('Model' > 'Utility function' > 'Weight editor') of the software [14], to find out the final score for the root criterion. However, some decision rules had to be manually assessed: for the 'Plant species selection' criterion only 2.5% (2 out of 81) of the decision rules were determined by the panel of experts. Finally, a five-value scale ('Excellent', 'Good', 'Medium', 'Poor', and 'Unacceptable') was adopted as the final score of each plant species assessed. This procedure led to a slightly different distribution of initial weight (45% for 'Potential yield', 30% for 'Economic importance', 14% for 'Seed availability', and 11% for 'Level of knowledge available'), as shown in Table 2.

Table 2. Tree of attributes, assigned weights, and evaluation scale used in the present study.

Criteria and Indicators	Weights (%)	Evaluation Scale
0 Plant species selection		Excellent, Good, Medium, Poor, Unacceptable
1 Potential yield	45	Low, Medium, High
1.1 Annual yield	33	Low, Medium, High
1.2 Salinity tolerance and its impact on yield	67	Low, Medium, High
2 Seed availability in Italy and surrounding countries	14	Low, Medium, High
2.1 Source of seed	27	Low, High
2.2 Cost of seed per unit	45	Low, High
2.3 Availability of genetically selected strains	27	Low, High
3 Level of knowledge available	11	Low, Medium, High
3.1. Availability of biological/botanical features	50	Low, High
3.2. Availability of protocols for hydroponic cultivations	50	Low, High
4 Economic importance of the species	30	Low, Medium, High

Table 2. *Cont.*

Criteria and Indicators	Weights (%)	Evaluation Scale
4.1 Potential use of the species	27	Low, Medium, High
4.1.1 Species used as human food	25	Low, High
4.1.2 Species with pharmaceutical and cosmetic use	75	Low, High
4.2 Economic value of the species	30	Low, Medium, High
4.3 Nutritional characteristics of the species	21	Low, Medium, High
4.3.1 Protein content and amino acid profile	50	Low, High
4.3.2 Energy content	50	Low, High
4.4 Nutraceutical characteristics	21	Low, Medium, High
4.4.1 Vitamin content	75	Low, High
4.4.2 Mineral content	25	Low, High

Bold letters indicate aggregated criteria or sub-criteria; grey highlighted rows indicate criteria.

To identify the potential species and their features for the evaluation, an extensive literature analysis was conducted. The cut off criteria for preliminary selection of the candidate species were their potential salinity tolerance and commercial use. The bibliography search was carried out through scientific databases by the advance document search tool within Scopus (trademarks of Elsevier B.V. Copyright © 2022, Elsevier, Amsterdam, the Netherlands.) and Google Scholar™ (trademark of Google Inc., Mountain View, CA 94043, USA). Based on the information obtained from the literature review, the experts assigned the score of each indicator and sub-criteria. A summary of the literature information is reported in Tables 3–7.

Table 3. Annual yield of the considered plant species under optimal growing conditions.

Plant Species	Annual Yield (kg m^{-2}) *	Optimal Salinity (g L^{-1})
A. tripolium L.	18.3 [38]	2.9–4.7 [b] [38,39]
A. hortensis L.	60.1 [39]	4.4–9.4 [b] [39]
B. vulgaris var. *cicla* L.	9.6 [26]–10.5 [40]	≈0–5.0 [26]
B. vulgaris ssp. *maritima* (L.) Arcang	11.6 [40]–40.2 [41]	7.3–14.6 [b] [42]
C. officinalis L.	26.4 [28]	0–2.9 [b] [43]
C. maritimum L.	3.1 [44]	5.8 [b] [44]
D. tenuifolia (L.) DC.	36.9 [43]	0–2.9 [b] [43]
I. crithmoides L.	43.7 [31]	6.3 [c] [31]
P. oleracea L.	57.9 [45]	1.6 [b]–6.3 [b] [46]
S. bigelovii Torr.	27.9 [47]	11.7 [47]
S. europaea L.	25.3 [48]	16.5–24.7 [48]
S. fructicosa (L.) L.	9.8 [48]	8.25–24.7 [48]
S. ramosissima J. Woods	0.20 [49]	0–3.4 [b] [49]
S. soda L.	6.4 [50]	4.5–8.9 [c] [50]
T. tetragonioides (Pall.) Kuntze	4.2 [51]	0.4–25.1 [b] [51]

* Yield was calculated on the basis of the production per each cultivation cycle and the number of cultivation cycles per year reported in the literature. [b] Calculated from NaCl concentrations. [c] Calculated from the value of electrical conductivity reported by Boyd [52] (multiplying the value of the electrical conductivity expressed in µS cm^{-1} × 0.00063).

Table 4. Selected strains, price, and seed companies that sell the seeds of the considered plant species.

Plant Species	Seed Company	Strains	Price (EUR per 1000 Seeds)
A. tripolium L.	Alsa Garden, Pennard plants		136 [53] 5.58 [54]
A. hortensis L.	Alsa Garden, Pennard plants		171.6 [53]–89.2 [54]

Table 4. *Cont.*

Plant Species	Seed Company	Strains	Price (EUR per 1000 Seeds)
B. vulgaris var. *cicla* L.	SAIS Spa	Verde a costa larga argentata Candida Sibilla Barese Bright Yellow Bright Lights Rubarb chard	2.00 [55] 2.00 [55] 2.00 [55] 2.00 [55] 9.40 [55] 9.40 [55] 2.00 [55]
	Semencoop	Lusiana [56] Barese [56] Liscia verde da taglio [56] Bright yellow [56] Rubhard chard [56] Rondinella [56]	
B. vulgaris ssp. *maritima* (L.) Arcang	Pennard plants		34.3 [54]
C. officinalis L.	B & T World Seeds		6.4 [57]
C. maritimum L.	Alsa Garden,		220 [53]
D. tenuifolia (L.) DC.	SAIS Spa	Giuditta Olivia	15.5 [55] 16.6 [55]
	RB sementi	Winner Florence	0.52 [58] 0.22 [58]
	Enza Zaden	Jolizia [59] Letizia [59] Prudenzia F1 [59] Tanazia [59] Tricia [59]	
	Semencoop [56]		
I. crithmoides	B & T World Seeds		56.9 [57]
P. oleracea L.	Alsa Garden		33 [53]
S. bigelovii Torr.	B & T World Seeds [57]		
S. europaea L.	Alsa Garden		7.90 [53]
T. tetragonioides (Pall.) Kuntze	Pennard plants		111.5 [54]
S. soda L.	Alsa Garden, Pennard plants		165.2 [53] –74.3 [54]

Table 5. Nutraceutical characteristics and main commercial use of the considered plant species.

Plant Species	Nutraceutical Characteristics	Edible Part	Commercial Use
A. tripolium L. [38,60]	Source of minerals.	Leaves	Fresh alone or mixed in salads and cooked (e.g., boiled), and ornamental.
A. hortensis L. [25,61]	Source of Vitamin C and saponins. Source of calcium, potassium, copper, and manganese. Source of vitamin C.	Leaves	Fresh alone or mixed in salads and cooked (e.g., boiled), animal fodder, herbal medicine, and ornamental.
B. vulgaris var. cicla; L. [62]	Source magnesium, calcium, and phosphorus. source of vitamins A, E, B3, B5, and B9.	Leaves	Fresh alone or mixed in salads and cooked (e.g., boiled) and modern pharmacology.
B. vulgaris ssp. *maritima* (L.) Arcang [63]	Source of vitamin E.	Leaves	Fresh alone or mixed in salads and cooked.
C. officinalis L. [43,64]	Source of vitamin C.	Leaves	Fresh alone or mixed in salads, herbal medicine.
C. maritimum L. [29,44]	Source of vitamin A, B2, C and potassium.	Leaves	Fresh alone or mixed in salads and cooked (e.g., boiled), herbal medicine.

Table 5. *Cont.*

Plant Species	Nutraceutical Characteristics	Edible Part	Commercial Use
D. tenuifolia (L.) DC. [43]	Source of vitamin C. Significant concentration of minerals	Leaves	Fresh alone or mixed in salads.
I. crithmoides L. [65]	Source of minerals.	Leaves	Fresh alone or mixed in salads and cooked (e.g., boiled), and animal fodder, ornamental, herbal medicine.
P. oleracea L. [32,66]	Source of potassium and magnesium. Source of vitamin A, vitamin C.	Leaves	Fresh mixed in salads, herbal medicine and used in modern pharmacology.
S. bigelovii Torr. [33]	Source of vitamins A and C, and minerals.	Shoots	Oilseed production, fresh food, animal fodder and herbal medicine.
S. europaea L. [34]	Source of vitamin C, carotenoids, and mineral elements	Shoots	Fresh alone or mixed in salad and cooked (e.g., boiled).
S. fructicosa (L.) L. [45]	Source of vitamins, minerals, and antioxidant compounds	Shoots	Fresh alone or mixed in salad and cooked (e.g., boiled).
S. ramosissima J. Woods [36]	Source of lipophilic phytochemicals, antioxidants, and nutrients as fiber magnesium, potassium, calcium, and iron.	Shoots	Fresh alone or mixed in salads and cooked (e.g., boiled) and substitute of salt, herbal medicine.
S. soda L. [53,67]	Source of calcium and iron. Source of vitamin A, C and K.	Leaves and stem	Processed food, herbal medicine and used in modern pharmacology.
T. tetragonioides (Pall.) Kuntze [25]	Source of minerals such as iron and calcium. Source of vitamin C.	Leaves	Fresh alone or mixed in salads, herbal medicine, and modern pharmacology.

Table 6. Protein content of the considered plant species.

Species	Protein Content (g 100 g^{-1} FW)
A. tripolium L.	0.9–2.1 [b] [68]
A. hortensis L.	17.0 [69]
B. vulgaris var. *cicla*	1.1 [70]
B. vulgaris ssp. *maritima* (L.) Arcang	3.4 [a] [71]
C. officinalis L.	4.2 [72]
C. maritimum L.	1.6 [29]
D. tenuifolia (L.) DC.	2.4 [b] [73]
I. crithmoides L.	2.4 [b] [31]
P. oleracea L.	1.5–3.0 [74]
S. bigelovii Torr.	1.5 [33]
S. europaea L.	3.1 [a] [75]
S. fructicosa (L.) L.	0.3–0.4 [48]
S. ramosissima J. Woods	0.8 [b] [76]
S. soda L.	1.8 [70]
T. tetragonioides (Pall.) Kuntze	3.09 [77]

[a] Calculated from organic nitrogen concentration. [b] Calculated from the protein value expressed in dry weight.

Table 7. Selling price of the considered plant species.

Species	Price (Euro kg^{-1})	Product
A. tripolium L.	n.d.	Fresh leaves
A. hortensis L.	7.5 [78]	Fresh leaves
B. vulgaris var. *cicla* L.	1.0–1.5 [79]	Fresh leaves
B. vulgaris ssp. *maritima* (L.) Arcang	0.6–0.8 [79]	Fresh leaves
C. officinalis L.	10.3 [80]	Dry leaves
C. maritimum L.	0.7–1.3 [79]	Fresh shoots
D. tenuifolia (L.) DC.	14.9 [81]	Fresh leaves
I. crithmoides L.	1.9–2.2 [79]	Fresh leaves
P. oleracea L.	0.3 [82]	Fresh leaves

Table 7. *Cont.*

Species	Price (Euro kg^{-1})	Product
S. bigelovii Torr. *S. europaea* L. *S. fructicosa* (L.) L. *S. ramosissima* J. Woods	6 [34]	Fresh shoots
S. soda L.	4–4.5 [83]	Fresh stem and leaves
T. tetragonioides (Pall.) Kuntze	24 [84]	Fresh leaves

The aggregated criteria and the respective indicators were evaluated as follows:

- Potential yield. Plants with high annual yield were selected (Table 3). For each plant species, the annual yields used for the analysis were obtained under optimal growing conditions, assuming that soilless culture and foliar application of mineral nutrients can overcome the effect of high salinity on plan mineral nutrition, thus avoiding the occurrence of nutrient deficiencies [85]. Optimal salinity levels of the species evaluated in the current work are reported in Table 3. Plants with the highest annual yield in the scenario conditions and higher resistance to salinity, scored 'High' in both indicators (i.e., 'Annual yield' and 'Salinity tolerance and its impact on yield').
- Seed availability in Italy and surrounding countries. The supply of seeds from seed companies,, which offer high-quality seeds of different genotypes at a competitive price, was considered the best option. Therefore, a 'High' score was assigned to the 'Source of seed' indicator. Relatively cheap seeds of the crop species under evaluation are currently supplied by some seed companies (e.g., SAIS, Cesena, Italy; Enza Zaden Italia S.r.l., Tarquinia, Italy). Thus, a 'High' score was assigned for the lower priced seeds to the 'Cost of seed per unit' indicator. Moreover, most of the species evaluated are not cultivated on a large scale. For this reason, genetically selected varieties are not available for these species, and their seeds are difficult to find or sold on Internet at relatively high prices (Table 4). If certified seeds of well identified varieties are available, 'High' score was assigned to the 2.3 indicator (Table 2).
- Level of knowledge available. Scientific literature can help to develop a proper cultivation protocol for each species. Thus, previous experience of cultivation in soilless systems were positively considered in this evaluation and a 'High' score was assigned to the 'Availability of protocols for hydroponic cultivations'. The main hotspots considered were propagation and cultivation technique, crop protection strategy, and environmental and nutritional needs. If this information is available, a 'High' score was assigned to the 'Availability of biological/botanical features' indicator.
- Economic importance of the species. Halophytes and salt-tolerant glycophytes are cultivated for many purposes, including food production and the extraction of active principles of medicinal or nutraceutical interest [86]. If plants are already used for food production, a 'High' score was assigned to the 'Species used as human food' indicator. For the present evaluation, plant species that have been used in modern pharmacology and have the potential for drug manufacturing, obtained a better score (Tables 5 and 6); thus 'High' score was assigned to the 'Species with pharmaceutical and cosmetic use'. Leaf vegetables can be a good source of minerals, vitamins, antioxidants, minerals, dietary fibers, and polyunsaturated fatty acids, as reviewed by Tripathy et al. [87]. As a consequence, a 'High' score was assigned for 'Vitamin content' and 'Mineral content' indicators. Moreover, the content of harmful compounds, e.g., nitrates and oxalates, has to be taken into account to evaluate the quality of a leafy vegetable [88]. Vegetables with higher protein and energy content scored 'High' for 'Protein content and amino acid profile' and 'Energy content' indicators, respectively.

Due to their growing popularity, wide acceptance in gourmet cuisine and medicinal properties, halophytes and salt-tolerant glycophytes can reach relatively high sale prices. Halophyte and salt-tolerant glycophyte are mainly marketed by specialized buyers/sellers

(Table 7). Plants with already higher market price, scored 'High' for the 'Economic value of the species' indicator.

The weights assigned to the aggregated criteria, sub-criteria, and indicators were selected by consensus by the panel of experts. 'Potential yield' and 'Economic importance of the species' were chosen as the most influenced aggregated criteria for the choice (weights equal to 47 and 30%, respectively). 'Seed availability' and 'Level of knowledge available' were considered less influent for the decision process. Thus, weights assigned were equal to 13% and 10%, respectively.

The relevance of the model structure was evaluated by the sensitivity analysis, through the 'plus/minus-1 analysis' function of the software, performed individually per species. This analysis investigated the effects on aggregated criteria caused by changing the value of each sub-criteria by one qualitative value down or up, independently of others [14].

3. Results and Discussion

The scores assigned to each criterion and indicators and the effect of the sensitivity analysis of each species for 'Low salinity' scenario and 'High salinity' scenario are reported in Tables 8 and 9, respectively. The final results of the model of both scenarios are reported in Table 10.

Table 8. Assigned scores and results of the considered plant species (with % of relevance of each indicator) and sensitivity analysis for criteria, for the lower salinity (10 g L^{-1}) scenario.

Criteria and Indicators	Weight (%)	*A. tripolium*	*A. hortensis.*	*B. vulgaris var cicla*	*B. vulgaris spp. maritima*	*C. officinalis*	*C. maritimum*	*D. tenuifolia*	*I. crithmoides*	*P. oleracea*	*S. bigelovii*	*S. europaea.*	*S. fructicosa*	*S. ramosissima*	*S. soda.*	*T. tetragonoides*
1. Potential yield	**45**	**M**	**H**	**M**	**H**	**L**	**M**	**M**	**M**	**M**	**H**	**H**	**M**	**M**	**M**	**M**
1.1. Annual yield	33	H	H	M	H	M (+)	L	H (−)	H	H	M (−)	M	L (+)	L	L (+)	L (+)
1.2. Salinity tolerance and its impact on yield	67	M (+)	H (−)	M (+)	H (−)	L (+)	M (−)	L	M (−)	M	H (−)	H	H	M (−)	H	H
2. Seed availability in Italy and surrounding countries	**14**	**L**	**L**	**H**	**L**	**L**	**L**	**H**	**L**	**L**	**L**	**L**	**L**	**L**	**L**	**L**
2.1. Source of seed	27	L	L	H	L	L	L	H	L	H	L	L	L	L	H	L
2.2. Cost of seed per unit	45	L	L	H	L	L	L	H	L	L	L	L	L	L	L (+)	L
2.3. Availability of genetically selected strains	27	L	L	H	L	L	L	H	L	L	L	L	L	L	L	L
3. Level of knowledge available	**11**	**M**	**M**	**H**	**M**	**L**	**M**	**H**	**L**	**H**	**M**	**H**	**L**	**M**	**L**	**L**
3.1. Availability of biological/botanical features	50	H	H	H	H (−)	L	H-	H	L	H (−)	H (−)	H	L	H	L	L
3.2. Availability of protocols for hydroponic cultivations	50	L	L	H	L	L	L	H	L	H (−)	L	H	L	L (+)	L	L
4. Economic importance of the species	**30**	**M**	**H**	**M**	**M**	**M**	**M**	**L**	**M**	**H**	**M**	**H**	**H**	**H**	**H**	**H**
4.1. Potential use of the species	**27**	**M**	**M**	**H**	**M**	**M**	**M**	**M**	**M**	**H**	**M**	**M**	**M**	**M**	**H**	**H**
4.1.1. Species with pharmaceutical and cosmetic use	25	L	L	H	L	L	L	L	L	H (−)	L	L	L	L	H	H
4.1.2. Species used as human food	75	H	H	H	H	H	H	G	H	H (−)	H	H	H	H	H	H
4.2. Economic value of the species	30	H	H	L (+)	L	H	L	L	M	L	H	H	H	H	H	L
4.3. Nutritional characteristicsof the species	**21**	**M**	**H**	**M**	**H**	**H**	**M**	**M**	**M**	**H**	**L**	**H**	**M**	**M**	**L**	**H**
4.3.1. Protein and amino acids content	50	H	H	L (+)	H	H	L	L	L	H (−)	L	H	L	L	L	H
4.3.2. Energy content	50	L	H	H	H	H	H	H	H	H (−)	L	H	H	H	L	H
4.4. Nutraceutical characteristics	**21**	**M**	**M**	**H**	**H**	**L**	**H**	**L**	**M**	**H**	**H**	**H**	**H**	**H**	**H**	**H**
4.4.1. Vitamin content	75	L	L	H	H	L	H (−)	L	L (−)	H (−)	H	H	H	H	H	H
4.4.2. Mineral content	25	H	H	H	L	L	L	L	H	H	H	H	H	H	H	H
Plant species selection		**M**	**G**	**M**	**G**	**P**	**M**	**M**	**M**	**G**	**G**	**G**	**M**	**M**	**M**	**M**

Bold letters indicate aggregated criteria or sub-criteria; grey highlighted rows indicate criteria; symbols means that a 'plus/minus 1' change in the indicator's score affects the 'Plant species selection' value positively (+) or negatively (−); H: High, M: Medium, and L: Low for criteria score; G: Good, M: Medium, P: Poor, and U: Unacceptable.

Table 9. Assigned scores and results of the considered plant species (with % of relevance of each indicator) and sensitivity analysis for criteria, for the higher salinity (35 g L^{-1}) scenario.

Criteria and Indicators	Weight (%)	*A. tripolium*	*A. hortensis.*	*B. vulgaris var cicla*	*B. vulgaris* spp. *maritima*	*C. officinalis*	*C. maritimum*	*D. tenuifolia*	*I. crithmoides*	*P. oleracea*	*S. bigelovii*	*S. europaea.*	*S. fructicosa*	*S. ramosissima*	*S. soda.*	*T. tetragonoides*
1. Potential yield	**45**	**M**	**M**	**L**	**M**	**L**	**L**	**M**	**M**	**M**	**M**	**H**	**M**	**L**	**L**	**M**
1.1. Annual yield	33	H (−)	H (−)	M	H	M (+)	L	H (−)	H (−)	H (−)	M	M	L (+)	L	L	L
1.2. Salinity tolerance and its impact on yield	67	L	L	L	M (+)	L (+)	L (+)	L	L	L	M (±)	H	H	L (+)	L (+)	M (−)
2. Seed availability in Italy and surrounding countries	**14**	**L**	**L**	**H**	**L**	**L**	**L**	**H**	**L**	**L**	**L**	**L**	**L**	**L**	**L**	**L**
2.1. Source of seed	27	L	L	H	L	L	L	H	L	H	L	L	L	L	H	L
2.2. Cost of seed per unit	45	L	L	H (−)	L	L	L	H	L	L	L	L	L	L	L (+)	L
2.3. Availability of genetically selected strains	27	L	L	H	L	L	L	H	L	L	L	L	L	L	L	L
3. Level of knowledge available	**11**	**M**	**M**	**H**	**M**	**L**	**M**	**H**	**L**	**H**	**M**	**H**	**L**	**M**	**L**	**L**
3.1. Availability of biological/botanical features	50	H	H	H (−)	H	L	H	H	L (+)	H (−)	H	H	L	H	L	L
3.2. Availability of protocols for hydroponic cultivations	50	L	L (+)	H (−)	L	L	L	H	L (+)	H (−)	L	H	L	L (+)	L	L
4. Economic importance of the species	**30**	**M**	**H**	**M**	**M**	**M**	**M**	**L**	**M**	**H**	**M**	**H**	**H**	**H**	**H**	**H**
4.1. Potential use of the species	**27**	**M**	**M**	**H**	**M**	**M**	**M**	**M**	**M**	**H**	**M**	**M**	**M**	**M**	**H**	**H**
4.1.1. Species with pharmaceutical and cosmetic use	25	L	L	H	L	L	L	L	L	H (−)	L	L	L	L	H	H
4.1.2. Species used as human food	75	H	H	H	H	H	H	G	H	H (−)	H	H	H	H	H	H
4.2. Economic value of the species	30	H	H	L	L	H	L	L	M	L	H	H	H	H	H	L
4.3. Nutritional characteristics of the species	**21**	**M**	**H**	**M**	**H**	**H**	**M**	**M**	**M**	**H**	**L**	**H**	**M**	**M**	**L**	**H**
4.3.1. Protein and amino acids content	50	H	H	L	H	H	L	L	L	H (−)	L	H	L	L	L	H
4.3.2. Energy content	50	L	H	H	H	H	H	H	H	H (−)	L	H	H	H	L	H
4.4. Nutraceutical characteristics	**21**	**M**	**M**	**H**	**H**	**L**	**H**	**L**	**M**	**H**	**H**	**H**	**H**	**H**	**H**	**H**
4.4.1. Vitamin content	75	L	L	H	H	L	H (−)	L	L	H (−)	H	H	H	H	H	H
4.4.2. Mineral content	25	H	H	H	L	L	L	L	H	H	H	H	H	H	H	H
Plant species selection		**M**	**M**	**M**	**M**	**P**	**P**	**M**	**M**	**G**	**M**	**G**	**M**	**P**	**P**	**M**

Bold letters indicate aggregated criteria or sub-criteria; grey highlighted rows indicate criteria; symbols means that a 'plus/minus 1' change in the indicator's score affects the 'Plant species selection' value positively (+) or negatively (−); H: High, M: medium, and L: Low for criteria score; G: Good, M: Medium, P: Poor, and U: Unacceptable.

Table 10. Final score for the considered plant species in two scenarios using DEXi method.

Species	**Scenario**	
	Low Salinity (10 g L^{-1})	**High Salinity (35 g L^{-1})**
A. tripolium L.	Medium	Medium
A. hortensis L.	Good	Medium
B. vulgaris var. *cicla* L.	Medium	Medium
B. vulgaris ssp. *maritima* (L.) Arcang	Good	Medium
C. officinalis L.	Poor	Poor
C. maritimum L.	Medium	Poor
D. tenuifolia (L.) DC.	Medium	Medium
I. crithmoides L.	Medium	Medium
P. oleracea L.	Good	Good
S. bigelovii Torr.	Good	Medium
S. europaea L.	Good	Good
S. fructicosa (L.) L.	Medium	Medium
S. ramosissima J. Woods	Medium	Poor
S. soda L.	Medium	Poor
T. tetragonoides (Pall.) Kuntze	Medium	Medium

3.1. Evaluated Characteristics of Plant Species and Its Overall Score

A. tripolium L. scored 'Medium' in both assessed scenarios (Table 10). Its optimal salinity level ranges from 2.9 to 4.7 g L^{-1} (Table 3) [38]. Moreover, *A. tripolium* L. gave a moderate yield under optimal conditions (Table 3). Its seeds are not easy to find and have a high sale price (Table 4). Waller et al. [89] evaluated *A. tripolium* L. growth in an RAS with European sea bass (*Dicentrarchus labrax* L.) using brackish water (16 g L^{-1}). Leaf production gained was 30 g per plant in 35 days of experimentation. Quintã et al. [90] concluded that *A. tripolium L.* is a good candidate for inclusion in saltwater aquaponic systems after evaluating its growth in nutrient conditions typical of aquaculture wastewater (1 mM of N and 0.2 mM of P) with brackish water (10 g L^{-1}). Halophytes of the genera *Aster* have gained popularity in the European markets and their demand is increasing as their leaves are a good source of minerals [60].

A. hortensis L. scored 'Good' for growing at 10 g L^{-1} of salinity, and 'Medium' at 35 g L^{-1} (Table 10). This species gave high annual yield under optimal conditions (Table 3) and grows well in a salinity range between 4.4 to 9.4 g L^{-1} [39] (Table 3). Seeds are not easy to find and are generally sold on e-commerce platforms at high prices (Table 4). There is limited information regarding the hydroponic cultivation of this species. The price of fresh leaves could be around EUR 5 kg^{-1} on e-commerce platforms (Table 7). In addition, the leaves of *A. hortensis* L. are a good source of Vitamin C, and minerals such as calcium, potassium, copper, and manganese, and have natural diuretic and laxative properties [61].

B. vulgaris var. *cicla* L., a very popular vegetable, resulted as a 'Medium' candidate for cultivation at both 10 g L^{-1} and 35 g L^{-1} of salinity (Table 10); its optimal salinity range is between 0 and 5.0 g L^{-1} [26] (Table 3). This species showed a medium leaf production (9.6–10.5 kg m^{-2}) (Table 3). Registered varieties and certified seeds of *B. vulgaris* var. *cicla* L. are available on the market from many seed companies and at low prices (Table 4). There is much information available about its biology and hydroponic cultivation [40,91–93]. It is a popular leafy vegetable around the world [94], and its leaves are usually sold at a lower price as compared to the other assessed species (Table 7).

B. vulgaris ssp. *maritima* (L.) Arcang scored 'Good' at 10 g L^{-1} and 'Medium' at 35 g L^{-1} (Table 10). This species showed a high annual yield under optimal conditions (Table 3); its optimal salinity range is between 7.3 and 14.6 g L^{-1} [42] (Table 3). Seeds are sold by small companies and e-commerce platforms at a high price (Table 4). Despite the existence of considerable scientific literature on the biological knowledge of this species [43], little is known on the hydroponic cultivation of this species. Puccinelli et al. [40] reported that *B. vulgaris* spp. *maritima* (L.) grown with brackish water (10 g L^{-1}) obtained a yield of about 13 kg m^{-2}. This plant has a relatively low sale price as compared with the other species evaluated (Table 7).

C. officinalis L. scored 'Poor' in both of the evaluated scenarios (Table 10). This is mainly due to its maximum threshold value of salinity which is 2.9 g L^{-1} (Table 3) [64]. Its annual yield is moderate compared with the other species assessed (Table 3). Seeds are sold on specialized online websites and there are no genetically selected strains of this species (Table 4). The information available about its botanical knowledge and its cultivation in hydroponic systems is limited. *C. officinalis* L. is used for salads and it is appreciated for its Vitamin C content, in the past, it was used to combat scurvy by the mariners [64].

C. maritimum L. achieved a 'Medium' and 'Poor' score for cultivation at 10 g L^{-1} and at 35 g L^{-1}, respectively (Table 10). Its optimal salinity for growing is 5.8 g L^{-1} [44] (Table 3), annual yield is low (Table 3) and seeds are relatively expensive and marketed by small seed companies (Table 4). There is much information in the literature about biological and botanical aspects of *C. maritimum* L. [44,95], which has been cultivated in floating system [44] or in pots with sand [96]. *C. maritimum* L. is considered as a functional food and is largely used for its nutritional and health-promoting value as it is rich in vitamins, carotenoids, polyphenols, and other bioactive constituents [97]. In addition, *C. maritimum* L.

contains essentials oils and different sugars, organic acids, and minerals [96]. However, its shoots are sold at a relatively low price, compared to the other species evaluated (Table 7).

D. tenuifolia (L.) DC. scored 'Medium' in both of the evaluated scenarios (Table 10) and its optimal salinity range is between 0 and 2.9 g L^{-1} [43] (Table 3). This species showed a high annual yield (Table 3). Cheap seeds are marketed by several seed companies (Table 4), and information are available of the biology and hydroponic cultivation (floating system) of this species [43]. This crop has gained greater importance as vegetables and culinary herb in Europe. *D. tenuifolia* (L.) DC. contains significant levels of poly-glycosylated flavonoids, which protect the colonic epithelium from free radical attack [43]. Leaves of *D. tenuifolia* (L.) DC. are usually sold at a low price compared to the other assessed species (Table 7).

I. crithmoides L. was considered a 'Medium' candidate for aquaponics at 10 g L^{-1} and 35 g L^{-1} of salinity (Table 10), as its optimal salinity is 6.3 g L^{-1} [31] (Table 3). *I. crithmoides* L. gives a high annual yield (Table 3) compared with the other species assessed. There are no registered varieties and the seeds are sold only by small seed companies at a relatively high price (Table 4). There is limited information available about biology and hydroponic cultivation of this plant [31,65]. *I. crithmoides* L. is a source of minerals and it is consumed in salads or cooked, as animal fodder, and in herbal medicine (Table 5) [65]. Its leaves are sold at a medium price, compared to the other species (Table 7).

P. oleracea L. scored 'Good' in both the salinity scenarios assessed (Table 10). This species presented a high annual yield in optimal conditions and its optimal range of salinity is 1.6–6.3 g L^{-1} (Table 3) [46]. Seeds are widely available at relatively high prices by several companies in Mediterranean countries (Table 4). The botanical knowledge of this species is extensive. In addition, *P. oleracea* L. has been tested in hydroponics with satisfactory results [32,66]. This species is a source of vitamins (e.g., Vitamin A, Vitamin C) and minerals (e.g., potassium, magnesium) [66] and it has been employed in herbal medicine and modern pharmacology due to its analgesic and anti-inflammatory properties [98].

S. bigelovii Torr resulted as a 'Good' and 'Medium' candidate for the cultivation at 10 and 35 g L^{-1} of salinity, respectively. Moreover, *S. europaea* L. resulted to be a 'Good' candidate for cultivation at 10 and 35 g L^{-1} of salinity (Table 10). *S. bigelovii* Torr. presented the optimal growth at 11.7 g L^{-1} of salinity [47] and *S. europaea* L. between 16.5 and 24.7 g L^{-1} (Table 3) [48]. Both species give a medium annual yield (Table 3), compared with the other assessed species, the cost of seeds is relatively high, and there are not registered varieties (Table 4). There is much information in the literature about the biological and botanical aspects of *S. bigelovii* Torr [47,48,99] and *S. europaea* L. [34,90,100,101]. In contrast, there are many studies on the hydroponic cultivation of different *Salicornia* species [102]. S. *bigelovii* Torr. has been hydroponically cultivated with perlite [99] or sand [47] as a substrate or in the floating system [103]. Moreover, *S. europaea* L. has been cultivated in the floating system [90,100], aeroponics [34] and in silica sand [101]. *S.bigelovii* Torr has been introduced to the U.S. and European markets as a special green vegetable, and its succulent young shoots are in high demand in gourmet cousine due to their salty taste and high nutritional value [104]. Besides, *S. europea* L. has very high levels of Vitamin C, carotenoids [105], and proteins (Table 6). The demand of *S. europaea* L. is growing in the European markets and its sale price is relatively high (Table 7).

S. fructicosa (L.) L. resulted as a 'Medium' candidate for the cultivation at 10 and 35 g L^{-1} of salinity (Table 10); the optimal salinity range is between 8.25 and 24.7 g L^{-1} (Table 3) [48]. This species presented a low annual yield (Table 3) as compared with the other species assessed. There are not registered varieties and its seeds are difficult to find. The available information on the biological and botanical features and hydroponic cultivation of *S. fructicosa* (L.) L. is limited [48,99]. *S. fructicosa* (L.) L. has been cultivated in perlite-filled pots [48,103]. Its young fleshy tips have a high demand in gourmet cuisine due to their salty taste and its content of minerals and vitamins [34] and are usually sold at a high price (Table 7).

S. ramosissima J. Woods resulted as a 'Medium' candidate for cultivation at 10 g L^{-1} of salinity, while it resulted as a 'Poor' candidate at 35 g L^{-1} (Table 10). Optimal salinity level is between 0 and 3.4 g L^{-1} for this species [49] (Table 3); its annual yield is low (Table 3) and seeds are difficult to find. There is much information about the biological and botanical aspects of *S. ramosissima* J. Woods [106], but very few works have been carried out on soilless cultivation [107]. However, *S. ramosissima* J. Woods is a multifunctional (food and pharmaceutical) cash crop [34]; for these reasons, its shoots are sold at a relatively high cost (Table 7).

S. soda L. got 'Medium' and 'Poor' scores at 10 and 35 g L^{-1}, respectively, (Table 10); its optimal salinity range is between 4.5 to 8.9 g L^{-1} [50] (Table 3). This plant showed a low annual yield (Table 3) compared to the other species assessed. The seeds of *S. soda* L. are relatively easy to find in Italy [37], but the price is relatively high (Table 4). Information on cultivation in hydroponic systems is scarce, although there is scientific evidence of the positive performance of this species grown in saltwater aquaponics. For instance, Pantanella [108] reported a production of 2.2 to 3.2 kg m^{-2} of *S. soda* L. grown in a saltwater (10 g L^{-1}) aquaponics with grey mullet (*Mugil cephalus*) as companion fish species. This species is consumed as a gourmet vegetable around the world and mainly in Italy [37]. It is a good source of Vitamin A, C, K, calcium, and iron. In herbal medicine, it has been used as a treatment of hypertension, constipation, and inflammation [67]. Alkaloid extracts from this plant showed good results for the treatment of Alzheimer's disease [86] (Table 5).

T. tetragonoides (Pall.) Kuntze scored 'Medium' in both scenarios (Table 10). This species grows well in a salinity range between 0.4 and 25.1 g L^{-1} [51], although it gives a low annual yield (Table 3). Its seeds can be found on e-commerce platforms at high sales prices (Table 4). The information available about its botanical knowledge and its cultivation in hydroponic systems is scarce. However, the market prices for *T. tetragonoides* (Pall.) Kuntze could reach up to EUR 24 kg^{-1} [84] (Table 7). It is consumed fresh or cooked and used in herbal medicine. The extract from the leaves of *T. tetragonoides* (Pall.) Kuntze has anti-obesity, anti-hyperlipidemic, and anti-hyperuricemic effects [109]. In addition, this species is a source of iron, calcium, vitamin C, and has a high protein content (Table 6).

The present model helps to point out the main issues in the decision process. In this case, resulting from Tables 8 and 9, were criterion 2 ('Seed availability in Italy and surrounding countries') scores that are nearly always low for the plant species considered. This suggests how the scarce availability of certified seed and registered varieties is one of the main constraints for a commercial application of saltwater aquaponics in the Mediterranean area.

3.2. Sensitivity Analysis

The results of the sensitivity analysis show how a plus/minus 1 change in the scores reported in Tables 8 and 9 affects the overall score. The 'plus/minus 1′ analysis indicates that the indicators 'Annual yield' and 'Salinity tolerance' (under 'Potential yield' aggregated criterion) had a larger influence on the final score in both scenarios: 6/15 and 9/15 times, respectively, in the scenario at 10 g L^{-1} and 7/15 times for both indicators in the scenario at 35 g L^{-1}. The remaining indicators had less influence on the final score in a range of 0/15 to 4/15 times each (Tables 8 and 9).

The model was very sensitive as the ranking of candidate plant species when the qualitative value of low-weight sub-criteria was modified, especially in the aforementioned indicators. This result was expected as a decision-making model is more sensitive to input variables when its structure is simple and uses a low number of criteria [15]. The low number of criteria and the limited qualitative values adopted to avoid the previously mentioned 'combinatory explosion' of the decision rules, determined a quite high sensitivity of the model itself. Even a change in the qualitative value assigned to low weight sub-criteria was able to induce changes in the result (candidates ranking).

3.3. General Considerations

The model proposed in this work is implemented with the open-access MCDM software, DEXi. The model includes several attributes regarding agronomic, nutritional, and economic features of the candidate plant species for saltwater aquaponics, ordered in a hierarchical structure defined by decision rules. The model provides a general tool for the selection of plant species that can be easily adapted to local constraints or additional features.

The model gives a final evaluation consisting of a single score for each species in the two scenarios considered. In this section the assigned scores are explained and supported with the literature information. The DEXi model can be used to highlight hotspots for the decision problem, such as, in this case, the availability of registered varieties and certified seeds on the market.

The proposed model addresses the problem at a general level [18] and uses discrete descriptive attributes, thus imposing a simplification of a more complex problem and offering qualitative evaluation of the species selected. An improvement in this evaluation could be the combination with other models, such as the use of impact categories from Life Cycle Assessment (LCA) as indicator for the DEXi as proposed by Le Féon et al. [12] or GIS-based decision model to also take into consideration spatial or geographical limitations to site selection [110]. Another important issue of the proposed decision model is the limited evaluation scale for the indicators and basic criteria, which gives the final user a few possible options. This choice is also proposed by Craheix et al. [15] to avoid the so called 'combinatory explosion' of the decision rules.

So far, the model has been validated only by experts in previous works [18]. Thus, this model required additional validation, and or an ex-post comparison of its predictions with field results.

4. Conclusions

The results of the present study suggest that *S. europaea* L. and *P. oleracea* L. were the most suitable species for production in saltwater aquaponics at 35 g L^{-1}. Strengths of these species were the 'Level of knowledge available' and the 'Economic importance of the species'. However, other species could be good candidates for saltwater aquaponics at a lower salinity. Indeed, at 10 g L^{-1}, the best candidate species were *S. bigelovii* Torr., *B. vulgaris* ssp. *maritima* (L.) Arcang., *A. hortensis* L. along with *S. europaea* L. and *P. oleracea* L. The scarce availability of certified seed and registered varieties is one of the main constraints to a commercial application of saltwater aquaponics. The DEXi analysis resulted in being a relatively easy and effective tool, which can be used for the selection of proper species in similar contexts. In addition, MCDM can help to identify the hotspots for production processes. In future it will be interesting to apply other qualitative and/or quantitative MCDM to verify and integrate the results obtained in the present work. Moreover, MCDM could be applied to select species in different environmental conditions and different geographic contexts. Furthermore, the combinations of models for the selection, respectively, of fish or plant species in aquaponics would allow to know how the compartments (RAS and soilless cultivation) affect each other. Another possible improvement is integrating the impact categories obtained by LCA analysis within the decision model methodology.

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