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An Overview of Wastewater Treatment and Reuse in The Gulf Cooperation Council Countries

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ABSTRACT

The human population generates a substantial amount of waste, and if it is discarded without any treatment it can lead to environmental degradation. This is commonly executed by discharging substantial amount of untreated wastewater in the waterways. Wastewater can be generated from numerous locations but for this review the principal areas concerned are municipalities and industries. The focus of the current study relies on performing a thorough review on expressing the benefits of treating wastewater, assessing Gulf Cooperation Council (GCC) reuse regulations associated with wastewater reuse, identifying different wastewater treatment technologies, and evaluating previous research implemented on this field across the GCC region. Various case studies about treatment technologies and reuse regulations are analyzed in this review for each country within the GCC. The findings show that treating wastewater holds many benefits such as reducing environmental pollution and can aid in helping nations with limited access to fresh water to meet their demand. The technologies for treating wastewater are discussed, such as: conventional filtration, chemical, biological treatment, and different membrane technologies. The review conveys that although treating water has many benefits, there are still many challenges associated with the cost, public perception, and management policies that need to be resolved. To improve wastewater treatment policies effective management can show greater potential for mitigating the freshwater shortage in the GCC countries. Also, since each GCC country has different policies regarding wastewater management, more research should be conducted in the future to adapt as the GCC territory is competing to produce new wastewater treatment plants to accommodate their growing demand for fresh water.

Keywords: Wastewater reuse, wastewater treatment, GCC Countries, Membrane Technologies, Qatar

1.0 INTRODUCTION

In general, all countries in the world produce waste such as solid, liquid and even air contaminants. Waste is a common byproduct of the 21st century industrialization. The main pollution sources for wastewater include wastewater outfalls, dredged materials, chemical wastes, and operational discharges from offshore installations. Safeguarding the water supply for the community is mainly dependent on the country's technological as well as its industrial development. The treatment and disposal of liquid waste is still a major challenge for many urban areas, particularly in the developing countries. Creating and implementing laws for the protection of water from contamination undeniably has a major role in maintaining a regular and

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coherent functioning of water preservation. Due to water scarcity, high water consumption rates and environmental pollution, all the countries across the world are interested in proper wastewater treatment. However, the imperativeness deviates within each country depending on numerous factors of which some are: the advancement of the country, its population size, the condition of the discharged water. The current study focusses on municipal and industrial liquid waste (wastewater) treatment and its management in Gulf Cooperation Council (GCC) countries.

Figure 1 presents the number of studies (by year) carried out, which represents the research conducted within the GCC on wastewater treatment. The database showed 4019 studies, with 1039 papers in 2022 and 98 papers only during 2012. Thus, an evident increase in the number of studies based on wastewater treatment was noted in GCC countries in the last 10 years, which depicts that the GCC is aware of the need to reuse treated wastewater due to water scarcity issues. Moreover, the increase of research also suggests the relevance and importance of wastewater treatment and reuse. During the past decade, the topic of wastewater treatment and disposal in the GCC countries has been generating a great deal of controversy. Several questions were raised about the costs of operating wastewater treatment and waste management plants that are located throughout the region. Most citizens of GCC countries prefer using treated water for schemes such as: flushing toilets, and for non-edible crops, because of the higher cost of desalination of seawater. The need for additional infrastructure investments in order to treat and dispose of wastewater coming from businesses and homes was questioned. Moreover, some have questioned whether the presence of wastewater treatment and disposal plants can reduce the costs associated with climate change mitigation strategies.

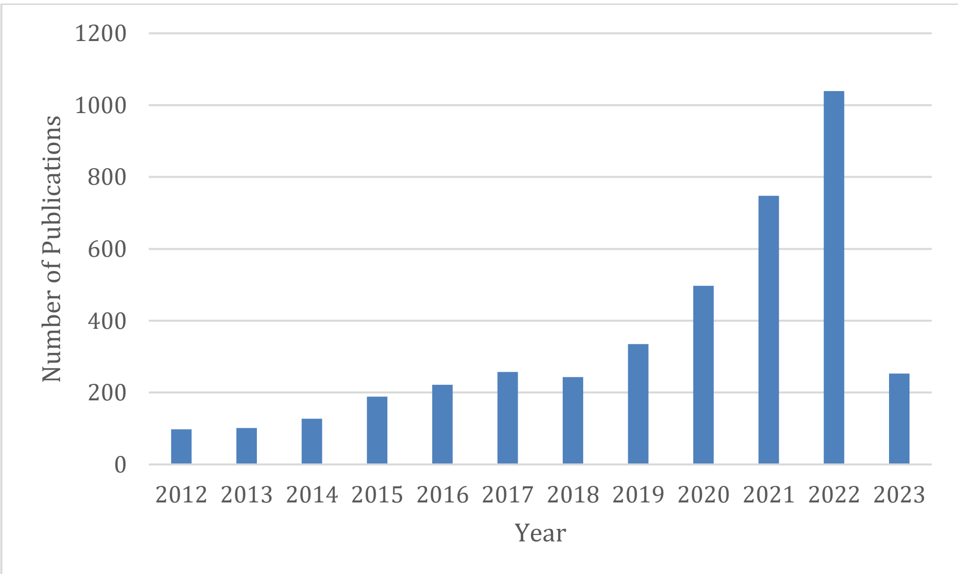

Figure 1 The number of publications (by year), where the keyword 'wastewater treatment' was found in the title, abstract, or keywords, with country affiliation any one of the following, Qatar, Saudi Arabia, United Arab Emirates, Kuwait, Bahrain, or Oman. Data extracted from the scopus.com database (Accessed on March 2023)

Although the issues related to the cost and usage of utilizing treated wastewater are excessive, reusing wastewater has several benefits which may aid in resolving the GCC water scarcity issues. A major advantage of wastewater reuse is that it reduces pressure on freshwater sources [1]. As a result, wastewater can be used as an alternative irrigation source, particularly for agriculture. Agriculture consumes about 70% of global freshwater for crop cultivation and animal husbandry. Freshwater deliveries utilized for agricultural uses, such as landscaping in commercial and residential areas, irrigation in a public and private place, can be relieved by using recycled treated wastewater (TWW). Treated and recycled municipal wastewater supports a cost-effective supply that can reduce the pressure on the freshwater sources such as reservoirs, rivers, and groundwater. Another important advantage of wastewater reuse is the cost savings from not having to remove the groundwater. The energy for pumping groundwater can account for up to 65 percent of the costs associated with the irrigation [1]. Furthermore, nutrients present in wastewater allows for fertilizer cost savings, resulting in closed and environmentally friendly nutrient cycle that is preventing the indirect return of macro- (particularly N_2 and phosphorus) and microelements to water bodies [2].

In the GCC countries, the yearly wastewater collected in 2016 is around four billion m^3, with three hundred waste material treatment plants treating 73% of it [2]. Despite the severe lack of water, solely 39% of treated wastewater is reused, with the rest being dropped into the ocean. Although, the percentage of treated waste material is considerably high compared to other countries around the world, the lack of freshwater resources, the increase of demand and due to the GCC being a water stressed region, an increase in wastewater treatment is required to reduce the pressure on the current freshwater reserves and resolve the water scarcity problems. Treated waste material may be safely used to grow food and feed crops. Countries within the GCC such as Kuwait and Saudi Arabia have accounted to possibly use wastewater for irrigation, which can aid in managing the water resources efficiently for agricultural purposes [1]. Moreover, in Bahrain, the treated wastewater is processed at the tertiary level each year, with 11 million m3 used for gardening and road landscaping [1]. The tertiary treatment is the final and highest level of wastewater treatment. It involves additional advanced processes that aim to remove any remaining contaminants, solids, nutrients, and other impurities from the water. Tertiary treatment can include processes like filtration, disinfection (using chemicals or UV light), and advanced biological treatments. UAE and Oman use treated wastewater for irrigation of golf courses, roads, and recreational areas. Qatar uses around 25 million m^3 per year treated wastewater for various applications. GCC countries ought to expand the usage of TWW in agriculture, and the increased TWW use in agriculture will reduce the strain on freshwater resources. To mitigate future risks and dangers associated with the wastewater discharge to the surroundings, proper wastewater management systems ought to be developed [2]. This review includes information based on the possible risks and benefits related to the usage of treated wastewater, assessment of GCC regulations associated with wastewater reuse, identification of different wastewater treatments, reuse technologies, and evaluation of previous research implemented on this field across the GCC region. This research is critical as it can be used to resolve the global crises of water scarcity in various countries around the world. Due to depletion of the freshwater resources, the treatment of wastewater is crucial as it can aid in meeting the growing demand for fresh water and can reduce the environmental pollution. In this review, several technologies and policies are discussed for treating industrial and municipal wastewater. Moreover, the regulations after the treatment method are explained for each GCC country to aid in understanding the critical factors of the wastewater treatment and management policies. Then various case studies about treating and reusing wastewater are examined to provide information which can be used in the future to implement and improve the wastewater management techniques and policies in the GCC region. To the best of our knowledge, no paper has discussed comprehensively the GCC wastewater production, wastewater treatment challenges, wastewater reuse regulations, along with the related wastewater treatment and reuse related research in GCC countries.

2.0 TREATED SEWAGE EFFLUENT (TSE) PROCESS

TSE process involves the integration of different technologies based on the characteristics of the impurity in the effluent. The major stages in this process include preliminary, secondary, tertiary treatment, odor control, and sludge handling [3], [4]. Each of these stages has specific technologies used to enhance production. The system should have preferable technology for each stage depending on several aspects such as project complexity, available materials for construction, project location, and the technology's general effectiveness. Reusing treated wastewater has a positive impact on the environment and leads to exerting less stress on the current freshwater resources [5].

2.1 Wastewater Treatment Stages

2.1.1 Preliminary Treatment

First the preliminary stage of water processing seeks to remove coarse materials or other huge debris from the wastewater [6]. The main operation in preliminary treatment includes sludge reception, fine screening, grit removal and storage in tank. These processes apply to all types of waste waters including but not limited to mixtures of industrial/domestic, industrial, municipal, and agricultural waste waters [7]. Beginning with septage tanks, the water transported for discharge can be accepted by the tank in each day and pumped to the inlet works to combine with other inlet flows [8]. The wastewater is screened to protect the treatment plant from blockage, by removing large objects such as rags, cans, and plastics from the wastewater. Overall, the screening automatically removes the larger materials making them acceptable for the other processes involved in the preliminary stage [9]. On the other hand, the grit removal process involves the separation of heavier inorganic material such as grit and gravel from the wastewater to prevent pumps from wearing out quickly and blocking pipes. Grit removal also protects the mechanical parts of the plant from unnecessary wear and tear. A common type of grit removal system is an aerated grit chamber that will settle any substance which is heavier than the organic matter from the wastewater, and then remove the settled grit by pumps [10], [11].

2.1.2 Secondary Treatment

After the treatment of wastewater in the preliminary stage, the water progresses to a secondary phase. The technologies used in secondary treatment include anaerobic, anoxic, and aerobic process configuration and biological nutrient removal. The secondary treatment (biological treatment) is aimed at removing solid sediments, soluble biological oxygen demand (BOD) and nutrients in wastewater which takes place in the bioreactors using microorganisms [12]–[14]. There are bioreactors, which can contain anaerobic, anoxic, and aerobic zones and each of the zones can aid in the removal of nitrogen and phosphorus from the wastewater [15], [16]. Moreover, these sediments include residual organics and suspended solids. During this stage decomposable dissolved and colloidal organic matters are removed using aerobic methods [17]. Aeration is provided in the aerobic stage to feed the required amount of oxygen for metabolizing the organic matter in wastewater and to ensure adequate mixing between the microorganisms and organic matter occurs. Common systems used to aerate the reactors are subsurface and mechanical. Where the subsurface system involves the supply of air into the wastewater through submerged diffusers or other methods and the mechanical system uses blades, or other mechanical drivers to feed air from the surrounding environment into the wastewater [18].

The sedimentation tanks (clarifiers) are used in secondary treatment, and here the biological solids or sludges are settled by gravity. The treatment includes the activated sludge process (ASP) and nutrients removal. In the ASP, the treated effluent flow to the top and the settled sludge flows to the bottom of the tank and is either returned to the bioreactors as recycled activated sludge (RAS) to support the biomass or sent as surplus activated sludge (SAS) [19]–[22]. A dispersed growth reactor acts as a modified ASP with extended aeration or basin containing a suspension of the wastewater and microorganisms. The aeration tank is supplied with oxygen, and its contents are mixed vigorously [19]. Oxygen transfer efficiency, the type synonymous with a sequential batch reactor, is necessary because the process consumes the most energy in ASPs [23]. Also, the efficiency improves the feasibility of the ASP.

Microorganisms are then separated from the liquid through sedimentation. The byproducts of secondary treatment will later undergo the sludge processing process. On the other hand, the sequential batch reactors act as fill and draw-activated sludge systems for secondary treatment. They are categorized into the cyclic activated sludge system, and the intermittent cycle extended aeration system. These systems are differentiated based on whether the process is continuous or discontinuous [19]. The other biological wastewater treatment processes which can also be used include the rotating biological contactors (RBC) and trickling filters [19], [24]–[26]. They are beneficial since no ponding is needed; they wet the medium completely, use unlimited oxygen, produce low noise and odor, and require less space or land to set up. However, they are costly since they incur power loss during treatment and are hard to maintain. The shaft bearings and mechanical drive units of RBCs need frequent maintenance [27]. However, the advantages of RBCs and trickling filters are that they have good sludge features, short hydraulic retention time, and high biomass retention levels [28]. Under the nutrient removal process, wastewater is treated using biological nitrogen removal (BNR) via denitrification and nitrification. Moreover, anoxic tanks or selector zones are used in enhanced biological phosphorous removal (EBPR) using phosphorous accumulating organisms (PAOs). Overall, the RBC, tricking filters, and nutrient removal processes are used for a full treatment or final polishing of wastewater [19].

2.1.3 Tertiary Treatment

Tertiary or advance wastewater treatment is performed when secondary treatment fails to remove specific sediments from the sewage. The process is named tertiary since it is an advancement of the high-rate secondary treatment process applied for the additional treatment that is needed to remove suspended and dissolved substances. Tertiary treatment usually involves different processes such as chlorination, granular medium filtration (GMF), ultrafiltration (UF), ultraviolet disinfection, TSE balancing tanks, and lagoons.

After secondary treatment it will be discharged into chlorine tanks which will be used for disinfection, and it helps for the partial destruction of disease-causing organisms. The main objective of chlorination process is to reduce the bacteria in the effluent of secondary treatment and to provide residual chlorine to avoid the growth of the bacteria and algae in tertiary filters by storing the water in these tanks for a few minutes. Hence, chlorination is a good option for wastewater with a high number of bacterial and viral pathogens [29]. Finally, the treated sewage effluent is stored in TSE tanks prior to pumping into TSE network. The design lagoons are to store the excess TSE. The TSE of non-potable water reuse will be filled in tankers, which will be pumped through the station and sent to additional treatment or external use such as irrigation, road washing or will be pumped into tankers for onward distribution.

2.1.4 Sludge Treatment

Sludge is the byproduct of the whole wastewater treatment process. It contains both organic and inorganic material, which is usually a liquid stream that is being deposited downstream of the bioreactors in the clarifiers [30]. This activated sludge comprises two types; return activated sludge which is returned to the bioreactors as a food source, and surplus activated sludge which is sent to the solids area for processing [31]. It is categorized into preliminary, secondary, tertiary, and imported sludge. Sludge can be eliminated by reducing its production, recycling it, recovering energy from it, or appropriately disposing of it. Sludge treatment is categorized into volume reduction separate and skim (SAS) balancing tank, thickening, aerobic digestion, dewatering, imported sludge, thermal dryer, and bagging plant) and solids reduction, which involves digestion or incineration. It can also be significantly stabilized by chemical and biological processes, a conventional technique for stabilization uses worms and microorganisms to convert waste into nutrient-rich compost [19].

2.1.5 Odor Control

Wet chemical scrubbers and granular activated carbons (GAC) are the main techniques used to control odor. Under wet chemical scrubbers, the air stripping is done using sodium hydroxide or sodium hypochlorite. GAC beds, on the other hand, absorb the odor. GAC works best with ozonation to remove odorant residuals [32]. Another common technique used to control odor is stabilization ponds [33]. They are simple, have a high efficiency in removing pathogenic organisms, and do not require electricity. However, they do come with major drawbacks, like the need for large tracts of land and susceptibility to algae. Regardless of such drawbacks, the wastewater stabilization ponds are still an effective low-cost means of managing wastewater [34]–[40].

In general, only KSA tends to use the primary stage, but the rest of the countries in the GCC do not. Additionally, secondary and territory treatment is used by facilities present in the UAE, KSA, Qatar and Oman. However, Bahrain and Kuwait use the tertiary treatment level alone, but Kuwait introduces the additional reverse osmosis process as well for the wastewater reuse procedure [41].

3.0 GCC COUNTRIES WASTEWATER PRODUCTION

According to Aleisa *et al.* [41], the total production of wastewater in GCC countries is 2.853 Bm^3/year during 2009. The wastewater generally consists of various pathogens such as bacteria, viruses, and parasites which can lead to harmful effects such as: decrease of oxygen levels in the sea causing loss of aquatic life, buildup of nitrous oxide and increase of methane, the gas contributing to global warming. The sample results that have been compiled from various geological points on the GCC shores revealed that the contaminants play a significant role in distributing and transporting the pollutants through the wind along the gulf marine environment. According to Table 1, Qatar generates the highest amount of wastewater per capita compared to the other GCC countries. Comparatively, Oman produces 30.66 per capita of wastewater yearly making it the country which creates the lowest amount of wastewater per capita in the GCC [41].

Table 1 Comparison of population collected wastewater and treated wastewater in GCC countries (Adapted from Ref [40], [42])

GCC Country	Population (millions) [40]	Volume of collected wastewater (hm^3) [42]	Volume of treated wastewater (hm^3) [42]
Oman	5.11	68	67
United Arab Emirates	9.89	746	733
Qatar	2.88	208	203
Bahrain	1.7	158	70
KSA	34.81	2500	1604
Kuwait	4.27	320	247

4.0 CHALLENGES OF WASTEWATER TREATMENT

Wastewater treatment, and the distribution of treated water for reuse are expensive, particularly at the tertiary treatment level. All the Gulf Cooperation Council countries lack the financial resources to sustainably operate and maintain their wastewater treatment facilities [17]. In GCC countries, there is presently no wastewater tariff system in place. Globally, the GCC region ranks highest in terms of domestic water and energy consumption, but lowest in terms of per capita freshwater sources [43]. Some Arab countries rely on the international money to assist operation, maintenance, and restoration of existing treatments facilities, which are often outdated and in poor working order. The skilled and motivated employees are better managed if the systems are present, and such large investments should be reallocated to construct new technologies. Another key impediment to the usage of treated wastewater is the consumer's psychological barrier, where the population assumes an "unhygienic" element that can contribute to health concerns, is present in the treated wastewater [44]. This is arguably the hardest challenge to overcome out of all the above-stated challenges.

Many GCC nations lack strategies and standards for the treated wastewater reuse from collection to reuse. Treated wastewater is a crucial resource of water that can aid in providing water to the water scarce areas of the world. However, there are restrictions associated with wastewater use concerning public awareness, cost, technology and government strategies and policies. According to Mu'azu *et al.*, Saudi Arabia has extensive water scarcity issues, and have tried to focus on reusing treated sewage effluent as an alternative water resource. However, many issues related to the awareness of TSE, and lack of suitable technologies have been raised [45]. Negative public perception of treated wastewater can be resolved by providing education and awareness campaigns to ensure the benefits and risks are projected thoroughly to the population. Moreover, appropriate technologies should be applied on the treatment of the wastewater focusing on the quality standards of the water and by ensuring that an efficient pipeline distribution system is setup to provide the water to landscapes, agriculture, and other appropriate uses. Additionally, appropriate legislation and strategies need to be applied by the government to increase the usage of treated wastewater as the current freshwater resources are being depleted at an alarmingly fast rate [45].

The proposed reuse possibility dictates the required quality of the water and, as a result, the treatment to be employed. This forward-thinking strategy gives planners a larger master plan for treated wastewater management and more reuse flexibility. The current uncontrolled TSE released into the environment in GCC countries is the primary concern related to the region's limited fresh water supply, and it adds to global warming [46].

Treatment and reuse of wastewater are becoming increasingly important as the world's population and economy develops, to protect public health and minimize unacceptably higher levels of degradation of the environment. Moreover, suitable wastewater management is necessary for preventing the contamination of aquatic bodies and conserving the sources of pure water [47]. Farmers must be able to afford water to get the most out of this resource. Another issue is the cost of treated wastewater transportation from a Sewage Treatment Facilities to agricultural areas, as most of the large sewerage treatment plants are in densely populated areas. Furthermore, the water reuse schemes face considerable social difficulties. The most delicate and crucial problem is farmers, retailer, and consumer acceptance. The GCC countries face numerous issues in terms of securing freshwater supplies and meeting rising food demand. Wastewater reuse has the potential to contribute significantly to food security [2], [48], [49]. Thus, the wastewater treatment field requires more investment.

During the past decade, the debate surrounding the costs of wastewater treatments in the GCC region has been extensive. Various studies have been published comparing the costs of wastewater reusing in the United Arab Emirates (UAE) versus the costs of treating and disposing of wastewater at the wastewater treatment and reuse facilities [42]. While most studies conclude that the cost of water treatment in the GCC region is higher compared to other regions [50]–[52], few contend that such costs can be lowered by adopting the latest technology [2], [42], [53], [54]. Though all these arguments have merit, there is a potential conflict of interest with the impact of wastewater treatment on the cost of water utilities for businesses.

The controversy surrounding wastewater treatment plants in GCC is still persistent. One is the potentially detrimental effect that improper disposal of wastewater could have on the environment. Another is the fact that it can be very difficult to dispose the unwanted waste without relying on potentially costly and inconvenient alternative solutions, such as ground water [42]. In addition, there is the question of consent, which is needed for most wastewater treatment plants to operate.

Sewage treatment plants generally receive their water from a variety of sources. The major sources are storm water runoff [55]–[57], municipal sewage pipes [58], [59], and private wells [60], [61]. Storm water runoff commonly flows away from residences, highways, commercial properties towards various water channels and may lead to harming the marine environment. While storm water carries some pollutants that can be harmful to the environment, they are typically washed away by high tides. Many local municipalities also provide their wastewater from storm water runoff with the goal of reducing flood risks. Private well water systems typically channel their water through special filters to treat it properly with additional filtration before it is released into the environment.

The risk of wastewater contamination in many parts of the world is reduced by using sophisticated treatment systems that employ reverse osmosis, granular carbon, and ultraviolet light. Membrane filtration technologies, like the use of membrane bioreactors, ultrafiltration or nanofiltration, and adsorption, have proven particularly effective at removing micropollutants from both drinking water and wastewater [62]. Unfortunately, these systems are unable to eliminate all the pollutants present in the wastewater. For instance, in the UAE, the wastewater from domestic households and the wastewater generated by industries are sent to different treatment plants that do not have the necessary equipment to remove all the contaminants in a treated discharge [18]. As a result, these discharged wastewaters have numerous health and environmental risks.

Sewage is generally disposed of in wastewater treatment plants, but sometimes is used to water lawns and gardens. The wastewater from such places may contain traces of pesticides, herbicides, pharmaceutical drugs, and other hazardous drugs [62]. These drugs are present in trace amounts because plants use them to control algae growth, weed growth, and reduce the amount of nitrogen in the soil. When they are used in gardens, they tend to build up in the water table and eventually end up in drinking water. The only way to treat these hazardous drugs is to dilute them with water and then let the water pass through a special filter that reduces their toxic effects. However, these drugs are already present in the water at a low level and no wastewater treatment plant can remove them.

Another major environmental risk associated with reusing treated sewage in GCC countries is contamination of the soil and aquifer that are located adjacent to the treated sewer lines. Some drugs have been found in groundwater, posing serious water contamination threats. Thus, reusing treated sewage is unwise. This practice also results in heavy environmental pollution and further stress on the already strained sewage treatment plants and water resources. To minimize the risks associated with reusing treated sewage, people should be aware of the harmful effects that these hazardous wastes can cause to the environment and human health. This includes lung cancer, infertility, birth defects, death, and chronic health problems. For this reason, most GCC countries have banned the reusing of this waste.

5.0 WASTEWATER REUSE REGULATIONS

5.1 Wastewater Reuse Regulations in Qatar

The primary objective of the wastewater reuse regulations in Qatar is to promote the safe storage and reuse of domestic and industrial wastewater. In Qatar, the treatment rate is 58% compared to the total wastewater generated [41]. Wastewater is often pumped to power plants where it is used for domestic purposes. However, it must not be used for experimental purposes because the discharge of harmful discharges into the sea may lead to detrimental effects. This regulation prohibits the discharge of sewage into the sea without any prior notification or research. This is a significant regulation, which has been implemented to ensure the safety of the sea life and environment [63].

In Qatar, the Ministry of Energy and Industry (MEI), the Ministry of the Environment (MoE), and the Public Works Authority (PWA) are in charge of the regulatory framework meant to regulate and manage industrial wastewater. The PWRC was founded in 2004, and Emiri Resolution number 40 in 2019 changed its organisational framework and duties in 2019. Each organisation is interconnected, and the MoE must approve any application for an industrial permit submitted to MEI that also contains a wastewater discharge permit. Domestic and commercial wastewater outputs are evaluated, and frequently the application is given a conditional approval. Each application must always show that it can adhere to the authority's established guidelines for wastewater discharge.The only restriction that is in place is the stipulation that these regulations be strictly obeyed. Failure to comply can lead to heavy penalties as well as charges for environmental degradation. Any violation of these regulations can lead to the immediate shutdown or suspension of operations. There is also a big problem with the overuse of water, which leads to the development of waste and polluting the environment. This can be stopped by following the regulations strictly and taking immediate measures to remedy the situation [64].

5.2 Wastewater Reuse Regulations in Bahrain

Bahrain has authorized a lot of legislation to control water use and regulate groundwater but is yet to consolidate it into comprehensive law. Bahrain's constitution states that all natural resources are state property, and the state is entrusted with their management as a common good. By that rationale, groundwater is public/state property. Bahrain has eleven wastewater treatment plants, most of which use aeration technology with 150 Mm^3/year capacity. The fraction of treated wastewater in Bahrain compared to the total wastewater is 50% [41]. The largest wastewater treatment plant (WWTP) is Tubliand with a design capacity of 200K m^3/day. TWW is used in agricultural purposes and sand washing. And the cost of tertiary treated water is \$1.1/m^3 and out of that \$0.13–0.27/m^3 for redistribution, \$0.4/m^3 for sewage collection, and \$0.53/m^3 for treatment [41].

The Ministry of Works, Municipalities Affairs, and Urban Planning in Bahrain oversees wastewater management, groundwater preservation, and agriculture. The Agricultural Affairs department manages sustainable groundwater resource utilization, assigns treated wastewater for irrigation, and collaborates with authorities to establish guidelines for reuse. Sanitation Affairs manages treated wastewater production, distribution, and monitoring, coordinating with sectors like agriculture, groundwater, and landscaping. The department collaborates with the Ministry of Health to ensure wastewater allocation aligns with public health protection and environmental preservation. The Amiri Decree No. 11 in 1991, as amended by Law No. 33 in 2006, pertains to the crucial matters of sanitation and drainage. The legislation effectively prohibits the disposal of waste and pollutants into both wastewater networks and surface runoff networks, thereby safeguarding the integrity of our natural environment. The legal framework established by Law 33/2006 serves as a crucial instrument in governing the provision of sanitation services, the proper treatment of wastewater, and the responsible reuse of treated wastewater and sludge [64].

5.3 Wastewater Reuse Regulations in UAE

The Department of Energy, in accordance with Law No. (11), assumes the crucial role of establishing policies, standards, and regulations for the Energy Sector. This sector encompasses all individuals, corporations, and entities engaged in activities related to Recycled Water and Wastewater in Abu Dhabi has been implemented on January 2021 [65]. The UAE's water resources legislation is a complex system intertwined with the federal structure, with each emirate issuing its own laws and decrees to regulate and safeguard its water resources. Law No. 18 facilitates licensing of wastewater and sewerage services entities, allowing them to connect to the Abu Dhabi Sewerage Services Company's network. Law number 12 empowers the Abu Dhabi Sewerage Services to engage in the sale of treated wastewater to various entities, promoting sustainable water management practices in the region [64].

Moreover, the Ministry of Environment and Climate Change in UAE has issued decrees to protect the country's water and other resources, and this includes the ban of certain pesticides. Pollution is illegalized in the country, and a fine range of AED 5,000-AED100,000 can be applied depending on the type of crime [18]. UAE treats 58% of 284 Mm^3 generated sewage water, and Abu Dhabi urban area alone produces 550K m^3 [41].

5.4 Wastewater Reuse Regulations in Oman

In Oman, the use of wastewater and sewage effluent must always be done in accordance with the legislation on wastewater quality and quantity, with the purpose of protecting the environment. Wastewater reuse and disposal shall not be allowed in several cases. The ratio of treated wastewater produced over the total amount is 41% in Oman [41]. First is when the reuse or discharge will adversely affect public health, this can be when there is a high level of pathogenic organisms and fecal coliforms or where there is a high energy level which may cause an ecological imbalance. Second is when there is a high level of chlorine, phenols, pesticides, heavy metals, or other toxic substances. Lastly, the reuse of wastewater shall not be permitted when its quality is deteriorating. Wastewater is being reused in Oman, but only in specific circumstances. Both physical and chemical parameters of the treated wastewater will be continuously monitored. The goal is to keep the quality of water high and the risk of illness low [66].

Water management is a critical aspect of environmental governance in Oman, with numerous governmental organizations playing pivotal roles in this domain. The primary entity in question is the Ministry of Regional Municipalities and Water Resources (MRMWR), which holds significant importance in the context of environmental conservation and sustainability. In 2001, the esteemed Royal Decree No. 114 was enacted with the noble purpose of safeguarding our precious environment and curbing the perils of pollution. Bahrain's legislation regulates waste handling, disposal, pollution management, and permits, ensuring safe discharge of untreated wastewater into ecosystems. Furthermore, in 2001, two crucial legislations were enacted with the primary objective of promoting effective governance of municipal wastewater and safeguarding the environment and the well-being of the general public. The initial legislation pertains to the preservation and safeguarding of the natural environment, as well as the mitigation of pollution, as stipulated in Royal Decree No. 114 established on 2001. According to the provisions outlined in Article 20 of this legislation, it is strictly forbidden to release any form of hazardous waste, substances, or other environmental pollutants into wadis, watercourses, groundwater recharge areas, rainwater or flood drainage systems, as well as alfa and their respective channels discharge systems. It is imperative to note that the reuse or discharge of treated wastewater without obtaining a permit from the MRMWR is strictly prohibited [64].

5.5 Wastewater Reuse Regulations in Saudi Arabia

Saudi Arabia is making use of the vast number of decentralized wastewater treatment plants in the country to treat wastewater better and to minimize the environmental pollution. Saudi Arabia has been on the forefront in the development and implementation of sustainable wastewater reuse for the past decade. Industrial cities are being created to house large numbers of plants, and regulation has been introduced to protect the interests of all stakeholders [67]. The treated percentage compared to the total wastewater produced in Saudi Arabia is 69% [41].The water regulator which acts as the governing and enforcing body is created to aid in securing the interests of all stakeholders.

Furthermore, the Saudi Industrial Property Authority is responsible for the development of industrial cities. There are a lot of different standards for the effluent, and they can vary depending on the state. It is important for citizens to ensure their effluent is up to the standards that are necessary for the specific application. Table 2 shows the country's effluent levels of the primary wastewater treatment plants in Saudi Arabia.

In the regulation, article 1 of Decree 26, the technical requirements for the disposal of untreated (raw) sewage water, the technical requirements for sewage water treatment plants in large complexes (governmental and private), and the technical requirements for the use of treated sewage water in afforestation and irrigation of municipal crops is issued by the Minister of Municipal and Rural Affairs in 2003. Moreover the penalties and charges related to the treated sewage water system and its reuse state that violations of any provision of this law or its implementing regulations shall be detected, and penalties will be imposed and applied to violators in accordance with Articles 22, 23, and 24. Furthermore, the competent party has the authority to assess the fine for offences or infringements not specified in these regulations, provided that they are within the limits of the offences specified in the sewage water system and its reuse, and that the offence is approved by the competent minister or whomever he authorizes [68].

Table 2 Saudi Arabia's waste treatment plants pollutants and allowable effluent quality levels. Reference [69]

Pollutants	Allowable effluent level
Physio-chemical pollutants	
(a) Floatables	none
(b) PH	6–9 pH units
(c) Total suspended solids (TSS)	15 mg/l (max)
(d) Temperature	Meteorology and Environmental Protection Administration (MEPA) determine the thermal properties of discharged water to fit the properties of receiving water and such properties are determined on a case-by-case basis
(e) Turbidity	75 NTU (max)
Organic pollutant	
(a) Biochemical oxygen demands (BOD)	25 mg/l
(b) Chemical oxygen demand (COD)	150 mg/l
(c) Total organic carbon (TOC)	50 mg/l
(d) Total Kjeldhal nitrogen (TKN)	5 mg/l
(e) Total chlorinated hydrocarbons	0.1 mg/l
(f) Oil and grease	8 mg/l (not to exceed 15 mg/l in any individual discharge)
(g) Phenol	0.1 mg/l
Nonorganic pollutants	
(a) Ammonia (as nitrogen)	1.0 mg/l
(b) Arsenic	0.1 mg/l
(c) Cadmium	0.02 mg/l
(d) Chlorine	0.5 mg/l

Pollutants	Allowable effluent level
(residual)	
(e) Chromium (total)	0.1 mg/l
(f) Copper	0.2 mg/l
(g) Cyanide	0.05 mg/l
(h) Lead	0.1 mg/l
(i) Mercury	0.001 mg/l
(j) Nickel	0.2 mg/l
(k) Phosphate (total) as phosphorous	1.0 mg/l
(l) Zinc	1 mg/l
Biological pollutants	
(a) Total coliform	1000 MPN per 100 ml

5.6 Wastewater Reuse Regulations in Kuwait

The Kuwaiti Government has a commitment to protect the public by enacting new measures and laws to help safeguard water usage.The wastewater that is treated in Kuwait is about 75% compared to the total generated output of wastewater [41]. Kuwait has minimal annual renewable water resources, mostly consisting of groundwater inflow from Saudi Arabia, estimated at about 20 million cubic meters [70]. To this end, the Kuwaiti Government has issued the necessary management measures to safeguard water usage and wastewater treatment. In Kuwait, decree number 5 in 2012 and decree number 5 issued the regulation on industrial wastewater transportation, which aims to establish a system to control the transport and disposal of industrial effluents in safe environmental ways that prevent impacts that are harmful to public health, safety, and well-being. The Kuwait Institute for Scientific Research (KISR), a research facility, was established in 1967 to meet Kuwait's need to replenish its water supplies and is working on ways to recycle wastewater effluent [64]. Moreover, Kuwait has put in place wastewater quality control regulations in order to protect public health and supply clean water for drinking and other purposes.

In recent years, many wastewaters treatment plants have been built in urban areas of GCC to relieve the stress on existing plants and to capitalize on the increasing need to provide fresh water for homes, businesses, and industries. Table 3 below depicts the wastewater guidelines for agricultural purposes and the treatment stages used for each GCC country. In spite of all the advances in wastewater treatment and reuse, there are still problems associated with sewage wastewater. As the population continues to grow in cities around the world, more wastewaters will inevitably end up in landfills, threatening both the environment and human health. In response to this problem, most landfills should start to include features intended to trap wastewater, including vertical and horizontal wells designed to recycle wastewater and septic tanks designed to treat and filter the water.

Table 3 GCC reuse guidelines for wastewater used in agriculture and treatment levels. Reference [41], [42]

		Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	UAE
Level of treatment:		Tertiary	Tertiary-RO	Secondary and Tertiary	Secondary and Tertiary	Primary, Secondary and Tertiary	Secondary and Tertiary
Parameters	Units						
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
NH3-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

6.0 DIFFERENT TECHNOLOGIES FOR WASTEWATER TREATMENT

There are several treatments that can be used to treat wastewater. In this section they are sectored into conventional, chemical, and biological and membrane-based technologies. Recently, membrane technologies have developed as a popular solution for reclaiming water from various wastewater streams for re-use. Hence, this section examines and analyses the most recent membrane technology in wastewater treatment thoroughly.

6.1 Converntional Techniques

One of the earliest wastewater treatment technologies employed was physical methods, which remove impurities using physical forces. The majority of wastewater treatment process flow systems still employ them. When water is seriously polluted, several techniques are frequently used. Screening, filtration, and centrifugal separation are the three basic wastewater treatment techniques that are most frequently utilised, followed by sedimentation and gravity separation. When suspended materials don't settle through sedimentation or gravity, coagulation is used to help them do so. This treatment method is used in the filtration method for drinking water that can be extracted from natural reserves or artificially. As seen on Figure 2, it is applied before sedimentation and filtration to enhance the capacity of the treatment process to eliminate particles. Additionally, coagulation and flocculation can also be applied to the wastewater treatment process to enhance the quality to meet the required standards. Coagulation is a process used in the neutralization of charges and formation of a gelatinous mass that traps particles, hence, creating a mass that is big enough to be trapped or settle in the filter [71]–[73]. Flocculation involves the moderate stirring or agitation of the solution to reduce turbidity in the water [67], [74]–[76]. Turbidity is the measure of suspended particles in the water, which causes cloudiness. The addition of coagulants with opposing charges to those of the suspended solids is done for neutralization of the negative charges on dispersed solids such as organic substances [77]. Whereas ,flotation is a typical and essential part of a traditional water treatment facility. By securing them to air or gas, flotation removes pollutants such as greases, oils, biological compounds, and suspended particles.

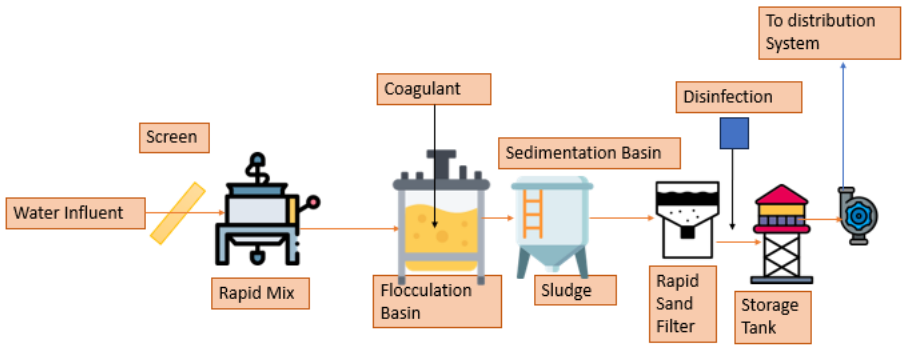

Figure 2 Schematic representation of a filtration treatment plant

6.2 Chemical and Biological Treatment

Wastewater treatment techniques can be chemical is which they require chemical reactions to remove impurities. They are always used in conjunction with biological and physical techniques. Due to the fact that they are additive processes, chemical procedures have a disadvantage over physical ones. This is crucial to consider if the effluent is going to be recycled, because by chemical reactions the impuritiy can be transformed into a harmful byproduct which then needs further treatment. Precipitation, neutralisation, and disinfection are a few chemical techniques.

Moreover, because they are used to create safe drinking water, biological water treatment technologies are essential parts of a wastewater treatment plan. These methods include aerobic, anaerobic, and bioremediation processes. This treatment method uses microorganisms such as bacteria, protozoa, and other microbes in the treatment of wastewater. Microbes are integral to the biological treatment process [78]–[81]. Microbes like *Cellulosimicrobium, Aeromonas, Micrococcus, Microbacterium, Methanospirillum,* and *Sphingobium* are known to have exceptional biodegradation potential for many xenobiotic contaminants in water and even soil environments. The accumulated pollutants from the biological treatment process settle out of the solution in a sludge that is easily dewatered. The solid waste removed is then disposed of.

Biological wastewater treatment is divided into three main categories:

- Aerobic treatment- This process uses aerobic bacteria or microbes to break down the waste [82], [83]. These microbes use oxygen in the process and produce carbon dioxide and microbial biomass.
- Anaerobic (anoxic) treatment- This process applies microbes that do not require oxygen. The microbes break down the organic waste to produce methane, carbon dioxide, and excess biomass [84], [85]. Anaerobic digestion is more suitable for circular bioeconomy.
- Anoxic treatment- The microbes used in this process use other molecules, apart from oxygen for growth. These microbes can remove sulfates, nitrates, nitrites, selenates, and selenites from the wastewater. Anoxic treatment can sustain chemical oxygen demand [86] and has an efficiency rate of 86% [87].

In this treatment method, the amount of organic waste that is decomposed by the microorganisms is measured through BOD. This refers to the amount of dissolved oxygen needed by the microorganisms to break down the organic matter into smaller particles. An increase in the level of BOD signifies a high concentration of organic material in the wastewater [86].

6.3 Membrane Technologies in Wastewater Treatment

A membrane is an obstacle or barrier that restricts the selective movement of elements through it, hence, separating two phases. Membranes have been applied in different sectors for a long time. Continuous studies have been carried out to improve the membranes to increase their efficiency in their different functions [88]–[93]. Membranes can be grouped into isotropic and anisotropic membranes. Isotropic or symmetric membranes have an even composition and physical structure. They are mainly used for microfiltration purposes. Anisotropic or asymmetric membranes have an uneven membrane area and are composed of a top thin layer and a bottom thick layer which acts as the support section of the membrane. Anisotropic membranes are mainly used in microfiltration, ultrafiltration, and reverse osmosis procedures. Membranes can also be organic, or inorganic based on their material composition. The movement of components through the diverse types of membranes can be equilibrium-based or non-equilibrium-based [94].

6.3.1 Reverse Osmosis

This is the most used membrane technology in water treatment. Its application extends from pretreatment to post-treatment of wastewater. The separation of media in this method depends on hydraulic pressure. RO is the most efficient in the separation of small particles like bacteria or monovalent ions such as sodium ions and chloride ions, with approximately 99.5 percent efficiency. RO is also the most used method in the desalination of seawater and wastewater treatment. During the RO process, there is the generation of a strong hydrostatic pressure that can overcome the inherent osmotic pressure of the feed. Some of the areas in which they RO can be applied can include urban wastewater treatment, vegetable oil factory, textile industry, and metal finishing industry [95], [96].

In research carried out by Al-Maadheed *et al.* [95], the team removed antibiotics from hospital effluent and other wastewater treatment plants in Doha, Qatar. The samples were collected from old and new wastewater treatment plants. Their research deduced that RO is required to remove the harmful antibiotics from the sample as the current treatment technique was not efficient. The samples were then analyzed to establish the concentrations of eight antibiotics. Preparation of the samples was done through automated solid-phase abstraction then liquid chromatography analysis. The results from the tests of the eight selected antibiotics showed a recovery of 47.5-98%. Only three antibiotics (amoxicillin, penicillin, and erythromycin) had a concentration that was below the detection limit (0.1μg/L). Most of the antibiotics showed a significant statistical correlation with each other. The variations between the concentrations of the selected antibiotics from the old and new wastewater treatment plants were insignificant ($P \geq 0.05$). Penicillin and metronidazole had the highest removal rates (99.44%) while ciprofloxacin and clavulanic acid were not removed from either effluent even after ultrafiltration. This study showed that hospital effluent is not the major source of antibiotics in wastewater. However, a high concentration of antibiotics can be associated with the direct disposal of the effluent into the sewer system. The study recommended an extensive study of other pharmaceutical products and contaminants that are present in wastewater in Qatar. An investigation should be conducted to determine their metabolites and biodegradation products and the improved treatment technologies such as RO, that can be applied and remove a high percentage of the contaminants [95].

Similar to RO, there is ultrafiltration, microfiltration and nanofiltration, however, they vary based on the pore size of the membrane and pressure limit.

6.3.2 Forward Osmosis

This is the normal osmosis process in which water molecules move from a hypotonic solution to a hypertonic solution through a semipermeable membrane. The concentration gradient generates the required osmotic pressure that drives the water molecules from the feed solution (low concentration) to the draw solution (high concentration). Figure 3 is the schematic representation of the forward osmosis, reverse osmosis, and pressure retarded osmosis processes. This procedure continues as long as there is a concentration gradient. The process stops once an equilibrium of chemical potential is achieved. This process is applied in the treatment and concentration of wastewater streams. This process has a low energy consumption since there are no external pressure requirements. The properties of products such as beverages and pharmaceuticals are also maintained since there is no pressure or heat application; this makes the customization of the products to be easy. Some of the areas where this process is applied include raw municipal wastewater treatment, domestic wastewater treatment, sewage treatment, and coke-oven wastewater treatment [97]–[99].

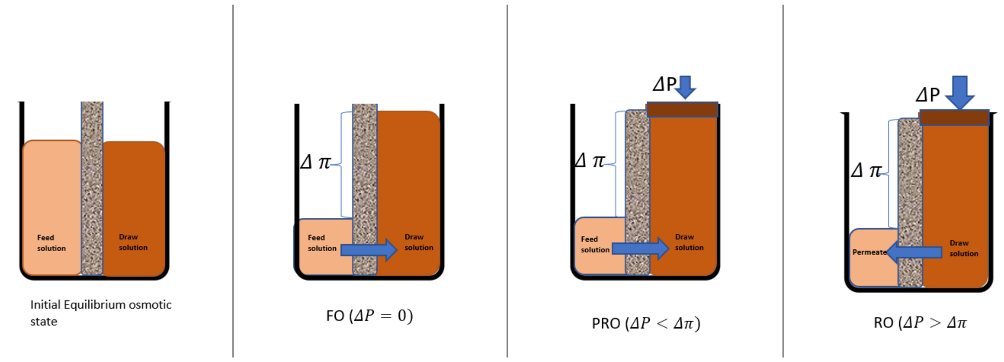

Figure 3 Schematic representation of the forward osmosis, reverse osmosis and pressure retarded osmosis process

A study was conducted by Mahri *et al.* [100] to investigate whether an electro-osmotic thermal process model can be used to enhance forward osmosis combined with membrane distillation. The experiment incorporated an electroosmotic membrane bioreactor (eOMBR) in the feed side of a FO system used in the treatment of municipal wastewater. Desalination brine is used to draw fresh water from the feed side to the draw side through osmosis. The less concentrated brine was redeveloped using heat through direct contact membrane distillation (DCMD). Two processes, eOMBR and DCMD are combined in a process known as an electro-osmotic thermal process (eOTP) and modelled before assessing its performance. The assessment was done by measuring the osmotic water permeation, internal concentration polarization variable, and reverse salt diffusion flux. These indicators were affected by the operation properties like sludge retention time in eOMBR, internal concentration polarization coefficient, and draw inlet concentration. eOTP performance was assessed regarding how electric field affects the association between operation properties and the indicators. The results showed that the performance of eOTP increases when the current density levels were lower. Higher temperature intensities on the draw side led to an increase in water productivity if the current density was maintained at 5 A/m^2. It was concluded that electro-thermal effects increased the probability of wastewater and brine reuse [101].

Another study by Pal *et al.* [102] was conducted to model an FO-NF system that would be used in the treatment of tannery wastewater. The model was validated using trial data of a semi-experimental unit that used tannery wastewater. The flat sheet cross flow FO membrane ensures approximately all the chromium is blocked and reduces the pollution load of the wastewater (chlorides, sulphates, and chemical oxygen demand) by 98%. The FO module enables the achievement of a water flux of approximately 48 L/m^{2}h. The NF system that was applied downstream enabled the recovery of more than 98% of the NaCl draw solute to be recycled in the FO loop. The modelled FO-NF system predicted the system performance relatively accurately, has a low relative error (<0.1), high Wilmot d-index, and high overall correlation coefficient. Hence, conveying that this model for the FO-NF system can eventually be used for industries at a larger scale to treated wastewater [102].

6.3.3 PRO

By exploiting the Gibbs free energy of mixing, pressure retarded osmosis (PRO) can efficiently transform the osmotic pressure of a saline solution to hydraulic pressure. Although the thermodynamic underpinnings of the PRO process are well established, several parameters still need to be tuned for an economically viable process implementation. One of the most crucial PRO process factors, membrane performance nearly always determines how applications and scale-up implementations are carried out. The power density of a PRO membrane is typically used to assess its performance under specific flux and applied pressure circumstances. The "go, no-go point" in the process of economically evaluating a PRO membrane is often its maximal performance. A large portion of historical and present research on PRO processes has been devoted to developing membranes, with a particular emphasis on the thin film composite (TFC) membrane structure. Research on high-efficiency thin film nanocomposite (TFN) membranes is being pushed farther into the PRO membrane field by the integration and development of nanomaterials. Recent years have seen a surge in interest in PRO, which has the potential to be a significant source of non-intermittent renewable energy. PRO could potentially reduce the negative environmental effects of brine outflow from desalination in Gulf countries' desalination systems. The Gulf region has the biggest desalination capacity in the world, with a total capacity of 11 million m3/day (about 45% of the global total) [30], [97], [103].

The study by [104] work investigates the viability of using PRO to power Kuwaiti desalination and wastewater treatment facilities. To determine the power density using a PRO system, they developed a zero-dimensional model. To obtain more accurate findings for power densities, the model takes concentration polarization and salt leaks into account. They investigated the PRO process's potential for usage as an effective green energy source and as a way to lessen its negative environmental effects. With the current PRO system, their model makes use of the usual characteristics of the RO membranes. Under the predetermined testing circumstances, the model predicted the water flux (Jw) and power density (W). The computed values and the values for the membrane properties (A and B), mass transfer coefficient (k), and solute resistivity (K) were in good agreement. The improvement of membrane properties and the optimization of system operating parameters may increase the output of power from PRO plants. Their findings demonstrate that PRO is a practical method for producing green energy in Kuwait from TWE and brine [104].

6.3.4 Pervaporation

This is a process that applies both evaporation and membrane permeation in the separation of liquid mixtures based on preference. The fed components diffuse through the membrane due to a concentration gradient between the components and consequently evaporate at the membrane's downstream phase. Recovery of the liquid is done by condensing the evaporated vapor. This process is mainly used to separate water-ethanol mixtures. Several experiments and research have been conducted to investigate the viability of this process in wastewater treatment [105]–[110] . Results showed that it can be used in the removal of specific contaminants or treatment of wastewater for micro-irrigation purposes. Figure 4 is the schematic representation of the pervaporation process. Pervaporation membranes play a huge role in promoting the required separation; hence, they are designed with a higher affinity to the target component. They increase water flux and mechanical properties and are beneficial in the desalination process. The pervaporation process is environmentally friendly and energy-saving [107], [110].

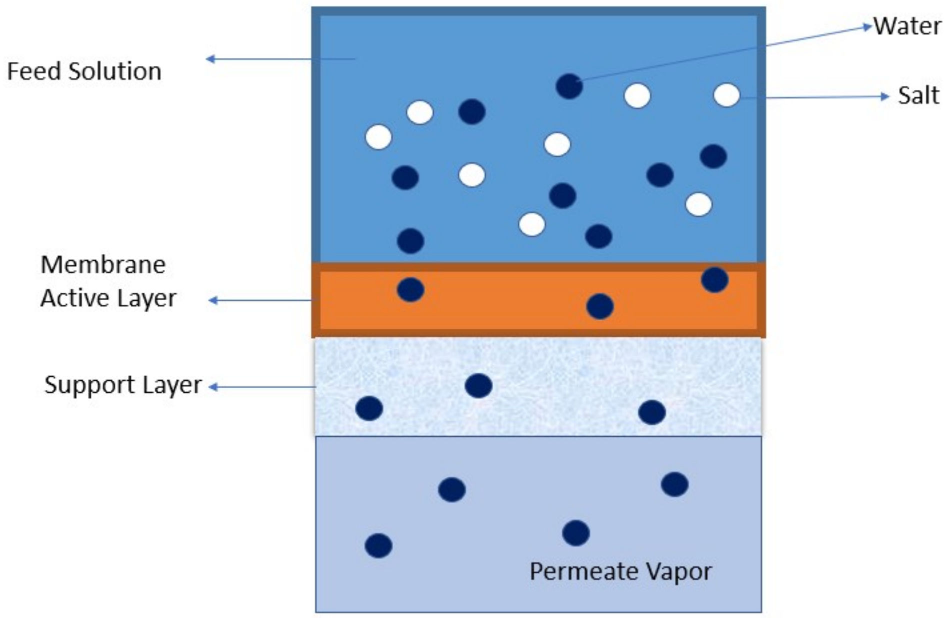

Figure 4 Schematic representation of the pervaporation process

Alharbi *et al.* [110] applied pervaporation using a poly (dimethylsiloxane)-based sealer membrane to extract organic volatile contaminants in over-saturated water. The poly (dimethylsiloxane)-based sealer which was applied in the experiment was SILICONE 1200. Several volatile organic liquid compounds that represented a major part of organic contaminants were released daily into the water for the research. The contaminants that were released were ketones, aldehydes, aromatics (toluene), organ sulfides (thiophene), alkyl halides (chloroform), and alphatic hydrocarbons (heptanes). The assessment was done during the mass transfer of the contaminants and their mixtures were done as they passed through the SILICONE 1200 membrane to estimate the outcome of the separation procedure. Based on the outcomes, the system of diffusion followed a Fickian model. To establish optimal conditions regarding total flux and selectivity, measurement of parameters that affected the pervaporation outcome was done. The parameters investigated were temperature, membrane thickness, and stirring rate. Application of the optimum parameters was done to separate the organic mixture from polluted water using a dynamic pervaporation procedure. The results proved that pervaporation can be used in the removal of selected volatile organic compounds in polluted water with high flux [110].

Kujawski *et al.* [107] applied pervaporation and combined it with adsorption to remove phenol from solutions demonstrating wastewater from phenol generation and cumene oxidation procedure. The transportation and separation characteristics of combined membranes in pervaporation of water–acetone, water–phenol, and water–phenol–acetone mixtures were established. The results showed that all the membranes exhibited selectiveness towards phenol. The best selectivity was exhibited by the PEBA membrane which is not readily available on a commercial scale. Therefore, only PERVAP-1060 and PERVAP-1070 can be used practically. An investigation was also conducted to determine phenol adsorption on the different Amberlite resins. Different grades of Amberlite were applied, and a type of Amberlite exhibited the best properties in decontaminating the aqueous phenol solutions. This study showed that the adsorbent bed can be regenerated efficiently using sodium hydroxide solution [107].

6.3.5 Electro-Dialysis (ED) and Electro-Dialysis Reversal (EDR)

ED and EDR are processes that apply both electricity and ion-permeable membranes to separate dissolved ions from water. An electric potential is used to move the ions from the hypotonic solution to the hypertonic solution via an ion-permeable membrane [110]. The process uses two membranes; one is permeable to only cations whereas the other is permeable to only anions. The application of an electric current causes the migration of ions through oppositely charged membranes. This results in a feed stream with no ions and a concentrated stream that is rich in ions. ED and EDR are used in wastewater treatment to remove total dissolved solids and different ionized constituent particles [111]. There is less membrane fouling because the electrodes are reversed periodically. Water molecules are dissociated through the effects of current [112]. The processes require little pretreatment for feed water and have a high water-recovery rate. ED is not appropriate in high salinity streams since the removed ions are proportional to the desalination energy. Also, it cannot remove non-ionized substances like bacteria and viruses which might cause harm during use [113]. Some of the areas that these processes can be applied include in treatment of municipal wastewater, tannery wastewater, and almond industry wastewater [98].

Several studies were conducted on this technology in several GCC-based universities, such as Qatar University. The research by Sevda *et al.* [113] aimed at desalination of brackish water and bioelectricity generation using after wastewater treatment. Since there is a low supply of potable water compared to the demand, desalination of seawater is necessary. However, membrane and thermal desalination processes have a high energy requirement. Microbial desalination cell (MDC) is one of the latest technologies that show the capability of simultaneous desalination and wastewater treatment. The only energy that is required during the MDC process is that of pumping water. The anode of the MDC contains exoelectrogenic bacteria that oxidize biodegradable substrates in wastewater and the electrons are transferred to the anode electrode. The electrons move externally to a cathode electrode and are used in the reduction of electron acceptors like oxygen. An MDC derives its concept from a microbial fuel cell (MFC). However, an MDC has a central chamber that is in the middle of the cathodic and anodic chambers that is made by a pair of cation and anion exchange membranes. The central chamber serves as a desalination chamber similar to that of electrodialysis. The potential difference between the two oppositely charged electrodes causes the movement of ions from the desalination chamber. The sodium cations move to the cathodic chamber while the chloride anions move to the anodic chamber. This enables the removal of salts from the saltwater. Application of MDC technology can be appealing in the GCC regions where there is a need for desalination of seawater using cheaper means. This technology can be combined with other common desalination processes. [113]

Another research carried out by Alsheyab *et al.* [114] assessed the combination of wastewater treatment and recovery of resources such as energy, water, nitrogen, phosphorous, and added-value products. This can offset the cost of wastewater management to create profits. Therefore, wastewater is perceived as a solution to societal problems. Mass flow examination was applied to evaluate the maximum accessibility of main wastewater components such as solids, nutrients, organic compounds, chloride, alkalinity, and sulfide. The evaluation established that, in Qatar, there are over 290,000 metric tons (MT) of total solids, 81,000 MT of chloride, 77,000 MT of organic compounds, 6,000 MT of nitrogen, 880 MT of phosphorus, and 2,800 MT of sulfide. These components are entrenched in approximately 176 million cubic meters of urban wastewater yearly. One of the potential implementation strategies is the application of anaerobic digestion with biogas generation; the organic matter that is in Qatar's wastewater relates to over 27 million cubic meters of methane per year which is equal to over 270 GWh. The recovery of other components such as nitrogen and phosphorus were recommended [114].

6.3.6 Membrane Distillation

This is a growing membrane technology that is still being researched. It involves the application of heat in the separation of substances based on their volatilities. This process is mainly advantageous in sorting out the feed solutions that have high water concentrations. The process can apply low-grade heat energy in the generation of the required vapor pressure variance between the two membrane sides: feed and product sides. The transportation of water vapor through the hydrophobic microporous membrane is dependent on the pressure gradient across the membrane. Some of the areas where this technology can be implemented include the treatment of wastewater from the dairy, textile, and nano-electronics industries. The membranes used in this process should have a low resistance to mass transfer, low thermal conductivity, and low affinity for water to prevent unnecessary wetting of the membrane. This process can use energy from renewable sources and the recovered waste heat can be used for other uses. It requires a lower hydrostatic pressure than reverse osmosis.

A study was conducted by Alkhudhiri *et al.* [111] in a GCC-based university to investigate the possibility of using air gap membrane distillation to remove mercury, arsenic, and lead. Samples of synthetic industrial wastewater containing the selected elements in different concentrations were primed and treated using air gap membrane distillation (AGMD). This method has a huge potential of removing heavy metals. The experiment applied commercially available membranes with pore sizes of 0.2, 0.45, and 1 μm. The effectiveness of the membranes with various heavy metal concentrations was tested under the operation variables. The results showed that AGMD can be applied in the effective removal of heavy metals. The membranes that had the highest removal efficiency were of two types since they recorded over 96% for heavy metals with different concentrations. The pH value had no significant effect on the efficiency of extracting the heavy metals. It was also determined that the energy consumption had a little dependency on metal type and membrane pore size [111].

Another study by Kalla *et al.* [112] reviewed the application of membrane distillation to treat oily wastewater. The study introduced various oily wastewater sources and their components. They mainly focused on the oily wastewater resources and the different membrane distillation configurations that are used in their treatment. The integrated membrane distillation techniques that were used in the treatment of oily wastewater were also reviewed. The study found out that pore wetting or membrane fouling can be reduced by an integrated membrane distillation system and applying pre-treatment steps such as microfiltration and ultrafiltration [112].

6.3.7 Hybrid Membrane Process

The system using RO-FO is still being explored so that concurrent processes of wastewater treatment and desalination of seawater can be carried out. Firstly, in FO the feed is low salinity wastewater, and the draw consists of seawater. FO treatment provides a reduced volume of wastewater and dilutes the seawater. Then, desalination from the seawater is conducted by RO and brine concentrate is produced. The brine produced in the RO process is fed back into the FO draw tank to increase the concentration gradient. This process can reduce wastewater and produce clean water simultaneously and is applicable in places with low external energy requirements in the separation of solvent-solute solutions.

A study was conducted by Hafiz *et al.* [98] to simulate a hybrid NF-FO-RO process that would be used in the production of irrigation water from treated municipal wastewater. It was necessary to improve the quality of treated wastewater so that it can meet the standards of irrigation water. NF was applied at the first stage, for the production of permeate using relatively low energy. Two membrane combinations were applied to extract more water from the brine produced by the NF process. The simulation results indicated that applying a hybrid FO-RO system produced a higher efficiency than when using the RO process alone to extract additional water from the brine. There was also a reduction in energy consumption by 27% when FO was used as a transitional process between NF and RO. The ultimate quality of the treated water produced met the irrigation standards for food crops [98].

A study was conducted by Vinardell *et al.* [94] to establish the viability of the combined application of reverse osmosis, forward osmosis (FO), and anaerobic membrane bioreactor (AnMBR) technologies to the treatment of municipal wastewater with energy and water generation. The AnMBR influent was pre-concentrated using FO. A draw solution was regenerated, and water produced using RO. The final treatment of the wastewater and production of energy was done using AnMBR. When the FO recovery was limited to 50% in the closed-loop system, the lowest wastewater treatment cost was approximately 0.81€/m3. However, when the FO recovery percentage increases the cost of the wastewater treatment increases substantially. Hence, in this study increasing the recovery to 80% and 90% increases the cost to 1.01 and 1.27 €/m3 respectively. The cost of producing fresh water in an open-loop system that maximized water production was 0.80 €/m^3 while that of a closed-loop system was 1.16 €/m3. Analysis showed that water production was limited by the low FO membrane flux. It was also established that FO membrane flux of 10 liters per square meter per hour would reduce the cost of applying this technology [94].

RO usually has a high energy requirement which increases the cost of wastewater treatment. RO membranes are also prone to fouling. This reduces efficiency and increases the cost of application further. FO, a process driven by osmosis, has increased in popularity even though it still has a low recovery rate. Membrane fouling also affects FO despite its numerous advantages. A review was conducted to differentiate RO and FO fouling [113], [114]. The findings showed that a lack of hydraulic pressure in the FO process reduces the rate of membrane fouling. Additional studies were recommended to determine factors that affect fouling for different processes and the strategies that can be taken in cleaning the membranes to improve their performance [115].

7.0 WASTEWATER TREATMENT AND RELATED RESEARCH IN DIFFERENT GCC COUNTRIES

Similar to other countries, the standards for using treated water for different applications varies and includes several components that need to be within a suitable limit. Wastewater treatment needs to fulfil the required standards, using the appropriate technologies and facilities. In this section the treatment plants and relevant requirements of treating wastewater are mentioned for each GCC country. As seen on Table 4, each GCC country has facilities which are used to treat the wastewater and then reuse in a certain percentage.

Table 4 Number of treatment facilities for wastewater treatment, capacity and percentages of treated and reused wastewater [41], [42]

Countries	No of plants	Treatment capacity (Mm^3/year)	Treated and collected wastewater (%)	Reused amount of the treated wastewater (%)
UAE	86	556	98	55
KSA	97	1730	64	16
Qatar	23	123	98	100
Oman	66	69.3	99	100
Kuwait	6	239	77	61
Bahrain	22	81.5	44	90

7.1 Wastewater Treatment in Qatar

Wastewater in GCC countries is constantly rising, Qatar for example, is one of the countries with the lowest quantities of fresh-water resources and in spite of that, its overall population has the highest water consumption per capita (more than 500 L/day/person). Therefore, this country is completely reliant on technologies such as wastewater treatment. And since the wastewater is increasing yearly in the state of Qatar, so is the amount of treated water [116].

Since the world's population is growing extensively and the need for natural resources is constantly rising, a few successful countries, such as Qatar has the ability to transform a large wastewater treatment plant into a source of income, merely by combining advanced resource recovery (such as water, nitrogen and energy) with wastewater treatment [116].

Following the law, wastewater in Qatar has to be treated properly before being reused or thrown out to nearby areas. In Qatar, the public works authority (Ashghal) is in charge of treating the wastewater in the country by constructing and coordinating wastewater treatment plants. The wastewater contains toxic substances such as pathogens, artificial chemicals, and organic materials. As high amounts of organic substances can cause oxygen depletion or eutrophication; in which the concentration of nutrients such as nitrogen and phosphorus increases and causes algal blooms. Such algae may yield toxins, which can be harmful to many aquatic creatures. Below Table 5 shows the various types of wastewater plants across the state of Qatar, including their capacities:

Table 5 Wastewater plants across the state of Qatar, including their capacities

Sl. No.	**Plant**	**Total Capacity (m^3/day)**
1	Doha North	439,000
2	Saililyah	280,000
3	Naijah	180,000
4	Lusail	60,000
5	Doha industrial area	90,000
6	Al Thakhira	56,000

Thus, the overall capacity is 1,105,000 $m^{3/}$day, aside from the small startup projects in Al Shamal, Shahaniyah, AumSallah, North Camp and Al Khareeb. Hence, the accumulated treated wastewater capacity is awaited to reach an even bigger capacity by 2030 [117].

7.2 Wastewater treatment in Saudi Arabia

In Saudi Arabia, there are some decentralized wastewater treatment plants, with a portion of the plants being private and others claimed by the Saudi government. Figure 5 is the general wastewater processing flow diagram in Saudi Arabia [118]. The decentralized wastewater treatment plants are associated with the treatment, and removal or reuse of wastewater from discrete homes, gathered homes, separated networks, ventures, and institutional offices. In the city of Riyadh there are more than 77 decentralized wastewater treatment plants (with an absolute limit of

178,000 m^3/d). Currently, there are five consolidated treatment plants (with wastewater limits going from 3000 to 200,000 m^3/d and an absolute limit of 634,000 m^3/d). There are two concentrated sewage treatment plants that are at present under development, with limits intended to reach 200,000 m^3/d. During the planning of this project, an agreement was finalized for the development of another sewage treatment plant to create tertiary treated wastewater with a normal limit of 400,000 m^3/d and the extreme limit of 640,000 m^3/d. There are expansion designs for the wastewater plant to be extended to 1,200,000 m^3/d soon. The totality of the incorporated sewage treatment plants in the capital Riyadh are run under the General Directorate for Water (GDWR), which is part of the Ministry of Water and Electricity. Additionally, in the city of Riyadh, about 170,000 to 200,000 m^3/d of the treated water discharge is used for landscaping and agricultural watering. Also, around 15,000 to 20,000 m^3/d is utilized by industries, and the remaining water is discharged into Wadi Al-Batha, which contributes to groundwater recharge [118]. Table 6 shows some of the main wastewater treatment plants in Saudi Arabia.

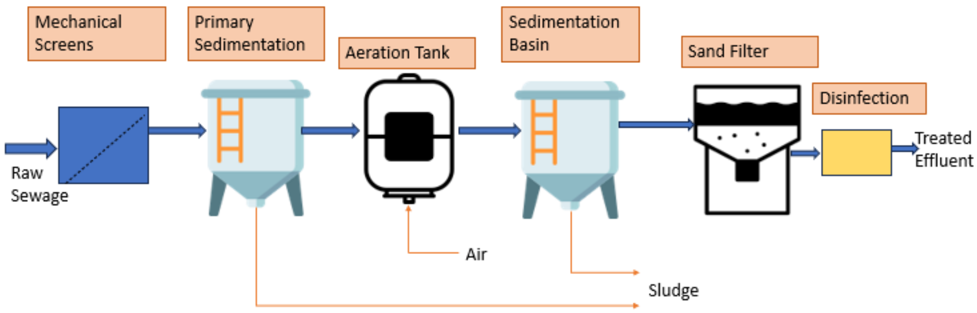

Figure 5 General wastewater processing flow diagram in Saudi Arabia

Table 6 Some of the main wastewater treatment plants in Saudi Arabia

Wasteewater Treatment Plant	Designed Capacity (m³/day)
Northern Plant of Riyadh Wastewater Treatment Plant (NP-RSTP)	200,000
Southern Plant of Riyadh Wastewater Treatment Plant (SP-RSTP)	200,000
King Saud's University Wastewater Treatment Plant (KSUSTP)	9,100
Al-Imam University's Wastewater Treatment Plant (AIUSTP)	4,800/11,520
Diplomatic Quarter Wastewater Treatment Plant (DQSTP)	10,000
National Guards' Housing Compound's Wastewater Treatment Plant (NGSTP)	11,000

A study by Ghanem *et al.* [120], examined the economic aspects of using treated wastewater for green fodder production, a set of economic equations was used, a method of using multiple criteria, and a scoring method to determine priority. Almost 67% of agricultural water was consumed by green fodder, according to the study. Thus, the priority of using treated wastewater belongs to the region of Riyadh first, then the eastern territories, the Qassim region, Hail, Makkah Al-Mukarramah, Tabuk, Asir, Al-Jawf, Jizan, Madinah, Najran, the northern borders, and Al-Baha last. There are 53.05 thousand hectares of land which can be used for the harvesting of the fodder crops, and 953.75 thousand tons can be produced. A net gain of 382.73 million Saudi riyals was achieved by the Saudi agricultural economy by treating wastewater to make it usable. The cost of treating wastewater is 2126.22 million Saudi riyals, while the benefits obtained are 2508.95 million Saudi riyals. This study therefore recommends the use of treated wastewater for green fodder production [120].

7.3 Wastewater treatment in United Arab Emirates

The Abu Dhabi Sewerage Service Company (ADSSC) at present operates two significant wastewater treatment plants in the UAE, together with 24 limited scope wastewater processing facilities, and 236 pumping stations (80% situated in Abu Dhabi) and more than 7400 km of the sewer mains (66% likewise in Abu Dhabi). Additionally, ADSSC is also accountable for managing and executing the system development needed to help for future development. Two of the biggest wastewater treatment plants, providing the capital Abu Dhabi city and the surrounding region, are the Mafraq and Al AinZakhar plants. The biggest wastewater treatment plant in Abu Dhabi (the Mafraq plant) has a mean flow per day of 360,000 ± 16,000 m^3/day. The Mafraq plant comprises of an ordinary initiated wastewater treatment followed by sand channels, chlorination of water and fragrance control for the fluid part and mesophilic anaerobic processing for the sludge. The nature of the wastewater treated in the Mafraq plant is in fact reasonable with the reuse principles recommended by the Regulation and Supervision Bureau (RSB). Nevertheless, one significant issue with the expansion of the industry, is that the heavy metal concentration may significantly rise in the wastewater treatment facility. Hence, the greater part of the sludge in Abu Dhabi is utilized for soil composts, although a little rate goes to landfill. The measure of recovered wastewater used for water system is generally 170 Mm^3/year, while 287 Mm^3/year of recovered wastewater is used for water system in recreational areas and greening of street boundaries and focal traffic roundabouts, yet no recovered wastewater is utilized for horticulture. Henceforth, industrial water use in Abu Dhabi is around 46 Mm^3/year, which is totally acquired from inward desalination plants that are found inside modern offices. Water utilized in industry is split into three primary classes: measuring water with consumable water prerequisite, washing water with consumable to more minor water quality and cooling water (ocean water quality for interior cooling). Recently, using treated wastewater in Emirates has progressed among its population and evolved during the most recent couple of years, for instance one organization in the UAE has marked a huge agreement covering the conveyance of 20 mobile wastewater treatment plants with 12 filtration units, each to the Dubai district. Moreover, the UAE utilizes around 389 Mm^3/year of wastewater for metropolitan uses, of which 287 Mm^3/year are utilized for watering parks and suitable facilities. In any case, the recovered wastewater use in area cooling is treated in nearby offices worked by the lodging organizations. The interest for recovering the wastewater for reuse in metropolitan applications is required to increase in the future. The United Arab Emirates has different attractions for sightseers in various places explicitly between the time span from 1993 and 2000; and even more during the latest years from

2015 to 2021. In this way, the quantity of hotels and customer hospitality in Dubai expanded by 37%, from 18,638 to 25,571 rooms. However, there is no information accessible on water utilization by vacationers in the UAE. Approximately 130 Mm^3/year of treated wastewater is utilized in agriculture and landscaping; the rest (579 Mm3/year) is obtained from groundwater assets. In the approaching future, a deeper understanding of the benefits of reusing treated wastewater due to its nutrient and organic nature will allow the efficient use of treated wastewater in landscaping, agriculture, and other suitable facilities across the UAE [121].

Wastewater is a significant and unpredictable water asset in Abu Dhabi. There are two main sewage treatment plants in Abu Dhabi City and Al Ain city, both treat practically 95% of sewage and work slightly over their plan limit. The city of Abu Dhabi gathers 146 Mm^3/year while Al Ain gathers around 36 Mm^3/year. The remainder of the 5% is treated by smaller units to serve more networks. Treated sewage outflow per individual each day is assessed to be 130 for the population of 1.4 million in Abu Dhabi. Whilst, some treated sewage effluent is utilized for landscaping, approximately 35% is discarded into the Gulf [122].

7.4 Wastewater treatment in Kuwait

The country of Kuwait also stands out in the collection of wastewaters across many regions. It helps its citizens by eliminating fees allocated for wastewater collection, whether it is wastewater coming from the Kuwaiti government, or even shopping malls and centers, not to mention the water from the surface. However, water coming from the rain is usually collected in a different system compared to the rest of the wastewater, which is discarded into the ocean without any treatment. Overall wastewater produced by the population roughly reached 1Mm^3/d and around 154.6 m^3 d/capita/y, also assumed to be equivalent to 70% and up to 80% of the freshwater usage. Like every other country worldwide, Kuwait's wastewater production is rising yearly by around 3.6%. To control and observe the redistribution of treated effluent, almost all the treated effluent is initially kept in reservoirs at the Data Monitoring Center, which have a total capacity of 38 K m^3. Untreated wastewater is dumped into the sea in a total of 25% of cases. According to a study by Aleisa *et al.* [128] the quantity of pollutants released into the ocean will rise again if the expansion and development projects on the wastewater treatment plants do not begin within a suitable time frame. This wastewater contains a range of pathogens, including microorganisms, parasites which can lead to buildup of nitrous oxide and create methane gas, thus resulting in harming the environment. Al-Abdulghani *et al.* [129] demonstrated that high amounts of phosphate and nitrogen were observed in Sulaibikhat Bay (South-West area of the straight) because of its proximity to anthropogenic activities. The excess concentration of phosphate and nitrogen leads to rapid growth of algae (eutrophication). Moreover, loss of biodiversity can occur as the level of oxygen decreases in waterways due to excess algae, causing the aquatic species to suffer and become extinct. Tests gathered at various profundities from the GCC shores were examined utilizing physical, compound, and microbiological scientific methods. The outcomes demonstrated that the pollutants are carried through the wind along the Arabian Gulf and this leads for the contaminants to be transported to the marine biological system [128]. There are five wastewater treatment plants in Kuwait. These are Alriqqa, Um Alhayman, Sulaibiya, Kabd and Alkhiran (pilot plant). Aljahra wastewater treatment plant has been converted to a major pumping station feeding Kabd wastewater treatment plant. Kuwait's wastewater plants operate by the governmental sector except for Sulaibiya and some wastewater treatment plants have five years operation contracts by private companies. The wastewater plants in Kuwait have raised treatment quality from secondary to tertiary since 1984 [128].

Kuwait has significant wastewater treatment plant development projects, including sewage collection, legitimate treatment, and expanded treated wastewater reuse that will bring about a 100% inclusion of sterile administrations inclusion. The imminent tasks will likewise move all wastewater plants and major pumping stations out of local locations for sterile and sporting reasons. What's more, the planned wastewater treatment projects intend to further develop upkeep rehearses by shortening pumping stations. Pumping stations will be diminished to five significant stations rather than 60 minor ones. The imminent wastewater treatment plant projects have been separated into 16 phases, 8 of which have effectively been finished [123]. Table 7 shows the wastewater treatment plant development projects of Kuwait.

Table 7 The wastewater treatment plant development projects of Kuwait [120], [121]

Project	Description
Expanding the Sulaibiya wastewater treatment plant	Capacity expansion from 425,000 cubic meters per day to 600,000 cubic meters per day
Expanding the Um Alhayman wastewater plant	Capacity expansion from current volume of 20,000 cubic meters per day to 650,000 cubic meters per day
Developing the Egaela pumping station	The correlation of this pumping station will be with the existing stations to address the wastewater management needs of Ahmadi and Mubarak Al Kabeer regions and have a capacity limit of 360,000 cubic meters per day
Developing the pumping station at Alriggae	Create capacity limit of 800,000 cubic meters per day, strategically poised to replace the function of 29 existing pumping stations
Replacement of deteriorated pumping and lifting stations	To improve functionality and resilience for the future of WWTP
The construction of new pipelines with increased depths	To enhance the water flow efficiency
Installation of alternative flow sewer vents	Will be strategically designed to accommodate future demands and requirements
Expansion of the Ardiya Pumping Station	Is projected to accommodate approximately 600,000 cubic meters per day

7.5 Wastewater Treatment in Bahrain

As of late, Bahrain has demonstrated itself to be a leader in the journey for advancement in the Middle East as well as the whole globe. The fabulous water-front of Bay of Bahrain, the advanced city of Diyar-Al-Muharraq or the Bahrain monorail are just a portion of the indications of a country developing quickly. With the significant lump of its Gross Domestic Product (GDP) emerging from the administrations area, Bahrain is a significant financial center point in the GCC which describes itself with the spirit of working together and an inviting migration strategy.

Bahrain's own population is nearly 1.3 million housed in a space of 710 sq. kms. This implies one of the greatest population rates on the planet, projected to develop at a rate of 4.6% every year. Thus, for supporting the growing population and their demand for adequate quality of water resources an effective water management system is a critical requirement in Bahrain. The effective management of the water services consists of water treatment for one-time utilization and a comprehensive methodology which includes the appropriate treatment of the subsequent wastewater. Additionally, this methodology ought to integrate the recycling of water to improve the water cycle [126].

The optimistic idea of wastewater management is being put to execution in the country of Bahrain by the Madinat Salman WWTP, which has a daily wastewater flow of 40,000 m^3. The Engineering, Procurement and Construction of the plant was granted to VA Tech Wabagas a team with Belhasa projects. The extent of the request grant likewise incorporates 5 years of operations and management (O&M) program. The site is based on 13 islands of recovered land which records 750 hectares of absolute plant region. Some of the most important characteristics of this WWTP includes the interaction plan. It starts with the delta chamber and a 85,000 m^3 each day terminal lift pumping station which sits at a profundity of 21 meters. The water from the profound sewage gravity network is pumped through this depth with the assistance of a dry well pump. Moreover, the core of the plant is the tertiary treatment which renders it further virtue through circle channels and sterilization utilizing chlorination. The plant runs on the way of thinking of asset recuperation for the climate to the most extreme degree. The gathered sewage is processed, thermally dried, and packed away through a programmed sacking plant available to be purchased to ranchers as fertilizer [126].

This project positively impacts around 100,000 individuals as it effectively manages water resources with a possibility to recover water from sewage at the city of Madinat Salman in the developing realm of Bahrain. The plant is a feature model and provides the foundation for resolving the issues based on the wastewater treatment process in Bahrain as well as the whole GCC district [126].

In addition to the Madinat Salman WWTP, Bahrain's Ministry of Works, Municipalities Affairs and Urban Planning is trying to foster another sewage treatment plant (STP) in the southwest space of Bahrain. The service has welcomed advisors to present recommendations for the agreement to give pre-consultancy administrations to planning the Southwest STP. The expert will be entrusted with deciding the limit of the new STP and evaluating the potential for extension to oblige the future trunk sewer and essential TSE. The undertaking is important for Bahrain's endeavors to grow and redesign its sewage organization, which regularly battles to manage stream levels. In September 2020, the service granted an expected $364m agreement for hiring workers for the extension of the Tubli wastewater plant. The consortium delegated for the work includes Saudi Arabia's Azmeel, UAE-based Tecton and Germany's WTE Water Technology. The development will twofold the limit of the Tubli plant from 200,000 cubic meters a day (cm/d) to 400,000 cm/d. Tubli is at present preparing in excess of 300,000 cm/d of wastewater, prompting crude sewage releases into the ocean [127].

7.6 Wastewater treatment in Oman

Over the next 20 years, the Sultanate of Oman intends to invest $7bn to advance wastewater development. According to a study implemented by an Oman Observer, the investment is part of the country's commitment to achieving Sustainable Development Goal 6 (SDG6), which is one of 17 global goals set by the United Nations General Assembly in 2015 for the year 2030 [128]. Another study carried out by the Supreme Council for Planning (SCP) found that 86 percent of the nation's drinking water needs were satisfied by desalinated water, and the remaining 14% by groundwater [129] .

Thus, the Omani government plans to increase investments in wastewater treatment and reuse, since desalinated water production increased from 196 million m^3 per day in 2011 to 311 million m^3 per day by the end of 2018. In addition, the report mentioned that 98% of the urban population relies on sewage disposal and around 97% of the rural population relies on sewage collection. Currently, the country uses 68 wastewater treatment plants, which produce about 94 million cubic meters of wastewater each year. This water is used primarily for irrigation, farming and cosmetic reforestation. As part of the National Strategy for the Use of Tertiary-Treated Wastewater 2040, Oman seeks to expand the construction of sewage treatment plants and extend the sewage network lines at a cost of $7 billion, equivalent to $381 million annually. Therefore, groundwater pollution is expected to be reduced by treating and reusing wastewater. Further, the report highlighted that the Sultanate intends to create sustainable freshwater availability and supply by 2030 by balancing supply and demand and using nonconventional sources (treated wastewater) which are currently used to replenish coastal aquifers. Additionally, by implementing water demand management (WDM) policies and changing crop production patterns and irrigation patterns, Oman hopes to increase the available water use efficiency to around $47.50 per cubic meter in 2018, primarily in the agricultural sector as it consumes 83 percent of available water [62], [129].

8.0 WASTEWATER REUSE AND RELATED RESEARCH IN DIFFERENT GCC COUNTRIES

8.1 Wastewater Reuse in Qatar

Rough climate, severe drought, and environmental change make persistent water deficiencies in the Middle East. Practical difficulties as well as financial problems have raised the challenges in water management at public and institutional levels. The study conducted by Dare *et al.,* [128] delved into crucial aspects concerning wastewater treatment systems and the practice of wastewater reuse within Qatar. It meticulously tackled a range of issues, encompassing the assessment of various reuse strategies' pros and cons, a comprehensive juxtaposition of treated wastewater quality, and the diverse applications it can serve. Moreover, the study skillfully pinpointed challenges intertwined with the management of such systems, encompassing both administrative hurdles and the intricate social dimensions associated with the reuse of wastewater resources.

Water quality investigations and conferences with farmers, business partners, and water specialists and agribusiness specialists were directed. Future chances and difficulties for treated wastewater reuse in agribusiness are distinguished based on the closeness of the treatment facility to the suitable applied location, water quality, and inspiration of farmers. In Qatar, despite the huge interests in delivering great treated wastewater using advanced treatment innovations, there is little interest in it. Water guidelines, laws and acts, and activity plans desperately should have been coupled and coordinated for execution of such a process, with the sole aim of reusing water. Thus, with the growing population and climate variability contributing to the increased pressure on traditional water resources, it will become increasingly important to use treated wastewater and other reclaimed water in the region and throughout the arid world in the future. Despite Qatar's high effluent quality and the immense public investment in water production and wastewater management, the public is still hesitant to adopt treated wastewater as an alternative to freshwater in the country [125]. Figure 6 is the Aggregated water use balance in 2021, in Qatar which is used to depict the TSE used and lost from the net desalinated treated water. The table below (Table 8) outlines the characteristics, cost, and technology of Qatar’s plants:

Table 8 Qatar’s reusable water plant details [117], [125]

Plant Technology	**Doha South Sewage Treatment Works**
Year Built	1960 and then expanded in 2013
Design Capacity (m^3/d)	245,000 m^3/day
Actual Flow (m^3/d)	245,000 m^3/day
No of person reached	900,000
Cost to Construct	$350,000,000
Source of Capital	Government
Energy Consumption	0.2 kWh m-3
Applications of Treated Wastewater	Landscape (60 percent), groundwater injection (40 percent)
Application of Stabilized Sludge	Soil conditioner
Excess Treated Water	Stored in tanks or dispersed outside Doha into natural sinks
Typical Equipment	Screens, grit removals, primary settling tanks, aeration tanks, final settling tanks, chlorination, tertiary treatment sand filters, digesters, sludge pressing plant, surplus activated sludge thickeners

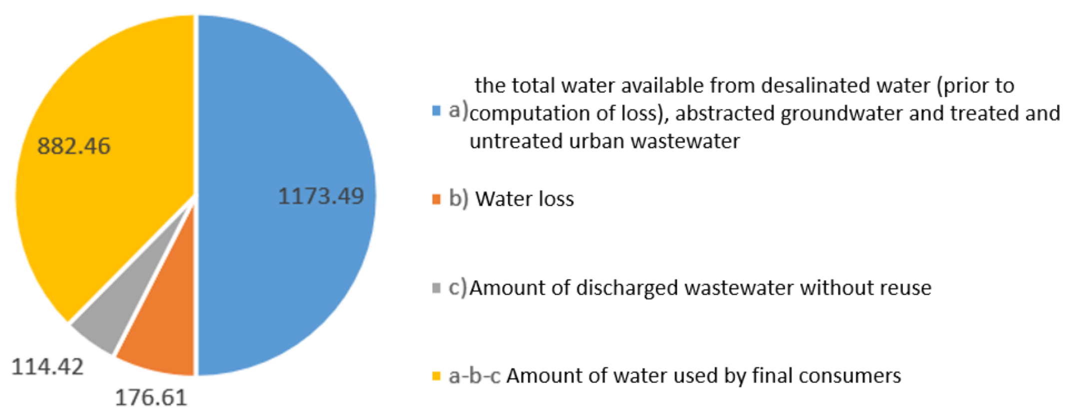

Figure 6 Aggregated water use balance (million m3 per year) in Qatar

The results of this study confirmed that many wastewater treatment facilities evaluated can produce effluent that is compatible with agricultural applications under appropriate maintenance and monitoring conditions; however, decentralized monitoring and decentralized management are significant risks to public and environmental health. Additionally, a dynamic approach should also be considered for the daily and seasonal variability of water quality. Thus, the viability of treated wastewater reuse is highly dependent on the regional water policies, the national and local water governance measures, health considerations, and consumer perceptions [125], [131].

8.2 Wastewater Reuse in Saudi Arabia

The treatment of wastewater is a critical step for sustainable water resource management, especially in water-stressed countries located in arid regions that depend on groundwater and desalination to meet their needs. A study carried out Mu'azu *et al.*, [43], [118] analyzed the socio-demographic variables influencing public perceptions of reusing wastewater for non-domestic purposes. A structured questionnaire was used to collect data from 624 households in the Dammam Metropolitan Area, Saudi Arabia, and descriptive and inferential statistics were used to analyze the data. Figure 7 presents the different research problems, their findings, and recommendations. The findings of the logistic regression show that the possibility of households accepting the reuse of treated mixed wastewater is affected by the gender ratio (OR) of 2.71–2.18, residence (OR = 1.32–1.03) and age (OR = 1.22–0.18) and level of education (OR = 1.33–0.98) compared to mixed wastewater, treated gray wastewater is more acceptable. Even among the educated class, these findings highlight the difficulty the country might face in accepting the public acceptance of treated wastewater for uses other than domestic use. Taking steps to segregate wastewater streams and conducting intensive campaigns to change negative perceptions of treated sewage effluent are important elements to meeting the country's growing water needs sustainably. According to the study, the country will need to fully reuse and recycle treated wastewater for a wide variety of non-conventional uses if it wishes to significantly reduce its reliance on desalinated water and non-renewable groundwater. Figure 8 presents the water reuse sectors in Saudi Arabia in 2018 [43].

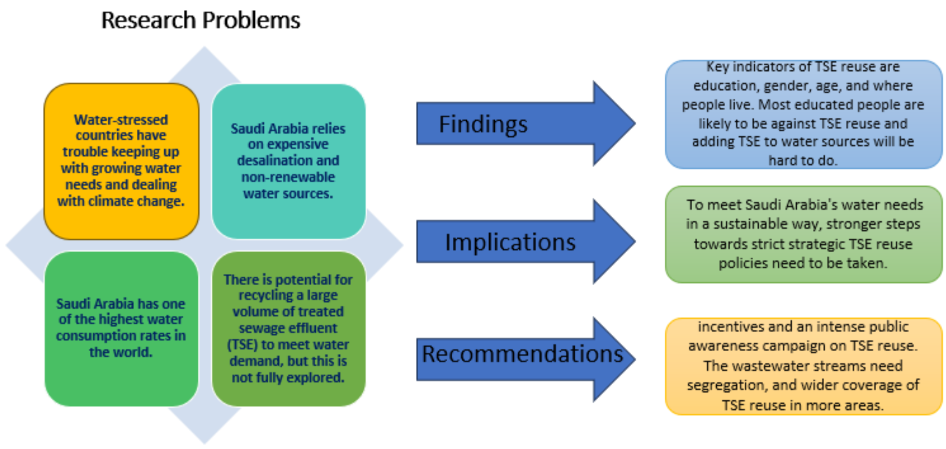

Figure 7 Different research problems, their findings, and recommendations

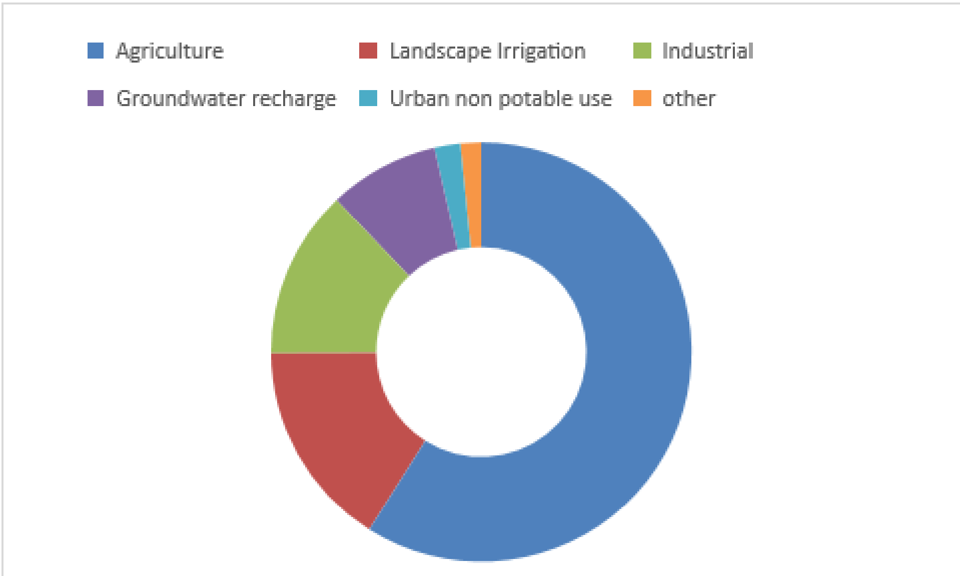

Figure 8 Water reuse sectors in Saudi Arabia

8.3 Wastewater reuse in United Arab Emirates

Due to the rapid growth of the country's urban population and its limited fresh-water resources, the need for freshwater in UAE has increased significantly. Thus, in order to meet the growing demand for water, a sustainable water cycle is crucial. In many regions, wastewater is an essential water source that can meet many of the needs of the population. It is, however, necessary to overcome technical, institutional, and social barriers in order to propagate the use of treated wastewater. In addition to that, it is essential to ensure the sustainable adoption of this strategy in the broadest range of stakeholders through the development of an economically viable model [131]. Approximately two billion liters of wastewater will be treated daily at the overall 75 municipal wastewater treatment plants the United Arab Emirates (UAE).

Despite the large amount of products that are recovered for reuse, a significant amount is discarded due to no demand [118].

A case study was done by Bhattacharjee *et al.,* [131] on a privately-owned sewage treatment plant in Sharjah in the United Arab Emirates (UAE) and this study discussed the challenges and opportunities encountered during the commercialization of wastewater reuse. The results of the study showed that treating wastewater required less energy and is more economical than desalinating water, thus making it a more reliable and sustainable source of water. Based on the results of this study, lack of reclaimed water distribution networks and unfavorable end-user perceptions of reclaimed water use are two critical factors limiting reclaimed water's economic viability. In response to these challenges, several approaches have been recommended, including the establishment of pipeline networks, introducing government policies, and engaging the public more. It should be considered in the near future to utilize reclaimed water with environmental benefits through aquifer storage and recovery [131].

8.4 Wastewater Reuse in Kuwait

Kuwait faces constant demands for water due to rapid population growth, urbanization, and agriculture. Thus, most of the country's drinking water is derived from desalination, with very small amounts from underground aquifers. Using wastewater effluent for irrigation purposes at least, could provide an excellent source of water to supplement this declining water supply. In addition to reducing fresh water supply needs, wastewater effluent can minimize wastewater disposal to the environment. In order to reduce the usage of desalinated water and to prevent overstressing depleted aquifers, water recycling is being considered by the country as a viable alternative. Nevertheless, among the countries with the best sanitation coverage, Kuwait is ranked fifth, with five wastewater treatment plants serving the metropolitan and suburban areas, with a combined capacity of 239 million m^3/y. Kuwaiti treatment and reuse practices of domestic wastewater are assessed in a study executed by Aleisa and Al-Shayji [123], which highlighted effluent types, quantities of treated and reused water, future plans, challenges, costs, and tariffs, and provided recommendations to better utilize treated water. The study showed that approximately 75% of Kuwait's wastewater is treated and 58% of it is reused, with a total of 154.6 m^3/capita/year produced by a single person on average. This shows an overall increase of 3.6% yearly. Water reclaimed from sewage treatment plants accounts for 19% of the total water consumed by the agricultural sector. Treated effluent (TTE) consists of 270 K m^3 of irrigation water used for landscaping and fodder, but not for food production. Irrigation of crops and natural reserves is carried out with 318 k m^3/d of treated effluent. As TTE contains essential nutrients for plant growth, compared to RO permeate (ROP) that does not have the essential nutrients, it is a better option for crop irrigation, including raw crops like vegetables and fruits. Ideally, ROP is used by municipalities to restore depleted aquifers and create subsurface reservoirs for providing water for security purposes. Moreover, the national standard for treated reclaimed water uses in agricultural should be modified to allow wider reuse of TTE and ROP without damaging public health. Further, additional tests are needed for wastewater treatment plants inflow to ensure it adheres to chemical and biological standards in order to protect bioactivity in aeration tanks and effluent quality [41].

The result of this study showed that in Kuwait, the cost of 1K imperial gallons of desalinated water is $8.10, whereas the tariff is worth less at $2.40. It costs the Kuwaiti government $1.65 per 1K imperial gallons of tertiary treated effluent (TTE) and $2.55 for treated (RO) or ROP. Consumers pay $0.549 for ROP and US $0.36 for TTE. As a result, government subventions for water and electricity lead to the large difference in cost and tariff per 1 K imperial gallons and the total cost of desalinated water is three times greater than ROP and five times greater than TTE [41], [123].

8.5 Wastewater Reuse in Bahrain

Wastewater reuse is a critical aspect in Bahrain that is thoroughly researched to provide suitable polices and solutions for water scarcity. The UK's Bluewater Bio has been awarded a project to upgrade the Tubli wastewater treatment plant in Bahrain, which will more than double the capacity of the plant. The company will provide engineering, procurement, and construction (EPC) services. Back in 2013, two of the plant's 10 aeration lanes were converted to hybrid activated sludge process (HYBACS), generating 100,000 m^3/d of water for reuse from treated sewage effluent (TSE). As part of the tertiary treatment system, the TSE is filtered and ozonated for reuse in irrigation. With the recent contract addition, TSE will have a total of 230,000 m^3/d of aeration capacity available for reuse. In addition to operating and maintaining the HYBACS systems, Bluewater Bio will also maintain both systems for 22 months. In Bahrain, the 1.4 million-person Tubli wastewater treatment plant is the largest of its type. A patented hybrid activated sludge process, HYBACS enables a conventional wastewater treatment plant's clarifier and aeration tank to handle a higher load of activated sludge. In the system there is a SMART unit, a patented technology that doubles the production of hydrolytic enzymes by naturally occurring bacteria, allowing the activated sludge stage to load more effectively [132].

8.6 Wastewater Reuse in Oman

A governmental company (Haya Water) produces 70,000 m^3 of treated wastewater per day in the capital Muscat, Oman. As part of the municipal treatment program, treated effluents are used for irrigation, and excess treated effluents are discharged into evaporation ponds near the major Muscat treatment plants. Environmental concerns, such as health and aesthetic concerns, are raised by these evaporating ponds. In addition, the treatment plants in Muscat will produce a higher concentration of treated effluents in the coming years. Thus, for treated effluents to be reused in this region with limited water resources, sustainable and beneficial recycling options are essential. The project implemented by Baawain *et al.,* [129] involves implementing a comparison of a number of potential reuse alternatives for treated wastewater in Muscat, Oman. Six of the options include: urban recycling, agriculture recycling, industrial recycling, groundwater recharge, potable recycling, and energy generation. This project's guiding goal is to conserve water resources by recycling treated municipal wastewater for various purposes. Water demand for industries will become less, and enterprises will become more prosperous. Industries will also be introduced to reliable and potentially less expensive water sources over the next few decades. The produced water quality and the recycling standards determined that the following three options were more suitable for Muscat: 1) urban recycling, 2) industrial recycling, and 3) agricultural recycling. To verify the suggested ranking of reuse options, a cost benefit analysis will need to be conducted [129].

Lastly, the results of the sampling program and the comparative study showed that urban reuse, industrial reuse, and agricultural reuse were the most suitable reusing options in Muscat [129].

9.0 OUTLOOK

The global demand for water is disproportionate with the supply on the most populated continent of the world, Asia and specifically, in the GCC region. Reclaimed water use and wastewater treatment are important measures to achieve the sustainability of the water management system and solve the supply and demand inconsistency. The study done by Liao *et al.,* [133] evaluated the impacts of possible factors on wastewater treatment and reclaimed water use, including GDP level, availability of water resources, withdrawal of water, water stress, using the data collected from 48 typical Asian regions and countries. Per capita GDP and water stress are significant factors affecting wastewater treatment and reclaimed water use, according to the study. The development of wastewater treatment is conducive to the development of reclaimed water in most Asian countries, even though it is still at the beginning stages. Thus, researchers believe that the results of this study can contribute to improving water management and sustainability in many Asian countries, including the Middle East [133].

The GCC should be putting into practise cutting-edge wastewater treatment technology that will be greatly influenced by the need to minimise carbon emissions, strict restrictions, and a push for water reuse. The GCC should be adopting wastewater treatment technologies in the future and making major strides towards their full-scale and widespread application. Moreover, technology for wastewater treatment will be built around gas production and recovery. With subsequent separation from wastewater, it is possible to produce ammonia (NH_3), methane (CH_4), hydrogen (H_2), and carbon dioxide (CO_2). This method provides a secure way to obtain clean streams that may be used to produce chemicals or renewable energy. Ultimately, the GCC should employ water reuse and improved wastewater treatment methods in order to address the difficulties of water scarcity.

10.0 CONCLUSION

The dependency on freshwater resources in GCC countries is an underlying issue that has caused various problems to arise. The rate at which the renewable resources are depleted can accelerate water scarcity in these regions, and eventually lead to loss of water quantity and quality. Since the GCC region is mainly a dessert climate, this causes external issues as there is limited rainfall and extremely hot temperatures. Moreover, the contamination caused due to improper wastewater disposal can lead to excessive environmental risks and hazards. The primary solution to resolve the water scarcity issues and reduce the stress on the freshwater sources in the GCC region are recycling and treating the wastewater. Wastewater treatment and reuse play an essential role in maintaining the safety of the environment as well as human life, as it is a sustainable method to recycle water and make use of it without relying on the transport of fresh water from other countries outside the GCC. However various elements with regards to the treatment technology, management and policy need to be implemented to attain a sustainable solution.

Currently, the annual waste material collection is around four billion-M^3, with three hundred waste material treatment plants treating 73% of it. Achieving a system of reusing and treating wastewater needs a good amount of time for management, planning, thorough administrative evaluation, a productive design, excellent storage capacities and distribution networks to reach the public. It is now technically feasible to produce water of virtually any quality using wastewater reclamation and purification technologies, and those advancements will continue. Due to the gradual evolution of technologies and the understanding of health and environmental risks, it is now possible to produce reclaimed water of a specified quality to meet multiple water use objectives. The final decision to collect reclaimed wastewater is mainly based on economic, legislative, and public policy factors related to the need for a reliable source of fresh water and water pollution control in large-scale cities. In the case of the GCC, the financial planning is crucial, considering some of the Arab countries rely on the international money to help with operation, maintenance, and repair of existing treatments facilities, which are often outdated and in poor working conditions. Not to mention the assumption of the population presuming that treated wastewater is still unfit to be utilized or somehow unsanitary. Integrated water treatment and reuse planning should successfully allow a water utility to serve short-term needs and improve fresh water supply dependability even as it reduces water consumption. It is imperative to have accurate cost figures when planning and administering wastewater reclamation and reprocessing facilities. Since more steps are being implemented such as the preliminary treatment, secondary treatment, tertiary treatment, sludge treatment and even odor control, it can lead to increase the expenses. Various of the relevant studies discussed in this review paper convey distinct and detailed research done for each country in the GCC region; in order to obtain a clear understanding of the outcome within the results, related to the reuse and treatment of wastewater.

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