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# Challenges and Prospects of Using Treated Wastewater to Manage Water Scarcity Crises in the Gulf Cooperation Council (GCC) Countries

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Received: 4 June 2020; Accepted: 7 July 2020; Published: 12 July 2020



**Abstract:** The Gulf Cooperation Council (GCC) countries are located in the driest part of the world with an annual per capita water availability of 500 m<sup>3</sup> compared to the world average of 6000 m<sup>3</sup>. Agricultural water demand, which is more than 80% of the total water consumption, is primarily met through the massive exploitation of groundwater. The enormous imbalance between groundwater discharge (27.8 billion m<sup>3</sup>) and recharge (5.3 billion m<sup>3</sup>) is causing the excessive lowering of groundwater levels. Therefore, GCC countries are investing heavily in the production of nonconventional water resources such as desalination of seawater and treated wastewater. Currently, 439 desalination plants are annually producing 5.75 billion m<sup>3</sup> of desalinated water in the GCC countries. The annual wastewater collection is about 4.0 billion m<sup>3</sup>, of which 73% is treated with the help of 300 wastewater treatment plants. Despite extreme water poverty, only 39% of the treated wastewater is reused, and the remaining is discharged into the sea. The treated wastewater (TWW) is used for the landscape, forestry, and construction industries. However, its reuse to irrigate food and forage crops is restricted due to health, social, religious, and environmental concerns. Substantial research evidence exists that treated wastewater can safely be used to grow food and forage crops under the agroclimatic conditions of the GCC countries by adopting appropriate management measures. Therefore, GCC countries should work on increasing the use of TWW in the agriculture sector. Increased use of TWW in agriculture can significantly reduce the pressure on freshwater resources. For this purpose, a comprehensive awareness campaign needs to be initiated to address the social and religious concerns of farming communities and consumers. Several internal and external risks can jeopardize the sustainable use of treated wastewater in the GCC countries. These include climate change, increasing costs, technological and market-driven changes, and regional security issues. Therefore, effective response mechanisms should be developed to mitigate future risks and threats. For this purpose, an integrated approach involving all concerned local and regional stakeholders needs to be adopted.

**Keywords:** wastewater reuse; agriculture; desalinated water; heavy metals; water scarcity

## 1. Introduction

The world population is projected to be 9.7 billion by 2050, 26% higher than today [1]. Most of this increase will be in developing countries where access to water for agriculture and human needs is already under stress, with 1.2 billion people lacking access to safe drinking water, and another 2.5 billion lack sanitation facilities [2]. Due to expanded urbanization and industrialization, the demand for water has increased. The increasing gap between water supply and demand, along with the projected effects of climate change, has put enormous pressure on agriculture to reduce its share of freshwater use and look for alternative sources [3]. Scientists around the globe are consistently working on developing

alternative water resources and finding new ways of conserving water. Therefore, it is high time to refocus on the reuse of wastewater for irrigation and other purposes.

The Gulf Cooperation Council (GCC) countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) are also facing severe water shortages, which jeopardize sustainable development and restrict human, industrial, and agricultural expansion [4]. Rapid urbanization and increasing living standards have further exacerbated the problem. Although arable land in GCC countries is averaging only 4.3% of the total land area, average water use for agriculture is 70% of the renewable water resources and is even higher in Saudi Arabia, UAE, and Oman [5,6]. Despite this water use, the average contribution of agriculture to the gross domestic product (GDP) is only 0.8%. However, massive oil and gas reserves in the region compensate for the scarcity of land and water resources in GCC countries. The GCC countries control around 40% of the global oil and 20% of the natural gas reserves resulting in massive state revenues [7].

The increasing demand for water by domestic and industrial sectors is threatening the ecosystem services, food security, and the environment. The annual per capita water use in the GCC countries is 560 L/day compared to the world average of 180 L/d. This four-fold increase in water consumption over the last two decades is caused by a rising population and unplanned agricultural expansion. Therefore, improving the productivity of marginal land and water resources in GCC countries is imperative to increase the food supply and avoid the adverse environmental effects of land degradation [3,8]. The marginal water resources such as poor quality saline water, treated wastewater, and produced water from the oil industry are now successfully used for agricultural crop production and aquaculture in many countries [9,10]. Currently, an estimated 380 billion m<sup>3</sup> of wastewater is collected annually across the globe and expected to reach 574 billion m<sup>3</sup> by 2050 [11]. Currently, about 36 million hectares are irrigated with the wastewater, of which 29 million hectares are using untreated wastewater [12]. Farmers in urban and peri-urban areas of nearly all developing countries are using untreated wastewater for irrigation [13].

The treated and untreated municipal wastewater is being used for agriculture in several parts of the world [14,15] because it supplies additional nutrients and improvements in crop production during the dry season [11]. Farmers in many Asian and African countries deliberately use untreated sewage as it offers socio-economic and environmental benefits such as the reduction in effluent disposal problems [16,17]. Several studies have shown that leafy vegetables (such as spinach, cauliflower, lettuce) accumulate higher amounts of heavy metals than do nonleafy species when irrigated with wastewater [10,18,19]. Despite this caution, smallholder farmers continue to grow these vegetables using untreated sewage to enhance their household incomes. For instance, in African cities, 60–100% of vegetables are produced using untreated wastewater [13]. Furthermore, wastewater is also widely used for aquaculture in Africa and Asia [12,20].

During the last two decades, the use of treated wastewater for agriculture has also increased in the GCC countries. Currently, more than one-third of the available treated wastewater (TWW) is used to irrigate nonedible crops and fodder [21,22]. However, TWW use is primarily restricted to landscaping, gardens, and road ornamentals. The use of TWW to irrigate food crops is minimal due to health, environment, social, and religious concerns [23]. Farmers are hesitant to grow food crops using TWW due to the fear of losing customers for their products. In all GCC countries, the gap between water supply and agricultural water demand is met through extensive groundwater exploitation. Uncontrolled and unregulated groundwater abstraction has resulted in excessive lowering of groundwater levels, degradation of groundwater quality, salt-water intrusion into freshwater aquifers, and rising pumping costs. The current trends of groundwater exploitation are not sustainable and immediate action is required to put a brake on groundwater abstraction to protect this vital natural resource to ensure potable water supply to urban and rural communities.

The TWW represents one of the most promising alternatives to meet agricultural water demand and make more fresh water available for domestic and industrial uses. The use of TWW in agriculture can contribute positively to improve the socio-economic conditions and sustainable development

of the GCC countries. This is very important considering that large volumes of TWW will become available in the future due to population increase and the expansion of urban sewage networks in the large cities of the GCC countries. Therefore, robust plans need to be developed for the sustainable use of TWW; otherwise, vast quantities will have to be discharged into the sea. Since water is the key driver in achieving Sustainable Development Goals (SDGs), developing a global vision on wastewater use is needed to improve the effectiveness of national policies [24].

This paper reviews the current status of available water resources in the GCC countries. It considers the future water demands and discusses the challenges and opportunities to use the TWW in GCC countries to bridge the gap between supply and demand. The increased use of TWW is also vital for this region because groundwater is fast depleting due to overexploitation, which will have direct consequences for the agricultural development and food security of this region.

## 2. Physical Settings

The GCC countries cover most of the Arabian Peninsula, which is characterized by deficient and sporadic rainfall and long dry summers with temperatures ranging between 35–50 °C. The geomorphology of this region is typical of the desert surroundings with substantial crude oil and gas reserves. The average annual rainfall in most of the GCC countries is less than 150 mm, which is received in minimal amounts and does not generate any significant runoff. However, precipitation is higher (>500 mm/year) in the mountainous region of Oman to the east and Asir Mountains to the southwest of Saudi Arabia. This higher rainfall causes occasional runoff benefiting areas in Oman and the UAE.

The total area of the GCC countries is 2.6 million km<sup>2</sup>, with an estimated total population of 60 million. Saudi Arabia is the largest country occupying about 85% of the total area of the GCC countries, with a population of 34.8 million (Figure 1). Bahrain occupies 695 km<sup>2</sup> area, with a population of 1.70 million. The population density in Bahrain (800 inhabitants/km) is the highest in all GCC countries. The total area of Oman is 300,000 km<sup>2</sup>, with a population of 5.1 million. Kuwait covers only 17,818 km<sup>2</sup>, with a population of 4.3 million. The population of Qatar is 2.9 million, and it occupies 11,610 km<sup>2</sup>. The United Arab Emirates occupies an area of 77,700 km<sup>2</sup>, with a population of 9.9 million. Over the last two decades, the population of GCC countries has increased substantially due to the influx of foreign workers from developing countries.



Figure 1. Map of the Gulf Cooperation Council (GCC) countries.

### 3. Water Resources of the GCC Countries

#### 3.1. Surface Water and Groundwater Resources

The GCC countries are categorized as hyper-arid with aridity index  $<0.03$  [25], with average annual rainfall that ranges from 70 to 140 mm, except in the coastal zone along the Red Sea in south-western Saudi Arabia and along the Gulf of Oman on the eastern shore, where the annual rainfall reaches up to 500 mm [26]. On the other hand, the potential yearly evaporation ranges from 2500 mm in coastal areas to 4500 mm in the center of Saudi Arabia [23]. Due to scarcity by nature and increasing trends in population growth, this region is becoming most water stressed, with an average per capita freshwater availability of about  $70 \text{ m}^3/\text{year}$  (Table 1). This value is much lower than the absolute water poverty line of  $500 \text{ m}^3/\text{year}$ , below which water becomes a primary constraint for human life [27]. Due to increased agricultural activity and rapid urban expansion, the water demand in GCC countries has increased from 5 billion  $\text{m}^3$  in 1970 to 35 billion  $\text{m}^3$  in 2015 [23]. Currently, 78% of the water demand in GCC countries is met through surface water harvesting and exploitation of groundwater, 16% by desalinated water, and 6% by using treated municipal wastewater [22,23].

The lack of renewable water resources constrains the sustainable agricultural production and socio-economic development in the GCC countries. The water availability in Bahrain, Kuwait, and Qatar is meager due to their geographical location. However, over the last few years, Saudi Arabia, Oman, and the United Arab Emirates have done considerable work in developing their water resources through the construction of dams and other storages. Therefore, Saudi Arabia has the highest annual renewable water resources (2.4 billion  $\text{m}^3$ ), followed by Oman (1.4 billion  $\text{m}^3$ ) and the United Arab Emirates (1.5 billion  $\text{m}^3$ ) [7]. The agriculture sector uses more than 70% of the available water resources. The problems of water losses in agriculture and urban water supply networks make up to 50% of the total water supply. Therefore, controlling losses by improved management will be crucial to meet the increasing future water demand.

The GCC countries do massive groundwater exploitation to meet their agricultural and urban water requirements. The annual groundwater abstraction in the GCC countries is estimated at 27.8 billion  $\text{m}^3$  compared to the average yearly recharge of only 5.3 billion  $\text{m}^3$  [23]. This considerable imbalance between groundwater recharge and discharge (discharge is five times higher than the recharge) is the primary cause of the fast depletion of groundwater resources with severe implications on increased energy use for groundwater extraction and deteriorating water quality. Two types of groundwater aquifers exist in GCC countries. First are the renewable shallow aquifers found in the alluvial deposits along the flood plains, and the second is non-renewable fossil groundwater deep aquifers. These deep aquifers have a finite life as well as varying quality, which is suitable only for agricultural purposes [22]. Unregulated groundwater abstraction from these deep aquifers will have severe consequences on the sustainability of this natural resource. Table 1 summarizes the available water resources in the GCC countries.

**Table 1.** Summary of water resources in the GCC countries.

Countries	Population (millions) <sup>a</sup>	Average Annual Rainfall (mm) <sup>b</sup>	Average Potential Evaporation (mm/year) <sup>b</sup>	Annual Renewable Freshwater Resources (hm <sup>3</sup> ) <sup>c</sup>	Average Annual Freshwater Availability (m <sup>3</sup> /capita) <sup>d</sup>	Average Water use by Agriculture (% of total) <sup>e</sup>	Added Value to the GDP (%) <sup>e</sup>	Average Annual Groundwater Abstraction (hm <sup>3</sup> ) <sup>b</sup>	Average Annual Groundwater Recharge (hm <sup>3</sup> ) <sup>b</sup>
Bahrain	1.70	80	1650–2050	116	70	45	0.3	155	150
Kuwait	4.30	110	1900–3500	20	5	54	0.4	496	160
Oman	5.10	50–300	1900–3000	1400	275	89	1.3	1218	900
Qatar	2.90	75	2000–2700	58	20	59	0.1	250	50
Saudi Arabia	34.8	70–500	3500–4500	2400	70	88	1.9	21595	3850
UAE	9.90	90	3900–4050	150	16	83	0.7	3536	190
Total	59.7	60–190	2475–3300	4144	76	70	0.80	27250	5300

<sup>a</sup> [1]; <sup>b</sup> [22]; <sup>c</sup> [23]; <sup>d</sup> calculated from the available data.; <sup>e</sup> [7].

### 3.2. Desalinated Water Resources

The GCC countries have invested heavily in desalination plants to meet the growing water demand. The collective desalination production capacity of the GCC countries is more than 60% of the world's total capacity. At present, the full annual installed desalination capacity of the GCC countries is estimated at 7725 hm<sup>3</sup>, with the majority of this capacity installed in KSA (36.4%) and UAE (34.4%) [28]. It is estimated that the desalinated production capacity of GCC countries will be doubled by 2050. In the GCC countries, a large proportion of the desalinated water is used to supply potable water for households. The demand for desalinated water will continue to rise with the rising population and economies [7,29]. Currently, the share of desalinated water to municipal water supply ranges between 55% in Saudi Arabia to 100% in the UAE (Table 2) [23].

**Table 2.** Desalinated water capacity, production, and use in the GCC countries.

Countries	No. of Plants <sup>a</sup>	Total Installed Capacity (hm <sup>3</sup> ) <sup>a</sup>	Desalinated Water Produced (hm <sup>3</sup> ) <sup>a</sup>	Desalination Energy Requirements (kWh/m <sup>3</sup> ) <sup>b</sup>	GHG Emissions (CO <sub>2</sub> e/m <sup>3</sup> ) <sup>b</sup>	Share of Desalinated Water in Municipal Water Supply (%) <sup>b</sup>
Bahrain	5	313	242	20	13	90.1
Kuwait	10	1036	712	13	13	84.2
Oman	52	280	280	20	21	73.7
Qatar	9	624	560	20	11.3	97.3
Saudi-Arabia	313	2812	1947	20	21	55.1
UAE	50	2660	2004	15.4	15	100
Total	439	7725	5745			

<sup>a</sup> [28]; <sup>b</sup> [22].

The primary desalination processes used in the GCC countries include the multi-stage-flash (MSF) and reverse osmosis (RO) technologies. The MSF system is used to desalinate seawater, whereas RO systems are used for brackish groundwater. Desalination is a capital-intensive industry. The total investment in the desalination sector in the GCC countries is estimated at US\$ 16–20 billion, which is expected to reach US\$ 60 billion by 2050 [23]. MSF technology is preferred in GCC countries due to its reliability and simplicity in operation and maintenance. Over time, the cost of these technologies has reduced. For example, the price of RO technologies has reduced from US\$ 5.5/m<sup>3</sup> in 1979 to US\$ 0.55/m<sup>3</sup> in 1999 [7]. Currently, the average unit cost of desalinated water in the GCC countries is about \$1.45/m<sup>3</sup> [23].

The desalination process is highly energy-intensive. The GCC countries use a substantial proportion of their energy generation for water production. Conservative estimates suggest that electricity consumption for desalination in the GCC countries ranges from 7–20%. The energy consumption for desalination in the UAE is about 20% of their total energy production, followed by 13% in Qatar, 8% in Kuwait, Oman, and Bahrain, and 7% in Saudi Arabia [30]. Moreover, surface and groundwater withdrawals also consume energy. The estimates indicate that energy use for water production in the UAE and Qatar has reached 30% of their total energy consumption, whereas 15% of daily oil production in Saudi Arabia is consumed by desalination plants [29,31]. The energy use in the region for desalination plants is expected to triple by 2030 [32].

The GCC countries are now working on increasing their capacity to use renewable energies as a proportion of total energy use to operate desalination and treating wastewater. For example, Kuwait plans to expand the share of renewable energy up to 15% by 2022, Bahrain up to 5% by 2021, Qatar up to 20% by 2030, UAE up to 24% by 2021, and Saudi Arabia up to 54 gigawatts by 2040 [33]. Besides, nuclear power plants are also being built in the UAE and Saudi Arabia. The average energy consumption for desalinated water is the lowest in Kuwait (13 kWh/m<sup>3</sup>) compared to other GCC countries. The differences in energy consumption depend on the location and the technology used for desalination plants.

### 3.3. Treated Municipal Wastewater

The total annual designed capacity of the 300 wastewater treatment plants in the GCC countries is 3455 hm<sup>3</sup> [28,34]. The annual volume of wastewater collected in the GCC countries is 4000 hm<sup>3</sup>, out of which 2924 hm<sup>3</sup> (73%) is treated (Table 3). Oman, Qatar, and the UAE are processing almost all collected wastewater, whereas Bahrain managed the lowest (only 44% of the collected). Only 39% of the total TWW is reused for different purposes while the rest is discharged to the desert or sea. Oman and Qatar reuse 100% of their TWW, followed by Bahrain (90%), Kuwait (61%), the UAE (55%), and Saudi Arabia (16%).

**Table 3.** Wastewater collection, treatment, and reuse capacity in the GCC countries.

Countries	No. of Plants <sup>a</sup>	Annual Design Capacity (hm <sup>3</sup> ) <sup>a,c</sup>	Volume of Wastewater Collected (hm <sup>3</sup> ) <sup>a</sup>	Volume of Wastewater Treated (hm <sup>3</sup> ) <sup>a</sup>	Volume of Reused of Treated (hm <sup>3</sup> ) <sup>b</sup>	% of Treated of Collected (%) <sup>b</sup>	% of Reused of Treated (%) <sup>b</sup>
Bahrain	22	135	158	70	63	44	90
Kuwait	6	300	320	247	151	77	61
Oman	66	100	68	67	67	99	100
Qatar	23	110	208	203	203	98	100
Saudi Arabia	97	1970	2500	1604	257	64	16
UAE	86	840	746	733	403	98	55
Total	300	3455	4000	2924	1144	73	39

<sup>a</sup> [28]; <sup>b</sup> [22]; <sup>c</sup> [34].

In Saudi Arabia, the distribution network to supply TWW to end-users is very still minimal compared to other GCC countries. Trucks are the primary TWW suppliers. In addition, wastewater services in Saudi Arabia are suboptimal compared to wastewater services provided in other GCC countries. Kuwait and UAE are also still working on expanding their distribution network [34]. Another reason for the lower use of TWW for irrigation is that in Saudi Arabia and the UAE, TWW reuse guidelines are stricter due to social and religious concerns. Moreover, in recent years, the UAE and Saudi Arabia have significantly increased their wastewater treatment capacity. The reuse of TWW could not keep pace with the generation capacity, which results in a lower TWW reuse percentage for these two countries.

Studies have shown that full utilization of TWW in the GCC countries can meet 11% of the total water demand and reduce fossil groundwater exploitation by 15% [22,23]. This means that by adopting proper management measures, the reuse of TWW could play an essential role in bridging the gap between demand and supply of freshwater resources in the GCC countries. However, considering the fast depletion of groundwater resources, it remains crucial to reduce groundwater extraction for irrigation. This objective can be achieved by altering cropping patterns, such as reducing the area under fodder cultivation. Instead, less water consuming crops such as perennial grasses should be planted to reduce the burden on water resources.

## 4. Challenges of Wastewater Use for Agriculture in the GCC Countries

In developed countries, food and forage crops are widely irrigated by TWW due to strict follow up of environmental standards and management procedures. Other common uses of TWW include recharge to groundwater, landscaping, construction, industry, and aquaculture. The reuse of TWW for irrigation in these countries has yielded positive economic benefits. In many Arabian countries such as Jordan and Morocco, TWW is widely used to grow all food crops. However, in developing countries, untreated wastewater is widely used for agriculture. Farmers in urban and peri-urban areas in Asia and Africa deliberately use undiluted wastewater as it provides nutrients and is cheaper than other water sources [35]. In many West African countries, 60–80% of the vegetables are grown

using untreated wastewater [13]. This practice can have harmful impacts on human health and the environment due to the buildup of pathogens and heavy metals [10]. Elevated levels of heavy metals in soils irrigated with wastewater pose health risks to the local inhabitants such as cardiovascular, kidney, nervous system, blood as well as bone diseases [36,37].

The reuse of wastewater for different purposes depends on the degree of its treatment, i.e., tertiary level, secondary level, and the primary level. The tertiary level TWW is free from all health hazards and can be used to irrigate all crops. The secondary level TWW is suitable for nursery flowers and palm trees, cotton, vegetables but should not be used for cattle rearing with milk or meat. The primary level TWW can only be used for timber trees after taking strict precautionary measures such as isolated farms, and preventing direct contact of workers with the water.

International guidelines for use and quality standards of wastewater in agriculture exist to mitigate the environmental and health risks. Most GCC countries have established conservatively low-risk guidelines based on high technology and the high-cost approach. However, insufficient operational experience, high operational and maintenance costs, and regulatory control may have adverse effects [21]. Unlike Asian and African countries, wastewater use standards are strictly followed in GCC countries, which restricts its use in agriculture. The monitoring and evaluation of wastewater quality in the GCC countries is limited due to a lack of trained staff, advanced equipment, and associated costs. Besides, the overlapping roles of organizations involved in the collection, treatment, monitoring of quality, and public health protection remain a challenge [23]. Table 4 shows the guidelines for wastewater use in agriculture in GCC countries.

**Table 4.** Guidelines for wastewater reuse in agriculture in GCC countries.

Parameters	Units	Bahrain <sup>c</sup>	Kuwait <sup>b</sup>	Oman <sup>c</sup>	Qatar <sup>d</sup>	Saudi Arabia <sup>c</sup>	UAE <sup>a</sup>
Faecal coliforms bacteria	Per 100 mL	1000	<1000	1000	1000	1000	<1000
EC	µS/m	2000	2000	2700	700–2000	1000	2000
PH	-	6.5–9.5	6.5–8.5	6.0–9.0	6.0–8.4	6.0–8.5	6.0–8.0
NH <sub>3</sub> -N	mg/L	5	15	10	5	5	5
Nitrogen organic (kjeldhal)	mg/L	5	35	10	5	5	10
Phosphate phosphorus	mg/L	-	30	30	30	-	20
Biological oxygen demand (BOD)	mg/L	10	20	20	5	10	20
Chemical oxygen demand (COD)	mg/L	40	100	200	50	50	100
Total dissolved solids	mg/L	2000	1500	1500	500–2000	2000	1500
Total suspended solids	mg/L	10	15	15	50	10	50
Residual chlorine	mg/L	<0.2	<0.2	-	0.5–1.0	<0.2	0.5–1.0
Arsenic (As)	mg/L	0.1	0.1	0.1	0.1	0.1	0.05
Cadmium (Cd)	mg/L	0.1	0.01	0.01	0.01	0.01	0.01
Chromium (Cr)	mg/L	0.1	0.05	0.05	0.1	0.05	0.1
Copper (Cu)	mg/L	0.2	0.2	0.05	0.2	0.05	0.2
Iron (Fe)	mg/L	5.0	5.0	1.0	5.0	2.0	2.0
Lead (Pb)	mg/L	5.0	0.5	0.2	5.0	0.1	0.5
Magnesium (Mg)	mg/L	100	100	150	100	150	100
Mercury (Hg)	mg/L	0.001	0.002	0.001	0.001	0.001	0.001
Selenium (Se)	mg/L	0.02	-	0.02	0.02	0.02	0.02
Sodium (Na)	mg/L	300	-	300	-	300	500
Zinc (Zn)	mg/L	2.0	2.0	5	2.0	2.0	0.5

<sup>a</sup> [38]; <sup>b</sup> [39]; <sup>c</sup> [40]; <sup>d</sup> [41].

The reuse of wastewater is afflicted with environmental, economic, and social challenges. The collection and treatment of wastewater for reuse are costly, especially when the treatment level is



tertiary. In most of the GCC countries, wastewater is treated mainly at tertiary level. The tertiary-level treatment of wastewater does not thoroughly screen out the presence of bacteria such as total coliforms and *E. coli* from the effluent. This level of treatment also does not tackle the concentration of heavy metals, especially copper (Cu), iron (Fe), zinc (Zn) and chromium (Cr), which could pose a serious safety hazard if higher than permissible limits. The long-term effects of irrigation with treated wastewater might cause soil quality problems such as the accumulation of salts and heavy metals. These accumulations can lead to pollution of groundwater with heavy metals, nitrate, and organic matter, and changes in the physio-chemical properties of soils [42,43]. This situation may lead to elevated risks for human health by propagating pathogenic germs, especially for those who are in direct contact with the wastewater during the irrigation activity. Therefore, before proposing irrigation with wastewater, a comprehensive evaluation of its impacts on soil, plant, and human health needs to be accomplished.

Farmers in many Arab countries such as Jordan, Syria, and Tunisia are using TWW for growing all food crops (Alkhamisi and Ahmed, 2014). However, in GCC countries, its use is still restricted to nonfood items, due to health and environmental safety concerns. Although considerable work has been done in many countries to study the impacts of wastewater irrigation on soil and crop properties [17,44], the research on this issue in the GCC countries is still in its infancy. Therefore, farmers are not fully convinced and confident about the safety of reusing treated wastewater for irrigating food and feed crops. Another factor that affects the maximum use of wastewater is the fact that wastewater demand in the GCC countries is maximum during the growing season, whereas its production is continuous. Therefore, if wastewater is not treated correctly and stored securely, it can pose serious health and environmental threats [45]. Therefore, costly treatment and storage of wastewater is a bottleneck in maximizing the use of wastewater.

Lack of central transmission infrastructure (pipes, pumping stations, channels, and storage tanks) and the distribution networks are the major issues in the full use of TWW. Most of the treatment plants are located away from the agricultural areas for environmental concerns; therefore, transportation of TWW from sewage treatment plants to the farming areas becomes a risky and costly business. The technical risks in the shipping of TWW from plants to farmer fields may include failure of pumps, leakages, and maintenance of pressure in delivery pipes to regulate flow rates [5]. In the case of underground piping systems, digging costs are high due to the nature of soils present in GCC countries. It is estimated that for the full utilization of produced wastewater in the GCC countries, a capital investment of US\$ 2.3 billion, and an additional 10% of the capital cost would be required for the annual maintenance and operation of these installations [23].

The use of TWW for food and feed crops is minimal due to social, religious, technical (heavy metals accumulation in irrigated soils, microbiological pollutants, and industrial waste mixing) concerns. Consumers mostly avoid products grown with the TWW. Therefore, farmers are reluctant to grow food and feed crops using TWW due to the apprehensions that consumers will not accept their products. These concerns can be tackled by restricting the use of TWW for the selected safe crops and enforcing strict quality monitoring and process controls. Besides, mass awareness campaigns should be launched to educate people on the use of products grown with treated wastewater. The socio-cultural problems are also restricting the use of the full potential of treated wastewater. Consumers are more likely to accept the crops irrigated with the wastewater if they trust and understand the treatment process, environmental benefits, and issues of water scarcity. One strategy to build the trust of consumers could be to organize small-scale demonstrations on farmers' fields before executing full-scale water reuse programs.

The irrigation with TWW requires evaluation of economic benefits and assessment of nonfinancial aspects like the reduction of environmental pollution or health risks. The evaluation of TWW irrigation should consider the cost of treatment and distribution of TWW for irrigation, water use efficiency, and health and environmental risks [46]. In GCC countries, local agriculture is vital to attain some level of food security. However, agriculture in this region is highly dependent on scarce freshwater

resources (surface and groundwater) and, to a large extent, on subsidized energy prices [4]. In all the GCC countries, farmers are free to exploit groundwater as and when required without any charges. Therefore, the economic value of water used in agriculture is usually not considered while evaluating the feasibility of large agricultural farms. In the presence of highly subsidized groundwater, it will not be easy to convince farmers to use TWW for irrigation. Therefore, access to groundwater needs to be restricted through limits on withdrawals and slashing energy subsidies.

Under the current scenario, the energy use for water production and recycling in the GCC countries will be tripled by 2030 [22]. Therefore, many GCC countries are now considering adopting more advanced techniques for boosting agricultural production to reduce dependence on imported food. These may include greenhouses, vertical farming, hydroponics, and aquaponics. They will be more energy-intensive than current traditional farming systems. Moreover, many of these options would require freshwater resources for irrigation and run cooling systems of the greenhouse. It would, therefore, be essential to study the impact of these options on the energy footprints and sustainability of agriculture, which mainly depends on the marginal waters (reclaimed and TWW) across the region [6].

There is an apparent conflict between agricultural policies and available water resources in the GCC countries. They encourage the cultivation of fodder crops due to the large livestock population. Since fodder crops are water-demanding, it amplifies agricultural water demand and, eventually, groundwater extraction. Despite extreme water scarcity and interest in the use of modern irrigation technologies, traditional flood irrigation methods are widely practiced by the majority of farmers. Currently, flood irrigation is practiced on 75% of agricultural land in Qatar, 72% in Bahrain, 63% in Kuwait, 60% in Oman, and 65% in Saudi Arabia. In the UAE, large-scale adoption of sprinkler and drip methods has helped in saving 40–60% of irrigation water [22]. Under the GCC-WUS initiative, GCC countries are working on an ambitious plan of increasing water-use efficiencies up to 60% by 2035 [22].

## 5. Prospects of Wastewater Use in the GCC Countries

The population of GCC countries is projected to reach 65 million by 2030 [1], which will increase the water and energy demand. Major growth will take place in urban areas, which will also increase the production of wastewater. Most of the GCC countries have recorded a 20–30% annual increase in the domestic and industrial water demands over the last two decades due to increased population and rising living standards [7]. The total irrigation water demand in the GCC countries was 20 billion m<sup>3</sup> in 2015. Under the Unified Water Strategy (GCC-UWS), all GCC countries are planning to increase water use efficiency to 60% from a current level of 35–40%. By achieving this target, irrigation water demand in 2035 will be reduced to 16.8 billion m<sup>3</sup>. As a result, the irrigation water savings for all the GCC countries during the period of 2016–35 would be 29 billion m<sup>3</sup> (Bahrain = 1.0; Kuwait = 2.9; Oman = 1.3; Qatar = 0.6; Saudi Arabia = 20.5; UAE = 2.7) [22]. However, these water savings will be beneficial only if farmers do not expand the irrigated area assuming water savings. In many irrigated areas of the world, the benefits of increasing water-use efficiency are neutralized due to an increase in the area irrigated by farmers.

Under the GCC-UWS, GCC countries are planning to increase the collection and treatment of wastewater, which means more wastewater will be available for reuse in the future. The produced wastewater in the GCC countries contains a variety of pathogens, including bacteria, parasites, and viruses, which causes accumulation of nitrous oxide and emissions of methane. Most of the wastewater treatment plants in the GCC countries use secondary and tertiary methods. However, in Kuwait, reverse osmosis and ultrafiltration membrane purification methods are also used to treat wastewater [47].

Due to increasing water scarcity and decreasing renewable water resources in the GCC countries, it is essential to use the treated wastewater to its full potential instead of disposing of it in the sea. The wastewater treated at the tertiary level (as is the case in most GCC countries) is considered highly safe for use in agriculture if proper soil and crop management practices are adopted. The use

of TWW can help in the conservation of freshwater resources and improved economic efficiency of investments in wastewater disposal and irrigation [5]. The presence of organic matter and micronutrients in the TWW may contribute to decreasing nitrogen and phosphate fertilizer requirements. Furthermore, nitrogen fertilizer application was reduced by 50% when TWW contained 40 mg N/L [48]. Experiments in Saudi Arabia have also shown that the use of TWW as supplemental irrigation increased crop production, water use, and nitrogen use efficiencies in addition to supplying plant nutrients.

Several studies have demonstrated the successful use of TWW for landscaping, forestry, crop production, and aquaculture [3,19,49]. In many Arab countries (e.g., Tunisia and Jordan), fruit trees, fodder crops (alfalfa and sorghum), industrial crops (cotton and tobacco), cereals, and golf courses are irrigated by TWW [50,51]. In Lebanon, Egypt, and Syria, wastewater is used for irrigation both after treatment and without treatment. In the GCC countries, treated wastewater is mostly used for forage production and landscaping, and the remaining is disposed into the sea despite substantial investment in its treatment. Currently, about 40% of the total TWW use in UAE, Kuwait, and Qatar is reserved for environmental and recreational purposes [52]. Depending on the effluent quality, TWW is also widely used for the construction industry in the GCC countries [53]. The TWW use for the construction industry in the GCC countries has increased from 0.3 billion m<sup>3</sup> in 1990 to 1.5 billion m<sup>3</sup> in 2015 (1.3% to 6% of the total water consumption) [22]. Therefore, expanding the use of TWW in the construction industry can substantially reduce the pressure on renewable water resources. For this purpose, strict quality standards for disposal and reuse of TWW may be slightly relaxed to ensure full utilization of secondary treated effluents.

Treated wastewater has also been extensively used to produce forage crops such as barley (*Hordeum vulgare* L.), sorghum (*Sorghum bicolor* L.) and maize (*Zea mays* L.). For instance, in Oman, sorghum, and maize crops are grown with the TWW were found to be 30% higher compared with those using freshwater resources. The barley yields with TWW irrigation were recorded 43% higher compared to freshwater irrigation. The presence of toxic elements in three fodder crops grown with the TWW was well below the standard safe limits. Studies also reveal that TWW irrigation increased yield and water use efficiency of maize without increasing heavy metal accumulation in the soil or plant leaves. The economic analysis showed that reusing TWW for growing crops such as barley, sorghum, and maize is economically viable with average internal rate of return (IRR) of 26% [54]. This implies that there is excellent potential for using TWW for fodder crops because it will have favorable environmental and socio-economic impacts [55]. In recent years, TWW use for fodder production and forestry has also increased considerably in other GCC countries [3].

Recently, the International Center for Biosaline Agriculture (ICBA) has performed considerable research to evaluate the impacts of using tertiary level treated wastewater to irrigate different food and feed crops. The study was done on six vegetables (lettuce, spinach, radish, eggplant, carrot, and tomato) to evaluate the uptake of heavy metals by soil and plants and the risks associated with the heavy metal transfer to humans as a consequence of the intake of vegetables irrigated with the TWW. The highest accumulation of iron (Fe) was found in lettuce, followed by spinach, whereas Zn and Cr were the second and third most accumulated elements in different vegetables. The eggplant and radish accumulated the least concentrations of all heavy metal elements [19].

Leafy vegetables were found to be more susceptible to absorb and translocate heavy metals than fruit and root vegetables [19]. Therefore, spinach and lettuce should be consumed in lesser quantities due to potential risks related to the accumulation of heavy metals in leafy vegetables. However, the overall build-up of heavy metals in plants was lower than the WHO and other wastewater use standards. Therefore, avoiding these vegetables can help in reducing human health hazards. An alternative could be the production of agroforestry species grown for fuel and timber.

The study also reveals that the physical and biological characteristics of the UAE sandy soils (like many other GCC countries) play an important role in the absorption and translocation of trace metals in the soil-plant environment. Since sandy soils have high infiltration and deep percolation losses along with high evaporation rates, accumulation of trace metals (Cd, Cr, Cu, Pb, Zn, Fe, Ni,

Zn) in these soils in these soils is minimal. Moreover, using a subsurface drip irrigation system can effectively protect farmers from direct exposure to heavy metals and pathogens [10]. Microbial load also varies significantly among different vegetables. Tomato and lettuce did not show any microbial load, whereas the microbial load in other vegetables was also within acceptable limits. Studies have shown that cooking might help in the reduction or complete elimination of microbial contamination in vegetables [56]. The study indicates that TWW in UAE (and other GCC countries) can be used to grow food crops without compromising on human health and environmental sustainability. However, this would require regular monitoring of TWW quality and more understanding of the impacts of TWW reuse on soil, plant, and human health under different agroclimatic conditions prevailing in the GCC countries.

The treatment level of wastewater has a direct impact on costs, hazards, and benefits. Most of the GCC countries lack financial resources for sustainable collection, treatment, and distribution of wastewater. At present, treated wastewater is supplied free of cost to end-users as a no tariff system exists in the GCC countries except Kuwait, which charges farmers a token fee for the use of wastewater [5]. Due to the growing monetary burden, many GCC countries are considering taking help from international donors to operate and maintain their wastewater facilities and to upgrade and replace old plants with the new systems. Therefore, there is a strong need to develop an effective cost-recovery mechanism to reduce the burden on governments and ensure the long-term availability of this valuable water resource.

The sustainable management of wastewater reuse also requires an integrated approach involving all relevant stakeholders who are responsible for the collection, treatment, distribution, and reuse of wastewater for agriculture and other purposes. Unfortunately, current institutional arrangements in the GCC countries are fragmented, which leads to poor coordination between the ministries. Increasing TWW use for vegetables would require more close coordination within different organizations because it involves more strict monitoring and evaluation of TWW quality and its impact on produced vegetables.

These inter-ministerial collaborations are crucial, considering the internal threats and risks to the supply system. They include system coupling (shortage or high cost of energy needed for treating wastewater), demographic and growth (increased production of wastewater due to local population increase or influx of foreigners) and scale and planning (the breakdown of mega plants or interruptions across the Gulf coast due to climate changes). The external threats may include climate change, technological and market-driven changes, and security issues [7]. These external threats could be better handled through improved collaboration between GCC countries.

These threats can occur independently or concurrently, resulting in increased costs and inhibiting the ability of the system to respond. The external risks are also associated with the reliance on the import of food supplies. With increasing water deficit, food imports may be affected due to non-availability or increased prices. Therefore, appropriate response mechanisms need to be developed for the timely mitigation of risks and threats. The most common responses may include increasing awareness, and research and development to improve management capabilities and address technological advancements.

Education and public awareness play a central role in the public acceptance of reusing reclaimed water. However, such programs should be part of an integral plan for reclaimed water distribution and tariff increases. Educational curricula must be further enriched regarding the adverse implications of water consumption on the environment and public health.

## 6. Conclusions

The Gulf Cooperation Council (GCC) countries have the lowest endowment of freshwater resources in the world. Despite this chronic water scarcity, more than 80% of the renewable water resources are used for agriculture. With increasing urbanization and improvements in living standards, water demand is increasing exponentially. The annual groundwater abstraction in the GCC countries

is estimated at 27.8 billion m<sup>3</sup> compared to the average yearly recharge of only 5.3 billion m<sup>3</sup>. This considerable imbalance between groundwater recharge and discharge (discharge is five times higher than the recharge) is the primary cause of the fast depletion of groundwater resources with severe implications on increased energy use for groundwater extraction and deteriorating water quality. The GCC countries are investing heavily in desalination and treating wastewater to reduce stress on groundwater resources. Desalinated water is used for domestic and industrial purposes, whereas groundwater is used for agriculture.

Despite massive investments, only 39% of the TWW is used for agriculture (landscape, forestry, and ornamental plants and grasses), whereas the remainder is siphoned to the sea. Studies have shown that by adopting appropriate management practices, TWW can safely be used for food and forage crops in the GCC countries. However, GCC countries need to think seriously about whether to continue growing fodder or shift to less water-demanding plants to reduce pressure on groundwater resources. Increasing water use efficiency to reduce water demand will be beneficial only if the irrigated area is not increased, assuming savings.

The increasing cost of treating and transporting wastewater from treatment plants to agricultural fields is another major challenge. With the increased capacity of treating wastewater in the UAE and Saudi Arabia, there is a need to expand the distribution network to optimize the beneficial use of TWW. The optimum use of TWW for agriculture is also constrained by social, health, environment, and institutional issues. There is a need to launch an effective awareness campaign to address social and religious concerns regarding the use of TWW for food crops. The standard guidelines may be slightly relaxed to increase the use of TWW in the construction industry. For sustainable use of TWW, an integrated approach involving all relevant local and regional stakeholders needs to be adopted. We also need a comprehensive assessment of the future internal and external risks and threats to the supply system and potential management measures required to mitigate these risks.

**Funding:** The Core-Budget of ICBA funded this research.

**Acknowledgments:** I am extremely grateful to Chris Perry for reviewing an earlier version of this paper. I am also thankful to my colleagues at ICBA and different ministries in the UAE for providing data and information used in this work.

**Conflicts of Interest:** The authors declare no conflict of interest.

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