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# Constructed Wetlands for Sustainable Wastewater Treatment in Hot and Arid Climates: Opportunities, Challenges and Case Studies in the Middle East

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**Abstract:** Many countries and regions around the world are facing a continuously growing pressure on their limited freshwater resources, particularly those under hot and arid climates. Higher water demand than availability led to over-abstraction and deterioration of the available freshwater resources' quality. In this context, wastewater, if properly treated, can represent a new water source added in the local water balance, particularly in regions of Colorado, California, Australia, China and in the wide region of the Middle East, which is characterized as one of most water-stressed regions in the world. This article summarizes the status of wastewater treatment and management in the Middle East and discusses the challenges, the various barriers and also the opportunities that arise by introducing the sustainable technology of Constructed Wetlands in the region. Furthermore, the aim of the article is to provide a better insight into the possibility and feasibility of a wider implementation of this green technology under the hot and arid climate of Middle East by presenting several successful case studies of operating Constructed Wetlands facilities in the region for the treatment of various wastewater sources.

**Keywords:** constructed wetlands; hot and arid climate; wastewater treatment; industrial wastewater; municipal wastewater; sludge treatment wetlands; Middle East

## 1. Introduction

Drylands, i.e., areas with low fresh water availability, cover approximately 45% of the Earth's terrestrial area and are further classified as hyper-arid (5.9%), arid (14.2%), semi-arid (16.4%) and dry sub-humid (9%) areas [1]. Among them, the Middle East region, i.e., the region extending from the southern and eastern shores of the Mediterranean Sea (e.g., Egypt) to the Arabian Peninsula and Iran, is among the driest areas and the most water-stressed region in the world. The average annual temperatures at sea level reach 25 °C and exceed 30 °C during summer months, with the annual precipitation being limited below 250 mm, and in many desert areas, being as little as 50 mm [2]. Most of the countries in the region are classified as arid or hyper-arid areas, being in extreme freshwater scarcity [1–3], while all countries in the region will enter that group by 2050 [4]. Although the region population represents more than 5% of the global population, the available freshwater resources are less than 1% of the world's freshwater resources (Figure 1; [5]). Most of the Middle Eastern countries already suffer from absolute water scarcity, i.e., their annual water supply from natural freshwater sources is below 500 m$^3$ per person to cover domestic, agricultural and industrial demand. Despite these facts, water demand in the region is increasing due to population growth, continuous urbanization and industrialization, and a growing agricultural sector, since many countries are running various long-term programs to diversify their economy and reduce their dependence on oil exports. As a result, freshwater withdrawal rate in the region is higher than the natural replenishment rate. In addition, climate change will further deteriorate this situation, as it is expected that annual precipitation will decrease, temperatures and evaporation rates will increase, and droughts will become more frequent in the region [5].

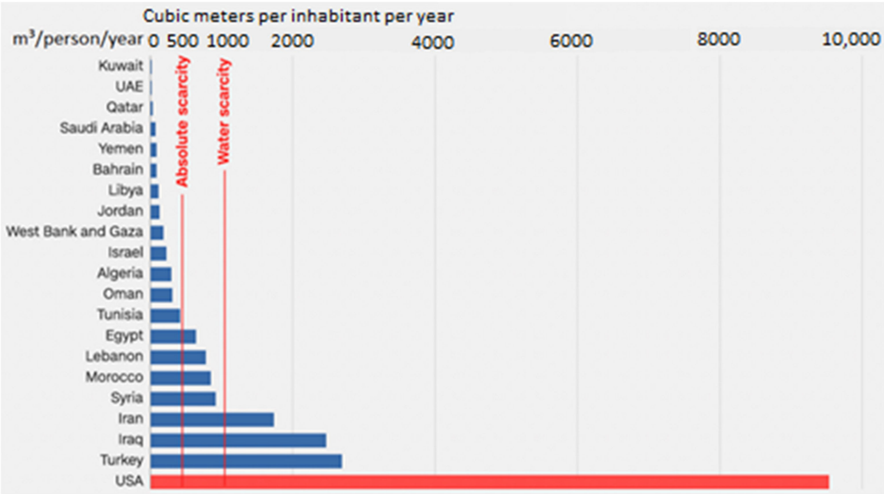


**Figure 1.** Naturally available freshwater resources in various countries in the Middle East and North Africa [2].

In addition, the over-abstraction and unsustainable use of groundwater resources occurring across the region of the Middle East and North Africa results in a lower aquifer water table and increased cases of sea water intrusion. In order to deal with these pressuring water-related problems, many countries in the region increased their efforts to identify other non-conventional water resources, such as desalinated brackish or saline water and treated wastewater, in order to close the gap between consumption and demand. Desalination has become a major supplement in the water supply; it is estimated that almost half of the global desalination capacity is installed in the Middle East, while some countries in the region cover more than 90% of their domestic needs with desalinated water [6]. However, this process is associated with a high negative environmental footprint since it demands a high energy input and the use of chemicals, while the generated brine is usually discharged into the sea, damaging the marine ecosystems.

Despite the apparent advantages, in most of the countries in the region, there is a lack of integrated wastewater treatment and reuse programs. Although there are few successful examples, the main issues have to do with improper treatment, illegal discharge of raw (untreated) wastewater into the environment, minimum reuse of treated effluents, limited innovation, lack of proper operation and maintenance, limited locally available expertise, among others. Hence, it is understood that a simple and easy technical solution that would also promote a more sustainable approach of wastewater management could boost the water/wastewater sector. Under this frame, the green technology of Constructed Wetlands (CWs) could be an appropriate technology to address the main issues in the wastewater sector in this region. This article discusses the main challenges of introducing and implementing CW systems in the Middle East and the opportunities that exist in the region for further development, while it also provides successful case studies of CW facilities for various wastewater sources in the Middle East region.

## 2. Challenges and Opportunities on Wastewater Treatment and Reuse in the Middle East

Groundwater resources in the region are utilized at a rate higher than their natural replenishment rate, resulting in a deteriorating water quality due to seawater intrusion. Groundwater pollution from domestic, agricultural and industrial activities also contributes to groundwater quality degradation. The problem is also enhanced by the limited sewerage coverage in most countries in the region [7] and the disposal of untreated or partially treated sewage in agricultural drains and other areas [5]. Sewage networks mostly exist in large urban areas, while rural or remote areas use septic tanks and cesspits. Thus, rural and remote areas in the region do not have access to wastewater treatment services or they are served by tanker trucks to collect and transport the wastewater to a centralized treatment facility [8], if available. For example, only 18% of urban areas of Iran are covered by a sewage network, while in Saudi Arabia (a country generally ranking better in the region), this coverage reaches 45% [9]. Centralized treatment is not an option for rural/remote areas with small and medium settlements due to various financial and technical barriers, which also means that a potentially valuable water source, i.e., treated wastewater, is not available in these areas where it is most needed (agricultural land). Typically reported figures on wastewater that is treated are often surprisingly high in some countries in the region, such as Oman, Sudan and Palestine [5], probably due to the limited wastewater volume that is collected and treated compared to the total wastewater generated volume. In many countries, the rate of collected wastewater that receives treatment does not exceed 1/3 of the total generated volume.

Overall, only approximately 40% of the region's wastewater is currently treated [6]. It is characteristic that the reuse of treated wastewater represents only 1% of the total water requirements in the region [5]. It is common that in most urban areas located near the coastline, wastewater is directly discharged into the sea (without any pre-treatment), as also is the case for partially treated wastewater [7,8]. It is estimated that the total production of municipal and industrial wastewater in the Middle East reaches 23 billion $m^3$ annually, of which only 1.6 billion $m^3$ is annually reused [5]. Particularly, in the richer, compared to the other Middle Eastern countries, Gulf Cooperation Council countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates—UAE), although 84% of the generated wastewater is collected and treated to secondary and tertiary stages, less than 15% of it is reused [10]. This again clearly indicates the high potential to further exploit this non-conventional water volume, adding in this way a new water source in the regional water balance.

Improper and insufficient wastewater treatment not only results in water resources pollution and degraded ecosystems, but also poses a significant public health risk. Of course, improperly treated wastewater is also not appropriate or safe for reuse, e.g., in agriculture. It is realized that the water and wastewater sector in the Middle East still lacks the necessary infrastructure. Although there are many moves towards opening this market to the private sector, most services related to water and wastewater management are still under the responsibility of governmental authorities and institutions. There are several factors that prevent further treated water reuse, such as social, technical and energy barriers and institutional and political constraints. At the political level, there is often confusion on who holds the responsibility for new initiatives, activities, and plans. The political structure usually does not allow for the involvement of other stakeholders, for example, from the local communities, while the multiple decision-making centers further complicate the process. In addition, the fact that typically, water resources (e.g., groundwater) are subsidized, does not promote public accountability for water use and conservation, since it is viewed as a cheap (i.e., underpriced) commodity [9]. Although in many cases, promising regulations are introduced, there is often a lack of enforcement and compliance.

The lack of an integrated water resources management further contributes to the mostly ineffective and weak institutional framework. In addition, social aspects and religious perceptions still cause some resistance towards the reuse of treated effluents, though reuse guidelines and legal standards are usually stricter than respective standards of the World Health Organization (WHO), especially regarding microbiological contamination. It is common that strict discharge standards are adapted following guidelines from developed countries [11], standards that are not only difficult but also expensive to reach, without considering the significant climatic, cultural and social differences. For example, typical five day Biochemical Oxygen Demand ($BOD_5$) concentration in raw wastewater can be up to five times higher than in western countries. It is characteristic that the WHO reuse limit for *Escherichia coli* (*E. coli*) or fecal coliforms, i.e., 1000 colony forming units (CFU)/100 mL, has been adopted by a few countries only (e.g., Morocco, Bahrain, Palestine), while in many countries in the region, the adopted limit is lower, e.g., 2.2 in Saudi Arabia and Qatar (monthly average), 100 in Jordan and Abu Dhabi, 20 in Kuwait and Dubai, and 200 in Oman [2,12]. The same also counts for most heavy metals and nitrogen limit values for reuse, whereas an unreasonably high elimination rate of this valuable nutrient is required in most national standards in the region.

The lack of local technical capacities and expertise closes the cycle of barriers. The cost recovery in the wastewater management sector is lower than that for irrigation and drinking water supply. The requirement to reach the abovementioned high effluent standards represents not only a technical but also a financial obstacle. Many facilities across Middle Eastern countries are outdated. This leads to poorly operated and maintained wastewater treatment plants. To this, the planning and financing of wastewater treatment plants in many cases does not consider the entire life cycle of such facilities. Often, authorities focus only on the investment required, without properly considering the maintenance and operation costs over 15–20 years, especially for conventional mechanical treatment technologies. This results in underperformed, overloaded facilities with frequent damages, a situation that is further magnified by the fact that most of these facilities are not operated by experienced and skilled staff. Subsequently, unplanned reuse that sometimes takes place reinforces the perception that treated water is of low quality and, thus, should be provided to end-users free-of-charge.

However, despite the diverse and multiple constraints, there is a continuous demand for water and sanitation services in the region. It is slowly but gradually realized at the institutional and policy level that the limited freshwater resources must be protected. Though there is still a lot to be done, major reforms and investments are planned for the following years to improve the combined performance of wastewater management plans, including sewage networks, treatment technologies and increased reuse of treated effluents. Local authorities are seeking, more frequently, experienced companies and external expertise, while public–private partnerships are already promoted, in order to deal with these challenges and share experiences and the required capital. In this context, this also translates to an opportunity to introduce effective treatment technologies. Particularly, given the nature of the problems in the region, sustainable solutions are required. Nature-based solutions (NBS) such as the natural treatment technology of Constructed Wetlands, can be an ideal option for wastewater treatment and management in the Middle East.

## 3. Implementing Constructed Wetlands in Hot and Arid Climates

### *3.1. Advantages*

The technology of CWs is not a new technological development. It is widely applied and established in central and western Europe, in north America and Australia, but it is rarely applied in the Middle East. However, this green technology has tremendous potential, especially under the climatic and social context of the region.

A complete sewerage coverage in the region is rather unlikely to occur, hence, there is an urgent need for decentralized solutions, considering also that most of the countries in the region have many small communities with populations of up to 2000 persons equivalent (PE). In general, centralized facilities using conventional treatment technologies have been mostly favored in the region by planners and decision makers, solutions that are typically energy intensive and costly to build and operate [13,14]. A universal application of such intensive technologies is not foreseen either, due to insufficient financial resources or due to a lack of technical and locally available expertise. Particularly for the small and medium communities, centralized solutions are not a sustainable solution from financial, environmental and social aspects [13]. On the other hand, the use of NBS as decentralized wastewater treatment systems appears nowadays as an appropriate alternative for small and medium agglomerations, even for peri-urban areas [15].

CW functions are based on natural materials and natural processes mediated by the interactions among the main system components, i.e., the substrate media, the plants, the wastewater and the microorganisms that naturally develop within the system [13]. Since in CWs, the use of non-renewable materials such as concrete and steel is limited, while the system is made of gravel, soil and plants, CWs possess a high in-country value. This means that most of the materials needed to build a CW can be sourced within the country, a parameter particularly important for reduced costs and the local/national economy as well [14]. The use of locally available resources and materials is crucial in the context of Middle Eastern countries, since there are many remote settlements, often isolated (e.g., in desert or mountainous areas). In this context, supply and logistics can also be an issue, especially in the case of conventional technologies, when most of the components are imported from other countries.

The high in-country value of CW systems is also consistent with the economic reforms that are undergoing in many countries in the region. Many countries are already running long-term programs to build a more diversified and resilient economy in the next 10–15 years, in which the development of national capabilities and local talent is a main target. Nowadays, in almost all of the related tenders in the water sector, the in-country value of a proposed solution is one of the key criteria in the decision-making process. Therefore, the technology of CWs and the associated high in-country value fits well with the vision developed in most countries in the region towards building effective and resilient supply chains and a network of local sourcing of goods and services.

In addition, CWs are, in general, a cost-effective solution with lower overall costs, especially for the operation phase of these treatment facilities [14,16,17]. Until recently, and in many cases still today, the selection of treatment technology is mostly based on the investment required, without studying in depth the maintenance and operation needs and the related costs. This often results in underestimated budgets allocated for the operation phase of conventional treatment plants, which affects their long-term financial sustainability and impacts their technical performance as well (e.g., lack of proper maintenance, overused and outdated electromechanical equipment, etc.). On the other hand, CWs have a much simpler and easier, and practically almost autonomous, operation with minimum maintenance needs and typically without even the need for onsite permanent specialized staff. Practical experiences also indicate that the operational costs could be even up to 90% lower compared to a conventional treatment technology [14,17,18]. These are important aspects for the effective long-term operation of CW facilities and their high associated levels of technical and financial reliability.

Another specific feature of the Middle East context is the vast variability of population density. Dense settlements occur only in the few fertile areas, while the remaining land is lightly populated or even not populated at all (e.g., in the deserts). This means that land availability is usually not a major issue when a wetland solution is considered, which overbalances the higher area demand of CWs compared to conventional and intensified technologies. This is a major difference compared to other regions in the world, such as in most European countries, where land availability is often an obstacle for the implementation of a CW solution.

Moreover, from a technical point of view, the climatic conditions in the Middle East region are particularly favorable for the development of CW solutions. Generally, it is already known that higher temperatures have a positive effect on CWs performance, as numerous studies have indicated (e.g., [14,19–21]). The average annual temperatures are within the range of 15–25 °C and exceed 30 °C during summer months, hence, provide optimal conditions for many biological processes and biological activity by microorganisms [22]. For example, the optimal ammonification and nitrification temperature range is from 40–60 °C and 30–40 °C, respectively, while denitrification rates also increase with increased temperatures up to 60–75 °C [14,23]. Furthermore, the warm climate also favors plant metabolism and growth in wetland systems; for example, it is reported that many reed species tend to remain green almost throughout the year [13,24].

In addition, CWs can significantly contribute to sludge management and handling particularly in remote locations. Generally, sludge management generated at conventional wastewater treatment plants can be problematic. A typical solution applied in the Middle East is simple drying beds; however, this creates the problem of removing the dewatered sludge every one or two weeks from the beds and disposing it in order to apply fresh sludge. The removed sludge from drying beds does not have the appropriate quality for land application or reuse, if such an alternative is even considered. Here, the sludge treatment wetland design can provide an effective dewatering and management solution, minimizing the day-to-day labor needs and providing final biosolids of good quality [14,25,26]. In addition, the vertical flow (VF) CW design, which can receive raw sewage and mineralize the organic solids, can be another solution for decentralized integrated wastewater and sludge management [14]. This would avoid the current practice of collecting wastewater from individual household septic tanks, wherever available, and transporting sludge with tanker trucks to a centralized treatment plant. Considering the favorable climatic conditions (dry and hot) that enhance the related biological and dewatering processes, CWs can be an ideal alternative to this issue.

### 3.2. Challenges

Despite the various advantages of implementing CWs in arid and hot areas, there are also some important concerns. Under these climatic conditions, CW functions may be altered compared to temperate and/or humid climates, which could potentially affect their expected ecosystem services. The main change in their behavior is the higher water losses via evapotranspiration (ET) (which in some cases, can even exceed 40%), i.e., evaporation and plant transpiration, which alters the water balance in these systems and may result in increased salinity values. Water losses through transpiration are reported being higher than open water evaporation in wetland systems in hot and arid climates [27–32]. This means that, if treated effluent reuse is considered, water losses through ET should be minimized.

High ET rates can be limited through simple but important design modifications and considerations. A key parameter is the selection of those wetland plant species with the higher Water Use Efficiency (WUE) index, i.e., with smaller transpiration needs but with high biomass productivity. This means that a proper study of the available local wetland plant species should be carried out to determine their water demand, if such information is not already available, in order to determine the WUE index (i.e., amount of water used via transpiration per unit of dry matter produced) and compare different plants [33–35]. Moreover, the CW systems should also be designed with the smallest possible area footprint that would comply with the desired effluent quality. For this, systems with subsurface flow should be preferred than free water surface (FWS) CWs, due to the higher evaporation rates occurring in the latter ones. Among subsurface flow CWs, VFCWs should further be preferred than horizontal subsurface flow (HF) CWs, since the typical unsaturated VF mode has much shorter retention time than the HF one, hence a smaller footprint. Artificial aeration is another design that can significantly reduce the overall footprint on the system [36–38]. Moreover, smart control of hydraulic loads applied to CWs under such climates could also contribute, e.g., treatment of domestic/municipal wastewater and greywater in separate CW facilities designed for the specific effluent quality required. In addition, the warmer climate implies that higher organic loads can be applied compared to typical loads applied in temperate or colder climates, due to the enhanced microbial activity, as explained above.

The enhanced transpiration activity of wetland plants in hot and arid climates has also been reported to enhance nitrogen removal [32]. Plants absorb more water to cover their needs, resulting in respectively large volumes of replacement water and nutrients pulled down into the substrate, promoting this way the nitrogen uptake by plants and microbes [39]. This plant-driven control of wetland hydrology has been reported in several CW systems [40–44] and appears to be an important mechanism in arid areas that relocates additional nutrient amounts available for uptake and processing. It is also reported that it has the potential to replace more than 20% of the total volume of water overlying the above-ground biomass during hot, dry months [32,44]. However, considering the strict nutrient (nitrogen and phosphorous) effluent quality standards required for reuse in irrigation in many countries in the Middle East (as discussed above), the need for high treatment performances to reach these standards will always result in designs with a large footprint. Thus, the adoption of rationalized standards would also be a way to keep the area demand of CWs within reasonable ranges, thus, also limiting water losses through ET.

These imply that typically, a careful study should be carried out before the implementation of a CW project in an arid climate, in order to identify regional plant species that could be used and determine their water needs first in pilot-scale units. The combined investigation of different plant species and wetland designs would indicate the respective water losses per plant and areal footprint; hence, the optimum combination can be selected with the highest WUE, i.e., minimum water losses and area demand. This comparison can be expressed with a useful index called Water Demand of Treatment (WDT), i.e., the water demand to remove one gram of pollutant (L/g), calculated as the ratio of ET rate ($L/m^2$/day) to the pollutant mass (e.g., $BOD_5$) removal rate ($g/m^2$/day) [45]. Such a study would reveal the wetland design with the smallest WDT, i.e., the most water efficient design.

Another parameter that should also be considered in the plant species selection process is the annual plant cycle. Such information is not always available in literature, considering that the hot and arid climatic conditions may alter the behavior of plant species also found in temperate climates. A recent study in the Middle East region revealed that five common wetland plant species, i.e., *Phragmites australis* (Cav.) Trin. ex Steud., *Typha domingensis* Pers. *Schoenoplectus litoralis* (Schrad.) Palla, *Cyperus* spp., and *Juncus rigidus* Desf., present different growth characteristics and annual growing periods [24]. *Phragmites* and *Juncus* showed no die-back and remained green throughout the year. On the other hand, *Typha* and *Schoenoplectus* showed die-back signs after the summer peak (July) and their growth cycle was estimated at 18 and 20 months, respectively [24]. *Cyperus* also showed dieback signs in late summer, but it continued producing new shoots even during the die-back period and, thus, maintained a dense plant coverage. It is also interesting that among the tested species in that study, *Cyperus* and *Juncus* showed the highest above-ground biomass values, while the lowest were recorded for *Typha* and *Schoenoplectus* [24]. It should be mentioned that this study took place in FWS wetlands treating an oily water with relatively limited amounts of nutrients.

Another concern when implementing CW projects is the management of the produced plant biomass. Plant productivity is another parameter that should be considered and that can be measured if pilot tests are carried out. As explained above, plants tend to be more productive in the warm climate of the Middle East. This means that CW systems typically have a higher biomass production rate compared to temperate climates. There is not a rule of thumb regarding the frequency of harvesting of the above-ground biomass, but practical experiences from operating CW facilities implies that this should take place every 2–3 years. Particularly in FWS wetlands, the continuous accumulation and increasing density of plant biomass as well as the development of root mats, if not removed for many years, results in the gradual build-up of the rootzone and the decrease in the freeboard depth compared to the initial design. Such a situation might impact the hydraulic efficiency of the system and create short-circuiting of the flow within the wetland and jeopardize plants' health and treatment efficiency. Harvesting of the reed biomass is not a difficult task in small CW facilities; usually, this is done by isolating one cell at a time and letting it dry before the harvesting, which is typically carried out using light machinery such as an excavator or a bobcat loader. In larger systems though, harvesting is a challenge and a detailed program should be implemented, while special tailor-made equipment may also be used. The harvested biomass is typically disposed to landfills, but there are some ongoing or already carried out studies on the reuse of the reed biomass for compost production and in anaerobic digesters for biogas production.

Another frequently asked and reasonable question regarding CW systems in hot and arid climates is the risk of mosquito growth and odor development. One of the most effective ways to mitigate this risk is again the proper design (and construction) of the CW. As explained above, regarding water losses minimization, the FWS design should be avoided, if possible, since an open water surface would contribute to mosquito breeding and odor emissions. Hence, the VF/HF design with subsurface flow is preferred, since in these systems, the water level is maintained below the gravel layer surface. In any case, the system should be carefully operated so that no hydraulic problems occur, e.g., stagnant water in FWS wetlands or overflow above the gravel layer in VF/HF systems due to clogging [46]. As already mentioned, the plant species used in the CW system should also be selected based on their biomass production (i.e., lower rates are preferred), hence, systems with submerged vegetation are increasingly used over systems with emergent vegetation [47]. The proper design, construction and management of a CW system (e.g., wetland type, sloped embankments, bottom slopes, hydrological control, vegetation management etc.,) is always the main factor to control this nuisance and to avoid measures such as use of biological/chemical mosquito control agents [47,48]. Already in the planning stage of a CW, it is critical to assess mosquito populations before and after construction and during operation in order to determine the relative change in mosquito populations, especially as vegetation coverage increases. Such information is important for mosquito risk assessment and management strategies in CWs.

Finally, as a relatively new technology in the region, the implementation of CW projects should always consider local cultural, social and religious characteristics and taboos, besides physical factors such as the climate, water resources, and onsite conditions. For this, the main stakeholders for the introduction of a new CW system should be identified and involved in the project development, i.e., water authorities, future users of the treated effluent, private and/or public service providers, local governmental authorities, developers and investors, financing and research institutes, any community-based organizations, educational institutions, among others. For example, besides the legal barriers, e.g., where effluent reuse is not allowed in some areas, or the need to comply with a very high effluent quality, across the Middle East, there is often a resistance in reusing treated wastewater for irrigation due to cultural and religious reasons; however, a gradual change in the perspective and understanding of local and national authorities is slowly taking place, which is a crucial factor to drive a change in people's thinking. In any case, it is important to ensure that any new CW solution is understood and accepted by all involved stakeholders and decision makers; in this, the demonstration of successful full-scale projects can be a decisive parameter.

## 4. Selected Constructed Wetlands Case Studies in the Middle East

In this section, few successful case studies of full-scale CWs implemented in the Middle East have been selected and presented, as summarized in Table 1. Although it is difficult to estimate the number of CWs in the region, it can be stated with relative safety that this number is rather small. In many countries, this number can be even below 10, while in few others, there can be one or two dozens of pilot or full-scale CW facilities of various sizes. The presented case studies in this section have been selected based on two main criteria: the wastewater source and the CW design. The goal is to demonstrate that different wastewaters (municipal and industrial) and designs have been and can be successfully implemented under the specific climatic conditions of the Middle East.

**Table 1.** Selected Constructed Wetlands case studies in the Middle East.

| Number | Country | Wastewater Type | Concept Design | Flow ($m^3$/d) | Area ($m^2$) |
|---|---|---|---|---|---|
| 1 | Oman | Domestic | VF-VF | 120 | 1340 |
| 2 | Oman | Municipal | VF-VF-recirculation | 25 | 1040 |
| 3 | UAE | Municipal | VF-VF | 216 | 6300 |
| 4 | Oman | Municipal | VF-Aerated HF-UV | 350 | 2900 |
| 5 | Oman | Domestic | Aerated VF (single stage, compact) | 15 | 28 |
| 6 | Oman | Domestic | Septic tank-HF | 1 | 20 |
| 7 | Iran | Industrial (glass industry) | Settling tank-HF | 10 | 160 |
| 8 | Jordan | Municipal sludge | STW | 10 | 720 |
| 9 | Jordan | Municipal sludge | STW | 50 | 4000 |
| 10 | Oman | Municipal sludge | STW | 5 | 330 |
| 11 | Oman | Industrial (oily water) | FWS | 175,000 | 4.9 mil. |

### 4.1. Municipal Wastewater Treatment in Vertical Flow Constructed Wetlands

This section presents few successful projects using the two-stage VFCW system, also known as French VF wetland, a design widely used internationally [14,49]. Most of these wetland facilities are located in temperate climates and in some cases, in tropical (warm and humid) climates [50], but only few exist under arid and hot climates such as in the Middle East. The French system includes two stages of VF wetlands filled with gravel media at a depth of up to 1 m; typically, there are three parallel beds in the first stage and two parallel beds in the second stage, which operate with alternating feeding and resting periods [14,20,50]. This system receives raw wastewater that is applied onto the surface of the first stage beds without pre-treatment, thus, the organics solids are separated, dewatered, and stabilized in time [14,51,52]. Every day, only one cell is loaded with raw wastewater, which is applied at regular intervals across the surface of the bed through a feeding pipe network, in order to ensure uniform distribution of the organic solids in the raw wastewater [14].

Such a CW facility has been designed and constructed in Oman (Bauer Nimr LLC, Muscat) for the treatment of wastewater from workers' camps of oil production facilities in a desert environment (Figure 2; [51,52]). Most of the wastewater volume is transported to the wetland facility via vacuum tanker trucks and offloaded directly into discharge pits. This wetland system is designed to treat 120 $m^3$/d generated by 600 PE [51]. The first stage of three parallel VFCW beds operates with an alternating cycle, i.e., two days of feeding followed by six days of resting, while the second stage has two parallel VFCW beds. The net treatment area of the CW beds is 1340 $m^2$ (Figure 2a). All beds are filled with gravel and planted with native plant species (i.e., *Phragmites australis* (Cav.) Trin. ex Steud., *Typha domingensis* Pers. and *Schoenoplectus litoralis* (Schrad.) Palla) [51,52]. It is important to note that this area faces every year sand storms that result in the dust/sand deposition on the surface of the gravel layer. One practical and easy way to control this phenomenon is the installation of a textile fence (Figure 2a).


**Figure 2.** (**a**) A French Constructed Wetland in the desert of Oman consisting of two stages with VF beds and (**b**) the irrigation field for treated effluent reuse ([52]; Courtesy of Bauer Nimr LLC).

The raw wastewater ($BOD_5$ > 700 mg/L, Chemical Oxygen Demand (COD) > 1000 mg/L, Ammonia Nitrogen (NH4-N) > 40 mg/L, Total Phosphorus (TP) > 8 mg/L, Electrical Conductivity (EC) > 1000 µS/cm) passes through the first stage wetlands, and then, is pulse loaded onto the second stage using a passive dosing siphon (no electricity used). The treated effluent is reused for irrigation of an adjacent field with local native trees through a free-flow subsurface irrigation system (Figure 2b). In this way, the treated water remains below the soil surface, thus, preventing the risk of human contact with the treated water, while the need for a disinfection system is eliminated. The facility does not have any mechanical or electrical components, thus, ensuring secure, simple, and long-term operation with minimal running costs. This wetland has operated for more than five years and the treatment efficiency complies with the wastewater discharge Standard B (Oman Ministerial decision 145/1993), i.e., $BOD_5$ < 20 mg/L, COD < 200 mg/L, NH4-N < 10 mg/L, TP < 30 mg/L, EC < 2000 µS/cm, Total Suspended Solids (TSS) < 30 mg/L [51,52].

A similar pilot VFCW was built in 2017 for research purposes by Haya Water (the governmental wastewater management company in Oman) at the wastewater treatment plant of Quriyat town (Figure 3). This pilot facility has a capacity of 25 $m^3$/day, and a total wetland area of 1040 $m^2$ [53]. This pilot wetland is the typical two-stage French system modified with effluent recirculation to further enhance the performance in terms of denitrification according to the stricter Standard A (Oman Ministerial decision 145–1993), i.e., $BOD_5$ < 15 mg/L, COD < 150 mg/L, NH4-N < 5 mg/L, TP < 30 mg/L, EC < 1500 µS/cm, TSS < 15 mg/L.

**Figure 3.** Aerial view of the pilot French Vertical Flow Constructed Wetland in Quriyat, Oman consisting of two stages with VF beds and effluent recirculation ([53]; Courtesy of Haya Water).

Only a few other successful projects using the French VFCW design have been constructed in the region. Another example facility (Ingenieurbüro Blumberg, Bovenden, Germany) exists in Al Hamra, Ras Al Khaimah, UAE (Figure 4), serving a residential area of 100 villas with 800 PE, equivalent to an inflow of 216 $m^3$/day [54]. The four first stage VF wetlands cover an area of 2700 $m^2$ and the four second stage VF wetlands an area of 3600 $m^2$. The inflow quality (COD of 446 mg/L, $BOD_5$ of 175 mg/L, NH4-N of 33 mg/L, TP of 12 mg/L, TSS of 308 mg/L) is typical for this type of wastewater source, while the treated effluent (COD of 22 mg/L, $BOD_5$ of 7 mg/L, $NH_4$-N of 1 mg/L, TP of 0.4 mg/L, TSS of 5 mg/L) is reused onsite for irrigation of green areas [54].

**Figure 4.** Aerial view of the French Constructed Wetland with two stages VF beds in Al Hamra, Ras Al Khaimah, UAE ([54]; Courtesy of Ingenieurbüro Blumberg).

### 4.2. Municipal Wastewater Treatment in an Aerated Constructed Wetland

Although the French VF wetland is widely used for raw wastewater treatment (providing sludge accumulation and stabilization) or for secondary treatment due to its lower area demand compared to other CW designs, further reduction in areal footprint has been achieved with the use of aerated wetland systems. The design of aerated wetlands is one of the latest advances in wetland technology. By providing air from an external aeration source (e.g., a side blower), oxygen availability increases and the aerobic processes are intensified, which means that the system footprint can be significantly reduced while reaching higher removal rates of organic matter and nitrogen [14,36–38,52,55].

Aerated wetland technology is mostly developed under temperate and cold climates so far [38]. Considering hot and arid climates, the number of research ([56]) and full-scale systems is extremely limited. One of the first full-scale aerated wetland facilities in the Middle East is in operation in Oman (Bauer Nimr LLC, Muscat) since 2018 under desert environmental conditions [52,57]. This CW facility receives wastewater from an adjacent remote settlement related to oil and gas exploration activities at a flow rate of 350 $m^3$/day, equivalent to approx. 1800 PE (assuming a daily water consumption of 200 L/PE). The wastewater includes domestic sewage from the residential and accommodation areas as well as flows from offices and kitchen facilities.

This CW has a total treatment area of the facility is 2900 $m^2$ and consists of two stages; the first stage is a VFCW and the second stage is an Aerated Constructed Wetland (ACW) with horizontal subsurface flow (Figure 5; [57]). The VFCW is separated in three parallel cells and receives raw wastewater (after coarse screening), i.e., it acts as the first stage of the French system for sludge accumulation and dewatering. Therefore, the feeding strategy is the intermittent loading and comprises feeding (1–2 days) and resting periods (2–6 days) [20]. The ACW is a saturated bed operating with continuous aeration. Artificial aeration is provided through a network of aeration drip lines placed at the bottom of the bed (just above the high-density polyethylene (HDPE) liner) connected to a side-channel blower (one working, one standby). Step-feeding with a small raw wastewater volume (screened inflow) is also applied in the ACW to provide an additional carbon source for denitrification, a practice that has been found to improve treatment performance in HFCWs [58]. The first stage VFCW is planted with native common reeds (*Phragmites australis* (Cav.) Trin. ex Steud.) and the second stage is a polyculture planted with *Typha domingensis* Pers., *Schoenoplectus littoralis* (Schrad.) Palla and *Cyperus laevigatus* (L.) Palla [57]. Finally, the ACW effluent passes through an ultraviolet (UV) unit for disinfection [52].

The CW system is designed to meet the irrigation Standard A (Oman Ministerial Decision 145/1993), i.e., $BOD_5 < 10$ mg/L, $NH_4$-N < 5 mg/L, Total Nitrogen (TN) < 20 mg/L. The system achieves almost complete organic matter degradation and ammonia nitrification, mainly as a result of the high oxygen provided via the artificial aeration. Similar high efficiency is also reported in other studies with aerated wetlands in temperate climates [59–61]. It is also noticeable that high efficiency is achieved in terms of TN removal, indicating that denitrification also takes place in the system despite being highly aerobic, a finding reported elsewhere too [62–64]. This is also an indication of the effective step-feeding strategy that supplies organic carbon available as an electron donor for nitrate reduction and provides an energy source for denitrification microorganisms. The net CW area requirement for this design is one of the lowest (1.6 $m^2$/PE) applied to reach this effluent quality. This facility demonstrates that the aerated wetland technology can be applied under the arid and hot climate of the Middle East, making such designs more attractive for areas where space availability is limited (e.g., peri-urban areas; [15]).

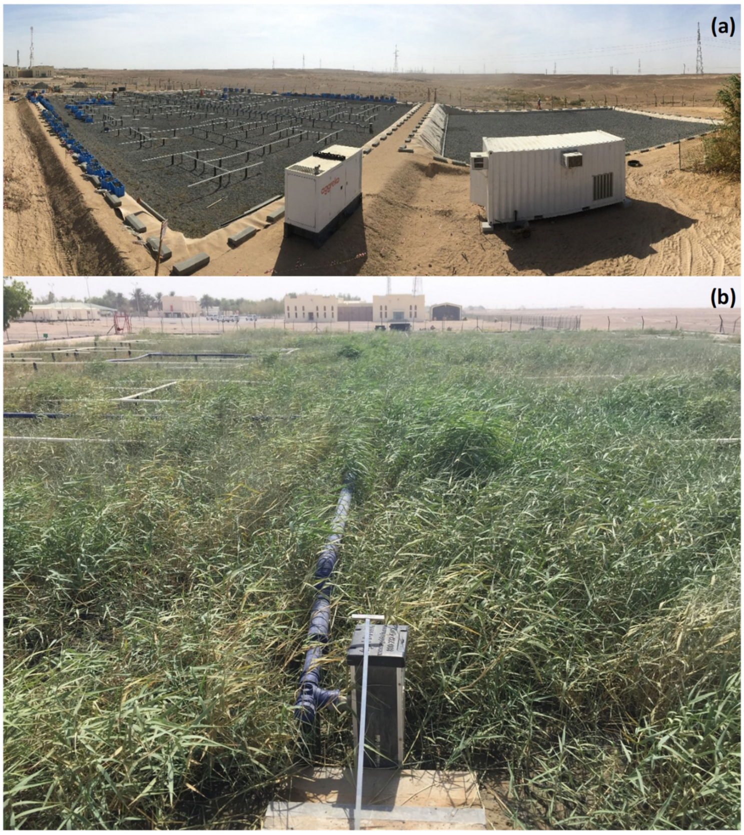


**Figure 5.** (**a**) Aerial view of the two-stage Constructed Wetland in Oman during plant establishment, comprising a first stage vertical flow CW and a second stage aerated horizontal flow CW, followed by UV disinfection, and (**b**) the first stage VFCW one month after initial planting ([57]; Courtesy of Bauer Nimr LLC).

### *4.3. Domestic Wastewater Treatment in a Mobile, Compact Aerated Constructed Wetland Unit*

The compact CWs are gaining attraction and few such designs have been adopted, e.g., using a passive VFCW for secondary [65] or tertiary [66] effluents or an aerated system for secondary effluents (e.g., the Phytocube, developed by Rietland, The Netherlands, and ARM Reed Beds, UK).

An innovative prototype compact and mobile CW design was developed in 2017 (Reedbox; Bauer Nimr LLC, Muscat, Oman) to receive raw domestic wastewater without pre-treatment [67]. The design is a VFCW combined with an aerated wetland in a single stage. Sludge is separated and dewatered on the filter media surface, as in the first stage of the French VF wetland, but the water level is maintained below the filter media layer, which is mostly saturated and aerated artificially. The filter media comprise of lightweight materials: the main layer is recycled HDPE, a material that was previously tested successfully for the first time in pilot wetland units for agro-industrial wastewater treatment [68], while a thin top layer of lightweight expanded clay aggregate (LECA) is also used [52,67]. The main structural element of this novel CW is a 12 m container (surface area 28 $m^2$), but a 6 m container can also be used for smaller volumes. It can serve a small population (up to 40 and 75 persons equivalent to 7 and 15 $m^3$/day, respectively) in areas where the public sewage network or a treatment plant is not available, such as in remote and isolated areas, which in the case of the Middle East would be remote industrial camps, small and medium settlements or oil rigs [67]. It can also provide an onsite wastewater treatment option for a block of flats, tourism facilities, hotels etc., as a compact system that can be easily installed without the need for permanent infrastructure [52].

*4.4. An Onsite Constructed Wetland for Household Wastewater Treatment*

A research and demonstration project was developed by the German University of Technology in Oman (GUtech) and the Research Council of the Sultanate of Oman in 2011 [69]; the EcoHaus project planned and built a net-zero-energy residential building on the GUtech campus [70]. The main goal was to identify locally adequate ways of building energy-efficient and sustainable buildings. The EcoHaus is a two-story house of approximately 250 m$^2$ surface, serving as the university's guesthouse. As part of this ecological approach, an onsite CW system was integrated in the project (Figure 6). The CW was designed to receive all sewerage (black and grey) water from the house and to provide a cost-effective and sustainable treatment so that the treated effluent could be reused for irrigating a garden or a green roof.

**Figure 6.** The demonstration unit for onsite wastewater management consisting of a septic tank and a horizontal flow Constructed Wetland at the EcoHaus project of the German University of Technology in Oman.

The design flow rate of the CW is 1 m$^3$/day, equivalent to 5 PE [69]. All wastewater from the EcoHaus flows with gravity into a covered septic tank (5 m$^2$) for primary treatment, i.e., settling of solids and flotation of fats and oils. The septic tank effluent overflows to a HFCW (15 m$^2$) by gravity. The water level in the HFCW is maintained approx. 5 cm below the gravel surface, thus, preventing odors and mosquito breeding. Initially, the wetland was planted with *Cyperus papyrus* (L.) Rikli plants. Unfortunately, the EcoHaus did not operate optimally for many years, since it was rarely in use and the plants died. However, in 2019, a replanting with local common reeds (*Phragmites australis* (Cav.) Trin. ex Steud) took place and the system was re-established with a regular inflow [69], while an irrigation field was also created for the treated effluent reuse in irrigation of local trees and shrubs. This demonstration wetland system at the GUtech has minimum energy consumption and maintenance requirements. It represents an excellent example of how wetland technology can be a green and simple solution for onsite wastewater management of single households in the Middle East region.

*4.5. Glass Industry Wastewater Treatment in a Horizontal Flow Constructed Wetland*

Industrial wastewater treatment with CWs represents specific challenges due to the complexity and varying pollutant composition and nature of these wastewaters [71]. Often, the approach to develop a wetland solution involves a first pilot phase, where different designs are tested in microcosms and optimized before their upscaling. This was the case with the glass manufacturing industry (Safety Glass Khorasan) in Mashhad, Iran, where a CW system was introduced to treat this industrial effluent [72]. The local climate is arid with annual precipitation ranging between 150–200 mm and average temperatures of 9 °C in winter and 28 °C in summer.

This project represents the first time where wetland technology was applied for the glass manufacturing industry, hence, it consisted of two phases: first an experimental unit was built, monitored and optimized, and then, the full-scale CW system was built based on the outcome of the experimental phase. The tested design consists of a sedimentation tank with two settling compartments and an integrated upflow filtration layer made of local natural cobbles to retain suspended solids and to promote natural flocculation of insoluble silica particles ($SiO_2$), followed by a HFCW. The wetland was planted with the indigenous pampas grass (*Cortaderia selloana* (Schult. and Schult. F.) Asch and Graebn.). The pilot system operated for three months. Once the operational parameters (e.g., hydraulic retention time, hydraulic loading rate, pollutants removal) were optimized, the full-scale wetland was constructed, treating 10 $m^3$/day of the industrial effluent (Figure 7).

**Figure 7.** The full-scale system of settling tank and a horizontal flow Constructed Wetland at a glass manufacturing industry in Iran for wastewater treatment and reuse (picture taken just after plants' establishment).

The settling tank and the HFCW surface areas are 9 and 150 $m^2$, respectively [72]. Pollutant concentrations in the factory effluent were on the average 127 mg/L $BOD_5$, 369 mg/L COD, 9650 mg/L TSS, 4 mg/L TN, 0.7 mg/L TP, and pH 9.5. As is obvious, the main challenges were the extremely high TSS influent concentration mostly made of silica particles (due to the nature of the glass manufacturing process) and the low nutrient concentration. The biodegradability ratio (BOD/COD) is around 0.34, which is low but not prohibitive for a wetland solution. The design proved to be highly effective with effluent concentrations of 13 mg/L $BOD_5$, 36 mg/L COD, 19 mg/L TSS, TN and TP < 0.5 mg/L [72].

The effluent quality not only met the Iran national standards for discharge to the sewer network but allowed for the reuse of the treated effluent in the glass manufacturing process, contributing this way to freshwater resources conservation in this water scarce region and reducing the operation costs for water and wastewater management for the glass industry.

### *4.6. Sludge Treatment Wetlands in the Middle East*

One of the first Sludge Treatment Wetlands (STW) in the Middle East was a pilot system built at the Al-Salt wastewater treatment plant in Jordan between 2011–2013, as part of the ACC (Adaptation to Climate Change) project "Decentralized Wastewater Management for Adaptation to Climate Change in Jordan" commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) in partnership with the Ministry of Water and Irrigation of Jordan and the University of Jordan [73]. Four previously unplanted drying beds of 160 $m^2$ area each were modified to STW beds receiving 8–10 $m^3$ of sludge from the conventional wastewater treatment plant [74] (Figure 8). After this demonstration phase, a STW system is currently under construction at Wadi Hassan in Jordan (Ingenieurbüro Blumberg, Bovenden, Germany) to treat 50 $m^3$/day of sludge with 3% dry solids content from an extended aeration wastewater treatment plant. The sludge loading rate selected is 70 kg ds/$m^2$/year and the area of the STW facility is approximately 4000 $m^2$.

**Figure 8.** The pilot Sludge Treatment Wetland beds at the Al-Salt wastewater treatment plant in Jordan [74].

A small STW was also built (Bauer Environment, Germany) at the Six Senses Resort in Zighy Bay, Dibba, Oman in 2010 (Figure 9). The goal of this project was the onsite sludge treatment to avoid transportation to a distant sludge treatment facility. This STW was designed to receive sludge from the conventional wastewater treatment plant of the resort at a rate of 5 $m^3$/day or 33 tons dry solids/year [52]. The treatment system has been in operation for more than eight years and is well integrated into the natural landscaping of the 5-star eco-tourism resort. No chemicals are used for the dewatering process, while energy is used only for sludge pumping and loading onto the bed. It is characteristic that the STW is located only 17 m away from the pool area of the resort and 70 m away from the villas and the hotel rooms, but no nuisance complaints have been received.

**Figure 9.** The Sludge Treatment Wetland at the Six Senses Resort in Zighy Bay, Dibba, Oman ([52]; Courtesy of Bauer Environment).

Another 2–3 STW facilities also exist in Bahrain, in UAE and in Qatar, however, with limited available information on their status [74]. In general, the use of CWs for sludge dewatering and drying in the region is extremely limited. However, the hot climate of the Middle East creates conditions favorable for the development of these systems, allowing for higher sludge loading rates to be applied due to higher ET rates and efficient airdrying, as also indicated by pilot STW units tested under a similar climate in Australia [75].

### *4.7. Oily Produced Water Treatment in a Surface Flow Constructed Wetland*

The oil and gas exploration and production activities generate one of the largest industrial wastewater streams worldwide. This water, also known as oily produced water, include contaminants such as residual hydrocarbons, salts and various organic and inorganic compounds (e.g., emulsion breakers, chemical additives, solvents, heavy metals etc.; [18]). Internationally, the most common management practice of oily produced water is disposal into deep wells [76], a practice that poses a significant environmental risk and is also energy intensive. Therefore, there is a need for a sustainable and cost-effective solution. The technology of CWs can provide a reliable ecological solution for the treatment of water contaminated with petroleum hydrocarbons, additives and phenols [61,77,78].

One of the largest CW systems is found at the Nimr oilfield in Oman, established for the treatment of oily produced water [18,78]. Deep wells are the common practice in that area for oily wastewater disposal. In 2008, the government oil company initiated the project for the design, building, owning, operation and transfer (Bauer Nimr LLC, Muscat) of a Constructed Wetland system. The facility started its operation at the end of 2010, with an initial treatment capacity of 45,000 $m^3$/day [18]. After three expansion phases (the last one completed in 2019; [79]), the treatment capacity increased and today reaches 175,000 $m^3$/day, a figure that represents more than 65% of the total oily produced water generated at that oilfield [52].

The climate in the area is a typical desert climate, with average air temperature increasing from January to June and exceeding 50 °C during the daytime, while precipitation is practically negligible. The treatment plant consists in 490 hectares of FWSCWs and 780 hectares of downstream evaporation ponds (EPs) (Figure 10; [52,79,80]), making it one of the world's largest commercial CWs. The oily wastewater is sent to the facility through a pipeline. The treatment train includes a first stage of separation and recovery of most (approx. 85%) of the oil content using a series of passive hydro-cyclone oil separators without the use of energy or chemicals. Then, the water is gravitationally distributed into the FWS wetlands via a long buffer channel, and the wetland-treated water flows downstream into the EPs [18].

**Figure 10.** Aerial view of the Constructed Wetlands and evaporation ponds for oily produced water treatment in Oman (Courtesy: Bauer Nimr LLC).

The FWSCWs are sealed with a bottom mineral layer made of locally available soil material in order to reduce the environmental impacts and costs associated to the HDPE liner. The wetland system is a polyculture planted with various local reed species (i.e., *Phragmites australis* (Cav.) Trin. ex Steud., *Typha domingensis* Pers., *Schoenoplectus litoralis* (Schrad.) Palla, *Cyperus* spp., and *Juncus rigidus* Desf.) to enhance the biomass production and the resilience of the ecosystem [18,78].

The inlet oily water is brackish, with total dissolved solids concentration exceeding 7000 mg/L [18,79]. Oil in Water (OiW) concentration is on the average close to 350 mg/L (in some cases, it exceeds even 500 mg/L), while nutrient concentration is low, i.e., TN and TP concentrations are lower than 2.5 mg/L [79]. The residual oil hydrocarbon concentration after the oil separation that enters the SFCW beds is biologically degraded, producing an oil-free effluent complying with the national standard (0.5 mg OiW/L; [18]). It has been found that the rhizosphere in the wetlands is rich in hydrocarbon-degrading bacteria [81], resulting in high rates of oil removal. The reed stems also act as a physical filter trapping floating oil, which is subsequently biodegraded by these microorganisms growing on the surface of the reed stems, roots and the soil surface.

This highly energy-efficient and reliable CW system practically converted a previously arid desert into a massive new ecosystem and habitat, demonstrating that CWs can be adopted to the hot and dry desert environment of the Middle East. Considering the close-to-zero energy demand of this CW system, the estimated total energy reduction exceeds 99% compared to the deep well disposal option [18], which also translates to significantly reduced greenhouse gas emissions (above 99%). At the same time, the large CW system in the desert provides a comfortable stop-over between Asia and Africa for more than 130 identified migratory bird species [80].

Furthermore, the effective treatment of the oily water opens the potential to reuse the treated water for irrigation. An initial research study was carried out in this wetland facility in Oman, where a research irrigation field of 22 hectares was established [18,82], and where various salt tolerant plants with market value such as biofuel, cotton, forage grass, among others, were tested. This research project provided significant information on the plant species that can survive under these specific harsh environmental conditions (water quality, climate) and yield a beneficial product. In addition, a compost trial that was carried out using the reeds biomass from the wetland beds as the main substrate showed that locally produced compost could be used in the irrigation field, closing, in this way, the waste materials cycle [52].

Another important aspect of this facility is the range of ecosystem services it provides. A study revealed for the first time that the presence of the CWs regulated the local microclimate; a 10 °C decreased temperature value was detected between the wetland body and a radius around the wetland of up to 1 km distance [83]. These first findings clearly indicate the positive effect a CW system can have on its surrounding environment, especially when implemented in a hot and arid area. The reduced temperature and the increased humidity also modify the local biodiversity and can reduce the energy consumption for cooling.

Wetland facilities like this large CW in Oman demonstrate in an emphatic way not only the technical feasibility and the high treatment capacity of wetland technology under the climatic conditions of the Middle East, but also prove in practice its sustainable character and present the various options provided by NBS for future transition to a circular water economy.

## 5. Conclusions

Wastewater treatment management in hot and arid climates remains problematic at large for various reasons. These areas suffer from extremely high freshwater resources shortage, which is typically covered through expensive and unsustainable desalination processes. Particularly in the Middle East, proper, effective and universal wastewater management faces several institutional, legal, technical, social and economic barriers. The green technology of Constructed Wetlands appears as an ideal sustainable wastewater treatment solution under hot and arid climates, such as in the Middle East, that can provide a feasible alternative to overcome these existing obstacles. Though there are still some challenges arising from the implementation of this technology, these can be sufficiently dealt with through proper design and construction. Constructed Wetlands are still not widely applied in the Middle East; however, there are already successful case studies for different applications (domestic, municipal and industrial wastewaters, sludge dewatering) in the region, that demonstrate not only the technical efficiency but also the sustainable character of this technology that can be easily adapted to such climatic conditions. Constructed Wetlands possess all the necessary credentials, proven even in large scale, to represent a feasible solution for wastewater treatment in hot and arid climates. They can also provide further options for beneficial reuse of the treated effluents and contribute to water conservation and climate change mitigation in water-stressed regions around the world.

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## Abbreviations

| | |
|---|---|
| ACC | Adaptation to Climate Change |
| ACW | Aerated Constructed Wetland |
| BOD | Biochemical Oxygen Demand |
| BMZ | German Federal Ministry for Economic Cooperation and Development |
| CFU | Colony Forming Unit |
| COD | Chemical Oxygen Demand |
| CW | Constructed Wetlands |

| | |
|---|---|
| EC | Electrical Conductivity |
| EP | Evaporation Pond |
| ET | Evapotranspiration |
| FWS | Free Water Surface |
| GUtech | German University of Technology in Oman |
| HF | Horizontal Flow |
| HDPE | High-Density Polyethylene |
| LECA | Lightweight expanded clay aggregate |
| NH4-N | Ammonia Nitrogen |
| NBS | Nature-Based Solution |
| OiW | Oil in Water |
| PE | Person Equivalent |
| STW | Sludge Treatment Wetland |
| TN | Total Nitrogen |
| TP | Total Phosphorous |
| TSS | Total Suspended Solids |
| UAE | United Arab Emirates |
| UV | Ultraviolet |
| VF | Vertical Flow |
| WDT | Water Demand of Treatment |
| WHO | World Health Organization |
| WUE | Water Use Efficiency |

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