



Review

Sustainable Agriculture in the Arabian/Persian Gulf Region Utilizing Marginal Water Resources: Making the Best of a Bad Situation

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Abstract: One way to encourage agricultural self-sufficiency in arid regions is to increase the productivity of conventional freshwater agriculture. Another way is to develop and implement novel strategies and technologies that do not deplete scarce freshwater. Here we describe several options for countries in the Gulf region to increase their agricultural production by taking advantage of a lesser used resource—marginal water. Marginal water can be treated sewage effluent, produced oilfield water, brackish groundwater or seawater. We describe how this resource can be used to grow salt-tolerant forage crops, microalgae and aquaculture crops. Policies needed to implement and/or scale-up such practices are also outlined.

Keywords: Arabian Gulf; Persian Gulf; GCC; microalgae; saline agriculture; halophytes; aquaculture; treated sewage effluent; produced water; aquafeeds

1. Introduction

As a result of the arid/hyper-arid climatic conditions, the majority of the area of the Gulf Cooperation Council Countries (GCC—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and UAE) is beset by a lack of freshwater resources. This lack of freshwater is an obvious constraint to development of conventional agriculture in this region. Arable land is quite limited, averaging around 4.25% of the total land area in the GCC region [1]. At the same time, water use for irrigation and livestock represent the biggest share of total water use, 45% in Bahrain, 54% in Kuwait, 88% in Saudi Arabia, 89% in Oman, 59% in Qatar and 83% in the UAE (FAO Aquastat for the year 2014). Local agriculture largely depends on the use of non-renewable groundwater supplies and suffers from poor practices such as low irrigation efficiency, leakages due to poor agricultural water networks and water-intensive cropping patterns [2]. Altogether, freshwater resources in the region are becoming threatened by agricultural water overuse and mismanagement. There are, however, opportunities for food production and/or landscape that do not entail the utilization of large quantities of freshwater.

One way forward would be to concentrate on conducting conventional agriculture more sustainably. There have been many attempts in the region to improve local agricultural production through the development of soil surveys and measures to improve productivity [3]. However, in reality, since the rate of groundwater recharge is so slow in this region, one could argue that any use of this fossil groundwater resource is not sustainable, as this is essentially a non-renewable resource. Similarly, use of desalinated water for agriculture will not be sustainable due to the high energy costs associated with the desalination process in the GCC region, namely between \$0.45 (subsidized) and \$1 per cubic meter [4].

Therefore, food imports are expected to increase in the region in order to meet the region's growing population. Sustainable local agriculture of some type needs to be developed or enhanced in order to provide some level of self-sufficiency using crops suitable for the desert climate [5].

Another way forward would be to try to make use of marginal or underutilized water sources. For example, the region does have access to seawater in the Arabian (Persian) Gulf. Additionally, there is also a large volume of brackish water that is too saline for conventional agriculture, which underlies much of the region. This brackish water is present naturally, and/or has increased due to the increased freshwater abstraction followed by seawater intrusion. For example, in Qatar in 2009, only 2% of the land area was underlain by high quality freshwater that is less than 1 part per thousand (ppt) salt and only 8% of the land was underlain by water less than 2 ppt salt [6]. In other words, over 90% of the land area is underlain by groundwater that is far too saline for any type of conventional agriculture; therefore, there is huge unutilized resource in Qatar and other Gulf countries that could be used for non-traditional agriculture.

Additionally, large quantities of treated sewage effluent are underutilized. And finally, there are large volumes of produced water available in the Gulf, that is, water that is produced in the process of oil and gas extraction, which could be used for agriculture. The potential to use such marginal water sources for food and landscape production will be explored here. In particular, we explore the use of marginal water to produce salt-tolerant plants (halophytes), micro-algae and mariculture products. To meet the food demand of the world's growing population, it is critical to develop novel agricultural systems that can take advantage of vast non-arable arid land areas and brackish water. Further, the challenges facing large-scale adoption of the highlighted alternatives for enhancing local agriculture will be discussed. Here we deem seawater as a marginal water source in the sense that it cannot be used for conventional agriculture, not meaning to imply that it is of poor quality.

2. Treated Sewage Effluent (TSE)

The use of treated domesticated wastewater or treated sewage effluent (TSE) for irrigating agricultural crops and landscapes is a widely used method to conserve and re-use water. TSE is widely used for these purposes in Gulf countries and other arid countries [7]. However, this TSE resource is underutilized. Currently, the wastewater treatment average in the GCC is around 56%, while only 43% of the treated wastewater in the region is being recycled, contributing to only 1.8% of total water supply [8]. One of the chief reasons for this wastage is due to poorly organized or fragmented distribution networks, which makes dispersal of this resource difficult or problematic. In Qatar, currently, a large percentage of the TSE that is utilized for agriculture is used to grow forage grasses (mostly Rhodes grass) to feed livestock (M. Atta, Qatar Ministry of Environment, personal communication). However, much of this grass-growing takes place adjacent to the sewage treatment plants. This is fine if your farming land is next to the sewage treatment plant. However, if your farm is distant from the sewage plant, (e.g., northern Qatar), then it is obviously difficult to gain access to this water. Wastage of the TSE is not only an environmental sustainability issue but also an economic one. So from a longer term perspective, it makes sense to develop more integrated wastewater distribution networks. The State of Qatar plans to more than double the allocation of TSE to agriculture/fodder production by 2020 and estimates that this will result in a three-fold increase in domestic livestock herd size.

Similarly, TSE can be wasted if it used to irrigate plants that require a great deal of water or very frequent irrigation. Use of drought tolerant plants (xerophytes), particularly native species, for landscaping can further reduce the demand on TSE. Although TSE is certainly an option for agriculture, many concerns exist as to its safety and social acceptability, particularly the accumulation of heavy metals that are toxic to humans and animals, as well as the potential to transmit pathogenic micro-organisms [9–12]. TSE typically has higher salt (200–3000 mg/L TDS), nutrient, solids and frequently metal content than conventional irrigation water [13–16] and it has been observed that these metals can accumulate in food crops. For example, a recent study in which TSE was used to grow okra

in Saudi Arabia found that the okra frequently accumulated Ni, Pb, Cd and Cr above safe limits and the authors concluded that the vegetable was not safe for direct consumption by human beings [17]. But other reviews have noted that high metal content in TSE is not a universal fact and can vary among localities [18].

Solids and nutrients such as nitrogen and phosphorus can improve the water holding capacity and the fertility of the soils, respectively [18], which can be particularly beneficial for arid land soils. The increased salt content of the TSE can increase salinity/sodicity of the soil especially in arid areas and this may or may not affect crop yields; basically higher salinity water will decrease yields [19], whereas lower salinity may not (e.g., [20]). Irrigation strategies such as using a high leaching fraction can be employed to decrease soil salinity and flush salts below the root zone [19]. In summary, TSE represents a useful water resource but systems need to be monitored to ensure that concentrations of heavy metals and salts are not becoming a problem.

3. Produced Water

Produced water, which is generated during the extraction of oil and gas from the ground, may also be a potential source for irrigation water, especially given the huge petroleum industry in the Gulf. Produced water is a combination of formation water that is trapped with oil and gas and the injection water that is used to enhance recovery rates of the oil and gas [21]. Produced water contains organic and inorganic chemicals where the salinity can range from close to freshwater to concentrated saline brine; aromatic hydrocarbons, some alkylphenols and a few metals from produced water are potential environmental concerns [21]. A wide variety of methods are available to treat produced water [22]. Currently most produced water in the Gulf is re-injected into the reservoir to maintain pressure, or injected into a disposal well.

Produced water from the Gulf tends to be saline—one study found 5 g/L TDS in produced water from a Qatar gas field [23] and much higher in Kuwait ~100 g/L [24]. Produced water from oilfields has been used to irrigate crops in California for over 30 years [25]. Perhaps produced water could also be used in the Gulf for irrigation or algae cultivation. If salt-tolerant crops or algae are grown, then depending on its salinity, perhaps the produced water would only need to be treated to remove hydrocarbons and would not need to be desalinated, thereby reducing costs.

4. Use of Saline Water for Terrestrial Agriculture

Most conventional crops are sensitive to salt in the irrigation water and depending on the crop, yields will generally begin to decrease with irrigation water conductivities of 1–3 ds/m [26]. There are, however, salt-tolerant plants, called halophytes that can grow and complete their life cycles in saline water. Halophyte species have been identified to produce a variety of useful products, including firewood or timber from mangroves for example [27]; fresh vegetables [28,29]; oilseeds [30–32]; grains [31]; medicine [33,34]; forages for livestock [35–37]; for phytoremediation [38,39]; biofuel [40–43]; as biofilters for saline aquaculture effluent [44,45] and ornamentals [46]. There have been efforts to grow some of these species in agricultural settings using seawater [30,31]. There are many halophyte species native to the Gulf that could be considered for potential crops for saline-water irrigation [47].

Perhaps the most promising use of halophytes in the GCC region might be for use as forage. Livestock, especially sheep, are widely grown for meat production in the Gulf. Large quantities of water are used to irrigate to grow these forages, such as Rhodes grass, for livestock. Many countries subsidize or recently ended subsidies for forage production. These subsidies led to increased use of fresh water for agricultural irrigation. For example, in the Emirate of Abu Dhabi, which ended subsidies to farmers for producing Rhodes grass in 2010, up to 59% of the total irrigation water volume was to grow Rhodes grass [48]. Not only is Rhodes grass subsidized but other feed ingredients such as wheat bran and barley are also subsidized. Developing locally-produced feed ingredients will not only increase food independence but will also be an incentive for the government to remove subsidies for feed ingredients and thereby reduce spending.

Halophytes can comprise a portion of livestock feed and in particular, sheep feed. It has been observed that in circumstances where sheep have access to halophytes and other low quality forage supplements, the animals remained healthy and could gain weight [49]. Similarly, when sheep in pens were fed halophytes mixed with grain, animals had modest weight gains and produced high lean meat [49]. Meat from sheep fed halophyte-based diets has been found to have high eating quality [49] and the high vitamin E levels in the halophytes improved the shelf life of meat and can potentially benefit human health [50].

The potential forage plants fall into two categories. Firstly, the grasses, which tend to exclude salts from their tissues, grow at low-moderate salinity and under irrigation they have been reported to produce up to 40 t DM/year [51–55]. Biomass yields of about 60 t/ha/year (fresh weight) for *Panicum antidotale* were reported when grown in saline soil (EC 10–15 mS cm⁻¹) and irrigated with brackish water (EC 10–12 mS cm⁻¹) [52]. The plant was subjected to analysis for both nutrient and anti-nutrient factors and cattle fed a *P. antidotale* diet achieved growth and meat production equivalent to those fed a conventional maize-based diet.

Other grasses have also been successfully used to replace ingredients such as maize forage in ruminant diets [56–58]. They produced similar biomass to conventional pasture plants and did not accumulate salt. However, the grasses tend to be low in nutritive value (metabolizable energy and crude protein), indicating that high quality supplements must also be added to ensure that the animals can grow quickly. Variation in nutritive value between plant species allows for the potential to select plants that can support higher levels of livestock production [59].

The second category are dicot plants that grow well under highly saline conditions, such as seawater. The dicot halophytes accumulate salt in their tissues, are succulent and tend to have high nitrogen content. These plants often have low biomass production when grown under extensive arid conditions [60] but this has been reported to increase to 20 t DM/ha under seawater irrigation for the oilseed halophyte *Salicornia bigelovii* [31]. Ruminants are moderately tolerant of salt and can grow well with a salt intake of up to 5% of the diet [61]. The high nitrogen levels in halophytes may be beneficial as ruminants fed adequate energy can convert plant nitrogen into protein. Therefore, these dicots can be included as a significant component of a total mixed ration to provide energy and a nitrogen source for protein production. It has recently been shown that halophytes can be included as a significant component of a feedlot diet in a series of experiments investigating how consumption of halophytes influences meat eating quality [49,50,62,63]. Sheep that were fed diets that contained a high proportion of halophytes exhibited moderate weight gain and produced meat with a high eating quality (determined by a taste panel) and the meat also had extended shelf life. Similar to the grasses, there is variation in nutritive value across these plants and their value as a feed component can be improved through management and selection [64,65].

5. Marginal Water to Cultivate Microalgae for Use as Feed

Although the production of algae for biofuel may not be economically feasible currently, there may be some value to grow algae for its protein content to be used as component of aquafeeds for aquaculture. Fish constitute a major source of animal protein in human diets. In addition to protein, fish also provide various polyunsaturated fatty acids (PUFA) which are very useful for human health. Capturing fish from the wild may not be sustainable in certain fisheries due to over-fishing. To meet the deficit in supply, fish farming is being developed in almost all parts of the world. The existing practice of farming fish, livestock and poultry mostly rely on terrestrial plants crops for the formulation of the feed; most of these plants require both arable land and freshwater. Therefore, expansion of fish farming will likely result in an increase in terrestrial feed production. The increase in feed production, would likely require energy and water-intensive irrigation systems. Furthermore, limited land and freshwater availability and widespread pollution are already creating pressure on the existing agricultural systems.

Microalgae and cyanobacteria (hereafter collectively referred to as microalgae) are photosynthetic microorganisms which are found virtually world-wide. Some species can double their biomass multiple times in a single day, under favorable growth conditions. The potential biomass production of selected microalgae strains can be an order magnitude higher than any other terrestrial plants (Table 1).

Table 1. Comparison of aerial biomass productivity of conventional feed sources with a few marine microalgae with commercial potential.

Feedstock	Yield (t/hectare)	Reference
Corn	9.4	[66]
Soybean	2.7	[67]
Wheat	5.7	[68]
<i>Nannochloropsis</i> sp. ϕ	80.3	[69]
<i>Nitzschia</i> sp. ϕ	78.8	[70]
<i>Isochrysis galbana</i> ϕ	86.1	[71]
<i>Phaeodactylum tricornutum</i> ϕ	63.7	[72]

ϕ Represent microalgae.

While seawater and saline groundwater are ideal water sources to grow microalgae, TSE could be another source of water for growing microalgae biomass. TSE could also be used as a makeup water to balance the daily evaporation loss. The availability of organic and inorganic compounds in the TSE could be beneficial for microalgal growth; however, certain toxic compounds and heavy metals, if present in high concentrations, could be absorbed into the microalgae biomass [73,74]. To eliminate or minimize the pathogens and other micro-organisms in the microalgae culture, a disinfection method should be applied to the TSE; some of the advanced wastewater treatment plants are applying chlorination before reusing the TSE. In case, if the concentration of heavy metals in the TSE is high, the TSE could be diluted with seawater or the brackish water [75].

Microalgae are composed of carbohydrate, protein, and lipids, as well as other secondary metabolites (e.g., pigments, vitamins, and minerals). The concentration of these metabolites can vary among strains and growth conditions. Protein content in certain microalgae and especially in cyanobacteria can exceed 50% of the dry weight (see Table 2). Furthermore, some of these strains have all the essential amino acids in the desired ratio, unlike conventional protein sources (e.g., cornmeal, wheat gluten meal and soy meal.) for proper protein synthesis (see Table 3). A few of the strains can produce copious amount of omega-3 polyunsaturated fatty acid (e.g., EPA and DHA) which terrestrial plants cannot synthesize. These fatty acids are beneficial for human health. Human dietary intake of these fatty acids is mainly derived from consuming wild and farmed fishes. However, the primary source of these fatty acids are the aquatic photosynthetic microbes. It was further reported that as per their nutritional value and digestibility, algae were on par or even exceeded many other sources of feed [76]. Taking advantage of their prolific growth rate and high protein content, researchers explored the commercial exploitation of these strains as single cell proteins beginning in 1960 [77]. However, large-scale deployment of this technology was not practiced because of higher production costs at that time and the algae odor (fish-like) proved problematic for direct human consumption. With the dwindling supply and increased price of fishmeal in recent times [78], it is becoming crucial to develop cost and energy effective techniques for microalgal biomass production.

Table 2. Metabolites composition of some of the microalgae and cyanobacteria.

Strains Name	Protein (%)	Carbohydrate (%)	Lipid (%)	Ref.
<i>Chaetoceros</i> sp.	33	12	20.9	[79]
<i>Dunaliella</i> sp.	25.7	40.2	18	[80]
<i>Isochrysis</i> sp.	47.9	26.8	14.5	[81]
<i>Nannochloropsis</i> sp.	30.3	9.6	21.8	[82]
<i>Phaeodactylum</i> sp.	49.5	45.5	5.5	[83]
<i>Synechococcus</i> sp.	63	15	11	[84]
<i>Tetraselmis</i> sp.	30.7	33.6	17.6	[85]
<i>Chroococciopsis</i> sp.	60.3	22.2	3.8	[86]

Table 3. The composition of essential amino acids (g/100 g protein) in different feed ingredients and microalga *Nannochloropsis* sp. and cyanobacterium *Chroococciopsis* sp.

EAA	Fish Meal (Herring)	Soybean Meal	Corn Meal	<i>Nannochloropsis</i> sp.	<i>Chroococciopsis</i> sp.
Histidine	2.4	1.442	0.91	1.5	0.8
Isoleucine	4.5	3.17	2.37	3.5	2.6
Leucine	7.5	5.53	10.26	6.7	7
Lysine	7.7	3.84	0.91	4.8	3.8
Methionine	2.9	0.81	1.09	1.8	0.4
Phenylalanine	3.9	2.76	2.79	3.9	6.3
Threonine	4.3	3.03	2.06	3.6	6.1
Tryptophan	1.2	0.57	1.3	1.7	-
Valine	5.4	5.59	2.85	4.6	7.8
Reference	[87]	[88]	[89]	[90]	[86]

6. Challenges in Large-Scale Cultivation of Microalgae

Current annual global production of microalgae biomass was estimated as 15,000 t [91]; every year, almost 1000 t of produced biomass is being used to grow mollusks, shrimp and other fishes [92]. Live microalgae feed is preferable for certain types of fishes and aquatic invertebrates. Whole microalgae biomass or even metabolites extracted from microalgal are being successfully studied as feed ingredients for fish, cattle, and poultry. The major challenge in the production of large-scale microalgal biomass as feed is the production cost. Microalgae can be grown in photobioreactors (PBR) or open raceway ponds (ORP). Although PBRs have more control in the cultivation of the strains, preventing contamination and evaporative water loss, construction, operation and maintenance of the PBRs can be very energy and cost intensive [91], especially for bulk feed. On the other hand, biological contamination, evaporative water loss, relatively lower biomass density are some of the major challenges for operating ORPs. Fast growing and halophilic microalgae are ideal ORP candidates to minimize the effect of contamination and evaporation. For a few strains, the growth conditions are so extreme (low pH, high pH, hypersaline) that other strains cannot contaminate them in large-scale operations. In order to grow other useful strains, appropriate growth conditions should be developed that can prevent or minimize contamination from unwanted microalgae and predators.

Only a few microalgal strains have been extensively characterized for their nutritional properties; however, these strains might require very specific climate conditions. Therefore, more strains need to be isolated and characterized, especially from the area where microalgal cultivation would take place. For example, the very high light intensity and extreme temperature in the GCC region require strains which can flourish in such environments. Researchers have studied the biomass and lipid productivities of *Nannochloris* sp., *Picochlorum* sp., *Desmochloris* sp., isolated from Red sea, as feedstock for biofuel [93]. Similarly, in Kuwait, there were a few small-scale indoor studies of *Nannochloropsis* sp. and *Chlorella* sp. [94,95]. Several *Dunaliella* species can grow in hypersaline water (as high as 25% salt content) and produce 2–10% of the cell weight as β -carotene; several groups in the region explored the potential of growing *Dunaliella* strains [96,97]. Although there

are multiple groups and companies conducting research on microalgae in the GCC region, only a few groups have demonstrated large-scale outdoor cultivation of selected strains. In Abu Dhabi, a larger, commercial-scale operation was initiated on a coastal island [96] but it has since ceased operating (Brown, personal observation). The Algal Technology Program (ATP) of Qatar University has a small-scale (1 hectare in size) research demonstration farm. ATP has isolated and preserved over 200 strains and microalgae and cyanobacteria from the surrounding environment [98]. Eleven marine cyanobacterial strains from the ATP strain bank were analyzed for paralytic shellfish toxins, microcystins, nodularins, anatoxins and cylindrospermopsins; none of the cyanobacteria had any of these toxins (data not published). On the contrary, some of these strains (*Synechococcus* sp., *Leptolyngbya* sp., *Chroococcidiopsis* sp.) produce high-value pigments like phycobiliproteins and carotenoids that could improve feed quality. Some of the promising strains (e.g., *Nannochloropsis* sp., *Tetraselmis* sp., *Chroococcidiopsis* sp., *Synechococcus* sp., *Chlorella* sp., *Scenedesmus* sp.) were successfully grown in the desert at a scale 200 L–100,000 L [85,86,99,100].

Typical depth of microalgae culture in ORP's can be in the range of 20–30 cm; the daily evaporative water loss can be 0.1–2.0 cm, depending on the climate condition. To maintain the culture volume and water salinity, addition of freshwater was practiced for outdoor cultivation of most of the marine microalgae—however, TSE or other brackish water can be added to ensure sustainability in freshwater-scarce regions. Some potential halophilic microalgae (e.g., *Tetraselmis* sp., *Dunaliella* sp.) have the ability to adapt to incremental salinity in culture and therefore the evaporative water loss can be balanced by adding seawater [85,101,102]. Coastal areas are an ideal place for the cultivation of microalgae as the collection and pumping of seawater would require minimal energy. In the case of using brackish groundwater, the cultivation site should be selected such that the elevation difference between the water source and the ORP is minimized.

About half of the microalgae biomass is comprised of carbon and it was estimated that 1.73 kg of carbon dioxide is required to produce 1 kg of biomass [103]. The solubility of atmospheric CO₂ in water is very low, which is inefficient to produce sufficient dense culture. Hence, an adequate amount of CO₂ must be supplied to the culture; the rate of CO₂ supply should match the growth rate of the biomass. CO₂ uptake rate will vary among microalgae strains; however, to reduce the cost of CO₂ utilization, efficiency should be increased. Although purified bottled CO₂ is commonly used in research and commercial microalgae production, to reduce the production cost, flue gas from the power plants could be utilized. Therefore, large-scale microalgal cultivation sites could be co-located with a power plant or any other industry that generates an adequate amount of flue gas. In addition to carbon, nitrogen needs to be supplied in a useful form. Urea and other ammonium salts are commonly used as sources of nitrogen fertilizer. However, the waste from livestock, poultry and fishery processing industries can be processed and recycled as sources of nitrogen.

The cell size (2–20 µm) and dilute concentration of microalgae in the culture (0.5 g/L), makes biomass harvesting an energy-intensive process, which could contribute to as much as 40% of the biomass production costs. Sedimentation, filtration, and centrifugation are some of the conventional microalgal harvesting techniques. Coagulation-flocculation could also be used to harvest some microalgae. Bio-based coagulants (e.g., chitosan, poly γ-glutamic acid and rice starch) have been found effective in harvesting freshwater microalgae [104–106]. Since the marine microalgae cultures usually have much higher ionic strength compared to that of freshwater cultures, these organic coagulants are often less effective for harvesting marine microalgae; polyvalent metal coagulants (e.g., alum, ferric chloride) are often used to harvest marine microalgae. Presence of higher concentration of metals in the harvested biomass is not desirable [107,108]; very recently, it was shown that dilute acidic water could be used to recover the iron from the ferric-chloride coagulated harvested *Chlorella* sp. biomass [100]. There were a few attempts to bioflocculate the desired microalgae with other microalgae [109] and yeast [110] in small-scale studies; despite the efficient harvesting, this method requires a large amount of bioflocculating microorganisms that could affect the harvested biomass quality. Whereas the sedimentation process requires less energy, the centrifugation process consumes the most energy.

However, only a few large cell size and colony forming microalgae undergo gravity sedimentation [86]. Microalgae are efficient in terms of nutrient utilization. However, after removal of the biomass, the harvested water often contains residual nutrients, which need to be recycled to improve the process economics and to prevent pollution. Usually, for large-scale biomass harvesting, two different methods are combined. In the first set, the biomass is separated from the bulk of the water using an appropriate method—the solid content in the harvested biomass slurry can be in the range of 1–2%. Next, the biomass slurry is further dewatered to 10–30% solid content by adopting different techniques, based on the final use. Since the biomass still has a great deal of water, it is important to preserve the biomass soon after the harvesting process. Spray drying, although very energy intensive, is commonly used to dry the biomass.

7. Marine Aquaculture

In addition to microalgae production, an obvious use of the seawater resource is to use it produce high value products such as finfish, shellfish or crustaceans such as shrimp. As many scientists have noted, overfishing of wild fish stocks is not sustainable and leads to ecological collapse (e.g., [111]). Marine aquaculture, if conducted in a sustainable fashion, offers a path for food production in the Gulf that can potentially ameliorate overfishing of wild stocks.

Given that revenues from petroleum resources are declining, combined with the reduced harvest of wild fish, many of the Gulf countries have invested or are planning to invest in aquaculture. Oman is currently considering investing in 24 aquaculture projects with a value of over 2 billion USD ([112]). Similarly, Saudi Arabia has developed many hectares of aquaculture ponds on its Red Sea coast and Qatar has requested tenders for companies to operate aquaculture facilities [113].

In addition to fish and shrimp, consideration could also be given to lower value species such as seaweeds (macroalgae). Seaweeds can be used for human food and also for industrial purposes such as for the production of hydrocolloids such as carrageenans, agar and alginates. Plus they have the added value of being able to uptake large amounts of nutrients, thus, cleaning the water and reducing eutrophication [114].

There are many challenges for the aquaculture industry in the Gulf. Firstly, if there is a desire to develop local capacity and expertise (as opposed to using skilled expatriate labor), then there will be a need to develop specially trained technical staff, with specialized knowledge across many disciplines. It has been observed that a successful aquaculture team should have mechanical and electronic skills, a strong working knowledge of water chemistry, fish nutrition and health management and that one of the most critical components of establishing a successful aquaculture operation is building a team capable of managing across this wide range of disciplines [115]. Additionally, to increase sustainability, the industry should strive to develop local fish feeds that utilize local ingredients where practicable. Care should also be taken to avoid overcapitalization/overdevelopment of the sector. Diseases are always a challenge for aquaculture operations.

The high temperatures and salinity of the Gulf can make it challenging to grow many species—the growth rates of most species will suffer in the hot summer temperatures. Selecting and improving locally-adapted species to culture will likely be more prudent than importing and growing non-native species. Lastly, over time, as the Gulf gradually becomes hotter and more saline due to climate change and due to the increase in desalination operations, it may ultimately not be feasible to raise fish in the Gulf in the more distant future.

8. Integrated Seawater Agriculture

Another potential way forward is to combine or integrate the terrestrial high salinity agriculture with an aquaculture operation for fish or shrimp and even microalgae. In such a system, seawater (saline groundwater could also be used) can be pumped to ponds on land where fish and/shrimp can be grown. The wastewater which leaves the ponds, which is enriched in nutrients such as nitrogen and phosphorus, can be used to irrigate terrestrial halophytes. Water that then drains from the halophytes

fields can then be polished by mangroves in a mangrove wetland or excess water could drain into a pond for microalgae production. Salinity of the water will increase as it moves through the system due to evaporation and transpiration from the plants. Typically, the halophytes will need to be irrigated in excess of their evapotranspiration requirements to provide a leaching fraction to leach salts below the plant root zone. A study of seawater irrigation of *Salicornia bigelovii* in a coastal desert found that the leaching fraction was 0.35, or about 35% of the total seawater applied at the surface leached below the plant root zone. The salinity of the leachate water increased to over 100 g/L by the end of the growing season, indicating that additional seawater or other water, e.g. TSE, might need to be added to the water draining from the halophytes if it was to be used subsequently for microalgae production or if it was to be recirculated.

The advantages of such a system is that the water only needs to be pumped once from the sea and the aquaculture wastewater is utilized as a fertilizer for the halophytes or microalgae. The aquaculture products would provide most of the income from such a farm and the halophyte biomass could be used as a biofuel feedstock. A recent study showed that for a theoretical integrated seawater agriculture system located in the Gulf, where the halophyte biomass was used to produce aviation biofuel, that such a system would generate 38 to 68% less greenhouse gases than conventional fossil jet fuel production and would yield an overall positive net energy balance [116].

Several such systems have been built, most notably in Eritrea and in Mexico. Although these systems may have functioned from a technical perspective, they were not successful business efforts. A comprehensive study of these efforts noted that these projects failed due to “political instability, mismanagement and community opposition” [117]. Developers of future projects in this area should therefore pay greater attention to the socio-economic aspects of such projects at the planning stages.

9. Discussion of Challenges with Scaling up

The willingness to accept the use of marginal water for food production on a wide scale depends on the maturity of technologies to deliver suitable, high quality crops. At the same time, the presented food production alternatives are at different levels of development and commercial readiness. The use of TSE for conventional crops is the most advanced and viable option in the short run. (Although mariculture is also an advanced food production technology in many regions, it can also entail significant economic investment and is frequently fraught with significant financial risk). The wastewater treatment rate in the GCC varies across countries from 41% in Oman to 75% in Kuwait, while the mean reuse rate does not exceed 30% due to fluctuations in water quality and the lack of distribution networks [8]. Expanding TSE reuse across the GCC is expected to increase and thus contribute to decreasing the reliance of groundwater use for agriculture. TSE can supply up to 10% of water demands in the region by the year 2020, if the current plans are realized and obstacles such as farmers' acceptance and adequate distribution networks are solved [118].

Similarly, using saline water for agriculture is an untapped resource that can help save vulnerable freshwater resources. This option is still not explored on a large scale in the region. Instead, the use of saline water for irrigation is sometimes seen as unsustainable as policymakers believe that it will salinize soils or aquifers. However, the suggestion here is to conduct saline agriculture only in areas with existing saline soils or aquifers, not in areas with high quality arable land. Nevertheless, the salinity of water and soil should be monitored in all areas to ensure productivity of agricultural lands in the future [3,119]. Therefore, for policymakers in the region, saline agriculture is yet to become accepted as a viable opportunity to produce animal feed or other crops.

As for microalgae, it might require special funds to move to advance its commercialization. Over the last few years, the cultivation of microalgae has been going through the transition from research and pilot-scale demonstration to full-scale commercial deployment. The fundamental aspects of large-scale microalgae cultivation are very similar to that of existing aquaculture and even agriculture. However, until now, microalgal cultivation neither falls under agriculture nor receives any benefits which are often given in agriculture. Consideration might be given to providing support to the microalgae

industry from either government or the private sector for continued research and development and subsequent commercialization.

There are key socio-economic challenges that can hinder the use of marginal water on a wide scale. First, the awareness and the availability of agricultural services trained on alternative production systems are necessary to promote marginal water use. Second, setting the right water pricing policies is crucial to encourage the use of marginal water. In fact, the overconsumption of water and the overuse of non-renewable freshwater resources in the region is associated with the high subsidies for water and energy services. Water and energy production systems are highly interlinked in the GCC. High amounts of cheap energy are used to desalinate water, which is then provided at subsidized prices and in some countries free of charge for national residents and also used in agriculture [120,121]. Although GCC countries have moved to gradually reduce subsidies, the lack of universal tariffs on water use and wastewater treatment is one of the key constraints to water reuse policies [8]. At the same time, energy subsidies account for over 8.5% of the GDP and 22% of public spending in the GCC region [122]. Reducing these subsidies can free up resources that can be invested in promoting alternative food production systems such as saline agriculture or the cultivation of microalgae.

Third, alternative production systems using marginal water need to be incorporated in clear national strategies for enhancing food and water security. Until now, the majority of options to reduce freshwater use in food production do not focus on marginal water. These options include improving irrigation technologies, increased land investments abroad, improving agricultural productivity, reducing food waste and exploring alternative food production systems such as vertical farming [123]. Moreover, desalinated water is used for irrigation in many GCC countries and this option might increase if renewable energies contribute to reducing the high energy costs associated with desalination [124].

Concerning national food strategies and policies, the majority of the GCC countries lack comprehensive food security strategies with high-level endorsement and commitment. In 2008, Qatar initiated a National Food Security Program (QNFSP), which established a master plan to diversify food imports, increase aquaculture and develop integrated systems at the farm level with water reuse schemes. Although this policy represents the most comprehensive set of soft (awareness, education, research) and hard (infrastructure and investments) measures, there is no evidence that its implementation was endorsed by all stakeholders and it is not clear whether it was put into action. In 2015, the UAE, in cooperation with the Food and Agriculture Organization (FAO) developed a National Policy for Food and Agriculture, which was endorsed in 2016 by the Climate Change and Environment Ministry. This policy foresees, among others, market-driven reforms and investments in marine aquaculture. Aquaculture is also being promoted in other GCC countries such as Saudi Arabia, which regards this sector as one of the most promising options for food production under the Saudi Vision 2030.

10. Conclusions

Here we show that marginal water sources such as TSE, produced water, saline ground water and seawater can be used to produce a variety of useful crops. Utilization of such marginal water sources can potentially spare scarce freshwater resources. There is a significant potential for utilizing such marginal water in the GCC region. This potential is currently not fully exploited despite important advancements in research on use requirements and sectors. Further research should focus on the economic feasibility of some of these technologies in the GCC. If the economics are favorable, then these technologies should be able to provide economic diversification in the GCC countries, which are trying to increase economic activity in the non-petroleum sectors. The adequate commercial scale of technologies using marginal water needs further research. Moreover, reforming the subsidization of freshwater, especially for agriculture uses, can encourage the utilization of marginal water. Additionally, these technologies could aid in increasing domestic food production, which is a stated strategic goal of many of the GCC nations. In fact, the GCC region is highly dependent on

global food markets despite many GCC countries using more than the global average of water for domestic agriculture. Advanced marginal water technologies can help reduce both freshwater use for agriculture and the dependence on food imports. For this, they need to be integrated in national strategic plans for food security. Such plans can develop clear targets and use incentives and public investments in order to promote the use of such technologies based on the individual commercial readiness of each of the technologies.

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